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COMPARATIVE STRENGTH PROPERTIES OF WOODS GROWN IN THE UNITED STATES
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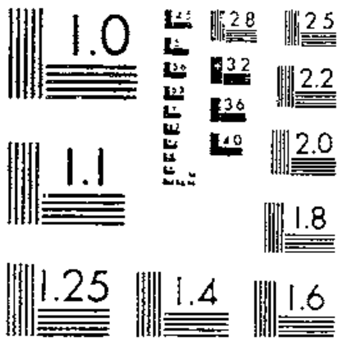

MICROCOPY RESOLUTION TEST CHART
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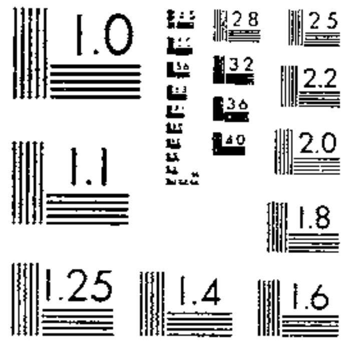

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NATIONAL BUREAU OF STANDARDS 1963-A

TECHNICAL BULLETIN No. 158 FEBRUARY, 1930

UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D. C.

COMPARATIVE STRENGTH PROPERTIES OF WOODS GROWN IN THE UNITED STATES

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FOREWORD

The information contained in this bulletin is of value in making comparisons of species of wood in order to determine the choice of species for specific uses. Technical terms have, as far as possible, been omitted from the body of the bulletin, and the various properties determined from over a quarter million tests have been combined into simple comparative figures. This bulletin supplements but does not supersede United States Department of Agriculture Bulletin 556, Mechanical Properties of Woods Grown in the United States, *(4)* [3] which presents the basic information from which the comparative figures have been derived. Since Bulletin 556 was issued additional tests have been made and some additional species have been tested. In all cases the comparative figures presented here are based on the latest available results. Bulletin 556 should be used when technical data on the properties of clear wood are required by engineers, archi-

[1] Acknowledgment is made to J. A. Newlin and T. R. C. Wilson of the Forest Product Laboratory for assistance in the preparation of this bulletin, and to W. A. Shewhart of the Bell Telephone laboratories for suggestions regarding variability analysis.

[2] Maintained by the *Forest Service, United States Department of Agriculture, at Madison, Wis., in* cooperation with the University of Wisconsin.

[3] Reference is made by italic numbers in parentheses to "Literature cited," p. 38.

tects, and others, or when, in the judgment of the user, it is more applicable than the comparative figures presented here.

Although this bulletin gives figures only on weight, shrinkage, and strength, it is of course evident that other properties and factors, such as resistance to decay, painting and finishing qualities, tendency to leach coloring matter, size and character of prevalent defects, marketing practice, and the like must also be considered in selecting a species or in determining the suitability of a wood for different uses. Attention is also called to the fact that, because of the considerable variation in properties of all species of wood, it is often possible to select individual pieces of a weak species exceeding in strength the average of a stronger one, and to segregate the wood of a species into classes according to weight and strength, so that each class may be directed to the uses for which the class is best suited. In this way the variability of wood may be turned from a liability to an asset.

Carlile P. Winslow,
Director, Forest Products Laboratory.

HISTORICAL

The strength of wood has always been an important factor in its use, but it is becoming even more significant with the increasing competition from other materials, the increasing production of new or little-used species, and the changing requirements of consuming markets. Considered broadly, three periods can be recognized in our forest history as affecting timber utilization: The land-clearing period, the timber-mining period, and the timber-crop period, which we are now entering.

During the so-called land-clearing period some of the best-known hardwoods, such as yellow poplar and black walnut, occupied the richer agricultural regions in the East before giving way to the plow. Together with the softwoods they furnished from selected logs abundant material to supply the building and other needs of the time. Consequently, lumber was used in greater quantities and in better grades than were actually required. Often the best species found their way into commonplace uses, as, for example, the employment of black walnut for floor joists, fence rails, and the like. Utilization of local supplies prevailed, and long expensive hauls were not required. While these forests were giving way to agriculture, timber was a by-product of land clearing, and economy was neither practiced nor necessary.

The period of timber mining, which followed, furnished the material to meet much of the industrial growth of the country. Only the most far-seeing could realize that such extensive forests as the magnificent white pine stand of Michigan and Wisconsin were exhaustible. The abundance of desirable species admirably adapted to the needs of the country, the short haul to market, and cheap labor resulted in a period of timber use with a per capita consumption far exceeding that of most other countries. The Nation became wood dependent, and timber, like ore, was removed without thought of replacement. As in the land-clearing period, lumber was still used in better grades than necessary, although there was a gradual awakening to the need of using wood more efficiently.

We are now on the threshold of the timber-crop period, which is based on the conception that timber is reproducible, like any other crop, except that the period of rotation is longer. Progressive lumber operators are carefully studying how to keep their forest lands actively growing timber, and a few are now operating on a sustained-yield basis. If forestry is practiced on land not suited to ordinary crops and if timber is efficiently utilized, the United States can reasonably be expected to meet most of its future timber requirements at least after an initial adjustment period.

NEED FOR INFORMATION ON PROPERTIES

Timber utilization in the present forest-crop period with its longer haul to market demands a higher degree of efficiency than that of previous periods, since modern competition necessitates that all materials be used to their best advantage to maintain their markets. A first requirement of efficient use is a knowledge of the properties. This knowledge is of value in several ways.

The increasing scarcity of certain species of timber which had become more or less standard in various wood-using industries, the wider competition in practically all markets, increased transportation facilities, and other factors are opening the field for other species. Through long use the properties which have made a species more or less standard are quite well understood, but it is not so generally known to what extent other available species possess these same properties, and to what extent they might supplement the established species.

Another need for information on properties is in the introduction of so-called little-used species. In the pushing of timber production into new regions, new species are encountered. Good crop management as conceived by many foresters and wood-utilization experts necessitates, at least so far as lumber and timber purposes are concerned, that certain species, such as western hemlock and white fir, be logged along with the well-known woods with which they grow rather than be left to dominate and propagate the succeeding crop. A knowledge of the properties is one of the first requirements in the use of alternate species and in the use of little-known woods.

PURPOSE

Wood utilization in the future must depend more and more on the true value of the product as determined by exact information on the properties rather than on rule-of-thumb practice. This bulletin presents exact information for the comparison of the strength properties of many of our native species. Other publications have usually presented strength data in technical terms familiar principally to architects and engineers, but here the technical values are combined into simplified comparative figures, which are more readily intelligible to the average person. For many purposes these simplified comparative figures will be found as useful as the technical values on which they are based.

The figures presented are especially applicable for two types of use (1) that relating to the alternation of one species with another and (2) that involved in selecting species for uses in which the strength requirements are known. The significance of the figures is shown and examples of their use are given.

PROPERTIES OTHER THAN STRENGTH

Although this bulletin presents figures only on weight, shrinkage, and strength, it should not be overlooked that other properties and factors must also be considered in the utilization of wood, and that the value of a wood for a given use is ordinarily based upon a combination of properties rather than upon a single property. Among other properties which may be of importance are nail-holding ability; splitting; tendency to warp; gluing qualities; painting and finishing characteristics; resistance to decay, weathering, and insects; insulating properties; and acid resistance. Information on these latter properties, however, does not come within the scope of this bulletin.[4]

The relative usefulness of any lumber may also depend upon the characteristics of the stock in its entirety, as well as upon the properties of the clear wood, and may be influenced by sizes available, degree of seasoning, and marketing practice. Thus the mechanical properties of the clear wood may indicate that a species is an excellent wood for boxes for bulk commodities, but the lumber may be unsuited for such use because of a characteristic tendency of the knots to loosen and fall out. Furthermore, the advantage of inherently low shrinkage or high nail-holding power in a species may be lost through the method of marketing or the use of the species before it is sufficiently dry.

IMPORTANCE OF STRENGTH

There are few uses of wood in which its serviceability is not somewhat dependent upon one or more of its strength properties. Airplane wing beams, floor joists, and wheel spokes typify familiar uses in which strength is the principal consideration. Often strength in combination with other important properties is required. Thus, telephone poles, railroad ties, and bridge stringers require not only the capacity to carry loads, but also resistance to decay. In addition, a large number of uses of wood, not usually thought of in connection with strength, are dependent, at least to some degree, on strength properties. For example, finish and trim for buildings should be sufficiently hard to prevent easy marring; window sash must have screw-holding ability to permit secure attachment of hardware, as well as adequate stiffness to prevent springing when the window is opened and closed. Even matches must have strength to prevent their breaking when being lighted. Information on strength is therefore essential not only for the design of such engineering structures as airplanes, buildings, and bridges, but also as a guide for the selection of suitable species for a great variety of uses, whether it be the soft, light woods or the inherently stronger ones that are required.

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[4] Information on properties other than those presented in this bulletin may be obtained from the Forest Products Laboratory, Madison, Wis.

EXPLANATION OF "STRENGTH"

Much confusion exists in regard to the meaning of "strength." In its broader sense, strength includes all the properties which enable wood to resist different forces or loads. In its more restricted sense, strength may apply to any one of the mechanical properties; in which event, the name of the property under consideration should be stated. If the several strength properties had the same relation to each other in all species, a wood which excelled in one strength property would be higher in all, and misunderstandings about the word "strength" would be less likely to occur. But such is not the case. A wood may rank better in one kind of resistance to load than in another. Longleaf pine averages higher than white oak in compressive strength (endwise), but is lower in hardness. Hence, it can not be said that longleaf pine is "stronger" than white oak without stating the kind of strength referred to. To be precise, in making a comparison of species, it is necessary to consider the kind of strength properties or combination of properties essential to the particular use, since different kinds of strength are essential in different uses. Thus, longleaf pine, because of its higher compressive strength (endwise), is superior to oak for use in short posts that carry heavy endwise loads, whereas oak, because of greater hardness, is superior in resistance to the wear and marring to which some floors are subjected.

NATURE AND SCOPE OF STRENGTH FIGURES

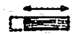
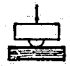
Several publications (*3*, *4*, *5*, and *10*) present figures upon the strength properties of wood for small clear specimens and for structural timbers containing defects. Although such technical strength figures can be applied to all strength problems, there are, nevertheless, many uses of wood involving the selection of suitable species where the conversion of technical figures into simple comparative figures as is done in this bulletin would serve equally well. Since the strength figures given are composite values, or, in effect, index numbers, they are mainly for comparative purposes and are consequently not suitable for calculating the load-carrying capacity of wood.

The comparative figures for 164 native species are given in Table 1. The figures are based on an extensive series of tests on small clear specimens of wood begun by the Forest Products Laboratory in 1910. Each kind of wood, with few exceptions is represented by five or more trees. Some of the specimens were tested green from the tree, others after thorough seasoning (*1*). Collectively, the results include for each species figures on over 25 strength and other properties obtained from 10 different kinds of tests (*4*).

The more important test results for each species have been averaged and combined into comparative or composite figures which represent six properties, namely, bending strength, compressive strength (endwise), stiffness, hardness, shock resistance, and volumetric shrinkage. Definite figures for these essential properties are presented in Table 1, from which numerical comparisons may be made among the different species. Average figures on specific gravity, weight per cubic foot, and radial and tangential shrinkage (p. 20) are also included. The methods of computing the comparative figures of Table 1 are described in Appendix 2.

