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UNITED STATES DEPARTMENT OF AGRICULTURE, WASHINGTON, D. C.

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STRUCTURE, OCCURRENCE, AND PROPERTIES OF COMPRESSION WOOD

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CONTENTS

INTRODUCTION

The wood of each tree species varies with the environmental conditions under which the trees grow. Under certain conditions wood is formed that is distinctly abnormal in its structure and properties. One such type of abnormal wood is the so-called compression wood formed on the lower, or compression, side of branches and of leaning tree trunks of all coniferous species. Other names applied to compression wood are hard grain, timber bind, pressure wood, Rotholz (German), Druckholz (German), bois rogue (French), and tenar (Swedish).

The outstanding undesirable characteristics of compression wood are high and irregular longitudinal shrinkage, low strength for its

[1] Acknowledgment is made to various members of the Forest Products Laboratory for assistance in the preparation of this bulletin. The authors are particularly indebted to Arthur Koehler, in charge, Section of Silvicultural Relations, for advice and assistance in carrying on this investigation; to J. A. Newlin, in charge, Section of Timber Mechanics, for assistance in planning and analyzing the mechanical tests; and to A. L. MacKinney, Appalachian Forest Experiment Station, for growth data on loblolly and longleaf pine.

[2] Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

weight, and such excessive hardness that the wood often is difficult to nail and to work with tools. As the result of the foregoing undesirable characteristics, compression wood when manufactured into ordinary lumber is accountable for much bowing and twisting and is unsatisfactory for uses where strength and neat workmanship are essential requirements.

PURPOSE

The purpose of this bulletin is to present a discussion of the appearance, occurrence, and certain physical and mechanical properties of compression wood. With such information this type of abnormal wood may be identified and eliminated from those uses in which it is particularly disadvantageous. In addition, information is presented on the growth conditions under which compression wood occurs so that by suitable forest-management practices it may be possible to reduce materially the amounts of compression wood in many stands of timber.

APPEARANCE AND STRUCTURE OF COMPRESSION WOOD

GENERAL APPEARANCE

Typical compression wood can be identified in logs by the presence of markedly eccentric annual growth rings. In addition there are unusually large amounts of summerwood in the wider portions of the rings as compared with the narrower portions (pl. 1, *A*). In lumber, compression wood usually can be distinguished from normal wood by its relatively lifeless appearance which results from lack of contrast between springwood and summerwood. The summerwood of compression wood appears less dense and less hornlike than that of normal wood (pl. 1, *B*). In general, the annual rings are relatively wide although in many instances this alone does not distinguish compression wood from normal wood.

Dry lumber containing compression wood frequently is bowed or twisted out of shape or severely cross-checked by the excessive and uneven longitudinal shrinkage. Such pieces are easily distinguished during handling in the storage yard or the manufacturing plant, and as a result pieces containing the worst compression wood are either eliminated at the mill or dropped into the lowest grades that go into less-exacting uses.

Compression wood is ordinarily formed on the under side of inclined stems and of branches, although it may be found in the interior of vertical trees or even on the upper side of inclined trunks.

VARIABILITY

Not only does compression wood differ from normal wood of the same tree or other trees of a given species, but it also varies within itself. In general, compression wood may be divided into two broad classes: (1) Pronounced compression wood, which is conspicuous and easily recognizable on sight; and (2) mild compression wood, which is not so easily recognized as being abnormal wood, but can be distinguished from normal wood by microscopical examination. Mild and pronounced compression wood blend into each other and mild compression wood blends into normal wood.

STRUCTURAL CHARACTERISTICS

In addition to the differences in the general appearance of compression wood and normal wood already mentioned, there are differences in the cellular structure, some of which are characteristic for the two types of wood. The lack of the relatively sharp line of demarcation between springwood and summerwood of the same annual ring of compression wood as compared with normal wood, is shown in plate 2, *A*. This is due to a gradual change in thickness of the walls of the fibers, or tracheids, of compression wood as compared with the more abrupt change in normal wood.

The greatest structural variations between compression wood and normal wood occur in the summerwood. The summerwood fibers of compression wood usually are nearly circular in cross section whereas those of normal wood are more or less rectangular. Intercellular spaces frequently occur in the summerwood of compression wood at the junction of four cells. Checks in the secondary walls of the cells are also found in the summerwood of compression wood. These may be seen when cross sections are examined through a microscope (pl. 2, *B*). In longitudinal views of the fibers the checks are spirally oriented with respect to the longest axis of the cell. Between the checks, especially in pronounced compression wood, minute striations are sometimes observed (pl. 2, *C*).

Spirally arranged striations and checks occur in wood freshly cut from living trees, as well as in wood that has been dried, and therefore are not due to shrinkage of the cell wall due to loss of moisture. Slitlike orifices in the bordered pits generally are found in both the springwood and summerwood of compression wood.

On a thin cross section of compression wood, as in plate 2, *B*, the summerwood fibers appear to rotate in a clockwise direction when focusing downward on them with a microscope. This apparition is due to the change in position of the spiral cracks in different optical planes through the section. The cracks when viewed in a longitudinal section (pl. 2, *C*) are inclined spirally like the thread in a right-handed nut; those appearing to be inclined in the reverse direction are seen from the opposite side in adjacent cell walls.

The secondary wall of wood fibers is composed of a large number of smaller elongated units called fibrils. These are inclined at an angle to the longest axis of the cells. This angle is referred to as the "slope" of the fibrils. The slope of fibrils is greater in the springwood than in the summerwood of both normal wood and compression wood. The slope of the fibrils is indicated microscopically by the orientation of the slitlike pit orifices, fissures, or striations in the fiber walls, already referred to, or by the angle of extinction in polarized light, all of which are similarly oriented when observed in the same wall.

The spiral thickenings that normally occur on the inside of the fiber walls of Douglas fir and a few other coniferous species are fewer in number and less distinct in compression wood than in normal wood. In pronounced compression wood they are confined almost wholly to the early springwood cells, whereas in normal wood they occur throughout the springwood and in the earlier formed cells of the summerwood. Their orientation has no relation to that of the fibrils.

The length of the tracheids in compression wood is generally less than that in normal wood. Compression wood tracheids in European spruce were found to be seven-tenths to eight-tenths the length of the normal wood tracheids (*8*).[3] The thickness of the cell walls of the summerwood of compression wood is approximately the same as that of normal summerwood, but the cell walls of the springwood in compression wood are slightly thicker than those of normal springwood. The cell cavities of compression wood generally are larger than in normal wood in both the springwood and the summerwood.

With the exception of the spiral thickenings the foregoing differences between compression wood and normal wood are general differences applying to all coniferous species. These differences are modified by growth conditions or species characteristics. For example, within the same or related species those trees that grow at a relatively slow rate produce compression wood with less definitely abnormal characteristics than those that grow more rapidly.

TABLE 1.—*Characteristics of wood structure in selected specimens*[1] *of mild and pronounced compression wood and in normal wood of various species*

Species	Type of wood	Shape of summerwood cells in cross section	Relative number of intercellular spaces	Relative number of spiral cracks in tracheids	Average slope of fibrils in tracheids		Average ring width	Average amount of summerwood
					Springwood	Summerwood		
					Degrees	*Degrees*	*Millimeters*	*Percent*
Douglas fir (*Pseudotsuga taxifolia*).	Normal	Rectangular	None	None	20.4	6.1	1.3	28
	Mild compression	Circular	Few to many.	Few to many.	26.1	19.9	1.7	39
	Pronounced compression.	do	Many	Many	34.4	22.6	3.8	53
Loblolly pine (*Pinus taeda*).	Normal	Rectangular	None	None	22.8	4.8	1.5	46
	Mild compression	Circular	Few	Many	30.9	23.1	2.8	49
	Pronounced compression.	do	Many	do	35.1	29.3	4.3	63
Ponderosa pine (*Pinus ponderosa*).	Normal	Rectangular	None	None	19.6	3.9	.8	18
	Pronounced compression.	Circular	Few to many.	Many	30.1	24.7	2.0	34
Redwood (*Sequoia sempervirens*).	Normal	Rectangular	None	None	23.9	8.3	.9	19
	Pronounced compression.	Circular	Many	Many	38.3	29.4	3.2	56
White fir (*Abies concolor*).	Normal	Rectangular	None	None	23.9	8.3	.9	19
	Mild compression	Circular	Few	Many	36.2	20.9	3.0	37

[1] Number of specimens varied from 5 to 10 for each type of wood.

Table 1 presents the structural characteristics of mild and pronounced compression wood in comparison with those of normal wood. These data were derived from selected samples within each species and do not necessarily represent averages for the species. They present a comparison of the compression wood and normal wood of the same tree. Although a direct comparison between species cannot be made because the data were derived from samples not in exactly the same relative positions within the mild or pronounced classes, nevertheless, it may be noted that pronounced compression wood generally has wider annual rings, a greater proportion of summerwood, and a greater slope of fibrils than normal wood. In addition, the summerwood fibers in pronounced compression wood are circular in cross section and are interspersed with intercellular spaces whereas those of normal wood are nearly rectangular and rarely have intercellular spaces. Mild compression wood is intermediate between

[3] Italic numbers in parentheses refer to Literature Cited, p. 31.

normal wood and pronounced compression wood in slope of fibrils, width of annual rings, and amount of summerwood. The number of the spiral cracks in the secondary walls vary little as between the two types of compression wood.

A comparison of the characteristics of the pronounced compression wood in loblolly pine (*Pinus taeda*)[4] with that in ponderosa pine (*P. ponderosa*) showed that the faster-growing species (loblolly pine) had a greater slope of fibrils in general and more intercellular spaces.

CHARACTER OF BENDING FAILURE

Failures of dry compression wood in bending as a beam are distinctly different from those of normal wood. Compression wood almost invariably has a brittle fracture, oftentimes in the form of a wide Y, whereas the fracture of normal wood usually is splintering. Occasionally the failures of compression wood have short, coarse splinters that form a zigzag pattern (*16*). Figure 1 shows typical static bending failures of normal wood and compression wood of Douglas fir.

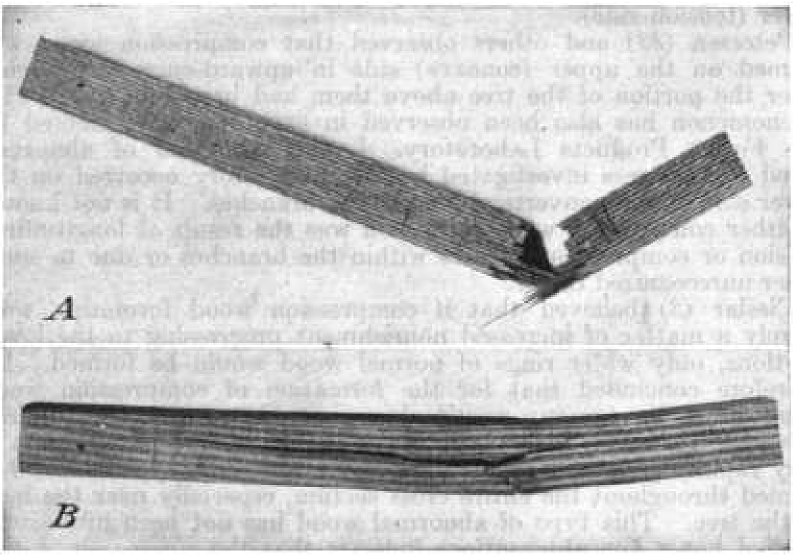


FIGURE 1.—Typical static bending failures of normal wood (*A*) and compression wood (*B*).

CONDITIONS UNDER WHICH COMPRESSION WOOD IS FORMED

Various authors (*2, 7, 13*) have reviewed the literature regarding the causes of the formation of compression wood. The theories most generally advanced are that compression wood occurs as the result of locally increased cambial activity due to (1) stimulation by longitudinal compression stresses and (2) stimulation by gravity.

Early workers recognized that this abnormal wood was found on the lower side of inclined stems and of branches and hence on the side under compression stress. Undoubtedly these observations gave rise to the name "compression wood" that is commonly used in the United States. Hartig (*8*) maintained that compression wood was

[4] The names employed by the Forest Service (*26*) for lumber and for trees from which it is cut are used throughout this bulletin.

a mechanical tissue arising as the result of longitudinal-compression stimulation occurring on the concave side of members bent by winds, by snow or ice accumulations in the tops, or by their own weight. At a later date he concluded (*9*) that gravity also acted as a stimulus, although in an unexplained manner.

Subsequently Burns (*1*), as a result of experiments, concluded that "the production of compression wood * * * seemed to be a morphogenic response to gravitation stimulus." Working with small white pine trees growing in containers he turned them on their sides so that the stems were horizontal and then pulled the stems sidewise at right angles to the force of gravity. Compression wood formed on the lower side of the stems, that is, at right angles to the direction in which the most important compression and tension forces were exerted. In other small horizontal white pine trees rotated 90° every 12 hours he found compression wood completely encircling the stems. When horizontal stems were bent upward by external force so that the lower side was under tension and the upper side under compression stress, abnormal wood was formed on the lower (tension side).

Petersen (*23*) and others observed that compression wood was formed on the upper (concave) side in upward-curving branches after the portion of the tree above them had been removed. This phenomenon has also been observed in experiments conducted by the Forest Products Laboratory. Later, formation of abnormal wood in the trees investigated by the Laboratory occurred on the lower side of the nonvertical portions of branches. It is not known whether compression wood formation was the result of longitudinal tension or compression stresses within the branches or due to some other unrecognized factor.

Cieslar (*3*) believed that if compression wood formation were merely a matter of increased nourishment progressing to the lower portions, only wider rings of normal wood would be formed. He therefore concluded that for the formation of compression wood there must be present a stimulus, most frequently longitudinal stresses. However, it has been observed by the Laboratory that in very rapidly growing vertical conifers an abnormal type of wood is formed throughout the entire cross section, especially near the base of the tree. This type of abnormal wood has not been intensively studied but a few observations indicate that the summerwood tracheids, particularly, have a larger slope of fibrils than normal summerwood. In this anatomical characteristic as well as in some physical properties, this type of wood apparently resembles compression wood.

The foregoing investigations and observations indicate that the physiological reactions in trees that produce compression wood are extremely complicated. Possibly work on plant hormones in relation to their effect on growth will in the future afford explanations for these phenomena not understood at the present time.

EFFECT OF AMOUNT OF INCLINATION AND VIGOR ON COMPRESSION WOOD FORMATION

While it was known that compression wood formed in many leaning trees, casual observations had indicated that readily recognizable abnormal wood did not exist in all leaning trees. It also had been observed that trees of vigorous growth formed compression wood even though they were only slightly inclined, whereas others which leaned a considerable amount but apparently lacked vigor had not formed recognizable compression wood. Studies were therefore undertaken to obtain quantitative information on the effect of amount of inclination and vigor on compression wood formation.

Investigation of ponderosa pine growing in the Black Hills showed that trees with moderate lean (3° to 5°) which had recently formed compression wood had a rate of diameter growth more than twice as great as those of similar lean in which compression wood formation was not noticeable. Similarly, trees with pronounced lean (5.5° or more) not forming recognizable compression wood were nonvigorous and increased in diameter at a rate of less than one-fifth that of the trees which were forming recognizable compression wood.

The occurrence of recognizable compression wood in several hundred loblolly and longleaf pine trees showed further that both vigor, as indicated by rate of diameter growth, and deviation from an erect position were important factors in the formation of compression wood. Figure 2 shows that with approximately the same inclinations the

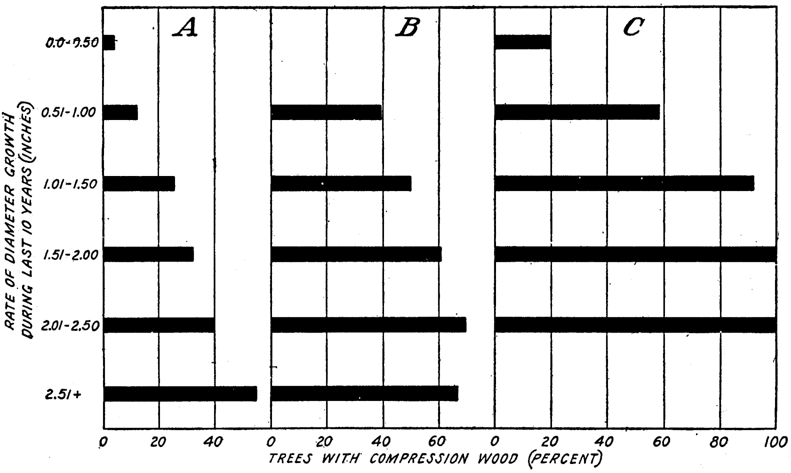


FIGURE 2.—Relationship of rate of diameter growth and various amounts of lean to percentage of trees having compression wood. Loblolly and longleaf pine, North Carolina and South Carolina: *A*, Slight lean; *B*, moderate lean; *C*, pronounced lean.

percentages of trees producing compression wood increased as the rate of diameter growth increased.

Trees that leaned slight amounts (0.5° to 2.5°) or moderate amounts (3° to 5°) had not all produced readily recognizable compression wood during the 10-year period investigated. In many instances a mild form of compression wood was identified by microscopical examination. Because the wood of these trees did not have the appearance of compression wood and the microscope revealed only slight variations from normal cellular structure, they were considered as having normal wood. It was in fact an intermediate gradation between normal wood and the mild compression wood previously described. Nearly all trees with pronounced lean, 5.5° or more, had formed compression wood during the last 10 years. Those that did not form compression wood showed evidence of extremely low vigor as is indicated by their slow rate of growth. In the trees with pronounced lean in which the compression wood was present, it was usually pronounced in character and consequently easily distinguished.

FACTORS RESPONSIBLE FOR INCLINATION OF TREE TRUNKS

The preceding paragraphs have pointed out that the amount of inclination is an important factor in compression wood formation. Factors that cause inclination of tree trunks therefore are important, especially in forest-management plans that look toward the reduction of compression wood formation.

In an uneven-aged stand, the smaller, suppressed trees are generally inclined toward openings in the crown canopy above them. Elongation of above-ground parts in general is reduced in direct light and increased in darkness and in diffused light. This phenomenon is explained as a phototropic response that retards elongation on the side toward the light, while the side away from the light continues to elongate at a faster rate thereby bending the top toward the light. Thus young trees developing under the crowns of overtopping trees almost invariably are inclined toward openings in the crown canopy. For the same reason, trees that arise from the same stump as sprouts or in close proximity to each other usually lean away from each other. This is especially true if they are approximately the same size.

Wind is another factor encountered in the lives of many trees that apparently is responsible for inclination of stems. Hartig (*8*) concluded that prevailing winds were responsible for the formation of compression wood in stands of spruce.

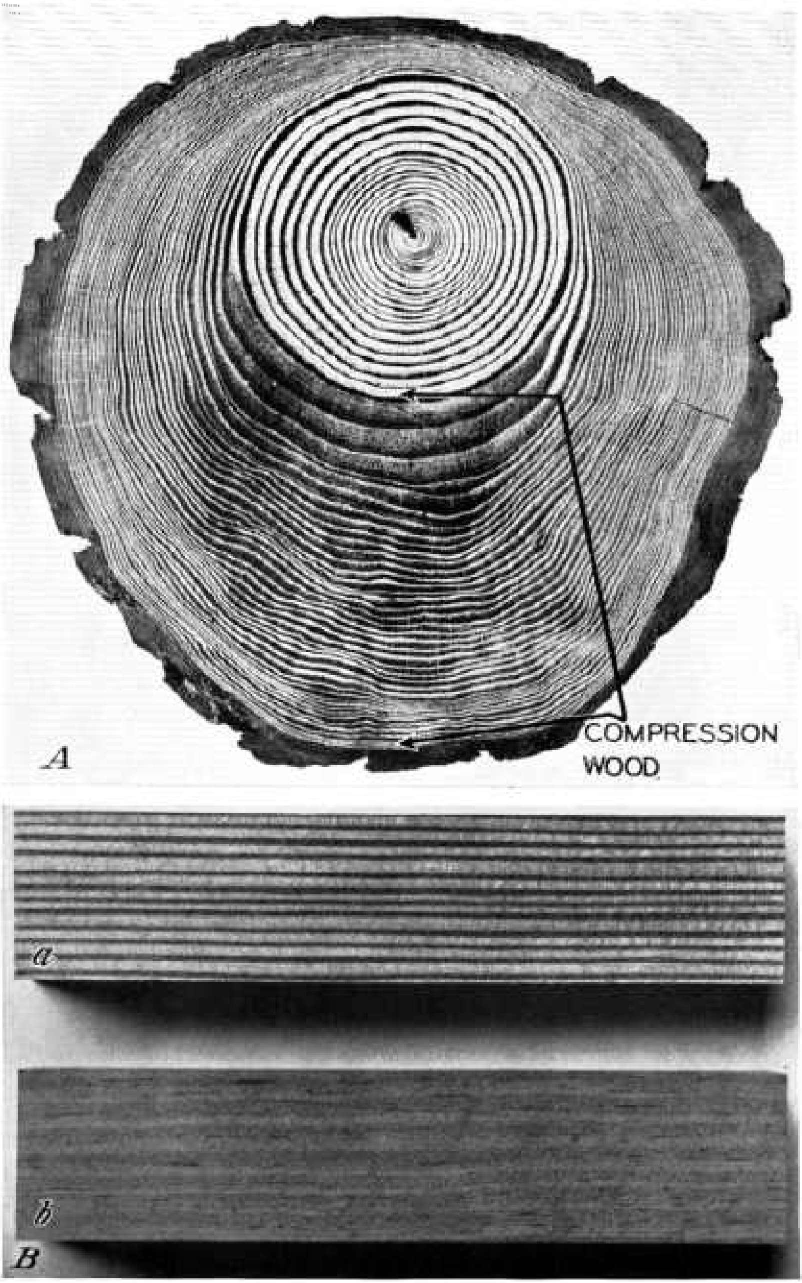
Violent storms have been known to bend young coniferous tops beyond the point where they would return to their original positions immediately after the storm had ceased (*25*). In other instances violent storms have been responsible for the partial uprooting of trees so that the whole trunks remained in an inclined position. Under such conditions compression wood is usually formed while the trees are in leaning positions.

Landslides, snowslides, and accumulations of snow in crowns, are known to cause trees to become inclined or bent over to a considerable extent. Plate 3, *A*, illustrates extreme bending in the lower portion of young trees as a result of snow loads. Falling trees, whether as the result of natural agencies or of logging operations, sometimes strike other trees and force them from their usual upright positions. Whether trees became actually tipped from the ground level up or bent beginning at some point above the ground level depends upon the security with which they are rooted, the shape of the bole, and the magnitude and point of application of the bending force.

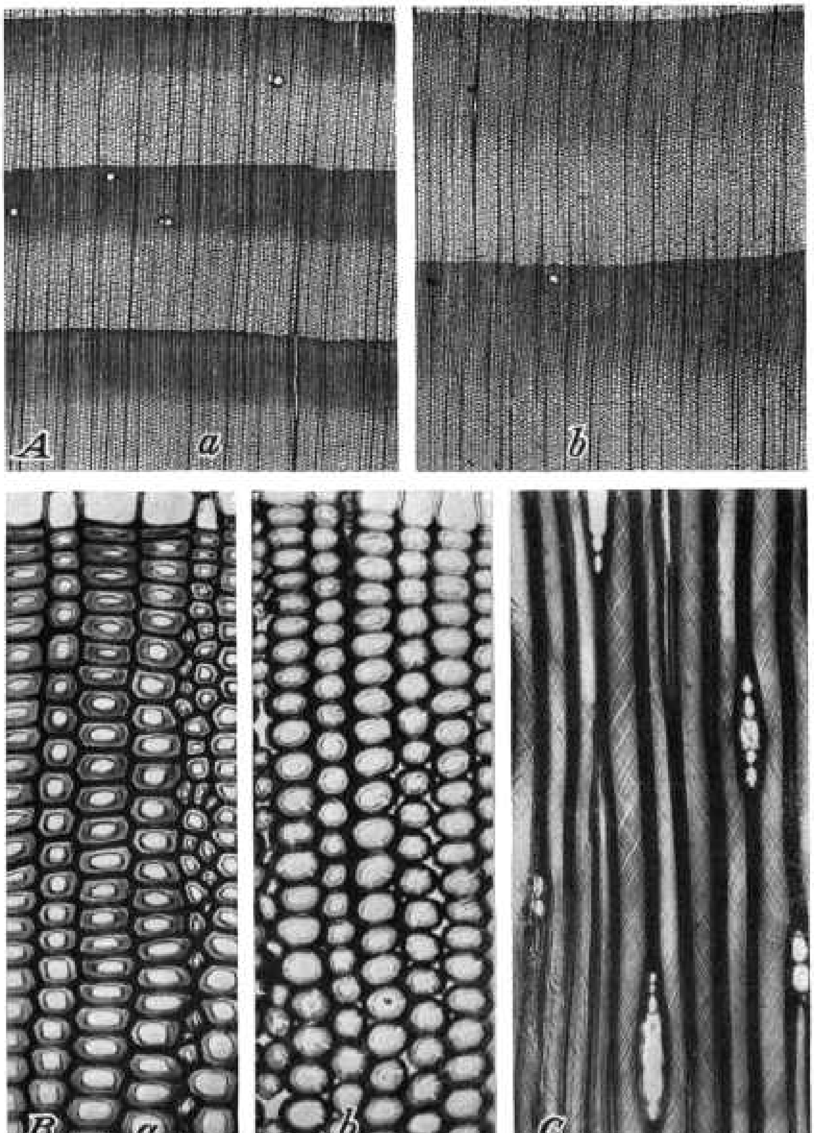
SPACING IN RELATION TO COMPRESSION WOOD FORMATION

Competition for light in well-stocked stands of timber, as previously mentioned, frequently is responsible for the inclination of some trees and the formation of compression wood in the inclined ones. Observations made in relatively young, even-aged stands indicate that the dominant trees are usually the straighter and that suppressed and intermediate trees are the more frequently inclined and crooked. As age advances and the suppression of the less vigorous individuals continues, it is the inclined trees, those in physical position to form compression wood, that are eliminated from the stand by natural suppression processes.