TABLE 1.—*Average comparative properties of the clear wood of species grown in the United States* [1]

[For definition of terms and discussion of table see "Explanation of Table 1" in text]

Common and botanical name of species	Trees tested	Specific gravity, oven dry, based on volume when green	Weight per cubic foot		Shrinkage from green to oven-dry condition based on dimensions when green			Composite strength values [2]				
			Green	At 12 per cent moisture content	Radial	Tangential	Volumetric (composite value)[2]	Bending strength	Compressive strength (endwise)	Stiffness	Hardness	Shock resistance
												
1	2	3	4	5	6	7	8	9	10	11	12	13
Hardwoods:	*Number*		*Pounds*	*Pounds*	*Per cent*	*Per cent*	*Comparative figure*	*Comparative figure*	*Comparative figure*	*Comparative figure*	*Comparative figure*	*Comparative figure*
Alder, red (Alnus rubra)	6	0.37	46	28	4.4	7.3	123	76	82	139	48	71
Apple (Malus pumila var.)	10	.61	55	47	5.6	10.1	170	85	75	139	119	146
Ash, biltmore white (Fraxinus biltmoreana)	5	.51	45	38	4.2	6.9	121	107	108	156	104	114
Ash, black (Fraxinus nigra)	11	.46	53	34	5.0	7.8	144	77	68	126	64	122
Ash, blue (Fraxinus quadrangulata)	5	.53	46	40	3.9	6.5	113	109	107	139	119	147
Ash, green (Fraxinus pennsylvanica lanceolata)	10	.53	49	40	4.6	7.1	122	107	106	157	107	116
Ash, Oregon (Fraxinus oregona)	3	.50	46	38	4.1	8.1	129	88	88	143	94	123
Ash, pumpkin (Fraxinus profunda)	3	.48	46	36	3.7	6.3	113	86	85	118	103	87
Ash, white (Fraxinus americana)	23	.55	48	42	4.9	7.9	132	113	106	168	107	153
Ashes, commercial white (ave. of 4 species [3])	43	.54	48	41	4.6	7.5	126	110	106	161	108	139
Aspen (Populus tremuloides)	11	.35	43	27	3.5	6.7	111	63	58	107	31	67
Aspen, largetooth (Populus grandidentata)	10	.35	43	27	3.3	7.9	116	66	69	130	38	63
Basswood (Tilia glabra)	8	.32	41	26	6.6	9.3	158	61	62	126	31	54
Beech (Fagus grandifolia)	17	.56	54	45	5.1	11.0	162	102	94	169	96	135
Beech, blue (Carpinus caroliniana)	12	.58	53	48	5.7	11.4	184	76	66	114	116	296

Birch, Alaska white (Betula neoalaskana)	10	.49	48	38	6.5	9.9	166	89	86	161	61	126
Birch, gray (Betula populifolia)	5	.45	46	35	5.2	------	147	61	53	85	54	147
Birch, paper (Betula papyrifera)	10	.48	50	39	6.3	8.6	158	78	68	137	58	158
Birch, sweet (Betula lenta)	10	.60	57	46	6.5	8.5	154	117	105	207	104	159
Birch, yellow (Betula lutea)	17	.55	57	43	7.2	9.2	166	106	98	174	86	171
Blackwood (Avicennia nitida)	6	.83	74	58	6.2	9.7	157	123	120	185	185	167
Buckeye, yellow (Aesculus octandra)	5	.33	49	25	3.5	7.8	118	58	56	112	31	52
Bustic (Dipholis salicifolia)	1	.86	77	62	------	------	------	------	------	------	------	------
Butternut (Juglans cinerea)	10	.36	46	27	3.3	6.1	100	64	68	115	40	80
Buttonwood (Conocarpus erecta)	7	.69	64	50	5.4	8.5	144	89	106	159	122	78
Cascara (Rhamnus purshiana)	5	.50	50	36	3.2	4.6	77	71	79	93	86	140
Catalpa, hardy (Catalpa speciosa)	15	.38	41	20	2.5	4.9	73	63	59	110	43	95
Cherry, black (Prunus serotina)	5	.47	46	35	3.7	7.1	113	93	100	150	72	112
Cherry, pin (Prunus pennsylvanica)	5	.36	33	28	2.8	10.3	129	62	63	117	41	77
Chestnut (Castanea dentata)	10	.40	55	30	3.4	6.7	111	68	70	112	50	69
Chinquapin, golden (Castanopsis chrysophylla)	5	.42	61	32	4.6	7.4	128	83	76	125	62	95
Cottonwood, black (Populus trichocarpa)	5	.32	46	24	3.6	8.6	123	60	61	119	29	59
Cottonwood, eastern (Populus deltoides)	5	.37	49	28	3.9	9.2	138	62	64	123	36	73
Dogwood (Cornus florida)	5	.64	64	51	7.1	11.3	194	100	101	124	154	192
Dogwood, Pacific (Cornus nuttallii)	5	.58	55	45	6.4	9.6	168	86	93	142	116	154
Elder, blueberry (Sambucus coerulea)	5	.46	65	36	4.4	9.0	149	72	76	115	68	109
Elm, American (Ulmus americana)	12	.46	54	36	4.2	9.5	145	85	74	130	66	123
Elm, rock (Ulmus racemosa)	10	.57	54	44	4.8	8.1	137	106	97	148	104	189
Elm, slippery (Ulmus fulva)	6	.48	56	37	4.9	8.9	138	92	89	140	72	162
Fig, golden (Ficus aurea)	1	.44	51	31	------	------	------	61	66	67	------	65
Gum, black (Nyssa sylvatica)	5	.46	45	35	4.4	7.7	133	83	78	118	78	80
Gum, blue (Eucalyptus globulus)	5	.62	70	52	7.6	15.3	226	134	148	233	132	134
Gum, red (Liquidambar styraciflua)	10	.44	50	34	5.2	9.9	150	86	77	134	60	99
Gum, tupelo (Nyssa aquatica)	6	.46	56	35	4.2	7.6	122	82	87	127	78	81
Gumbo-limbo (Bursera simaruba)	5	.30	38	22	2.3	3.6	77	39	38	66	30	32
Hackberry (Celtis occidentalis)	6	.49	50	37	4.8	8.9	138	76	72	108	74	145
Haw, pear (Crataegus tomentosa)	2	.62	63	48	------	------	------	95	87	107	127	193
Hickory, bigleaf shagbark (Hicoria laciniosa)	19	.62	62	48	7.6	12.6	195	126	105	165	------	308
Hickory, bitternut (Hicoria cordiformis)	11	.60	63	46	------	------	------	127	127	170	------	227
Hickory, mockernut (Hicoria alba)	19	.64	64	51	7.8	11.0	182	135	122	185	------	270

[1] Based on tests of small clear specimens, 2 by 2 inches in section except radial and tangential shrinkage which are based on width measurements of pieces 1 inch thick, 4 inches wide, and 1 inch long. Bending specimens are 30 inches long; others are shorter, depending on kind of test. This table is for use in comparing species either in the form of clear lumber or in grades containing like defects, except structural material. Structural material which conforms to American lumber standards should be compared by means of allowable working stresses, values for which are presented in the Appendix 1.

[2] The method used in establishing the composite values, each of which is based on combinations of several similar properties is presented in Appendix 2.

[3] *Fraxinus biltmoreana*, *F. quadrangulata*, *F. pennsylvanica lanceolata*, and *F. americana*.

TABLE 1.—*Average comparative properties of the clear wood of species grown in the United States*—Continued

[For definition of terms and discussion of table see "Explanation of Table 1" in text]

Common and botanical name of species	Trees tested	Specific gravity, oven dry, based on volume when green	Weight per cubic foot		Shrinkage from green to oven-dry condition based on dimensions when green			Composite strength values				
			Green	At 12 per cent moisture content	Radial	Tangential	Volumetric (composite value)	Bending strength	Compressive strength (endwise)	Stiffness	Hardness	Shock resistance
1	2	3	4	5	6	7	8	9	10	11	12	13
Hardwoods—Continued.	*Number*		*Pounds*	*Pounds*	*Per cent*	*Per cent*	*Comparative figure*	*Comparative figure*	*Comparative figure*	*Comparative figure*	*Comparative figure*	*Comparative figure*
Hickory, nutmeg (Hicoria myristicaeformis)	5	0.56	60	42	----	----	----	111	104	147	----	221
Hickory, pignut (Hicoria glabra)	60	.66	64	53	7.2	11.5	182	144	129	198	----	308
Hickory, shagbark (Hicoria ovata)	24	.64	64	51	7.0	10.5	170	133	123	185	----	258
Hickory, water (Hicoria aquatica)	2	.61	68	43	----	----	----	128	116	185	----	189
Hickories, pecan (ave. of 4 species [4])	23	.59	62	45	4.9	8.9	137	120	116	165	142	207
Hickories, true (ave. of 4 species [5])	122	.65	63	51	7.3	11.4	182	138	123	188	----	292
Hickories, pecan and true (ave. of 8 species [6])	145	.64	63	50	7.2	11.3	180	135	122	184	142	279
Holly (Ilex opaca)	5	.50	57	40	4.5	9.5	155	76	71	102	86	124
Hop-hornbeam (Ostrya virginiana)	5	.63	60	50	8.2	9.6	183	101	100	150	126	169
Inkwood (Exothea paniculata)	2	.73	71	56	6.6	10.9	184	124	110	182	181	154
Ironwood, black (Krugiodendron ferreum)	4	1.04	86	80	6.2	8.0	125	157	168	254	----	130
Laurel, mountain (Kalmia latifolia)	5	.62	62	48	5.6	8.8	144	97	100	110	143	113
Locust, black (Robinia pseudoacacia)	3	.66	58	48	4.4	6.9	103	157	168	220	161	170
Locust, honey (Gleditsia triacanthos)	6	.60	61	44	4.2	6.6	107	112	111	153	155	144
Madroño (Arbutus menziesii)	6	.58	60	46	5.4	11.9	173	86	88	117	114	93
Magnolia, cucumber (Magnolia acuminata)	5	.44	49	34	5.2	8.8	137	90	88	175	57	103
Magnolia, evergreen (Magnolia grandiflora)	2	.46	62	35	5.4	6.6	122	81	73	136	80	141

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Magnolia, mountain (Magnolia fraseri)	5	.40	47	31	4.4	7.5	126	76	73	142	51	81
Mangrove (Rhizophora mangle)	4	.80	77	67	5.4		123	176	155	270	251	164
Maple, bigleaf (Acer macrophyllum)	5	.44	47	34	3.7	7.1	113	83	86	132	73	78
Maple, black (Acer nigrum)	1	.52	54	40	4.8	9.3	140	93	89	149	97	135
Maple, red (Acer rubrum)	14	.49	50	38	4.0	8.2	128	93	87	158	79	110
Maple, silver (Acer saccharinum)	5	.44	45	33	3.0	7.2	114	69	71	106	65	93
Maple, striped (Acer pennsylvanicum)	4	.44	37	32	3.2	8.6	121	78	73	135	59	100
Maple, sugar (Acer saccharum)	22	.57	56	44	4.9	9.5	147	114	106	178	115	138
Mastic (Sideroxylon foetidissimum)	5	.89	77	65	6.1	7.5	123	112	125	183	208	97
Myrtle, Oregon (Umbellularia californica)	5	.51	54	39	2.8	8.1	116	72	76	89	106	144
Oak, black (Quercus velutina)	8	.56	63	43	4.5	9.7	142	98	91	146	102	128
Oak, bur (Quercus macrocarpa)	5	.58	62	45	4.4	8.8	129	82	81	104	112	114
Oak, California black (Quercus kelloggii)	10	.51	66	40	3.6	6.6	115	69	72	95	99	76
Oak, canyon live (Quercus chrysolepis)	3	.70	71	54	5.4	9.5	158	110	127	159	181	131
Oak, chestnut (Quercus montana)	5	.57	61	46	5.5	9.7	162	102	94	166	90	107
Oak, laurel (Quercus laurifolia)	5	.56	65	44	4.0	9.9	173	94	90	169	99	120
Oak, live (Quercus virginiana)	5	.81	76	62	6.6	9.5	152	142	130	228	240	148
Oak, Oregon white (Quercus garryana)	10	.64	69	51	4.2	9.0	133	86	80	107	153	127
Oak, pin (Quercus palustris)	5	.58	63	44	4.3	9.5	143	96	95	167	111	152
Oak, post (Quercus stellata)	10	.60	63	47	5.4	9.8	159	99	89	143	122	130
Oak, red (Quercus borealis)	33	.56	63	44	4.0	8.2	131	99	88	164	103	143
Oak, Rocky Mountain white (Quercus utahensis)	3	.62	62	51	4.1	7.2	121	70	67	78	137	78
Oak, scarlet (Quercus coccinea)	5	.60	62	47	4.6	9.7	140	115	107	181	120	175
Oak, southern red (Quercus rubra)	4	.52	62	41	4.5	8.7	153	83	76	153	86	83
Oak, swamp red (Quercus rubra pagodaefolia)	3	.61	68	48	5.2	10.8	163	131	122	215	123	162
Oak, swamp chestnut (Quercus prinus)	4	.60	65	47	5.9	9.2	180	100	95	171	103	132
Oak, swamp white (Quercus bicolor)	1	.64	69	50	5.5	10.6	172	122	114	184	122	165
Oak, water (Quercus nigra)	5	.56	63	44	4.2	9.3	154	110	95	196	101	138
Oak, white (Quercus alba)	20	.60	62	48	5.3	9.0	153	102	96	152	108	127
Oak, willow (Quercus phellos)	2	.56	67	49	5.0	9.6	175	96	86	167	106	116
Oaks, commercial red (ave. of 9 species [7])	70	.56	64	44	4.2	9.0	143	101	92	168	103	139
Oaks, commercial white (ave. of 6 species [8])	45	.59	63	47	5.3	9.3	155	99	93	149	109	125
Oaks, commercial red and white (ave. of 15 species [9])	115	.57	63	45	4.7	9.1	148	100	92	161	105	134

[4] *Hicoria cordiformis, H. myristicaeformis, H. aquatica*, and *H. pecan*.
[5] *Hicoria laciniosa, H. alba, H. glabra*, and *H. ovata*.
[6] Species under footnotes 4 and 5 combined.
[7] *Quercus velutina, Q. laurifolia, Q. palustris, Q. borealis, Q. coccinea, Q. rubra, Q. rubra pagodaefolia, Q. nigra, and Q. phellos.*
[8] *Quercus macrocarpa, Q. montana, Q. stellata, Q. prinus, Q. bicolor, and Q. alba.*
[9] Species under footnotes 7 and 8 combined.

TABLE 1.—*Average comparative properties of the clear wood of species grown in the United States*—Continued

[For definition of terms and discussion of table see "Explanation of Table 1" in text]

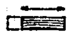
Common and botanical name of species	Trees tested	Specific gravity, oven dry, based on volume when green	Weight per cubic foot		Shrinkage from green to oven-dry condition based on dimensions when green			Composite strength values				
			Green	At 12 per cent moisture content	Radial	Tangential	Volumetric (composite value)	Bending strength	Compressive strength (endwise)	Stiffness	Hardness	Shock resistance
1	2	3	4	5	6	7	8	9	10	11	12	13
Hardwoods—Continued.	*Number*		*Pounds*	*Pounds*	*Per cent*	*Per cent*	*Comparative figure*	*Comparative figure*	*Comparative figure*	*Comparative figure*	*Comparative figure*	*Comparative figure*
Osage-orange (Toxylon pomiferum)	1	.76	62	----	----	----	89	----	----	----	----	----
Palmetto, cabbage (Sabal palmetto)	5	.37	54	27	----	----	250	40	36	55	21	49
Paradise-tree (Simarouba glauca)	4	.33	37	24	2.2	5.2	82	42	44	86	32	21
Pecan (Hicoria pecan)	5	.60	61	47	4.9	8.9	137	110	104	162	142	156
Persimmon (Diospyros virginiana)	5	.64	63	52	7.5	10.8	183	122	116	172	162	136
Pigeon-plum (Coccolobis laurifolia)	5	.77	73	55	4.4	7.8	145	108	118	184	189	114
Poisonwood (Metopium toxiferum)	4	.51	54	37	4.2	7.2	115	69	57	99	62	49
Poplar, balsam (Populus balsamifera)	10	.30	40	23	3.0	7.1	104	48	48	95	25	43
Poplar, yellow (Liriodendron tulipifera)	11	.38	38	28	4.0	7.1	119	71	68	135	40	58
Rhododendron, great (Rhododendron maximum)	5	.50	62	40	6.3	8.7	158	85	91	100	104	104
Sassafras (Sassafras variifolium)	5	.42	44	32	4.0	6.2	103	71	71	103	60	98
Serviceberry (Amelanchier canadensis)	5	.66	61	52	6.7	10.8	183	121	116	181	131	186
Silverbell (Halesia carolina)	5	.42	44	32	3.8	7.6	122	74	72	133	53	81
Sourwood (Oxydendrum arboreum)	5	.50	53	38	6.3	8.9	152	94	87	169	83	108
Stopper, red (Eugenia confusa)	3	.83	73	61	6.2	9.1	140	145	137	197	----	162
Sugarberry (Celtis laevigata)	5	.47	48	36	5.0	7.3	126	74	74	103	83	116
Sumach, staghorn (Rhus hirta)	5	.45	41	33	----	----	----	74	76	94	64	116
Sycamore (Platanus occidentalis)	10	.46	52	35	5.1	7.6	136	74	76	129	64	78
Walnut, black (Juglans nigra)	5	.51	58	39	5.2	7.1	116	111	113	167	88	124
Walnut, little (Juglans rupestris)	1	.53	55	40	4.4	4.6	101	91	86	118	----	126

Willow, black (Salix nigra)	10	.34	50	26	2.5	7.8	126	45	41	70	35	91
Willow, western black (Salix lasiandra)	5	.39	50	31	2.9	9.0	132	67	63	127	50	104
Witch-hazel (Hamamelis virginiana)	5	.56	50	43	-----	-----	188	108	88	129	107	187
Softwoods:												
Cedar, Alaska (Chamaecyparis nootkatensis)	8	.42	36	31	2.8	6.0	91	80	87	136	53	93
Cedar, incense (Libocedrus decurrens)	8	.35	45	26	3.3	5.7	81	70	81	97	47	53
Cedar, Port Orford (Chamaecyparis lawsoniana)	14	.40	36	29	4.6	6.9	106	82	90	168	43	79
Cedar, eastern red (Juniperus virginiana)	5	.44	37	33	3.1	4.7	78	67	87	80	81	114
Cedar, western red (Thuja plicata)	15	.31	27	23	2.4	5.0	76	60	74	108	38	52
Cedar, northern white (Thuja occidentalis)	5	.29	28	22	2.1	4.7	69	50	52	78	30	47
Cedar, southern white (Chamaecyparis thyoides)	10	.31	26	23	2.8	5.2	83	53	61	93	35	51
Cypress, southern (Taxodium distichum)	26	.42	50	32	3.8	6.2	104	79	92	136	52	76
Douglas fir (Pseudotsuga taxifolia) (coast type)	34	.45	38	34	5.0	7.8	121	90	107	181	59	81
Douglas fir (Pseudotsuga taxifolia), (inland empire type)	10	.41	37	31	4.1	7.6	112	80	90	159	58	72
Douglas fir (Pseudotsuga taxifolia) (Rocky Mountain type)	10	.40	35	30	3.6	6.2	103	75	83	142	52	67
Fir, alpine (Abies lasiocarpa)	5	.31	28	23	2.5	7.1	92	51	57	94	33	36
Fir, balsam (Abies balsamea)	5	.34	45	26	2.8	6.6	103	59	67	118	31	50
Fir, corkbark (Abies arizonica)	10	.28	29	21	2.8	7.4	90	51	57	104	27	38
Fir, lowland white (Abies grandis)	10	.37	44	28	3.2	7.2	105	72	82	156	43	72
Fir, noble (Abies nobilis)	9	.35	30	26	4.5	8.3	126	74	76	150	39	68
Fir, California red (Abies magnifica)	5	.37	48	27	3.8	6.9	114	78	74	134	52	71
Fir, silver (Abies amabilis)	6	.35	36	27	4.5	10.0	142	70	76	147	37	70
Fir, white (Abies concolor)	20	.35	47	26	3.2	7.0	95	72	73	127	42	60
Firs, white (ave. of 4 species[10])	45	.35	41	26	3.8	7.9	110	72	76	141	41	66
Hemlock, eastern (Tsuga canadensis)	20	.38	50	28	3.0	6.8	98	72	79	121	51	67
Hemlock, mountain (Tsuga mertensiana)	10	.43	44	33	4.4	7.4	114	81	88	131	64	99
Hemlock, western (Tsuga heterophylla)	18	.38	41	29	4.3	7.0	120	74	84	144	50	73
Juniper, alligator (Juniperus pachyphloea)	3	.48	42	36	2.7	3.6	73	63	76	60	107	79
Larch, western (Larix occidentalis)	13	.48	48	36	4.2	8.1	129	89	104	153	64	81
Pine, jack (Pinus banksiana)	5	.39	50	30	3.4	6.5	102	64	73	111	48	78
Pine, jeffrey (Pinus jeffreyi)	5	.37	47	28	4.4	6.7	103	68	71	116	44	63
Pine, limber (Pinus flexilis)	2	.37	39	28	2.4	5.1	80	69	69	107	39	54
Pine, loblolly (Pinus taeda)	10	.50	54	38	5.5	7.5	127	93	104	166	62	93
Pine, lodgepole (Pinus contorta)	28	.38	39	29	4.5	6.7	114	67	74	128	41	60

[10] *Abies grandis*, *A. nobilis*, *A. amabilis*, and *A. concolor*.

TABLE 1.—*Average comparative properties of the clear wood of species grown in the United States*—Continued

[For definition of terms and discussion of table see "Explanation of Table 1" in text]

Common and botanical name of species	Trees tested	Specific gravity, oven dry, based on volume when green	Weight per cubic foot		Shrinkage from green to oven-dry condition based on dimensions when green			Composite strength values				
			Green	At 12 per cent moisture content	Radial	Tangential	Volumetric (composite value)	Bending strength	Compressive strength (endwise)	Stiffness	Hardness	Shock resistance
												
1	2	3	4	5	6	7	8	9	10	11	12	13
Softwoods—Continued.	*Number*		*Pounds*	*Pounds*	*Per cent*	*Per cent*	*Comparative figure*	*Comparative figure*	*Comparative figure*	*Comparative figure*	*Comparative figure*	*Comparative figure*
Pine, longleaf (Pinus palustris)	34	.55	50	41	5.3	7.5	124	106	123	189	76	103
Pine, mountain (Pinus pungens)	5	.49	54	37	3.4	6.8	107	91	93	151	64	92
Pine, northern white (Pinus strobus)	18	.34	36	25	2.3	6.0	83	63	67	119	35	55
Pine, Norway (Pinus resinosa)	5	.44	42	34	4.6	7.2	116	85	91	163	46	84
Pine, pitch (Pinus rigida)	10	.45	50	34	4.0	7.1	110	80	76	146	56	96
Pine, pond (Pinus rigida serotina)	5	.50	49	38	5.1	7.1	115	89	103	154	64	90
Pine, sand (Pinus clausa)	5	.45	38	34	3.9	7.3	104	86	89	135	63	86
Pine, shortleaf (Pinus echinata)	12	.49	51	38	5.1	8.2	128	97	104	170	68	111
Pine, slash (Pinus caribaea)	10	.64	56	48	5.8	8.2	131	116	126	195	93	105
Pine, sugar (Pinus lambertiana)	9	.35	51	25	2.9	5.6	79	64	68	112	38	55
Pine, western white (Pinus monticola)	14	.36	35	27	4.1	7.4	118	69	75	137	35	65
Pine, western yellow (Pinus ponderosa)	31	.38	45	28	3.9	6.3	97	65	59	112	41	58
Piñon (Pinus edulis)	3	.50	51	37	4.6	5.2	99	60	75	108	73	65
Redwood [11] (Sequoia sempervirens)	5	.41	55	30	2.7	4.2	65	90	104	134	59	70
Spruce black (Picea mariana)	5	.38	32	28	4.1	6.8	112	68	70	143	40	82
Spruce, Engelmann (Picea engelmannii)	10	.31	39	23	3.4	6.6	102	55	57	100	32	45
Spruce, red (Picea rubra)	11	.38	34	28	3.8	7.8	117	72	80	138	41	68
Spruce, Sitka (Picea sitchensis)	25	.37	33	28	4.3	7.5	116	72	75	144	44	76
Spruce, white (Picea glauca)	15	.37	35	28	4.7	8.2	134	68	70	123	37	67
Spruces, (ave. of red, white, and Sitka [12])	51	.37	34	28	4.3	7.7	121	71	74	136	42	71

Tamarack (Larix laricina)	5	.49	47	37	3.7	7.4	128	84	96	147	53	85
Yew, Pacific (Taxus brevifolia)	5	.60	54	44	4.0	5.4	96	115	112	121	138	170
Percentage estimated probable variation of species average when based on 5 trees [13]	----	2.1	----	----	5.2	4.0	3.9	2.5	3.3	3.2	2.8	5.0
Percentage estimated probable variation of an individual piece	----	8	----	----	----	----	12	12	14	18	16	20

[11] The trees on which these values are based were somewhat higher in density than the general average for the species. It is, therefore, very probable that further tests which are now under way will slightly lower the present figures, although it is not expected that this will necessitate any change in the working stresses recommended for structural timber as given in Table 2.

[12] *Picea rubra*, *P. sitchensis*, and *P. glauca*.

[13] For percentage estimated variation of species when based on different number of trees see Table 6.