Overcrowding in young stands more frequently results in the formation of compression wood than does understocking, even though the trees in an understocked stand are more vigorous and are more sub-

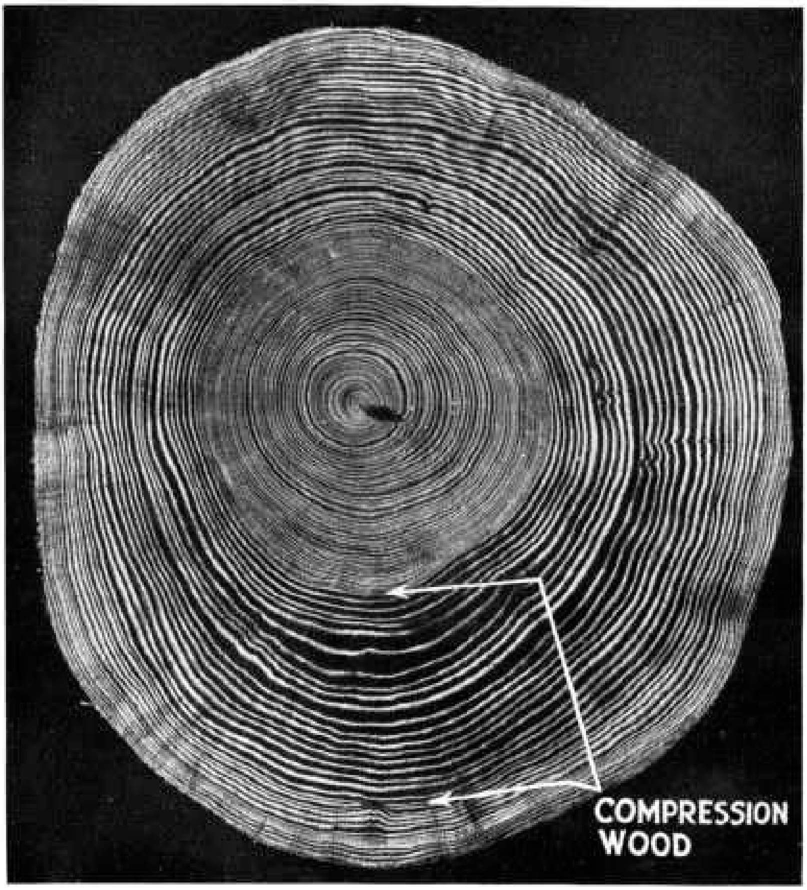


A, Cross section of a southern pine log with conspicuous compression wood. *B*, Small pieces of loblolly pine wood: *a*, Normal wood; *b*, compression wood, illustrating relative widths of annual rings and lack of contrast between springwood and summerwood, the latter being the darker layers.



A, Transverse sections of Douglas fir: *a*, Normal wood showing relatively sharp demarcation between springwood and summerwood of the same annual ring in comparison with *b*, compression wood in which sharp demarcation is lacking. The darker horizontal bands are summerwood. Photomicrographs × 20. *B*, Transverse sections of Douglas fir showing typical summerwood cells of (*a*) normal wood and (*b*) compression wood. Note checks in secondary cell walls, intercellular spaces, and circular cross-sectional shape of summerwood cells of compression wood. Photomicrographs × 250. *C*, Longitudinal section of Douglas fir showing typical summerwood cells of compression wood with spirally oriented cracks and striations in the secondary wall. Photomicrograph × 250.

Ponderosa pine trees in the Black Hills, South Dakota, showing various types of inclination: *A*, Young trees bent by snow loads with lower portion of stem arched upwards. Note up-turn of tip of tree in foreground. *B*, Tree with lower portion of trunk arched and upper portion straight, presumably due to tree becoming inclined while young with tip subsequently growing straight. *C*, Tree strongly inclined with straight trunk. This tree evidently became inclined late in life after lower part of trunk was too large to curve upward.



Cross section of a loblolly pine showing accelerated diameter growth and coincidental occurrence of pronounced compression wood following release by logging operation.

ject to wind forces because of their larger crowns. Investigations on about 150 trees show that young trees having their crowns free from competition with their neighbors formed smaller percentages of compression wood than did young trees grown in dense stands. This is believed to be the result of smaller percentages of inclined tree trunks in the open grown stands.

EFFECT OF RELEASE BY LOGGING ON THE FORMATION OF COMPRESSION WOOD

Observations in a partially logged stand of loblolly pine in Virginia indicated that, of the trees remaining, the percentage with compression wood increased in the years immediately after logging. During the period following logging the rate of diameter growth was markedly accelerated. As a result of these observations a study of the occurrence of compression wood was made on about 100 trees in a mixed loblolly and longleaf pine stand in South Carolina which had been logged over about 40 years previously and was again being logged.

The previous logging operations had removed nearly all the trees of merchantable size leaving only the smaller and nonmerchantable ones. Examinations at the stumps and at breast height at the time of the second logging indicated that the trees were for the most part 10 inches and less in diameter at breast height when the stand was first cut. This was determined by measuring the diameter of the wood formed before the logging operation of 40 years ago occurred.

The beginning of the new formation of compression wood in many of the trees coincided with the beginning of accelerated growth brought about by the removal of the surrounding trees (pl. 4). Some trees had formed compression wood previously to their release, but it nearly always became more pronounced after release had taken place. During the last 10 years some of the nonvertical trees, particularly those with slight or moderate inclination and nonvigorous growth, had ceased to form recognizable compression wood.

Figure 3 illustrates diagrammatically the percentages of trees that formed compression wood immediately before release, during the 20 years immediately after release, and during the last 10 years by lean classes as indicated by measurements made at the time the study was conducted.

Figure 4 shows that the average rate of diameter growth along four radii 90° apart during the 10 years immediately following release was about two and one-half times the rate before release and that during the four decades following release it had slowed down to about one and one-half times the rate before release. The trees increased in vigor following logging as a result of reduction of competition with surrounding trees. In addition, either logging damage or increased wind forces due to the opening of the stand presumably increased the inclination of some of the trees.

These data show that damage either as a result of wind action or incidental to logging, together with accelerated growth, is responsible for the increased percentages of trees with compression wood during the period immediately following release. Decreases in vigor of growth due to competition and in inclination due to the partial ability of tree stems to attain vertical positions probably are responsible for the decrease in the percentages of trees that formed compression wood during the last 10 years.

As previously stated the natural suppression processes remove many trees potentially capable of forming compression wood. Under natural conditions the suppressed trees that are inclined and crooked disappear as the stand approaches maturity. However, when

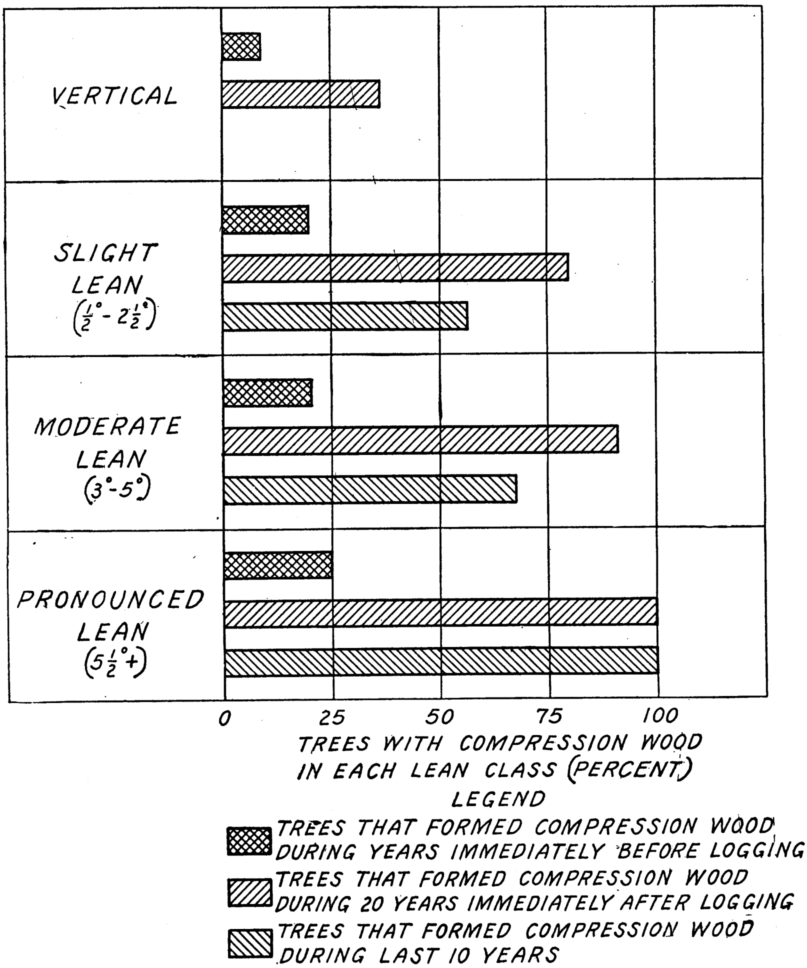


FIGURE 3.—Percentages of loblolly and longleaf pine trees by lean classes that had formed compression wood before and immediately after release by logging 40 years previously and during the last 10 years. Inclination determined just before felling.

removal of scattered trees occurs as a result of a commercial logging operation, it is usually the larger, more vigorous, straight-growing trees that are cut for forest products while the smaller, crooked, defective, and often inclined trees frequently remain. In addition, remaining trees may be inclined by damage incident to the logging operations. With natural suppression the crown canopy remains intact for the most part, whereas logging operations frequently leave large openings. Thus wind forces may become a more important factor in the future of a logged-over stand. The rate of growth following the natural removal of suppressed trees is not so markedly accelerated in the remaining trees as it is in those remaining after a commercial logging operation. The percentage of compression wood formed in trees, therefore, is expected to decrease as natural suppression processes proceed and to increase following the removal of trees by partial cutting operations as they are ordinarily conducted.

These data indicate the necessity, in partial cutting as a forest-management practice, of proper regard for such factors as removal of greatly inclined or crooked trees and the avoidance of large and irregular openings in the crown canopy in order that compression wood formation be held at a minimum. However, with reasonable precautions (pp. 29 and 30), it is believed that compression wood formation can be controlled within limits that reduce it to a relatively unimportant factor in timber production.

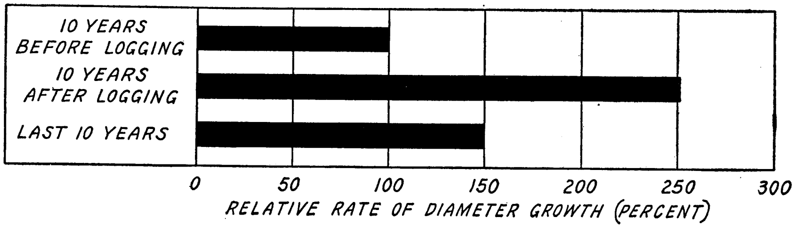


FIGURE 4.—Relative rates of average diameter growth during 10 years before logging a loblolly and longleaf pine stand, 10 years after logging, and the last 10 years before felling the trees. A period of approximately 40 years elapsed between the first logging of the stand and the felling of the trees here investigated.

OCCURRENCE OF COMPRESSION WOOD AT DIFFERENT HEIGHTS IN TREE

The factors responsible for the inclination of tree trunks may involve the entire length of the stem or only certain portions of it. Compression wood may be found along the entire length of the trunk or more commonly along limited portions of the trunk.

FORMATION AT ALL HEIGHTS

Relatively straight vertically growing trees may become inclined for their entire length (pl. 3, *C*) by mechanical agencies, such as wind, snow or landslides, and falling trees. When this happens compression wood forms on the lower side for all or most of the entire length of the stem, at least for a number of years after inclination. Poles and piling have been observed that showed compression wood on one side for most of their length in only one or two of the outer annual rings. It presumably resulted from recent inclination of relatively straight trees.

FORMATION IN THE LOWER PORTIONS

When straight trees have become inclined they do not necessarily retain their inclination through their entire length. Frequently the upper portions tend to assume vertical positions and new terminal growth nearly always is vertical. This is true of straight trees that are tipped by mechanical action as well as those bent as a result of the effect of light. The newly formed upper portions begin to curve upward very shortly after inclination has taken place. This is shown in plate 3, *A*, in which the tip of the inclined sapling marked with a piece of cloth in the foreground has curved upward. Sometimes, however, the upward curving is delayed when the newly formed portions are shaded from above by adjacent trees. The upward curving of inclined portions is explained by the fact that terminal portions of stems and branches of trees respond to geotropic influences as well as to phototropic influences (*5*, *6*, *21*, *27*), that is, they tend toward a vertical position unless other influences, such as shading from above, are more effective.

The upward curving tendencies are the greatest in the youngest portions of stems and branches. These tendencies may be so great as to cause distal portions of inclined stems and horizontal branches, up to approximately an inch in diameter, to curve upward (p. 6). As a result trees that have been inclined for many years usually have a gradual upward curve somewhere near the middle or lower part of the trunk. It has frequently been observed that the lower portions, usually one-fourth to one-third of the entire length of many trees, were inclined while those portions above often were practically vertical (pl. 3, *B*). In such instances compression wood formed in the inclined lower portions but was entirely absent or occurred in only a few annual rings near the pith in the lower part of the vertical portion.

Table 2 gives percentages of shortleaf pine (*Pinus echinata*) trees that formed compression wood at successive heights above the ground. The trees were growing in even-aged stands of three different age classes. In general there is a progressive decrease in the percentage of trees forming compression wood at successive heights.