VARIABILITY

Variability is common to all materials. If one tests pieces of wire from a roll, the loads necessary to pull the wire apart will vary for the different pieces. In the same way, the breaking strengths of different pieces of the same kind of string or rope will not be the same. Materials, however, differ considerably in the amount of variation or the spread of values.

Everyone who has handled and used lumber has observed that no two pieces, even of the same species, are exactly alike. The differences most commonly recognized are in the appearance, but differences in the weight and in the strength properties are of even greater importance. Fortunately, appearance and weight are related to strength. This relation, which is very definite in some species, affords the basis of grading and selecting wood for strength.

In determining the strength properties of wood many individual specimens of each species are tested, and consequently many individual test values are obtained. It would be very laborious and confusing to present the values for each individual test. The figures in Table 1 are, therefore, average values from tests on specimens selected to represent the different species of wood.

The strength properties of individual pieces may vary considerably from the averages shown. Therefore, the fact that one species of wood averages higher than another in a certain property does not mean that every piece of that species will be better than every piece of the other species. A percentage figure is shown in the last line of Table 1 to indicate the range above and below the average which may be expected to include half of all the material of a species.

Because of the variation among individual specimens, the more tests made on a species the greater is the probability that the average obtained will represent the true average. The number of test specimens must be limited, however, because of the expense of determining the properties, and as a result units of five trees have, in general, been used to obtain the test figure for a wood from any one site or locality.

For the more important species, two and often more 5-tree units representing different localities have been tested. The tests vary in number from about a hundred to many thousand for a species, making a total of over a quarter million for all species studied. The present figures (Table 1) are the best available determinations of the true averages, although the figures for the less important species, which are based on fewer tests, would be more subject to change on additional testing than those for the common species.

For the foregoing reason, and since individual pieces of wood or lots of material purchased for any use vary from the averages, too much emphasis should not be placed on small differences in average figures. The importance of such differences, however, will depend largely on the use to which the wood is put. Detailed information on the range of variations to be expected and a discussion of their significance are presented in Appendix 3.

SELECTION FOR PROPERTIES

The fact that a piece of wood differs in properties from another of the same species often makes it more suitable for a given use. This suggests the possibility of selecting pieces to meet given requirements. For example, selection may be made at the sawmill so that the heavier, harder, and stronger pieces go into structural timbers, flooring, or other uses for which the higher measure of these properties particularly adapt them, while the lightweight pieces may preferably be used for such purposes as trim or heat insulation; or selection may be made at the lumber yard when material of either high or low weight is required. By means of selective methods the variability of wood can be made an asset. Selection on the basis of freedom from defects is a common practice. Selection on the basis of quality of clear wood is much less common, but is frequently very desirable.

Aside from actual strength tests, the specific gravity or density gives the best indication of the strength properties of any piece of wood. Within any species there exists a relatively small range in the strength of pieces of like density.

When different species are considered, the range in strength for pieces of like density may be quite large. To illustrate the difference in density-strength relations between species, consider the values for Douglas fir (coast type) and red gum in Table 1. These woods are about equal in weight when dry per unit volume as shown by their specific gravities, but Douglas fir averaged 39 per cent higher in compressive strength than red gum and 18 per cent lower in shock resistance.

It may be shown, likewise, that certain species of wood of medium density are equal in some properties to species of higher density. Douglas fir (coast type) with only three-fourths the density of commercial white oak is about equal to the oak in bending strength and compressive strength, and excels it in stiffness. Hence, Douglas fir is higher for its weight in these properties than white oak. In hardness and shock resistance, however, white oak averages much higher than Douglas fir.

HOW TO USE THE COMPARATIVE STRENGTH FIGURES

The strength figures in Table 1 (columns 9 to 13) are not percentages but are index numbers. They have no significance other than to give relative position in comparing species of wood for any specific use with respect to the several properties listed. The figures on weight and radial and tangential shrinkage, on the other hand, are in unit terms which can be used directly in making calculations or estimates.

In order properly to interpret and apply the figures in a comparison of species, one should be familiar with the requirements of his particular use. Unfortunately, no thorough study has been made to determine the properties essential to most uses, although in many cases much general information is available concerning them. Long usage has in some cases established what properties are required, but opinion frequently differs as to their importance. The most effective application of the figures, therefore, calls for judgment.

WORKING STRESSES RECOMMENDED FOR COMPARING STRUCTURAL MATERIAL

For comparing structural material of grades in which the size, location, and number of defects are limited with reference to their effect on strength, the allowable working stresses of Table 2 (Appendix 1) are recommended in preference to the figures of Table 1. However, the figures of Table 1, although primarily for the comparison of species in the form of clear lumber, are second in importance only to permissible defects [5] in deriving safe working stresses (*S*). Other factors, such as differences in the variability of the clear wood, tendency of defects to develop in service, and tendency to run high or low in the grade, and the like, are, of course, also taken into account in determining working stresses.

Table 2 presents working stresses for a number of common species. Should working stresses be required for other species, they may be derived through the joint use of Tables 1 and 2. The method suggested is to assign to the species under consideration working stresses 10 per cent lower than are given in Table 2 for species having about the same comparative strength values. The 10 per cent reduction is suggested to provide for safety and to allow for the various factors that must be taken into account in assigning safe working stresses. If, however, the species on which working stresses are desired is known to be quite similar in all respects to the species used for comparison, the 10 per cent reduction need not be applied. (See example p. 18.)

EXAMPLES OF GENERAL COMPARISONS

1. Everyone knows how important strength is for shovel handles. Suppose that a manufacturer who has been using ash satisfactorily for shovel handles is offered a supply of hackberry as an alternate. How does hackberry compare with ash? Assuming the most important properties required in a shovel handle to be bending strength, hardness, shock resistance, lightness, and freedom from warping, then from Table 1 the following tabulation may be made:

	Bending strength	Hardness	Shock resistance	Weight (specific gravity)	Volumetric shrinkage
Ash, commercial white	110	108	130	0.54	126
Hackberry	76	74	145	.49	138

The lighter weight of hackberry would be an advantage. With the exception of shock resistance, hackberry is decidedly inferior to commercial white ash in the other properties listed. It would not only break more easily in bending, but because of its lower hardness it would also be more subject to mashing at the bolts or rivets. In addition, the slightly higher shrinkage indicates it would not stay in place so well as ash. The conclusion to be drawn from the comparison is not that hackberry is entirely unusable for shovel handles, but rather that average material could not be expected to be as satisfactory as ash.

[5] Tests on structural timbers have established the effect of knots and other defects on strength, and have afforded the basis for preparing structural grades which develop any desired proportion of the strength of the clear wood.

If the inducement is sufficient the user may feel justified in accepting a lower standard of service. By selection methods, however (see p. 15), a wood which averages weaker can frequently be used without lowering the standard of service. If the difference in the average strength of two species is not too great, individual pieces of the weaker species can be obtained which will exceed in strength properties the average of the stronger one. Thus, carefully selected hackberry would make an acceptable shovel handle and one that would be unquestionably better than a handle of poor-quality ash.

This comparison is based on the assumption that the two species would be used in the same sizes. It is possible to make up for certain limitations in the strength of a weaker species of wood by increasing the dimensions of the part. Redesign involving change of size, however, may not always be feasible. In shovel handles the diameter must be such that the handle can be grasped readily. When the usable size is fixed, only species that are strong enough in this size are acceptable. Such practical questions as size must be considered in any change of design or substitution of species.

2. As another example of the practical application of the figures in Table 1, let it be required to compare sugar maple, beech, and yellow birch for flooring. These species are similar in structure in that they all belong to a class known as diffuse-porous woods, which do not have a marked difference in spring wood and summer wood. Among the properties of importance in flooring are shrinkage and hardness. For a comparison of these properties the following figures may be taken from Table 1:

	Radial shrinkage	Tangential shrinkage	Volumetric shrinkage	Hardness
Sugar maple	4.9	9.5	147	115
Beech	5.1	11.0	162	96
Yellow birch	7.2	9.2	166	86

From the figures listed sugar maple, on the average, would be expected to show slightly less change of dimension with given moisture changes than beech or yellow birch, and to offer greater resistance to indentation, wear, and scratching. There is little difference in the volumetric shrinkage figures for beech and yellow birch. Beech, however, averages somewhat higher in hardness.

The comparisons just given do not consider appearance. Since all three species rank relatively high in the physical properties listed, choice may frequently be based on other factors, such as color or price.

3. Just as the figures of Table 1 may be used to select species which are high in certain strength properties, they also serve in choosing the woods to use where ease of manufacture, which is associated with low mechanical properties, is desired. For example, it is generally recognized that wood used to make patterns for metal castings should be readily fashioned to any desired shape and should not change in size. Northern white pine admirably meets these requirements, and has for years been a standard wood for patterns that do not receive such continual use as to require a harder wood. Suppose that because of the scarcity of northern white pine other species are desired. From Table 1 it may be noted that sugar pine and western white pine are much like northern white pine in those

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properties which seem to be of first importance, and would, consequently, be among the best species to consider for pattern stock.

4. The preceding examples involve comparisons of species of wood for uses where clear straight-grained material is required. For structural material of grades in which the size, location, and number of defects are limited with reference to their effect on strength by the basic provisions for American lumber standards (*8*), the sizes should be determined and comparisons made as far as possible by means of the safe working stresses of Table 2, Appendix 1, except where these are in conflict with stresses fixed by law. The safe working stresses of Table 2 take into account not only the weakening effect of the defects permitted in the grade, variability, duration of stress, and similar factors, but also the natural chracteristics of the species.

When working stresses or comparisons for structural purposes are desired among species not listed in Table 2, the method suggested on page 16 involving the joint use of Tables 1 and 2 may be applied. Suppose, for instance, that working stresses are desired for lodgepole pine. From Table 1 it may be noted that in bending strength, compressive strength (endwise), stiffness, and hardness, lodgepole pine falls within the range of average values for northern white pine, western white pine, western yellow pine, and sugar pine. For the same grades and conditions of use, therefore, lodgepole pine may be assigned working stresses 10 per cent lower than the values given in Table 2 for northern white pine, without further detailed knowledge of the species. If the fact is known that lodgepole pine is similar to northern white pine in other respects than strength of the clear wood, the 10 per cent reduction in working stresses may be omitted. Hence, if lodgepole pine were included in Table 2, it would be listed with the species which take the same working stresses as northern white pine.

SPECIAL USES

Innumerable comparisons can readily be made from the figures of Table 1. However, there is still another useful type of comparison, namely, that in which several of the different comparative strength properties are combined to give a single figure. This offers an effective way of handling certain problems and has been used in comparing woods for railroad ties and for airplane wing beams, as well as in classifying species for ladder construction. To combine properly the comparative figures of Table 1, however, requires an accurate basic knowledge of the figures, as well as judgment of their relative importance in the proposed use. Because of the complicated nature of these comparisons their further consideration is postponed to Appendix 2.

EXPLANATION OF TABLE 1

(See Table, 1, p. 6.)

COLUMN 1. COMMON AND BOTANICAL NAME OF SPECIES

Column 1 gives the common and botanical names of the various species of wood as adopted by the Forest Service (*7*).

There are a number of closely related species that are very similar in their mechanical properties that can not be distinguished from an examination of the wood alone and that are generally marketed as a group under a single common name, as, for example, commercial white ash. For several such groups the values listed for the individual species comprising the group have been averaged to give a single figure for each property. The species combined are indicated for each group.

COLUMN 2. TREES TESTED

The number of trees tested shows the extent of the work done on each species, and is an aid in estimating the reliability of the average figures. The greater the number of trees tested, the closer may the figures be expected to approach the true average of the species. (See discussion under Variability, p. 14.)

COLUMN 3. SPECIFIC GRAVITY

Specific gravity is the relation of the weight of a substance to that of an equal volume of water. The specific-gravity figures in column 3 are based on the weight of the oven-dry wood and its volume when green.

Column 3 affords an excellent means for making comparisons of the weight of the dry wood of different species. The specific-gravity value gives a direct indication of the amount of wood substance in a given volume.

The weight of oven-dry wood in pounds per cubic foot (based on the volume when green) can be calculated from column 3 by multiplying the specific gravity by 62.4, the weight of water in pounds per cubic foot. The difference between the weight of any oven-dry wood calculated in this manner and the corresponding weight when green is the average weight of moisture present per cubic foot in the unseasoned wood just as it comes from the saw. The moisture present in green wood is of course subject to large variations.

COLUMNS 4 AND 5. WEIGHT PER CUBIC FOOT

Ordinarily, wood is spoken of as "dry" or as "green" or "wet." In order to be specific, various stages of drying or dryness must be recognized in establishing the weight, not only because of the effect of the moisture content on weight, but because of change in volume with moisture changes. The weights of wood at two important stages are given in columns 4 and 5.

When wood is green,[6] or freshly cut, it contains a considerable quantity of water. After wood has dried by exposure to the air until its weight is practically constant, it is said to be "air dry." If dried in an oven at 212° F. until all moisture is driven off, wood is "oven dry."

The weight when green as given in column 4 includes the moisture present at the time the trees were cut, and is based on the average of heartwood and sapwood pieces as represented by test specimens taken from pith to circumference. The moisture content of green timber varies greatly among different species. Thus, in white ash it averages

[6] Green wood usually contains "absorbed" water within the cell walls and "free" water in the cell cavities. In drying, the free water from the cell cavities is the first to be evaporated. The fiber-saturation point is that point at which no water exists in the cell cavities of the timber but at which the cell walls are still saturated with moisture. The fiber-saturation point varies with the species. The ordinary proportion of moisture—based on the weight of the dry wood—at the fiber-saturation point is from 22 to 30 per cent. As a rule, the strength properties of wood begin to increase, and shrinkage begins to occur when the fiber-saturation point is reached in seasoning.

42 per cent, whereas in chestnut it averages 122 per cent.[7] The moisture content also varies among different trees of the same species and among different parts of the same tree. In most softwood species the sapwood has more moisture than the heartwood. For instance, the sapwood of southern yellow pine usually contains moisture in excess of 100 per cent, whereas the heartwood has only about 30 to 40 per cent moisture. Particularly in these species which have a higher moisture content in the sapwood, large variations in weight when green may occur, depending on the proportion of sapwood. Since young softwood trees contain a larger proportion of sapwood than old trees, their wood averages heavier when green.

The amount of moisture in air-dried wood depends on the size and form of the pieces and on the climate. The species vary widely in the rate at which they give off moisture in drying, and also in the rate at which they take up moisture during periods of wet or damp weather. The average air-dry condition reached in the northern Central States in material 2 inches and less in thickness, when sheltered from rain and snow and without artificial heating, is a moisture content of about 12 per cent. The figures given in column 5 are for this moisture content. The moisture content of thoroughly air-dry material may be 3 to 5 per cent higher in humid areas, and in very dry climates, as much lower. Large timbers will have a higher average moisture content when thoroughly air dry than small pieces.

When the moisture content in comparatively dry wood changes, two actions which counteract one another take place, so that the unit weight or weight per cubic foot changes but little. Thus, if the wood dries further, the weight per cubic foot tends to become lower because of loss in moisture, while at the same time it tends to increase because shrinkage causes more wood substance to occupy the same space. Conversely, if wood absorbs moisture both the weight and volume are increased.

An approximate method for estimating the weight of wood per cubic foot at a moisture content near 12 per cent is to regard a one-half per cent change in weight as accompanying a 1 per cent change in moisture content. For example, wood at 8 per cent moisture content weighs about 2 per cent less than at 12 per cent, whereas at 14 per cent moisture content the weight is about 1 per cent greater than at 12 per cent.

COLUMNS 6, 7, AND 8. SHRINKAGE

Shrinkage across the grain (in width and thickness) results when wood loses some of the absorbed moisture.[6] Likewise, swelling occurs when dry or partially dry wood is soaked or when it takes up moisture from the air, similar to a sponge getting larger when wet. Shrinkage of wood in the direction of the grain (length) is usually too small to be of practical importance.[8]

The figures in columns 6 and 7 are average values of the measured radial and tangential shrinkages of small clear specimens in drying from a green to an oven-dry condition. The radial shrinkage is that across the annual growth rings in a cross section, such as in the width

[6] See footnote 6 on page 19.

[7] The moisture content of wood is commonly expressed as a percentage of the weight of the oven-dry or moisture-free wood. If a specimen from an air-dry board weighed 112 grams immediately after being cut, and after oven drying weighed 100 grams, it is said to have contained 12 per cent moisture. In other words, the moisture content is the original weight minus the oven-dry weight divided by the oven-dry weight, which may be expressed as a percentage by multiplying by 100.

[8] Appreciable longitudinal shrinkage is associated with "compression wood," and other abnormal wood structure. (See p. 34.)

of a quarter-sawed board; the tangential shrinkage is that parallel to the annual-growth rings in a cross section, such as in a flat-sawed board.

Column 8 lists figures on the relative shrinkage in volume from the green to the oven-dry condition for the various species. These figures are computed from actual volume measurements of small clear specimens, combined with actual radial and tangential shrinkage measurements, the results of which are recorded in columns 6 and 7. Volumetric shrinkage values that are comparable with those of columns 6 and 7 may be obtained from column 8 by dividing the figures listed by 10.

The shrinkage which will take place in any piece of wood depends on a great many factors, some of which have not been thoroughly studied. In all species the tangential shrinkage is more than the radial, the average ratio being about 9 to 5. Hence, quarter-sawed (edge-grained) boards shrink less in width but more in thickness than flat-sawed boards. The ratio of radial to tangential shrinkage for a species is of value in determining the desirability of using quarter-sawed wood and indicates the checking which may be expected in large pieces containing pith. Ordinarily, the less the difference between radial and tangential shrinkage, the less is the tendency of such pieces to check in drying.

Air-dry wood is continually taking on and giving off moisture with changing weather or heating conditions. Time is required for these moisture changes, however, so there is always a lag between changes in the humidity of the air and their full effect on the moisture condition of the wood. The lag is greater in some species than in others. As a result some species having a large shrinkage from the green to the oven-dry condition do not cause as much inconvenience in use as woods with lower shrinkage, because they do not follow atmospheric changes so closely. The figures given do not take into account the readiness with which the species take on and give off moisture, and therefore should be considered as the relative shrinkage between woods after long exposure to fairly uniform atmospheric conditions or after the same change in moisture content.

COLUMN 9. BENDING STRENGTH

Column 9 gives figures on bending strength. Bending strength is a measure of the load-carrying capacity of beams, which are usually horizontal members resting on two supports. Examples of members subjected to bending are stadium seats, scaffold platforms, ladder steps, shovel handles, girders, bridge stringers, and floor joists. The figures for bending strength afford a direct comparison of the breaking strength of clear wood of the various species. They may also be used under certain conditions for comparing structural material in which defects are limited with reference to their effect on strength. (See p. 16.)

Bending strength in addition to other properties is essential in many uses, such as airplane-wing beams or spars, telephone and telegraph poles, mine lagging, railway ties, ladder side rails, pike poles, insulator pins, and wagon tongues. It is of less importance in studding, flooring, and subflooring.

If a species is low in bending strength it does not necessarily follow that it is unsuited for uses requiring this property. It does indicate, however, that larger sizes are required to carry given loads than are required for species which rank higher in this property.

COLUMN 10. COMPRESSIVE STRENGTH (ENDWISE)

The figures of column 10, compressive strength, apply to comparatively short compression members. Compression members are generally square or circular in cross section, usually upright, supporting loads which act in the direction of the length. The loads tend to shorten the piece. Some examples of endwise-compression members are upright members in grand stands, mine props, vertical pieces which support girders in buildings, and vertical scaffold frame pieces.

When compression members are of a length about 11 times the least dimension, the slenderness has increased to such an extent that stiffness begins to be a factor in the strength. The quantities in column 10 are applicable to short columns having a ratio of length to least dimension of 11 (or less) to 1.

If one species is lower in compressive strength than another, the difference may be compensated by using a member of correspondingly larger cross-sectional area.

COLUMN 11. STIFFNESS

When any weight or load is placed on a member, a deflection is produced. Stiffness is a measure of the resistance to deflection and relates particularly to beams. It is one of the properties required in ladder side rails, golf shafts, floor joists, girders, rafters, and other beams as well as in long columns. The figures in column 11 give the average stiffness of the different species. Generally beams of species having high stiffness values deflect less under a load than the same sized beams of species having lower stiffness values. Difference in stiffness between species may be compensated by changing the size of members.

COLUMN 12. HARDNESS

Hardness is the property which makes a surface difficult to dent or scratch. The harder the wood, other things being equal, the better it resists wear, the less it crushes or mashes under loads, and the better it can be polished; on the other hand, the more difficult it is to cut with tools, the harder it is to nail and the more it splits in nailing. Hardness is desirable in such uses as flooring, furniture, railroad ties, and small handles. Some lack of hardness, that is, a degree of softness, is particularly desirable for uses such as drawing boards. The greater the figure given in the table, the greater the hardness of the wood.

There is a pronounced difference in hardness between the spring wood and the summer wood of some species, such as southern yellow pine and Douglas fir. In these species the summer wood is the denser, darker-colored portion of the annual growth ring. In such woods differences in surface hardness occur at close intervals on a piece, depending on whether spring wood or summer wood is encountered. In woods like maple, which do not have pronounced spring wood and summer wood, the hardness of the surface is more nearly uniform.

COLUMN 13. SHOCK RESISTANCE

Shock resistance is the capacity to withstand suddenly applied loads. Hence, woods high in shock resistance withstand repeated shocks, jars, jolts, and blows such as are given ax handles, wheel spokes, and golf shafts. Hickory possesses this shock resistance property to the highest degree of any of the common and well-known woods. The greater the figure in column 13, the greater is the shock resistance of the species.

PERCENTAGE ESTIMATED PROBABLE VARIATION

The percentage figures in the bottom two lines of Table 1, exclusive of footnotes, offer a means of estimating the variability, a detailed discussion of which is given in the Appendix 3.

The percentage figures in the last line of Table 1 indicate the variation, above and below the average, which may be expected to include half of all the material of a species. For example, consider the bending strength of red alder in Table 1. The bending strength (column 9) is 76, and the variation of an individual piece is 12 per cent. From these figures it may be estimated that the bending strength of one-half of the red alder would fall within the limits 67 and 85. The approximate proportion of material of a species falling within certain other percentages of the Table 1 values may be estimated on the basis of the following relations:

75 per cent is within 1.71 times the percentage probable variation.
82 per cent is within 2.00 times the percentage probable variation.
90 per cent is within 2.44 times the percentage probable variation.
96 per cent is within 3.00 times the percentage probable variation.

The percentage figures in the next to the last line indicate that there is an even chance that the true average is within these percentages of the figures in Table 1. The percentages given apply to species which are represented by five trees. Percentages applying to species represented by various numbers of trees from 1 to 50 are presented in Table 6.

Mortality statistics upon which insurance rates are based tell very closely how many men of any large group will live to be a certain age, but they do not enable one to say whether John Doe at that age will be included among the living. In a similar manner, the variability figures given in the next to the last line of Table 1 permit one to estimate how many of the species of wood will have their averages raised or lowered by a specified amount by additional tests, but one can not say that red alder or any other designated species will be raised by this amount.

APPENDIX 1

For the aid of engineers, architects, and others who desire additional information on the application and derivation of the figures in Table 1 the following information is given. A study of the three appendixes is not essential for the use of Table 1 for comparative purposes.

STRENGTH OF STRUCTURAL MATERIAL

The figures in Table 1 are most directly applicable to the comparison of species for uses requiring wood free from defects. For structural material of grades in which the size, location, and number of defects are limited with reference to their effect on strength, the relative strengths of the species are better represented by allowable working stresses used in design. Working stresses for select and common structural grades conforming to the basic provisions of the American lumber standards are given in Table 2. They are technical in nature and have been arrived at from a consideration of the strength and variability of the clear wood, the relation of density to strength, the effect of defects in structural sizes, the effect of long-continued loading, and the inherent characteristics of the species, such as prevalence of knot clusters, tendency to check in seasoning, and prevalence of shakes. The figures in Table 1 are the average results of tests on clear wood of the different species; those of Table 2 are assigned values, based not only on tests, but on experience and judgment.