TABLE 2.—*Percentage of trees containing compression wood at successive heights above the ground, shortleaf pine, Arkansas*

Height in tree (feet)	Stand 15 years old			Stand about 25 years old			Stand about 45 years old		
	Trees examined	Trees with compression wood		Trees examined	Trees with compression wood		Trees examined	Trees with compression wood	
	Number	*Number*	*Percent*	*Number*	*Number*	*Percent*	*Number*	*Number*	*Percent*
1 to 9	39	17	44	63	48	76	32	23	72
9 to 17	39	8	20	63	31	49	32	19	59
17 to 25				50	22	44	32	7	22
25 to 33				11	2	18	29	3	10
33 to 41							25	4	16

Further examples of the upward-curving tendencies of inclined stems have been observed in trees growing on steep slopes in mountain sections. Apparently young trees with insecure rooting often due to shallow soil on rocky, mountainous slopes are forced from their usual vertical positions to inclined positions by such factors as landslides or snowslides, or accumulations of snow in the crowns. Later they curve upward so that most of the stems are nearly at right angles to basal portions. Such trees are descriptively referred to as "pistol-butted trees" (*13*). In them compression wood is commonly found on the lower sides in the lower portions of the tree.

FORMATION IN THE UPPER PORTIONS

While many forest-grown trees are inclined from a point near the basal portions as a result of the action of mechanical agencies or the effects of light during the early life of the tree, some are inclined only in the tops. Investigations (*8, 25*) show that violent winds sometimes cause sufficient bending within the upper portions of tree stems to result in the formation of compression wood on the under side of the bent portion of the stem. An examination of many trees having inclined tops showed that compression wood was formed during the first growing season after inclination had occurred and usually throughout the next growing season, but in the wood formed at the end

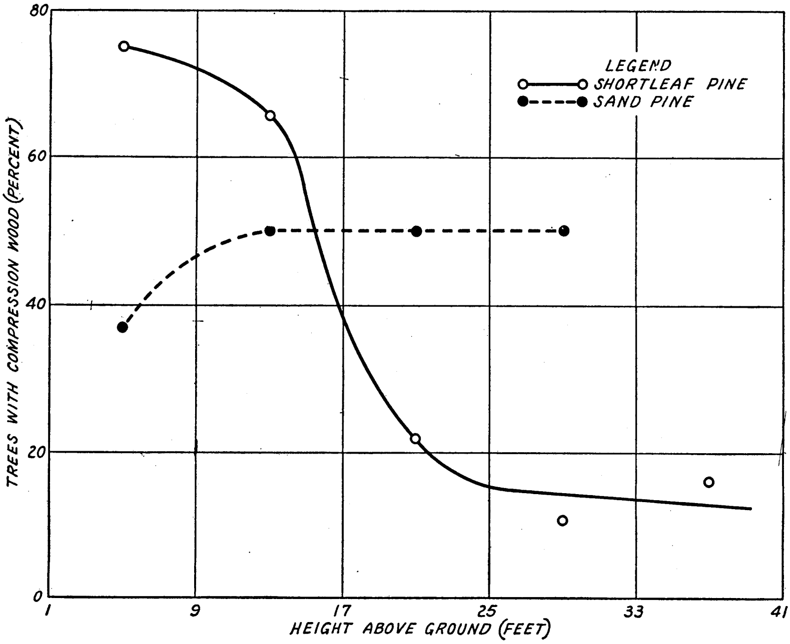


FIGURE 5.—Percentages of shortleaf pine and sand pine trees that had formed compression wood at various heights above the ground. The trees were about 45 years old.

of the following growing season compression wood was not present in most of the trees. The compression wood indicated that the tips of the trees had remained bent for most of one or two growing seasons, but that nearly all had regained an upright position by the close of the second growing season following the bending.

FORMATION IN CROOKED STEMS

Certain species of pines produce relatively straight stems whereas others, such as sand pine (*Pinus clausa*), and to a less extent pond pine (*P. rigida serotina*), usually are relatively crooked in their growth habits (pl. 5). An examination of the wood at various heights in the stems of sand pine showed that compression wood was found in about equal percentages in all portions of the entire length of the stem instead of being confined mainly to the lower portions as is the case in most coniferous species (fig. 5). Obviously, injuries may cause individual trees of any species to have crooked stems and consequently form compression wood throughout most of their length. Such individuals, however, are usually exceptional.

OCCURRENCE OF COMPRESSION WOOD IN THE CROSS SECTION OF STEMS

Just as compression wood occurs in various positions along the length of tree stems it also occupies various positions within the cross section at any height in tree stems.

OCCURRENCE NEAR THE PITH

The most common occurrence of compression wood in cross sections is within a few annual rings from the pith. Young stems less than 1 year to several years old are easily bent and therefore extremely subject to such factors as wind, growth, competition for light, pelting rains, and snow or sleet, all of which are known to cause inclination and subsequent compression wood formation. In general, compression wood near the pith does not extend farther radially than a few annual rings although it may continue for longer periods, even throughout the life of the tree. In mountainous sections small slender trees, 3 to 6 inches in diameter, that have been bent so that their upper portions are nearly horizontal commonly have compression wood on the under side of the stem. Though some trees may remain nearly horizontal for many years others gradually right themselves. An examination of many stumps of sugar pine, ponderosa pine, California red fir, and white fir in the Sierra Nevadas in California showed a frequent occurrence of compression wood within a few inches of the pith at stump height. In these same trees compression wood usually was absent near the pith at 30 to 40 feet above the ground, indicating that the upper portions of the trees had not been inclined. The compression wood at the base usually did not continue for more than a few years, indicating that the trees had returned to their normal positions. Since the rate of diameter growth had not lessened, decrease in vigor could not have been accountable for the discontinuance of compression wood formation.

In regions where heavy snowfall is uncommon, sleet or windstorms may similarly bend trees so that compression wood is formed. However, as previously mentioned, a common cause of inclination and compression wood formation close to the pith is competition for light, particularly in closely spaced stands. Plate 6, *A*, illustrates the occurrence of pronounced compression wood within a few annual rings of the pith.

FORMATION ALONG ONE RADIUS

In some instances as previously mentioned the formation of compression wood ceases after a few years, but in many others it continues throughout the life of the tree. It frequently becomes less pronounced toward the bark (pl. 1, *A*). Sometimes growth conditions are such that while the compression wood formation remains on the same side of the tree it becomes interspersed with apparently normal wood usually formed at a very slow rate (pl. 6, *B*). Under these conditions, regardless of whether the compression wood is continuous or intermittent, the tree must have been inclined in the same direction for the entire period of compression wood formation including the years of low vigor in which compression wood did not form (pp. 7 and 10).

FORMATION IN SEVERAL SECTORS

Occasionally compression wood occurs first in one sector and later in another of the same cross section. Plate 7, *A*, shows a cross section from a spruce tree in which compression wood was formed continuously in one sector for a number of years; later it was formed in the diametrically opposite sector of the tree. A period of approximately 5 years elapsed between the discontinuance of compression wood formation on one side and resumption on the other. What actually occurred in the life of the tree during these periods is unknown, but it may be surmised that during the 5-year period the direction of inclination in the tree was gradually changed. Other instances have been observed where compression wood has shifted from one sector to another at less than 180° to each other. Two or three such shifts occasionally have been observed in a single cross section.

Progressive shifting of compression wood formation from one sector to an adjacent sector has been observed in two trees. Plate 7, *B*, illustrates this unusual arrangement in which the compression wood appears as a coil on the cross section. The explanation of this peculiar phenomenon is at present unknown since the life histories of the two trees, one an Alaskan spruce (*Picea* sp.) and the other a California redwood (*Sequoia sempervirens*), are unknown.

OCCURRENCE IN OUTER LAYERS

Trees that become inclined by mechanical action will almost immediately begin to form compression wood on the lower side (*25*). Plate 8 shows a cross section of a large stem obtained within 1 or 2 years after it had been inclined. A thin shell of compression wood appears on one side.

OCCURRENCE IN BRANCHES

Since compression wood shrinks more longitudinally than normal wood (p. 16), dead branches on coniferous trees curve downward except in prolonged damp weather. The cross sections of branches of all coniferous species of trees are almost invariably eccentric and the lower sides are composed of compression wood. However, the characteristics of compression wood formed in branches varies with vigor of growth in the same manner as do the characteristics of that formed in the trunks. In the large branches of an open-grown tree very pronounced compression wood is formed while in the branches of a tree that grew in a dense stand the compression wood has much less pronounced characteristics.

PROPERTIES OF COMPRESSION WOOD COMPARED WITH THOSE OF NORMAL WOOD

CHEMICAL PROPERTIES

Comparative analyses of normal and compression wood of spruce and redwood show the lignin content of compression wood to be about 5 percent higher and the cellulose content about 8 percent lower than in normal wood (*4*). Compression wood of balsam fir is also reported (*11*) to have a higher percentage of lignin and a lower percentage of cellulose than normal wood.

Dense summerwood bands isolated from redwood compression wood have higher lignin content than do the springwood bands from the same annual growth rings (*4*). This difference is contrary to that generally found in the analyses of the springwood and summerwood of normal wood of any species.

PHYSICAL PROPERTIES

SPECIFIC GRAVITY

Specific gravity determinations (*1, 8, 27*) indicate that compression wood is usually heavier than normal wood. In a relatively lightweight species, like ponderosa pine, pronounced compression wood is on the average about 40 percent heavier than normal wood and in a relatively heavy species, such as loblolly pine, pronounced compression wood is on the average only about 15 percent heavier than normal wood (table 3). The specific gravity of the summerwood is usually lower in compression wood than it is in normal wood. This is explained by the fact that, whereas the cell walls in the summerwood of compression wood are approximately the same thickness as those in normal wood, the cell cavities are somewhat larger. Springwood of compression wood, on the other hand, is of higher specific gravity than normal wood (table 3), because the cell walls are slightly thicker in compression wood than in normal wood.

TABLE 3.—*Specific gravities of selected specimens of normal wood and of compression wood from the same trees*

Species	Average specific gravity					
	Several annual rings combined [1]		Springwood separately [2]		Summerwood separately [2]	
	Normal wood	Pronounced compression wood	Normal wood	Pronounced compression wood	Normal wood	Pronounced compression wood
Douglas fir	0.46	0.59	0.29	0.35	0.82	0.73
Loblolly pine	.52	.60	.32	.41	.85	.65
Ponderosa pine	.36	.50				
Redwood	.38	.51	.21	.43	.67	.70

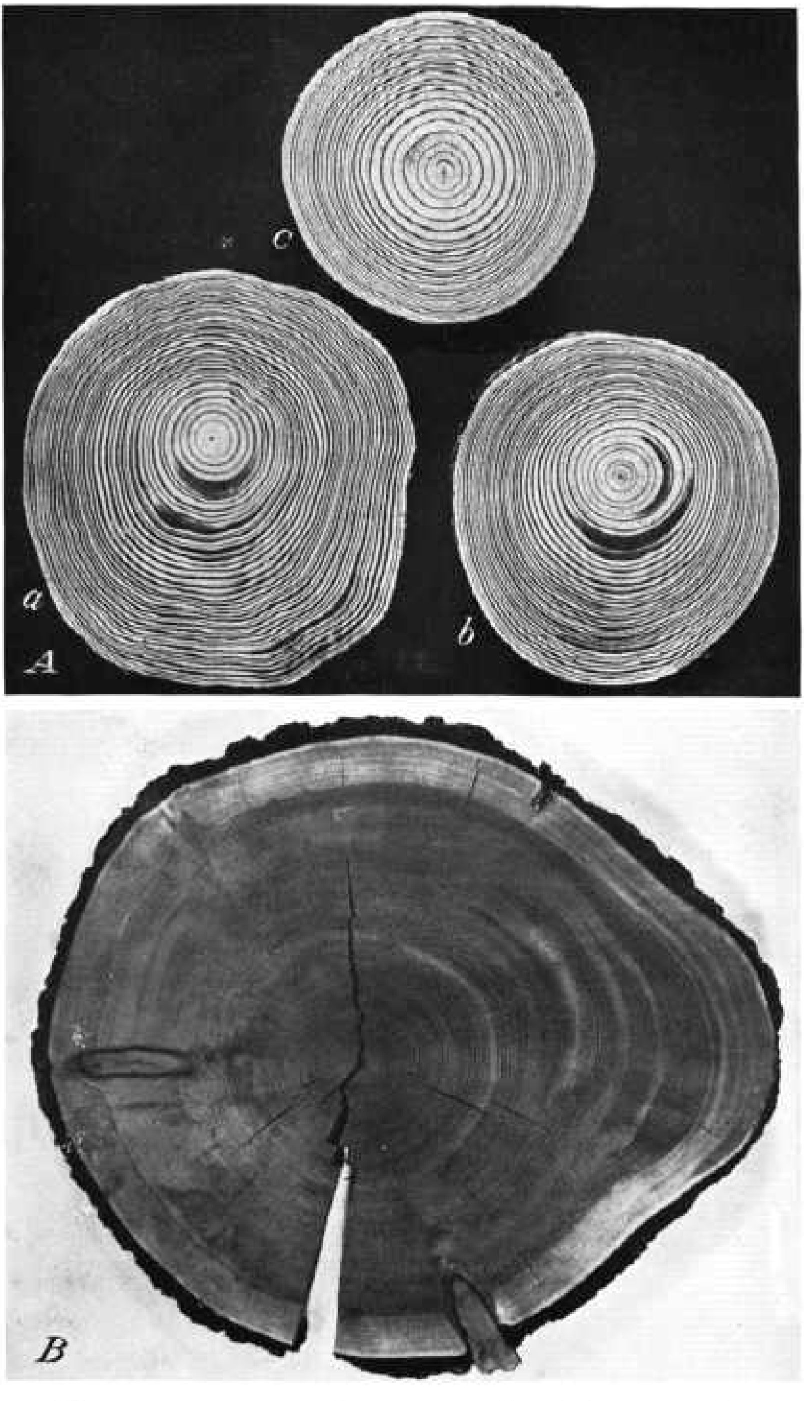
[1] Based on weight when oven-dry and volume when green.
[2] Based on weight and volume when oven-dry.