TABLE 2.—*Working stresses for timber conforming to the basic provisions for select and common structural material of American lumber standards* [1]

[As recommended by the Forest Products Laboratory, Forest Service, United States Department of Agriculture]

Species	Fiber stress in bending [2]									
	Continuously dry		Occasionally wet but quickly dried				More or less continuously damp or wet			
	All thicknesses		Material 4 inches and thinner		Material 5 inches and thicker		Material 4 inches and thinner		Material 5 inches and thicker	
	Select grade	Common grade	Select grade	Common grade	Select grade	Common grade	Select grade	Common grade	Select grade	Common grade
	Lbs. per sq. in.	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*
Ash, black	1,000	800	800	680	900	720	710	600	800	640
Ash, commercial white	1,400	1,120	1,070	910	1,200	960	890	760	1,000	800
Aspen and largetooth aspen	800	640	580	490	650	520	440	370	500	400
Basswood	800	640	580	490	650	520	440	370	500	400
Beech	1,500	1,200	1,150	980	1,300	1,040	890	760	1,000	800
Birch, paper	900	720	670	570	750	600	530	450	600	480
Birch, yellow and sweet	1,500	1,200	1,150	980	1,300	1,040	890	760	1,000	800
Cedar, Alaska	1,100	880	890	760	1,000	800	800	680	900	720
Cedar, western red	900	720	710	600	800	640	670	570	750	600
Cedar, northern and southern white	750	600	580	490	650	520	530	450	600	480
Cedar, Port Orford	1,100	880	890	760	1,000	800	800	680	900	720
Chestnut	950	760	760	650	850	680	620	530	700	560
Cottonwood, eastern and black	800	640	580	490	650	520	530	450	600	480
Cypress, southern	1,300	1,040	980	830	1,100	880	800	680	900	720
Douglas fir (western Washington and Oregon type) [3]	1,600	1,200	1,233	983	1,387	1,040	948	756	1,067	800
Douglas fir (dense) [3]	1,750	1,400	1,349	1,147	1,517	1,213	1,037	882	1,167	933
Douglas fir (Rocky Mountain type)	1,100	880	800	680	900	720	620	530	700	560
Elm, rock	1,500	1,200	1,150	980	1,300	1,040	890	760	1,000	800
Elm, slippery and American	1,100	880	800	680	900	720	710	600	800	640
Fir, balsam	900	720	670	570	750	600	530	450	600	480
Fir, commercial white	1,100	880	800	680	900	720	710	600	800	640
Gum, red, black, and tupelo	1,100	880	800	680	900	720	710	600	800	640
Hemlock, eastern	1,100	880	800	680	900	720	710	600	800	640
Hemlock, western	1,300	1,040	980	830	1,100	880	800	680	900	720
Hickory (true and pecan)	1,900	1,520	1,330	1,130	1,500	1,200	1,070	910	1,200	960

Larch, western	1,200	960	980	830	1,100	880	800	680	900	720
Maple, sugar and black	1,500	1,200	1,150	980	1,300	1,040	890	760	1,000	800
Maple, red and silver	1,000	800	800	680	900	720	620	530	700	560
Oak, commercial red and white	1,400	1,120	1,070	910	1,200	960	890	760	1,000	800
Pine, southern yellow [3]	----------	1,200	----------	983	----------	1,040	----------	756	----------	800
Pine, southern yellow (dense) [3]	1,750	1,400	1,349	1,147	1,517	1,213	1,037	882	1,167	933
Pine, northern white, western white, western yellow, and sugar	900	720	710	600	800	640	670	570	750	600
Pine, Norway	1,100	880	[illegible]	760	1,000	800	710	600	800	640
Poplar, yellow	1,000	800	[illegible]	680	900	720	710	600	800	640
Redwood	1,200	960	[illegible]	760	1,000	800	710	600	800	640
Spruce, red, white, and Sitka	1,100	880	800	680	900	720	710	600	800	640
Spruce, Engelmann	750	600	580	490	650	520	440	370	500	400
Sycamore	1,100	880	800	680	[illegible]	720	710	600	800	640
Tamarack (eastern)	1,200	960	980	830	[illegible]	880	800	680	900	720

[1] American lumber standards: Basic provisions for American lumber standards grades are published by the United States Department of Commerce in Simplified Practice Recommendation No. 16, Lumber, revised July 1, 1926; specifications for grades conforming to American lumber standards are published in the 1927 Standards of the Amer. Soc. for Testing Materials, and in Amer. Ry. Engineering Assoc. Bul., vol. 30, No. 314, dated February, 1929.

[2] Stress in tension: The working stresses recommended for fiber stress in bending may be safely used for tension parallel to grain.

[3] Exact figures given: In order to preserve the exact numerical relations among working stresses for grades involving rate of growth and density requirements the values for Douglas fir (western Washington and Oregon type) and for southern yellow pine have not been rounded off, as have the values for the other species.

TABLE 2.—*Working stresses for timber conforming to the basic provisions for select and common structural material of American lumber standards*—Continued

Species	Compression perpendicular to grain, select and common grades			Horizontal shear [4]		Compression parallel to grain (short columns having ratio of length to least dimension of 11 or less)						Average modulus of elasticity [5]
	Continuously dry	Occasionally wet but quickly dried	More or less continuously damp or wet	Not varied with conditions of exposure		Continuously dry		Occasionally wet but quickly dried		More or less continuously damp or wet		Not varied with conditions of exposure or with grade
				Select grade	Common grade	Select grade	Common grade	Select grade	Common grade	Select grade	Common grade	
	Lbs. per sq. in.	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*
Ash, black	300	200	150	90	72	650	520	550	440	500	400	1,100,000
Ash, commercial white	500	375	300	125	100	1,100	880	1,000	800	900	720	1,500,000
Aspen and largetooth aspen	150	125	100	80	64	700	560	550	440	450	360	900,000
Basswood	150	125	100	80	64	700	560	550	440	450	360	900,000
Beech	500	375	300	125	100	1,200	960	1,100	880	900	720	1,600,000
Birch, paper	200	150	100	80	64	650	520	550	440	450	360	1,000,000
Birch, yellow and sweet	500	375	300	125	100	1,200	960	1,100	880	900	720	1,600,000
Cedar, Alaska	250	200	150	90	72	800	640	750	600	650	520	1,200,000
Cedar, western red	200	150	125	80	64	700	560	700	560	650	520	1,000,000
Cedar, northern and southern white	175	140	100	70	56	550	440	500	400	450	360	800,000
Cedar, Port Orford	250	200	150	90	72	900	720	825	660	750	600	1,200,000
Chestnut	300	200	150	90	72	800	640	700	560	600	480	1,000,000
Cottonwood, eastern and black	150	125	100	80	64	700	560	550	440	450	360	900,000
Cypress, southern	350	250	225	100	80	1,100	880	1,000	800	800	640	1,200,000
Douglas fir (western Washington and Oregon type) [3]	[6] 347	[6] 240	[6] 213	90	72	1,173	880	1,067	800	907	680	1,600,000
Douglas fir (dense) [3]	379	262	233	105	84	1,283	1,027	1,167	933	992	793	1,600,000
Douglas fir (Rocky Mountain type)	275	225	200	85	68	800	640	800	640	700	560	1,200,000
Elm, rock	500	375	300	125	100	1,200	960	1,100	880	900	720	1,300,000
Elm, slippery and American	250	175	125	100	80	800	640	750	600	650	520	1,200,000
Fir, balsam	150	125	100	70	56	700	560	600	480	500	400	1,000,000
Fir, commercial white	300	225	200	70	56	700	560	700	560	600	480	1,100,000
Gum, red, black, and tupelo	300	200	150	100	80	800	640	750	600	650	520	1,200,000
Hemlock, eastern	300	225	200	70	56	700	560	700	560	600	480	1,100,000
Hemlock, western	300	225	200	75	60	900	720	900	720	800	640	1,400,000
Hickory (true and pecan)	600	400	350	140	112	1,500	1,200	1,200	960	1,000	800	1,800,000

Larch, western	325	225	200	100	80	1,100	880	1,000	800	800	640	1,300,000
Maple, sugar and black	500	375	300	125	100	1,200	960	1,100	880	900	720	1,600,000
Maple, red and silver	350	250	200	100	80	800	640	700	560	600	480	1,100,000
Oak, commercial red and white	500	375	300	125	100	1,000	800	900	720	800	640	1,500,000
Pine, southern yellow [3]	(6)	(6)	(6)	----------	88	----------	880	----------	800	----------	680	1,600,000
Pine, southern yellow (dense) [3]	379	262	233	128	103	1,283	1,027	1,167	933	992	793	1,600,000
Pine, northern white, western white, western yellow, and sugar	250	150	125	85	68	750	600	750	600	650	520	1,000,000
Pine, Norway	300	175	150	85	68	800	640	800	640	700	560	1,200,000
Poplar, yellow	250	150	125	80	64	800	640	700	560	600	480	1,100,000
Redwood	250	150	125	70	56	1,000	800	900	720	750	600	1,200,000
Spruce, red, white, and Sitka	250	150	125	85	68	800	640	750	600	650	520	1,200,000
Spruce, Engelmann	175	140	100	70	56	600	480	550	440	450	360	800,000
Sycamore	200	200	150	80	64	800	640	750	600	650	520	1,200,000
Tamarack (eastern)	300	225	200	95	76	1,000	800	900	720	800	640	1,300,000

[3] Exact figures given: In order to preserve the exact numerical relations among working stresses for grades involving rate of growth and density requirements the values for Douglas fir (western Washington and Oregon type) and for southern yellow pine have not been rounded off, as have the values for the other species.

[4] Joint details: The shearing stresses for joint details may be taken for any grades as 50 per cent greater than the horizontal shear values for the Select grade.

[5] Factors to be applied to average modulus of elasticity values: The values for modulus of elasticity are average for species and not safe working stresses. They may be used as given for computing average deflection of beams. When it is desired to prevent sag in beams values one-half those given should be used. In figuring safe loads for long columns values one-third those given should be used.

[6] Working stresses for the Common grade: The values given are for the Select grade. Working stresses in compression perpendicular to grain for the common grades of Douglas fir (western Washington and Oregon type) and southern yellow pine are 325, 225, and 200, respectively, for continuously dry, occasionally wet but quickly dried, and more or less continuously damp or wet conditions.

Since moisture influences the strength and the durability of wood, certain of the allowable working stresses are varied with the moisture conditions to which the timber will be exposed. All of the values in any one vertical column of Table 2 are on the same basis, and comparison of species may be made for the specified conditions of use. Allowable working stresses also depend on the grade of timber, as determined by the size and location of defects. The figures in Table 2 apply to timber conforming to the basic provisions of American lumber standards for select and common structural material (*2*, *8*).

EXPLANATION OF TABLE 2

(See Table 2, p. 24)

The following explanation of the values given in Table 2 may be of aid in their use:

Fiber stress in bending is a measure of the bending strength and is proportional to the load which can be carried by a beam of a given size. It is the same kind of strength measure as "Bending strength," as defined on page 21.

Compression perpendicular to grain is a measure of the bearing strength of wood across the grain. The surfaces of contact between a floor joist and a girder in a building are in compression perpendicular to grain. A high value in this property indicates that large loads across the grain can be supported without injury to the wood.

Horizontal shear is a measure of the capacity of a beam to resist slipping of the upper half upon the lower along the grain. This property becomes of great importance in beams whose depth is more than about one-twelfth the distance between supports.

Compression parallel to grain is a measure of the capacity of a short column to withstand loads acting in the direction of the length. It is similar to compressive strength (endwise) described on page 22. As the ratio of length to least dimension exceeds 11, the column becomes more slender and the capacity to carry end loads becomes more and more dependent upon stiffness until in long columns a length is reached where modulus of elasticity (stiffness) determines the load-carrying ability. The values given are consequently not applicable to columns in which the ratio of length to least dimension exceeds 11 to 1.

Modulus of elasticity is a measure of the stiffness or rigidity of a material. It indicates the resistance of a beam to deflection. It measures the same property as stiffness, described on page 22. The higher the modulus of elasticity, the less will be the deflection under a given load.

Working stresses for design will also be found in the report of the building code committee (*10*) and in standards of the American Society for Testing Materials (*2*).

APPENDIX 2

METHOD OF COMPUTING COMPARATIVE STRENGTH AND SHRINKAGE FIGURES IN TABLE 1

There is a need for a system of simplified strength figures for wood whereby comparisons may be made by the average wood user without employing highly technical terms. To supply this need the Forest Products Laboratory has developed a method of combining various test results into five composite strength values [9] for which data are given in Table 1. Any method of combining data must involve considerable judgment and must be somewhat empirical; consequently, differences of opinion may exist as to the best procedure. This appendix presents the method used in deriving the composite figures presented in Table 1.

The method involves (1) determining what properties should be combined in each composite figure; (2) reducing the values which have been obtained in different tests and which may be in various units to a common basis; (3) weighting the individual properties according to their estimated relative importance; and (4) weighting and combining the composite values for green and air-dry material in a single composite figure.