LONGITUDINAL SHRINKAGE

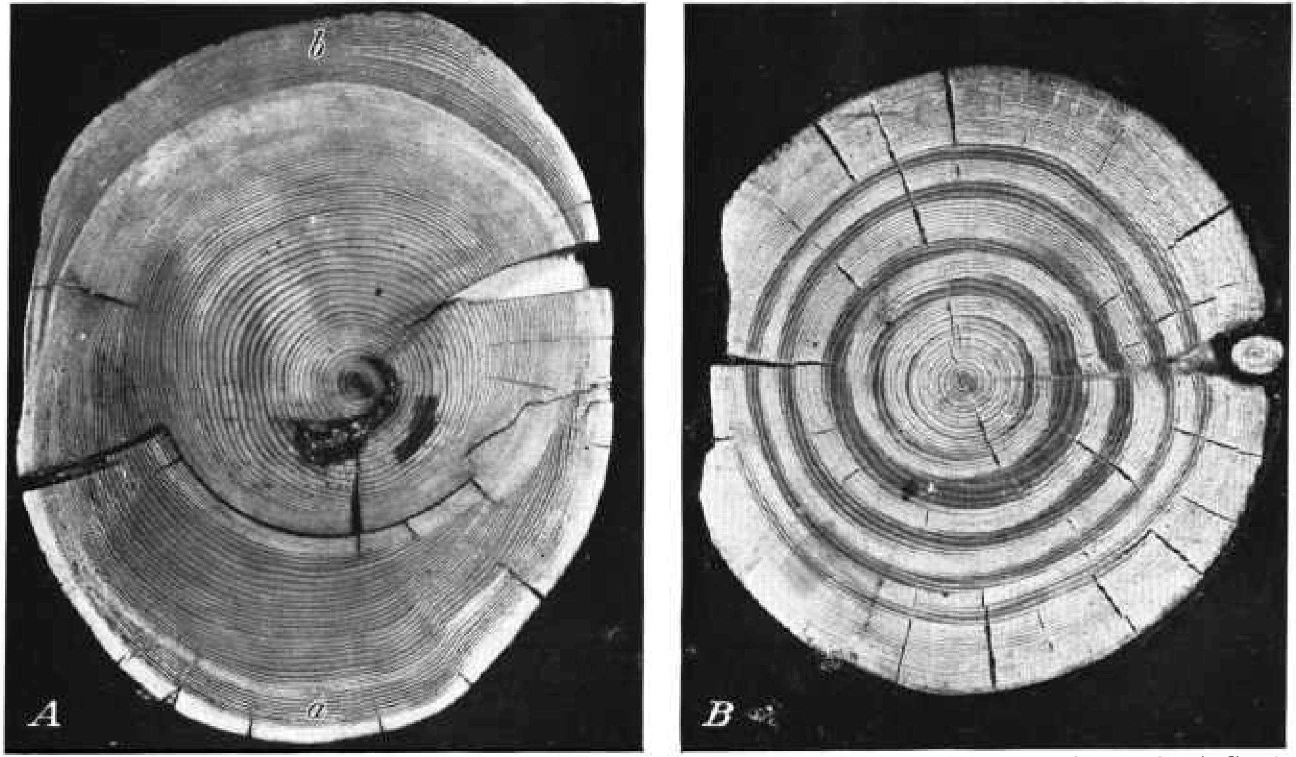
The loss of water from within the secondary cell walls is largely accountable for the shrinkage of wood. This water is principally held between the fibrils. As the water leaves the cell walls during drying the fibrils are drawn closer together with the result that shrinkage occurs mainly at right angles to the direction in which the fibrils lie. Cells that have the largest slope of fibrils with respect to the long axis of the cells therefore have the highest longitudinal shrinkage (*14*). Since compression wood has a large slope of fibrils its longitudinal shrinkage is correspondingly high.

The average longitudinal shrinkage of normal wood from the green to the oven-dry condition ranges between 0.1 and 0.2 percent (*15*). Variations in the longitudinal shrinkage of compression wood range from about 0.3 to 2.5 percent, although exceptional pieces containing

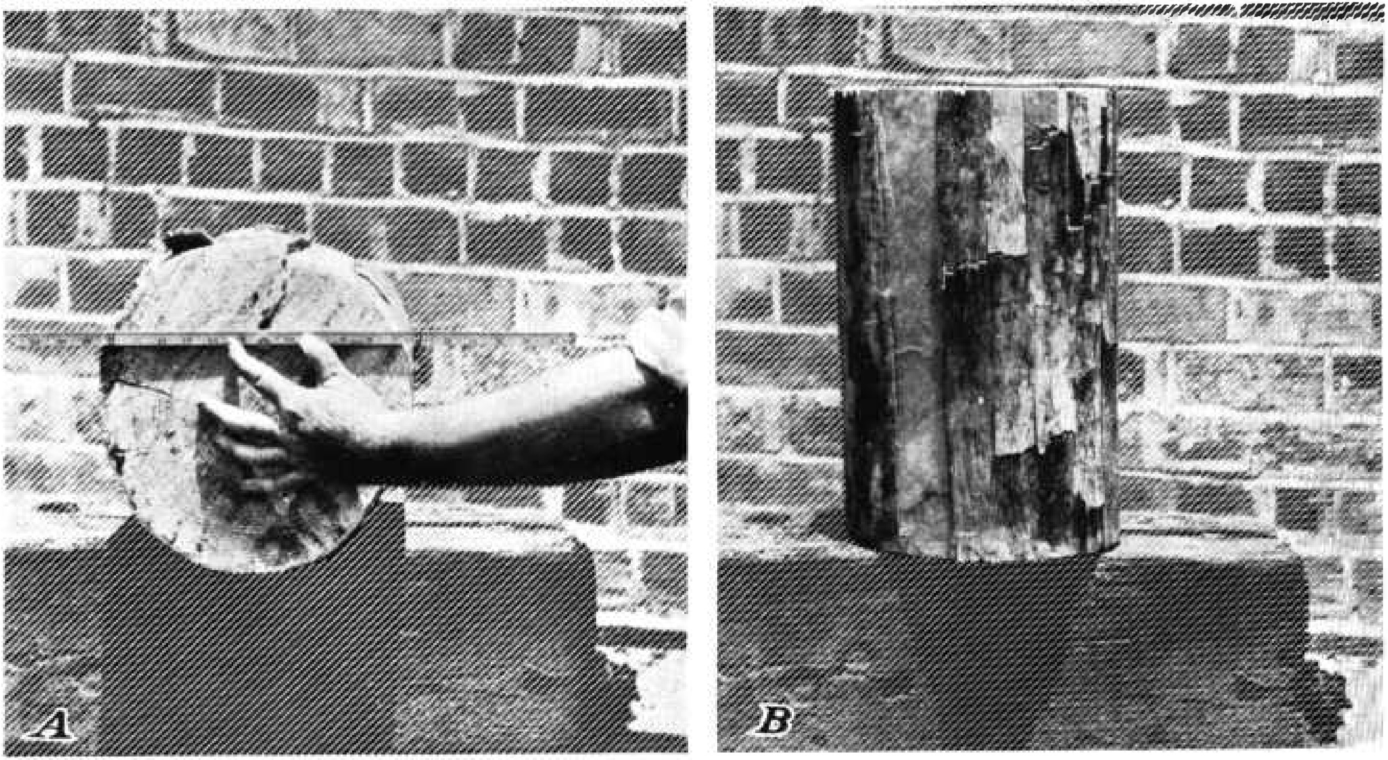
Sand pine stand (*A*) and an individual tree (*B*) showing relatively crooked and leaning growth characteristics.



A, Cross sections of a shortleaf pine showing pronounced compression wood formation close to the pith in *a* and *b* but no compression wood in *c*. These sections were taken 1, 16, and 30 feet above the ground level, respectively. *B*, Cross section of Douglas fir log showing compression wood interspersed with normal wood of much slower rate of growth.



A, Cross section of a spruce tree in which compression wood formed on one side (*a*), then practically ceased to form for 5 years, and then formed on the diametrically opposite side (*b*); *B*, cross section of a spruce tree illustrating progressive shifting of compression wood formation from one sector to an adjacent sector, thus forming a coil of compression wood.



Compression wood in the outer annual layer of a southern pine: *A*, Extent of the compression wood formed in the circumference is indicated by the arc above the ruler; *B*, characteristic shelling of the outer layer of the wood due to excessive longitudinal shrinkage of the compression wood.

very pronounced compression wood have been observed to have a longitudinal shrinkage as high as 5 percent. As a rule, the longitudinal shrinkage of compression wood is 2.5 to 13 times that of normal wood.

A board composed of both normal wood and compression wood has a low longitudinal shrinkage potential in one portion and a high one in another. One portion of the board therefore tends to shorten far more than another as the moisture content is reduced and as a result the piece usually becomes curved longitudinally. If deformation cannot take place, cross breaks may develop in the compression wood portion or longitudinal splits occur at the ends. The amount and character of deformation depends on the proportion of normal wood to compression wood, and the difference in the potential shrinkage of the two kinds of wood.

TRANSVERSE SHRINKAGE

Wood with relatively high specific gravity usually has greater radial and tangential shrinkage than wood of low specific gravity (*19*, *20*). Determinations of the transverse shrinkage of compression wood indicate that, although its specific gravity is usually higher than that of normal wood, its radial and tangential shrinkages are lower (table 4). Hartig (*8*) and Trendelenburg (*27*) also found the transverse shrinkage in compression wood to be lower than in normal wood.

TABLE 4.—*Average radial and tangential shrinkages of selected specimens of normal wood and of compression wood from the same trees*

[Shrinkages from green to oven-dry condition in percentage based on dimensions when green]

Species	Radial shrinkage					Tangential shrinkage				
	Normal wood specimens		Compression wood specimens		Ratio C/N	Normal wood specimens		Compression wood specimens		Ratio C/N
	Number	*Percent*	*Number*	*Percent*		*Number*	*Percent*	*Number*	*Percent*	
Douglas fir	6	3.4	8	2.5	0.74	5	5.9	7	4.2	0.71
Ponderosa pine	5	3.9	5	2.2	.56	4	6.4	10	5.1	.80
Redwood	5	1.5	5	1.4	.93	5	3.5	7	2.4	.69

MOISTURE CONTENT AT EQUILIBRIUM

The moisture content of compression wood averages slightly higher than that of normal wood (pp. 20 and 21) when at equilibrium with the same atmospheric conditions.

MECHANICAL PROPERTIES

Trees containing compression wood do not ordinarily have large portions of the bole composed entirely of this abnormal wood, and hence when such trees are cut into lumber many boards may be entirely free of compression wood while the remaining boards will contain varying amounts of this wood. Pieces of lumber composed entirely of compression wood are seldom found.

As previously indicated a piece of lumber containing both compression wood and normal wood will shrink with loss in moisture much more longitudinally in one portion than in another, resulting in bowing or distortion. The disadvantages encountered in service caused by the internal stresses set up in such material are not evident when testing the strength of small specimens under ordinary laboratory procedure. As a result, laboratory strength tests of small pieces are not a true index of the value of structural material containing both compression wood and normal wood. The cost, however, of collecting the material and testing specimens in structural sizes with varying amounts and types of compression wood is prohibitive. The results of tests given in this report are from small pieces of material composed entirely of compression wood or of normal wood. These tests give a very good idea of the inherent strength characteristics of these two types of wood.

Standard testing procedure calls for specimens 2 by 2 inches in cross section, but because of the difficulty encountered in obtaining specimens composed entirely of compression wood in this size, specimens 1 by 1 inch in cross section were used.

COMPARISON OF COMPRESSION WOOD AND NORMAL WOOD

Some of the mechanical properties of compression wood have been noted by various investigators (*1*, *8*, *10*, *16*, *18*, *27*) to be deficient, whereas others compare favorably with normal wood. Table 5 presents average results of strength tests made at the Forest Products Laboratory on small clear specimens[5] of normal wood and of compression wood of several species. Ratios of the strength of these two types of wood are given in both green and air-dry conditions.

Compression wood when tested green is as a rule higher in modulus of rupture, work to maximum load, total work, toughness, and maximum crushing strength parallel to grain, but lower in modulus of elasticity and tension parallel to grain than normal wood. Although the average of the toughness values of the five species is higher than that for normal wood actually some species are lower and others higher than normal wood. This property is very erratic and large differences are not surprising.

In general, high specific gravity in normal wood is indicative of high strength, but the greater weight of compression wood as compared with normal wood is not indicative of relatively higher values; in fact, in certain strength properties the values for compression wood are actually lower. When differences in specific gravity are considered green compression wood is, as a rule, lower in all properties except work to maximum load and total work. The values of these two properties are about those expected from the specific gravity.

Air-dried compression wood is usually higher than normal wood in modulus of rupture, work to maximum load, and maximum crushing strength parallel to grain, about equal in total work, but lower in modulus of elasticity and toughness. When differences in specific gravity are considered practically all mechanical properties of air-dried compression wood shown in table 5 are as a rule lower than normal wood.