[9] These five strength values are bending strength, compressive strength (endwise), stiffness, hardness, and shock resistance.

PROPERTIES STUDIED

The fundamental data used as a basis for establishing the comparative figures were obtained from a comprehensive study begun by the Forest Service in 1910 to determine certain mechanical properties of woods grown in the United States (*4*). Data on 25 or more different properties were obtained from standard tests (*1*) on small clear specimens of both green and air-dry wood. These properties, listed under the standard tests used for determining them, are as follows:

1. Compression parallel to grain:
   Fiber stress at elastic limit.
   Maximum crushing strength.
   Modulus of elasticity.
2. Static bending:
   Fiber stress at elastic limit.
   Modulus of rupture.
   Modulus of elasticity.
   Work to elastic limit.
   Work to maximum load.
   Total work.
3. Impact bending:
   Fiber stress at elastic limit.
   Modulus of elasticity.
   Work to elastic limit.
   Height of drop of hammer causing complete failure.
4. Compression perpendicular to grain:
   Fiber stress at elastic limit.
5. Hardness (load required to imbed a ball 0.444 inch in diameter to one-half its diameter):
   Side grain (radial; tangential).
   End surface.
6. Shear parallel to grain:
   Shear stress (radial; tangential).
7. Cleavage:
   Load per inch of width (radial; tangential).
8. Tension perpendicular to grain:
   Tensile stress (radial; tangential).
9. Tension parallel to grain:
   Tensile stress.
10. Shrinkage:
    Radial.
    Tangential.
    Volumetric.
11. Specific gravity.

In several instances two or more of these tests yield data on the same property. For example, modulus of elasticity (stiffness) values are obtained from three different tests. Likewise hardness is indicated by both the compression perpendicular to grain and hardness tests. Bending strength is indicated by fiber stress at elastic limit in impact bending and by fiber stress at elastic limit and modulus of rupture in static bending. The comparative figures (Table 1) are the result of combining the values for each group of similar properties. However, several of the properties just listed were not used in determining the figures in Table 1.

REDUCTION FACTORS

On account of the differences in the nature, significance, and magnitude of these related test results they should not be combined by a direct average. Combining such properties as work to maximum load and total work in static bending (inch-pounds per cubic inch) and height of drop in impact bending (inches), therefore, can best be done by first applying "reduction factors" to adjust the properties to a common basis. Numerical values of the reduction factors were established from formulas expressing the relation of each property to specific gravity. The specific gravity-strength relations determined from the average data for different species are given in Table 3. The equations as tabulated have recently been reestablished on the basis of all available data and for this reason differ somewhat from those previously published (*5*).

TABLE 3.—*Specific gravity-strength relations* [1]

Property	Unit	Moisture condition	
		Green	Air dry (12 per cent moisture content)
Static bending:			
Fiber stress at elastic limit	Pounds per square inch	$10200G^{1.25}$	$10700G^{1.25}$
Modulus of rupture	do	$17600G^{1.25}$	$25700G^{1.25}$
Work to maximum load	Inch-pounds per cubic inch	$35.6G^{1.75}$	$32.4G^{1.75}$
Total work	do	$103G^{2}$	$72.7G^{2}$
Modulus of elasticity	1,000 pounds per square inch	$2360G$	$2800G$
Impact bending:			
Fiber stress at elastic limit	Pounds per square inch	$23700G^{1.25}$	$31200G^{1.25}$
Modulus of elasticity	1,000 pounds per square inch	$2940G$	$3380G$
Height of drop	Inches	$114G^{1.75}$	$94.6G^{1.75}$
Compression parallel to grain:			
Fiber stress at elastic limit	Pounds per square inch	$5250G$	$8750G$
Maximum crushing strength	do	$6730G$	$12200G$
Modulus of elasticity	1,000 pounds per square inch	$2910G$	$3380G$
Compression perpendicular to grain:			
Fiber stress at elastic limit	Pounds per square inch	$3000G^{2.25}$	$4630G^{2.25}$
Hardness:			
End	Pounds	$3740G^{2.25}$	$4800G^{2.25}$
Radial	do	$3380G^{2.25}$	$3720G^{2.25}$
Tangential	do	$3460G^{2.25}$	$3820G^{2.25}$

[1] The values listed in this table are to be read as equations, for example: Modulus of rupture for green material $=17600G^{1.25}$, where G represents the specific gravity, oven dry, based on volume at moisture condition indicated.

For shock resistance the basis to which all component properties are adjusted is work to maximum load in static bending. Consequently, the reduction factor for work to maximum load is unity. The reduction factor for height of drop in impact bending is determined by its average relation to work to maximum load. For green material, the reduction factor is

$$\frac{35.6G^{1.75}}{114G^{1.75}}=0.31$$ [10]

The reduction factor for total work in static bending is likewise determined by its average relation to work to maximum load, and for green material is

$$\frac{35.6G^{1.75}}{103G^{2}}=0.41$$ [10]

when $G=0.50$. Reduction factors applicable to the values for air-dry material were established in the same manner.

Unity reduction factors were used for each of the three determinations of modulus of elasticity in arriving at the composite stiffness figure, rather than the equation relations, since the modulus of elasticity values are all measures of the same property and are in like units.

WEIGHTING FACTORS

In combining the mechanical properties into comparative strength figures, weighting factors were applied according to the estimated relative importance of the properties entering into the combination. In bending strength, for example, modulus of rupture was given a weight of 2 as compared to each of the fiber stresses at elastic-limit values because of the greater importance of the modulus of rupture, and because the determinations of the elastic limit from curves are subject to the personal equation.

Table 4 lists the mechanical properties which enter into the composition of each comparative figure, together with the corresponding reduction and weighting factors.

[10] When the equations of properties to be combined involve different exponents, the reduction factor obtainable varies with the specific gravity (G). In such cases the reduction factor used corresponds to a specific gravity of 0.50, this being approximately the average specific gravity of all species tested.

TABLE 4.—*Properties combined and reduction and weighting factors used in deriving comparative figures*

Property	Reduction factor: Green	Reduction factor: Air-dry at 12 per cent moisture	Weighting factor
Bending strength:			
Fiber stress at elastic limit, static bending	1.72	1.54	1
Modulus of rupture, static bending	1.00	1.00	2
Fiber stress at elastic limit, impact bending	.74	.82	1
Compressive strength (endwise):			
Fiber stress at elastic limit, compression parallel to grain	[1] 2.82	[1] 2.52	1
Maximum crushing strength, compression parallel to grain	[1] 2.20	[1] 1.805	2
Stiffness:			
Modulus of elasticity, static bending	1.00	1.00	2
Modulus of elasticity, impact bending	1.00	1.00	1
Modulus of elasticity, compression parallel to grain	1.00	1.00	1
Hardness:			
Fiber stress at elastic limit, compression perpendicular to grain	1.00	1.00	2
End hardness, hardness test	.80	.96	1
Radial hardness, hardness test	.89	1.24	1
Tangential hardness, hardness test	.87	1.21	1
Shock resistance:			
Work to maximum load, static bending	1.00	1.00	2
Total work, static bending	.41	.52	1
Height of drop, impact bending	.31	.34	2
Volumetric shrinkage:			
Radial plus tangential shrinkage (green to oven-dry)	[2] 1.00		1
Volumetric shrinkage (green to oven-dry)	[2] 1.00		2

[1] The reduction factors for compressive strength translate the values into terms of modulus of rupture so that the resulting values can be combined directly with "bending strength" to give a joint figure representing "bending or compressive strength" (formerly called "strength as a beam or post"). To get "bending or compressive strength" give "bending strength" a weight of 4 and "compressive strength (endwise)" a weight of 3.

[2] Apply to values which represent shrinkage from the green to the oven-dry condition.

In calculating the comparative strength values the average test results for each species were used. The comparative values for green material (A) and for air-dry material (B) were separately calculated and were then combined as follows:

$$\frac{2A+B}{3} = \text{comparative strength value (bending strength, etc.)},$$

where A = value as calculated from averages for green material,
B = value as calculated from averages for air-dry material (12 per cent moisture).

It may be noted that the averages for green material were multiplied by 2 and those for air-dry material by 1 in arriving at the comparative strength values. This gives the figures for green material an apparent weight of 2, but in reality they receive an actual weight somewhere between 1 and 2 because no reduction factor was used to bring the figures for air-dry material to the same magnitude as those for green material. However, the averages for green material were intentionally given a somewhat greater weight than those from the air-dry because a larger number of tests are included.

The final comparative figure, therefore, does not represent either green or dry material, but approximates a condition of 20 per cent moisture content. The calculated results are indicated to only two or three significant figures in Table 1 and have, consequently, lost their identity as far as stress units are concerned. As tabulated, they are in effect index numbers.

SAMPLE CALCULATION

The following example will illustrate in detail the calculation method:
(1) Required, the "bending strength" value for red alder (*Alnus rubra*).
(2) Given, the following average values (*4*) for the species, in pounds per square inch:

	Green	Air-dry [1]
Fiber stress at elastic limit, static bending	3,800	7,100
Modulus of rupture, static bending	6,500	10,000
Fiber stress at elastic limit, impact bending	8,000	11,700

[1] Adjusted to 12 per cent moisture.

(3) Calculation for green material (A):

	Strength value		Reduction factor		Weighting factor		Product
Fiber stress at elastic limit, static bending	3,800	×	1.72	×	1	=	6,540
Modulus of rupture, static bending	6,500	×	1.00	×	2	=	13,000
Fiber stress at elastic limit, impact bending	8,000	×	0.74	×	1	=	5,920
Total					4		25,460
Value for green material			25,460	÷	4	=	6,365 = A

(4) Calculation for air-dry material (12 per cent moisture content) (B)

	Strength value		Reduction factor		Weighting factor		Product
Fiber stress at elastic limit, static bending	7,100	×	1.54	×	1	=	10,930
Modulus of rupture, static bending	10,000	×	1.00	×	2	=	20,000
Fiber stress at elastic limit, impact bending	11,700	×	0.82	×	1	=	9,594
Total					4		40,524
Value for air-dry material (12 per cent moisture content)			40,524	÷	4	=	10,131 = B

(5) Bending strength $=\frac{2A+B}{3}=\frac{(2\times 6365)+10131}{3}=7620.$

The "bending-strength" values as calculated by the foregoing formula were divided by 100 before entering them in Table 1. This gives the value 76 for red alder, which agrees with the table.

The procedure for deriving the other comparative strength properties from the original data is similar.

SHRINKAGE IN VOLUME

The comparative shrinkage in volume figures (column 8, Table 1) were calculated according to the following formula:

$$\text{Volumetric shrinkage}=\frac{R+T+2V}{3}$$

where R = average radial shrinkage,
T = average tangential shrinkage,
V = average volumetric shrinkage.

The volumetric shrinkage values as calculated by the foregoing formula were multiplied by 10 before being entered in column 8 of Table 1.

Radial and tangential shrinkage measurements were made on specimens 1 inch thick by 4 inches wide by 1 inch long, and shrinkage in volume measurements on specimens 2 by 2 inches in cross section by 6 inches long.

LIMITATIONS

There are certain limitations to the use of comparative strength figures or index numbers because the individual basic properties are masked. Therefore, when the data on individual basic properties can be more logically applied than the comparative strength values, they should be used in preference (*4*).

Another possible limitation of the comparative strength figures is that they represent neither green nor thoroughly air-dry material. In most instances practically the same comparisons would result if figures from green material only or from air-dry material only were combined. This will not be true, however, if a species is exceptional in its moisture-strength relations. Redwood, one of the common commercial species, is such an example, being very high in strength for its density when green and increasing less in strength with seasoning than most other woods. Comparisons from Table 1 will give such species too low a rating for a use in which the material will remain wet and too high for a use requiring dry stock. The comparative figures, except shrinkage, may be considered to represent material at about 20 per cent moisture content for bending strength, compressive strength, stiffness, and hardness. Shock resistance is not affected greatly by moisture changes, but usually incurs a slight loss rather than a gain with decrease in moisture.

In spite of such limitations, the comparative values are useful for many types of comparisons. Whether comparative strength values or basic strength properties should be used is a matter of judgment.