[5] Static bending specimens, 1 by 1 by 16 inches, were tested over a 14-inch span center loading; compression-parallel-to-grain specimens were 1 by 1 by 4 inches; toughness specimens were ⅝ by ⅝ by 10 inches tested over an 8-inch span center loading; tension-parallel-to-grain specimens were ½ by ½ inch at the small central portion with an over-all length of 30 inches; and longitudinal shrinkage specimens ¼ by ¼ by 10 inches.

TABLE 5.—*Strength and related properties of compression wood and normal wood*

TESTED IN GREEN CONDITION

Species and type of wood	Number of specimens	Longitudinal shrinkage green to oven-dry: Percent	Longitudinal shrinkage: Ratio C/N	Moisture content[1]: Percent	Moisture content: Ratio C/N	Specific gravity[2]	Specific gravity: Ratio C/N	Static bending, Modulus of rupture: Pounds per square inch	Modulus of rupture: Ratio C/N	Static bending, Modulus of elasticity: 1,000 pounds per square inch	Modulus of elasticity: Ratio C/N	Static bending, Work to maximum load: Inch-pounds per cubic inch	Work to maximum load: Ratio C/N	Static bending, Work total[3]: Inch-pounds per cubic inch	Work total: Ratio C/N	Compression parallel to grain: Number of specimens	Maximum crushing strength: Pounds per square inch	Maximum crushing strength: Ratio C/N	Tension parallel to grain: Number of specimens	Tension value: Pounds per square inch	Tension value: Ratio C/N	Toughness: Number of specimens	Toughness value: Inch-pounds per specimen[4]	Toughness value: Ratio C/N	Deflection at maximum load: Inches	Deflection: Ratio C/N
Douglas fir:																										
Compression	74	0.67	3.94	43.3	0.74	0.513	1.20	8,010	1.18	1,016	0.74	14.88	1.92	34.44	1.83	74	4,150	1.27	3	10,880	0.79	45	182.2	0.98	0.68	1.51
Normal	69	.17	----	58.3	----	.428	----	6,780	----	1,369	----	7.77	----	18.79	----	66	3,280	----	4	13,850	----	29	185.0	----	.45	----
Normal wood values adjusted to correspond to specific gravity of compression wood[5]	---	----	----	----	----	----	----	8,940	.90	1,720	.59	12.40	1.20	29.68	1.16	---	4,120	1.01	---	----	----	---	235.5	.77	----	----
White fir:																										
Compression	33	.54	4.50	109.0	.58	.470	1.36	7,570	1.25	984	.83	14.42	2.23	46.63	2.45	33	3,580	1.29	---	----	----	22	140.8	1.09	.70	1.75
Normal	20	.12	----	187.1	----	.346	----	6,040	----	1,180	----	6.46	----	19.00	----	20	2,780	----	---	----	----	18	129.5	----	.40	----
Normal wood values adjusted to correspond to specific gravity of compression wood[5]	---	----	----	----	----	----	----	9,600	.79	1,730	.57	14.00	1.03	41.04	1.14	---	4,050	.88	---	----	----	---	270.0	.52	----	----
Loblolly pine:																										
Compression	21	1.60	11.42	77.2	.76	.584	1.13	8,490	1.04	919	.51	24.50	2.31	56.76	1.59	21	4,380	1.16	---	----	----	11	196.2	.78	1.07	2.33
Normal	8	.14	----	101.9	----	.519	----	8,170	----	1,804	----	10.59	----	35.69	----	8	3,760	----	---	----	----	6	251.4	----	.46	----
Normal wood values adjusted to correspond to spcific gravity of compression wood[5]	---	----	----	----	----	----	----	9,800	.87	2,100	.44	14.40	1.70	48.36	1.17	---	4,420	.99	---	----	----	---	335.0	.59	----	----
Ponderosa pine:																										
Compression	55	.80	3.81	87.5	.66	.467	1.32	6,120	1.32	842	.78	8.76	2.18	41.60	2.89	53	3,300	1.41	11	9,690	.82	50	173.4	1.72	.55	1.62
Normal	29	.21	----	133.3	----	.354	----	4,640	----	1,074	----	4.02	----	14.39	----	29	2,340	----	9	11,780	----	29	100.7	----	.34	----
Normal wood values adjusted to correspond to specific gravity of compression wood[5]	---	----	----	----	----	----	----	7,000	.88	1,510	.56	8.00	1.11	28.78	1.58	---	3,400	.97	---	----	----	---	209.0	.83	----	----

See footnotes at end of table.

TABLE 5.—*Strength and related properties of compression wood and normal wood*—Continued

Species and type of wood	Number of specimens	Longitudinal shrinkage green to oven-dry		Moisture content		Specific gravity		Static bending								Compression parallel to grain			Tension parallel to grain			Toughness			Deflection at maximum load	
								Modulus of—				Work														
								Rupture		Elasticity		To maximum load		Total			Maximum crushing strength			Value			Value			
		Percent	Ratio C/N	Percent	Ratio C/N		Ratio C/N	Pounds per square inch	Ratio C/N	1,000 pounds per square inch	Ratio C/N	Inch-pounds per cubic inch	Ratio C/N	Inch-pounds per cubic inch	Ratio C/N	Number of specimens	Pounds per square inch	Ratio C/N	Number of specimens	Pounds per square inch	Ratio C/N	Number of specimens	Inch-pounds per specimen	Ratio C/N	Inches	Ratio C/N
Redwood (virgin):																										
Compression	18	1.19	8.50	102.0	0.90	0.506	1.33	7,470	1.02	685	0.62	6.88	0.92	9.99	0.63	20	4,640	1.17	3	5,910	0.58	11	69.5	0.84	0.46	1.12
Normal	12	.14		113.7		.380		7,310		1,110		7.52		15.71		15	3,950		4	10,140		15	83.0		.41	
Normal wood values adjusted to correspond to specific gravity of compression wood [5]								11,200	.67	1,583	.43	15.35	.45	32.05	.31		5,800	.80					189.2	.37		
Redwood (second growth):																										
Compression	14	.49	2.88	57.8	.53	.494	1.39	8,660	1.32	1,126	.92	10 28	1.69	18.49	1.49	11	4,860	1.34				6	115.3	1.17	.48	1.30
Normal	9	.17		109.6		.354		6,550		1,221		6.07		12.40		6	3,620					6	98.5		.37	
Normal wood values adjusted to correspond to specific gravity of compression wood [5]								10,740	.81	1,845	.61	13.80	.74	28.15	.66		5,130	.95								

TESTED IN AIR-DRY CONDITION

Species and type of wood	Number of specimens	Shrinkage percent	Ratio C/N	Moisture percent	Ratio C/N	Specific gravity	Ratio C/N	Rupture psi	Ratio C/N	Elasticity 1,000 psi	Ratio C/N	Work to max. load	Ratio C/N	Work total	Ratio C/N	Number of specimens	Crushing strength psi	Ratio C/N	Number of specimens	Tension psi	Ratio C/N	Number of specimens	Toughness inch-pounds per specimen	Ratio C/N	Deflection inches	Ratio C/N
Douglas fir:																										
Compression	69	0.65	3.82	12.1	1.05	0.527	1.15	12,500	0.97	1,188	0.71	12.29	1.09	12.36	0.54	69	7,140	0.99	3	12,800	0.97	50	89.0	0.44	0.47	1.20
Normal	69	.17		11.5		.459		12,950		1,666		11.23		22.73		68	7,230		3	13,200		33	203.8		.39	
Normal wood values adjusted to correspond to specific gravity of compression wood [5]								16,000	.78	1,980	.60	15.90	.77	32.28	.38		8,600	.83					224.0	.40		
White fir:																										
Compression	33	.54	4.50	11.9	1.02	.509	1.36	12,700	1.21	1,108	.83	18.24	1.88	27.88	1.55	33	5,900	1.13				22	113.8	.98	.63	1.58
Normal	20	.12		11.7		.375		10,460		1,327		9.68		17.96		20	5,220					18	116.2		.40	
Normal wood values adjusted to correspond to specific gravity of compression wood [5]								16,600	.77	1,950	.57	20.90	.87	38.79	.72		7,500	.79					238.0	.48		

Loblolly pine:																										
Compression	17	1.15	8.22	11.7	1.05	.619	1.06	13,960	.88	1,156	.49	21.21	1.95	22.02	.67	17	7,200	.84	---	------	----	11	108.6	.63	.65	2.10
Normal	8	.14	----	11.1	----	.586	----	15,870	----	2,364	----	10.90	----	33.00	----	8	8,530	----	---	------	----	6	173.2	----	.31	----
Normal wood values adjusted to correspond to specific gravity of compression wood [5]	---	----	----	----	----	----	----	17,300	.81	2,540	.46	12.60	1.68	38.28	.58	---	9,180	.78	---	------	----	---	196.5	.55	----	----
Ponderosa pine:																										
Compression	56	.80	3.81	12.6	1.05	.499	1.34	11,710	1.19	1,019	.76	15.74	2.08	16.17	1.49	55	5,970	1.14	---	------	----	52	100.4	1.27	.59	1.69
Normal	28	.21	----	12.0	----	.372	----	9,840	----	1,345	----	7.56	----	10.82	----	29	5,210	----	---	------	----	29	79.2	----	.35	----
Normal wood values adjusted to correspond to specific gravity of compression wood [5]	---	----	----	----	----	----	----	15,300	.77	1,940	.52	15.70	1.00	22.50	.72	---	7,600	.79	---	------	----	---	182.0	.56	----	----
Redwood (virgin):																										
Compression	20	1.22	8.72	10.5	1.06	.510	1.34	8,890	.87	788	.63	6.51	1.08	8.11	.98	17	7,250	1.01	2	7,560	.85	12	64.4	1.00	.39	1.35
Normal	14	.14	----	9.9	----	.380	----	10,210	----	1,253	----	6.04	----	8.24	----	15	7,160	----	6	8,850	----	15	64.5	----	.29	----
Normal wood values adjusted to correspond to specific gravity of compression wood [5]	---	----	----	----	----	----	----	15,850	.56	1,810	.44	12.55	.48	17.14	.47	---	10,200	.71	---	------	----	---	124.3	.52	----	----
Redwood (second growth):																										
Compression	14	.49	2.88	9.9	1.11	.527	1.32	12,460	1.14	1,307	.92	9.26	1.34	9.56	.81	14	8,500	1.20	---	------	----	6	76.0	.84	.37	1.19
Normal	9	.17	----	8.9	----	.400	----	10,900	----	1,418	----	6.93	----	11.81	----	9	7,060	----	---	------	----	6	90.6	----	.31	----
Normal wood values adjusted to correspond to specific gravity of compression wood [5]	---	----	----	----	----	----	----	16,500	.76	2,006	.66	13.90	.67	23.62	.40	---	9,850	.86	---	------	----	---	------	----	----	----

[1] All air-dry specimens were kept together and subjected to same conditions. Moisture content of air-dry specimens at equilibrium with atmosphere at approximately 110° F. and 60-percent relative humidity.

[2] Based on weight when oven dry and volume green or at moisture indicated under air-dry condition.

[3] Total work is defined as the work absorbed to a 3-inch deflection or until the beam fails to support a load of 100 pounds.

[4] Toughness test specimens ⅝ by ⅝ by 10 inches, load applied at center over an 8-inch span.

[5] Values obtained by multiplying the normal wood strength value from test by the ratio of the specific gravity of compression wood to normal wood, this ratio first being raised to a power corresponding to that of the specific gravity strength equation for the property under consideration. The powers used were: Modulus of rupture, 1.5; modulus of elasticity and maximum crushing strength, 1.25; work to maximum load, total work and toughness, 2.5.

While compression wood, size for size, compares favorably in some of its properties with normal wood, individual pieces of this type of wood vary considerably more than normal wood; hence great differences in behavior are to be expected under service conditions. When combined with normal wood, it is even more undesirable and as previously mentioned is not to be used where good performance is desired.

COMPARISON BY SPECIES

The foregoing comparisons are based on average values for five species. When ratios for individual species are considered, large differences are found (table 5). The general characteristics of the compression wood in the different species tested also varied considerably; that is, some had mild and some pronounced compression wood. This variation probably was the result of the characteristics of the material available for the investigation rather than any actual difference in the average kind of compression wood associated with different species, since both mild and pronounced compression wood have been observed in many species of wood.

COMPARISON OF INCREASE IN STRENGTH OF NORMAL WOOD AND COMPRESSION WOOD IN DRYING

The average ratios for the various mechanical properties of compression to normal wood given in table 5 are, with two exceptions, considerably higher for green material than for air-dried material, indicating that compression wood in drying does not increase so much in strength as normal wood. Modulus of elasticity, which is relatively low in compression wood as compared with normal wood in both the green and air-dried condition, apparently increases during drying proportionately as rapidly in compression wood as in normal wood. Tension parallel to grain, which is the other exception, is based on too few tests to draw definite conclusions.

Compression wood, both green and dry, is considerably lower in modulus of elasticity and consequently deflects more with a given load and takes less load as a slender column than does normal wood. The maximum load for compression wood tested when green is also higher than that for normal wood. Since work to maximum load involves both load and deflection, the amount of work absorbed in bending to maximum load is considerably greater for green compression wood than for normal wood. A similar relation holds for total work. When based on air-dried material the work to maximum load is also greater for compression wood than for normal wood but not to the same degree as in green wood. The smaller difference is caused by the maximum load for air-dried compression wood frequently being lower than for normal wood (fig. 6). In total work, air-dried compression wood is often lower than normal wood because complete brash failure frequently occurs in compression wood soon after the maximum load is passed.

COMPARISON OF MECHANICAL PROPERTIES OF MILD AND PRONOUNCED COMPRESSION WOOD

Compression wood varies in characteristics from mild to pronounced. To determine the relation between the properties of the different types of compression wood a few arbitrarily selected specimens were given special attention, the results from which are given in table 6.

Pronounced compression wood is higher in specific gravity than is mild compression wood. When green it is also equal or higher in practically all mechanical properties shown in table 6 except modulus of elasticity. When air-dry, pronounced compression wood is lower than mild compression wood in modulus of rupture, work to maximum load, and total work. Modulus of elasticity also averages lower in air-dry pronounced compression wood than in mild compression wood, although in one of the two species tested the values were nearly equal. In maximum crushing strength, pronounced compression wood

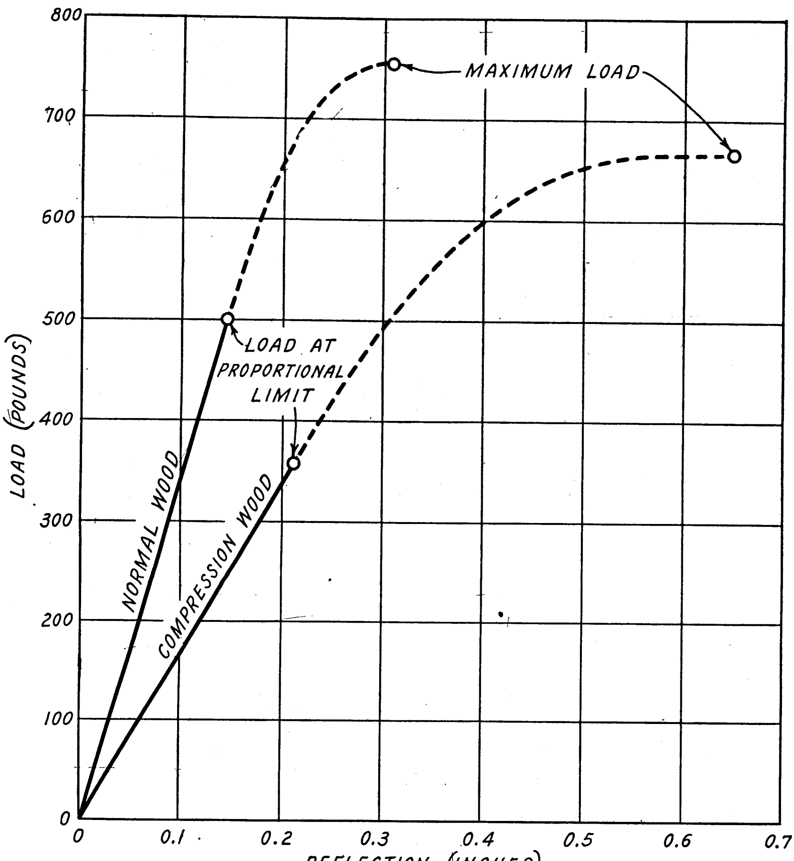


FIGURE 6.—Variation in average load and deflection for normal wood and compression wood of air-dry loblolly pine when tested in static bending.

is superior to mild compression wood. The ratios of pronounced to mild compression wood for modulus of elasticity and maximum crushing strength are very similar for green and air-dried material.

When adjustments in strength values are made for differences in the specific gravity and compared with normal wood, air-dried mild compression wood is superior to pronounced compression wood in all strength properties shown in table 6. With few exceptions the same is true of green material.

TABLE 6.—*Strength values of normal wood and mild and pronounced compression wood of loblolly pine and Douglas fir*

TESTED IN GREEN CONDITION

Species	Type of wood and expected strength value [1]	Specimens	Moisture content	Specific gravity [2]	Static bending: Modulus of rupture		Static bending: Modulus of elasticity		Static bending: Work, Maximum load		Static bending: Work, Total		Compression parallel to grain, maximum crushing strength	
		Number	*Percent*		*Lbs. per sq. in.*	*Ratio* (*actual*/*expected*)	*1,000 lbs. per sq. in.*	*Ratio* (*actual*/*expected*)	*In. lbs. per cu. in.*	*Ratio* (*actual*/*expected*)	*In. lbs. per cu. in.*	*Ratio* (*actual*/*expected*)	*Lbs. per sq. in.*	*Ratio* (*actual*/*expected*)
Loblolly pine.	Normal	6	98.9	0.527	8,190		1,806		10.6		36.0		3,820	
	Mild compression	3	92.9	.527	8,560		1,169		12.8		54.4		4,210	
	Expected value				8,190	1.04	1,806	0.65	10.6	1.21	36.0	1.51	3,820	1.10
	Pronounced compression	5	73.2	.596	8,540		817		26.9		60.1		4,470	
	Expected value				9,850	.87	2,106	.39	14.4	1.87	49.0	1.22	4,450	1.00
Douglas fir.	Normal	8	42.5	.460	7,990		1,562		8.4		27.3		3,950	
	Mild compression	5	79.0	.480	6,830		999		15.2		38.4		3,520	
	Expected value				8,510	.80	1,647	.61	9.3	1.64	30.3	1.27	4,160	.85
	Pronounced compression	5	27.4	.590	9,800		1,001		21.1		45.4		4,730	
	Expected value				11,620	.84	2,133	.47	15.7	1.34	50.9	.89	5,400	.88

TESTED IN AIR-DRY CONDITION

Species	Type of wood and expected strength value [1]	Specimens	Moisture content	Specific gravity [2]	Modulus of rupture	Ratio	Modulus of elasticity	Ratio	Work, Maximum load	Ratio	Work, Total	Ratio	Maximum crushing strength	Ratio
Loblolly pine.	Normal	6	11.1	0.583	15,920		2,380		10.9		32.1		8,480	
	Mild compression	3	11.5	.593	15,540		1,290		25.7		25.7		6,990	
	Expected value				16,330	0.95	2,430	0.53	11.4	2.25	33.5	0.77	8,660	0.81
	Pronounced compression	5	11.8	.648	13,160		945		22.7		22.7		7,320	
	Expected value				18,640	.71	2,716	.35	14.2	1.60	41.8	.54	9,680	.76
Douglas fir.	Normal	8	11.6	.510	15,140		1,945		15.0		33.8		8,230	
	Mild compression	5	12.7	.498	13,700		1,180		16.8		16.8		6,640	
	Expected value				14,600	.94	1,885	.63	14.1	1.19	31.8	.53	7,980	.83
	Pronounced compression	5	12.6	.604	13,170		1,212		12.4		12.4		8,330	
	Expected value				19,500	.68	1,402	.50	22.9	.54	51.6	.24	10,160	.82

[1] Expected values obtained by multiplying the normal wood-strength values from test by the ratio of the specific gravity of compression wood to normal wood, this ratio first being raised to a power corresponding to that of the specific gravity strength equation for the property under consideration. The powers used were: Modulus of rupture, 1.50; modulus of elasticity, 1.25; work to maximum load and total work, 2.5; and maximum crushing strength, 1.25.

[2] Based on oven-dry weight and volume at test.

RELATION OF SLOPE OF FIBRILS TO STRENGTH PROPERTIES

As previously mentioned, the slope of fibrils in the secondary cell wall of compression wood fibers is greater than that of normal wood. In pronounced compression wood the slope of fibrils is greater than that in mild compression wood (table 1). In certain mechanical

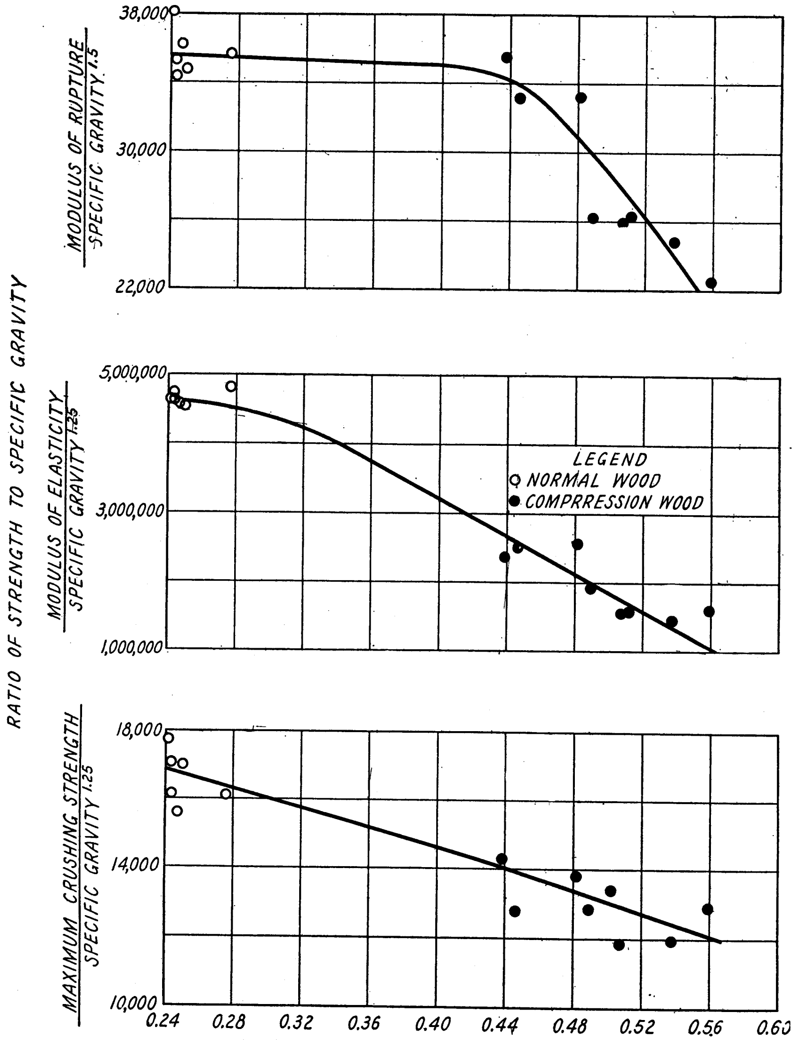


FIGURE 7.—Relationship of strength properties divided by specific gravity to the sine of the average slope of fibrils in the secondary walls of springwood and summerwood in air-dry normal wood and compression wood of loblolly pine.

properties compression wood has lower strength for its weight than does normal wood and pronounced compression wood is lower than mild compression wood. The greater slope of fibrils appears accountable for this deficiency in strength because failure occurs partly between the fibrils of the secondary cell wall. The ratio of strength plotted against the sine of the angle of the average slope of fibrils shows relationships between this structural characteristic and some strength properties after adjustment[6] is made for variations in specific gravity (fig. 7).

Figure 7 indicates that slight increases in slope of fibrils over that for normal wood weaken the wood in modulus of elasticity and maximum crushing strength along the grain. Modulus of rupture does not appear to be so quickly affected. Modulus of elasticity decreases at the most rapid rate with increase in slope of the fibrils; and maximum crushing strength along the grain at the least rapid rate. Thus in addition to specific gravity, the strength of clear wood is modified within certain limits by the slope at which the fibrils are oriented in relationship to the longest axis of the cells.

INFLUENCE OF COMPRESSION WOOD IN SOFTWOOD TIMBERS AND LUMBER

EXPANSION IN GREEN COMPRESSION WOOD

Green compression wood apparently is under compression stress in the tree or log for it expands longitudinally when released from the adjacent wood. In sawing along the junction between green compression wood and normal wood the part composed of compression wood immediately becomes slightly longer than that composed of normal wood when the two are separated.

This characteristic sometimes causes pinching of the saw in felling timber and in crosscutting logs. In this connection the term "timber bind" is frequently used by woodsmen. It is the usual practice to undercut the lower side of a leaning tree to be felled and to saw entirely from the opposite side. When the undercut does not extend completely through the compression wood on the under side of leaning trees, an expansion of the compression wood sometimes takes place that is sufficient to lock the saw firmly in the cut on the opposite side. Usually the saw can be released by increasing the size of the undercut, but sometimes the wood holding it must be chopped away. Pinching is frequently experienced in sawmills when a saw is cutting approximately on the junction between compression wood and normal wood because the expansion of green compression wood causes lateral distortion. Green boards containing both normal wood and compression wood may be crooked when they come off the saw as a result of the release of internal stresses.

EFFECT OF EXCESSIVE LONGITUDINAL SHRINKAGE OF COMPRESSION WOOD ON DEFORMATION AND CHECKING OF LUMBER

The comparatively high longitudinal shrinkage of compression wood is one of the principal causes of bowing, twisting, and splitting in log-run softwood lumber as it dries. As previously indicated, the shrinkage potential of compression wood in a board may be many times that of the normal wood. It is not uncommon to find lumber 1 inch or more in thickness that is badly bowed or even split by the differences in shrinkage of adjacent normal wood and compression

[6] Previous tests have shown that within a species modulus of elasticity and maximum crushing strength vary as the 1.25 power of the corresponding specific gravity and modulus of rupture varies as the 1.50 power of the specific gravity. Therefore to eliminate the effect of specific gravity these properties were divided by the corresponding specific gravities raised to the powers indicated above. In addition the average slope of fibrils was weighted on the basis of the proportions of springwood and summerwood and their respective slopes.

wood. Figure 8 illustrates bowing and splitting of boards resulting from the unequal shrinkage of adjacent compression wood and normal wood.

The longitudinal shrinkage of compression wood sometimes causes serious defects in poles and piling. Pieces of round timber with layers of pronounced compression wood, one or two annual rings in thickness, frequently shell or flake in the portion of the circumference

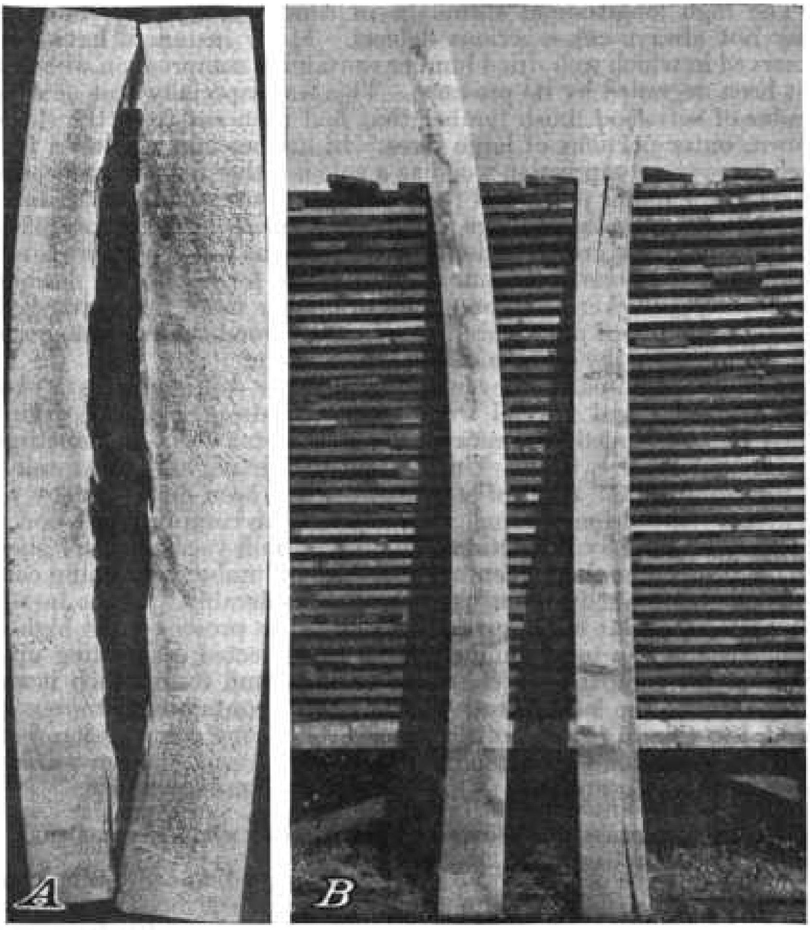


FIGURE 8.—Splitting and bowing in ponderosa pine lumber as a result of differences in longitudinal shrinkage within the same piece: *A*, Splitting of a 1½-inch board caused by a streak of compression wood along the pith centrally located in the board; *B*, bowing and splitting near the ends of 1½-inch boards caused by compression wood along one edge.

composed of compression wood (pl. 8). A pole containing such compression wood is hazardous for linemen since it may cause slipping of their climbing irons.

The high longitudinal shrinkage of compression wood is commonly accountable for the formation of checks across the grain in lumber (*24*). This usually occurs when the compression wood is bounded on two sides by normal wood. Since the compression wood under such conditions cannot compress the normal wood longitudinally, and since in itself it is weak in tension parallel to the grain, actual tension failure of the wood across the grain occurs as the compression wood shrinks (pl. 9).

The occurrence of compression wood on the lower side of branches often results in serious degrade of the lumber. Frequently in spike knots that are not entirely intergrown the logitudinal shrinkage stress will twist the knot from its original position so that it protrudes above the surface of the board.

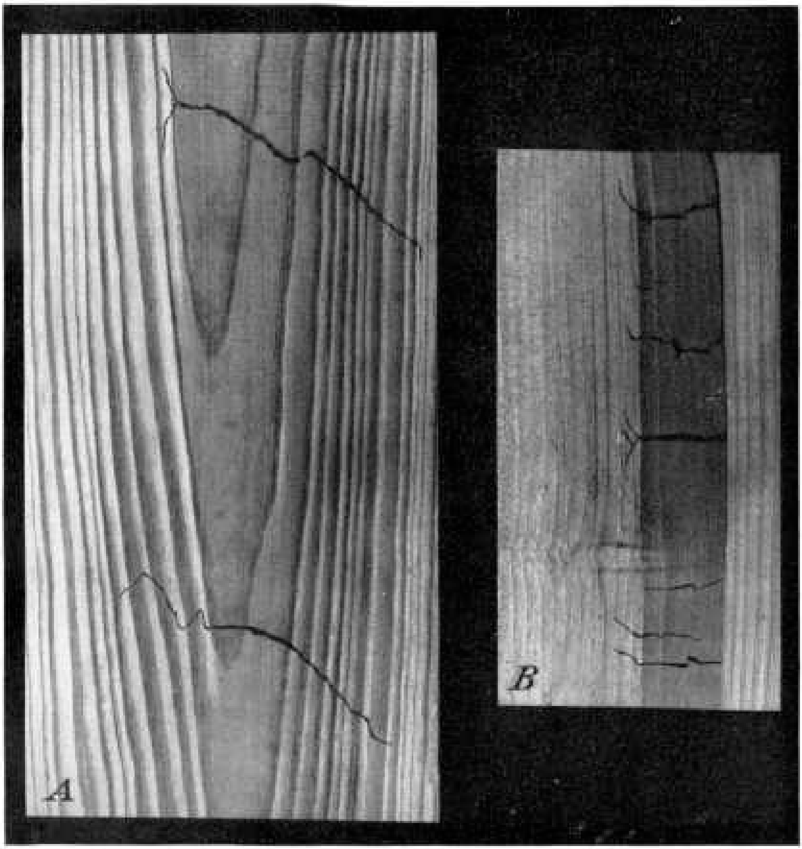
The high longitudinal shrinkage of compression wood, however, may not always cause serious defects. Many instances have been observed in which well-dried lumber containing compression wood has not been degraded by its presence. This was especially true of select grades of softwood finish lumber that had been cut from the slower grown, outer portions of large trees. In lumber manufactured from such trees the compression wood as a rule is either not pronounced or exists in the major portion of the board so that relatively little differential longitudinal shrinkage within the entire board takes place. Since young trees grown under forest conditions frequently are forced to inclined positions as a result of competition for light or by mechanical forces, the lower common grades of lumber more frequently have greater amounts of pronounced compression wood than do the grades cut from nearer the outside of the woody stem.

It has been noted that even though lumber containing both compression wood and normal wood remained straight during drying, when it was ripped or resawed the pieces cut from it sometimes became bowed or twisted. This bowing or twisting may be explained as the result of the relief of stresses that had been developed by the greater potential longitudinal shrinkage of the compression wood.

Data obtained by inspection of lumber in mill yards and dry sheds (*12*) indicate that the percentage of pieces of lumber containing compression wood wholly or in part varies considerably. These inspections indicate that compression wood may be present in as high as 25 percent of the total number of pieces inspected, depending upon grade of the lumber, and character of the stand from which it was cut. Despite the large percentage of boards containing compression wood, less than 5 percent of the boards containing compression wood were degraded for that reason. The degrade resulted from warping or cross checking incident to unequal longitudinal shrinkage.

EFFECT OF PROPERTIES OF COMPRESSION WOOD IN WOODEN STRUCTURES

Instances have been observed (*17*) in which siding containing compression wood nailed in place while at too high a moisture content developed openings at the butt joints varying in width from one-eighth to nine-sixteenths of an inch. Other observations have indicated that soft-wood flooring containing compression wood, if laid when at too high a moisture content, will develop similar butt-joint cracks. Excessive changes in the longitudinal dimensions of lath containing compression wood have caused serious buckling of plastered surfaces. A beam composed of compression wood in the upper portion and normal wood below may with loss in moisture bow downward to such an extent as to throw the entire load on adjacent beams. The resulting internal stresses may also be sufficient to cause tension breaks in the upper portion of a beam which is normally in compression. If the compression wood is on the bottom of a beam it will bow upward in



Checks across the grain in southern pine (*A*) and white fir (*B*) boards that developed as a result of excessive longitudinal shrinkage of compression wood. The wide darker colored band in each board is pronounced compression wood.

drying and often take most of the load off the adjacent beams although it is inherently weaker, and in addition will have large internal stresses caused by shrinkage. Internal stresses caused by unequal shrinkage may very easily combine with external forces in such a way as to cause premature failure of a beam (*10*). Hence a structural member containing any appreciable amount of compression wood is likely to give unsatisfactory service and should be avoided.

Lumber containing pronounced compression wood that is situated where it is subject to continuous moisture changes probably would continuously change its shape as the result of the unequal shrinking and swelling of the different portions.

Even if no checking or deformation due to unequal longitudinal shrinkage takes place, pieces of lumber or timbers containing compression wood may be sufficiently low in strength and stiffness to be undesirable in wooden structures that must support considerable loads. Since compression wood is frequently low in shock resistance for its weight it is particularly undesirable for use in airplanes, ladders, and other structures subjected to large and suddenly applied loads. Piling containing large amounts of pronounced compression wood is more likely to fail during driving under difficult conditions, such as into hard ground, than is piling free from compression wood.

On the other hand, lumber for many general uses may contain small amounts of mild compression wood without rendering unsatisfactory service provided it is dried to the proper moisture content for the particular use to which it is put and has not been seriously degraded during the drying. Material requiring a high degree of strength, capacity to stay in place, and lightness should receive a careful visual examination to detect the presence of compression wood. It is believed that from such a careful visual inspection it would be possible, to eliminate nearly, if not all, the individual pieces containing any pronounced compression wood that would make the continued use of such material unsatisfactory or cause premature failure. Material containing pronounced compression wood is undesirable for practically all lumber uses.

REDUCTION OF COMPRESSION WOOD FORMATION BY FOREST MANAGEMENT

Since many of the virgin coniferous forest areas have been depleted and the future softwood timber supplies must come, to a considerable extent at least, from second-growth stands, the possibilities of reducing the formation of compression wood by forest-management methods is important (*22*). Data given in earlier pages of this bulletin show that under certain growth conditions compression wood formation is more prevalent than under others. In young stands under a relative high degree of management more can be accomplished in reducing compression wood formation than in middle-aged or nearly mature stands. For the most part, this is because the older stands have already produced the amounts of compression wood likely to be formed. In such young even-aged stands thinnings should be made to remove overtopped trees if they are inclined, twin trees (two stems from a single stump), and defective or crooked trees. In addition, other trees, of course, should be removed to obtain the proper stocking. Such thinnings in young stands should produce the proper spacing to obtain approximately uniform growth and wood as free as possible from compression wood.

Frequently it is desirable to cut partially an uneven-aged stand of timber in which there are crooked and inclined trees as well as well-formed trees. If such a cutting is to be done as a forest-management practice with a view toward obtaining a cash crop from the present merchantable timber as well as improvement of the stand, it is necessary to remove as far as possible those trees that will produce compression wood in the future. It is therefore desirable to remove not only the extremely deformed and defective trees but also those that are appreciably inclined. Although many inclined trees tend toward vertical positions when released from competition, they form considerable amounts of compression wood before reaching erect positions.

In partially cut stands containing scattered trees, wind action as well as increased vigor frequently is responsible for increased compression wood formation. In partial cuttings made to improve a timber stand, the formation of compression wood will be lessened if large and irregular openings in the crown canopy are avoided and the action of violent winds thereby reduced.

SUMMARY

Compression wood is an abnormal type of wood occurring as a rule on the lower sides of nonvertical trunks and branches among all coniferous species of trees. Increase in the amount of deviation of trunks from a vertical position, or increase in rate of diameter increment of individual trees, or both, increases the formation of compression wood.

Under a microscope the summerwood tracheids of compression wood appear to be nearly circular in cross section whereas those of normal wood are more or less rectangular. The fibrils of the secondary cell walls in compression wood make a higher angle in relation to the longest axis of the cells than do the fibrils in normal wood and these walls contain microscopic checks.

The lignin content of compression wood as indicated by the species investigated is slightly higher and the cellulose content slightly lower than normal wood. The weight of pronounced compression wood is from 15 to 40 percent greater than normal wood. The longitudinal shrinkage of compression wood from the green to oven-dry condition varies from about 0.3 to 2.5 percent whereas normal wood has a shrinkage from about 0.1 to 0.2 percent. The transverse shrinkage of compression wood is less than that of normal wood.

When adjustments are made for differences in weight, compression wood is lower in practically all strength properties as compared to normal wood. The differences in the slope of fibrils in compression wood as compared to normal wood appears to have a close relation to the differences in strength properties. The increase in strength properties accompanying drying of the wood is not so great for compression wood as for normal wood. Compression wood is under compression in the log and when the stresses are released, such as by sawing, extension of the compression wood portion occurs.

Compression wood when manufactured into lumber is accountable for much bowing and twisting and is unsatisfactory for uses where strength and neat workmanship are essential requirements. Proper forest-management measures will hold compression wood formation to a minimum.

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