SPECIAL USES OF COMPARATIVE FIGURES

RAILROAD TIES

As illustrative of the special uses referred to on page 18, let it be required to sum into a single figure for each species the mechanical properties of most importance in railroad ties. Knowledge of the properties involved and their relative importance must be available (*9*) or assumed before attempting to arrive at such a figure. In ties bending strength is required to resist bending; compressive strength (endwise) to resist rail thrust against spikes; and hardness to resist rail cutting and mechanical wear. A method which has been used for combining these figures to obtain strength figures for crossties, in which hardness is given equal importance with bending strength and compressive strength combined (see footnote 1, Table 4), is as follows:

Multiply the value given in Table 1 for bending strength by 4, that for compressive strength by 3, and that for hardness by 7. Add these products and divide by 14 to get the final number. This may be expressed by the formula:

$$\text{Tie strength figure} = \frac{4D+3E+7F}{14}$$

where D=bending strength (column 9, Table 1),
E=compressive strength (column 10, Table 1),
F=hardness (column 12, Table 1).

The strength figure for a chestnut crosstie, as calculated by this method, is 59; that for white oak, 104; from which it is seen that white oak, as is well known, is the better as far as strength is concerned. Other factors must, of course, be taken into account in selecting woods for ties, especially resistance to decay. This again calls for judgment and experience in evaluating the relative importance of durability (resistance to decay) and strength, in accordance with service conditions.

AIRPLANE WING BEAMS

The comparative strength values were used by the Forest Products Laboratory as a guide for appraising the relative suitability of the different species for airplane wing beams. The properties considered were specific gravity, bending and compressive strength, stiffness, and shock resistance. The weights given each of these properties were as follows:

	Weight
Bending and compressive strength (combined)	1
Stiffness	1
Shock resistance	1.5

The values for bending and compressive strength, stiffness, and shock resistance were first expressed as ratios of the corresponding values for spruce, which was taken as the basis of comparisons. These ratios were then weighted as just shown and averaged. This average was divided by the specific-gravity ratio raised to the $\frac{3}{2}$ power to get the final index of suitability.

In this analysis the consideration of such factors as influence of size on the strength, stiffness, and buckling of thin parts, together with the essential requirement in aircraft of keeping weight to a minimum, necessitated that a power of the specific gravity be used. Here, again, judgment was called for in the proper selection and weighting of the factors involved.

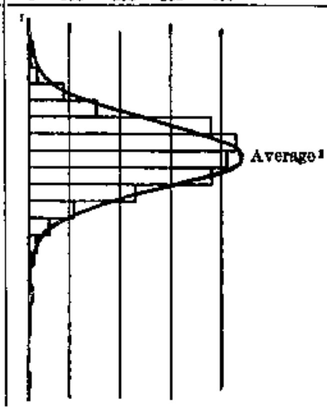
A somewhat similar system of analysis was used in classifying species in the development of the safety code for ladder construction. The data of Table 1 offer opportunity for many other types of analyses and comparisons, limited only by the judgment employed in their use.

APPENDIX 3

SIGNIFICANCE OF VARIABILITY

Brief reference has been made on page 14 to the variability of wood and other materials. It is important to know that wood is variable, but it is more important to know something of the nature and extent of this variability. The range of variability can be illustrated and better understood by considering the results of specific gravity determinations on 2,105 separate pieces of Sitka spruce which have been studied at the Forest Products Laboratory. These specific-gravity values are presented in Table 5, which lists the highest and lowest observed results, together with the number of pieces in different groups.

TABLE 5.—*Results of specific gravity determinations on 2,105 samples of Sitka spruce*

Specific gravity [1] group limits	Pieces in group		Variability diagram (number of specimens in group) 0 100 200 300 400
	Number	*Per cent*	
0.220 to 0.239	1	0.05	
.240 to .259	3	.14	
.260 to .279	18	.86	
.280 to .299	70	3.33	
.300 to .319	133	6.32	
.320 to .339	359	17.05	
.340 to .359	411	19.53	
.300 to .379	392	18.62	
.380 to .399	345	16.39	
.400 to .419	211	10.02	
.420 to .439	91	4.32	
.440 to .459	43	2.04	
.460 to .479	16	.76	
.480 to .499	3	.14	
.500 to .579	1	.05	
.520 to .539	4	.19	
.540 to .559	2	.09	
.560 to .579	1	.05	
.580 to .599	0	.00	
.600 to .619	0	.00	
.620 to .639	1	.05	

[1] Specific gravity oven-dry based on volume when green.
Average specific gravity equals 0.364; highest observed specific gravity 0.626; lowest 0.236.

It may be noted that the specific gravity of the heaviest piece [11] included in the series was two and two-third times that of the lightest, and that the number of very heavy and very light pieces is quite small. Most of the values are grouped quite closely about the average.

The manner is which the samples tend to group themselves about the average is called a frequency distribution, from which the chances of departure from the average can be estimated by computation. Such a calculation, assuming a so-called normal distribution and representative material, leads to the expectation that one-half of the Sitka spruce samples would be within less than 7.5 per cent of the average specific gravity, or between the limits 0.337 and 0.391, and that approximately only one-fourth would be below 0.337 and one-fourth above 0.391. The figure defining such limits, 7.5 per cent in this case, is called the probable variation. By actual count, 51.7 per cent of the pieces studied (1,089) have a specific gravity between 0.337 and 0.391, whereas that of 24.8 per cent (522) was below 0.337 and that of 23.5 per cent (494) was above 0.391. As might be

[11] The exceptionally heavy pieces of Sitka spruce result from an abnormal growth called compression wood frequently occurring in the underside of leaning trees and limbs. Compression wood also forms in other softwood species, and, unlike normal wood, it has a large endwise or longitudinal shrinkage which causes warping and twisting when it occurs in the same piece with wood of normal growth. Longitudinal shrinkage as high as 2½ per cent has been observed in compression wood, whereas the longitudinal shrinkage of normal wood is a small fraction of 1 per cent. Compression wood is very dense and includes what appears to be an excessive summer-wood growth. Compression wood in most species shows but little contrast in color between spring wood and summer wood. Large differences in weight from causes other than compression wood are also found. Thus, in certain softwood species some pieces are increased in weight because of the resinous materials they contain, while in some hardwoods, such as tupelo and ash, unusually light-weight wood is formed in the swelled butts of swamp-grown trees.

expected, the percentages determined by actual count do not agree exactly with the foregoing calculated percentages, but the agreement is sufficiently close to show the value of the theory in estimating the variability even when a normal distribution is assumed. The frequency distribution of the specific gravity values for these 2,105 samples of Sitka spruce is shown as a diagram in the last column in Table 5.

The figures in Table 1 are each based on tests of a number of pieces, some of which were above and some below the average, just as with the specific gravity of Sitka spruce. In using wood of any species one may desire to know the proportion of material within a given range in any property or to know the probable amount the averages may be changed by additional tests. After tests have been made it is of course easy from the results to determine the proportion of the test pieces which were within any given range, but one can only estimate the degree to which this test data applies to other specimens and to the reliability of the averages. In other words, one would like to know the true average values of each species, a quantity which can not actually be obtained. The best that can be done is to consider the laws of chance operative and thus estimate the probable variation which may be expected from given average values. Such is the basis of the suggestions and estimates of variability presented in Table 1 and Appendix 3.

It would be desirable to present the variation of each property of each species as determined from the detailed data. However, the extensive calculations involving all properties and species have not been completed; and even if available, their presentation would be more involved than the nature of this bulletin warrants. Although it is known that all species are not exactly equal in variability, it is felt that they are enough alike so that estimates made on the assumption of an equal percentage variability for all species in a given property will be sufficient for most practical purposes.

PROBABLE VARIATION

EXPLANATION OF FIGURES

The variability of each property is indicated by the probable variation figures in the last two lines at the bottom of Table 1. In the next to the last line is given the estimated probable variation of the observed species average from the true species average. The value listed applies only when the observed average is based on tests from five trees.[13] The values for other numbers of trees may be obtained from Table 6. In the last line of Table 1 is given the estimated probable

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[13] The method of calculating the variation of an individual tree is as follows:

$$\sigma^2 = \frac{\Sigma\left(\frac{a-\bar{a}}{\bar{a}}\right)^2 + \Sigma\left(\frac{b-\bar{b}}{\bar{b}}\right)^2 + \Sigma\left(\frac{c-\bar{c}}{\bar{c}}\right)^2 + \dots}{n_a + n_b + n_c + \dots}$$

where $\Sigma\left(\frac{a-\bar{a}}{\bar{a}}\right)^2 = \left(\frac{a_1-\bar{a}}{\bar{a}}\right)^2 + \left(\frac{a_2-\bar{a}}{\bar{a}}\right)^2 + \left(\frac{a_3-\bar{a}}{\bar{a}}\right)^2 \dots$

$a_1, a_2, a_3 \dots$ being averages for specimens from each of the n_a trees (usually 5) of species-locality a and

$$\bar{a} = \frac{a_1 + a_2 + a_3 \dots}{n_a}$$

$b_1, c_1, b_2, c_2, \bar{b}, \bar{c}, n_b, n_c \dots$, being similarly defined.

It may be seen that σ as thus defined is not the usual root-mean-square deviation but is somewhat analogous to the coefficient of variation. It is in fact the weighted root-mean-square value of coefficient of variation as obtained from a number of samples. This may be seen by writing the above formula in the equivalent form:

$$\sigma^2 = \frac{n_a\left(\frac{\sigma_a}{\bar{a}}\right)^2 + n_b\left(\frac{\sigma_b}{\bar{b}}\right)^2 + n_c\left(\frac{\sigma_c}{\bar{c}}\right)^2 + \dots}{n_a + n_b + n_c + \dots}$$

Correcting for size of sample, $\sigma' = \frac{\sigma}{0.8407}$ (6), 0.8407 being used because the modal value is 5. Probable variation = $0.6745\,\sigma'$.

variation of an individual piece [13] from the true average. The probable variation of 8 per cent for the specific gravity of an individual piece indicates that there is an even chance that a random specimen will fall within 8 per cent (above or below) of the average, and an even chance that it will differ more than 8 per cent from the average. To illustrate, suppose that the hardness of red alder is under consideration. The probable variation in hardness for an individual piece is found from Table 1 to be 16 per cent. Taking the hardness of red alder as 48, the hardness of one-half of the pieces will, on the average, fall between the values 40.3 and 55.7, while approximately one-fourth would be below 40.3 and one-fourth above 55.7. The greater the probable variation, the greater the difference that may be expected in values, and the less the certainty with which the average figures can be applied to individual pieces.

PROBABLE CHANGES IN OBSERVED AVERAGE

The extent of the probable change in the observed average for the different properties should be considered in comparing species. The estimated probable variation in the observed average of the species, when based on different numbers of trees, is given in Table 6.

TABLE 6.—*Percentage probable variation [1] of the observed average from the true average of the species, when based on material from different numbers of trees*

Number of trees	Specific gravity	Shrinkage			Bending strength	Compressive strength (endwise)	Stiffness	Hardness	Shock resistance
		Radial	Tangential	Volumetric					
1	4.7	11.6	9.0	8.8	5.5	7.3	7.2	6.3	11.1
2	3.3	8.2	6.4	6.2	3.9	5.2	5.1	4.5	7.9
3	2.7	6.7	5.2	5.1	3.2	4.2	4.2	3.6	6.4
4	2.4	5.8	4.5	4.4	2.8	3.6	3.6	3.2	5.6
5	2.1	5.2	4.0	3.9	2.5	3.3	3.2	2.8	5.0
10	1.5	3.7	2.8	2.8	1.7	2.3	2.3	2.0	3.5
15	1.2	3.0	2.3	2.3	1.4	1.9	1.9	1.6	2.9
20	1.0	2.6	2.0	2.0	1.2	1.6	1.6	1.4	2.5
30	0.9	2.1	1.6	1.6	1.0	1.3	1.3	1.2	2.0
40	0.7	1.8	1.4	1.4	0.9	1.2	1.1	1.0	1.8
50	0.7	1.6	1.3	1.2	0.8	1.0	1.0	0.9	1.6

[1] The percentage probable variation of the average of the species is a figure such that there is an even chance that the true average is within this percentage of the observed average in Table 1.

The average is always the most probable value. Occasionally the variation may be much larger than indicated, but the probability of occurrence of a variation decreases rapidly as the magnitude of the variation increases.

The importance of the differences between species with respect to averages is dependent on the magnitude of this difference in relation to the probable variation of the averages, as well as on how exacting the strength requirements are for the particular use under consideration.

HOW TO ESTIMATE THE SIGNIFICANCE OF DIFFERENCES IN THE AVERAGE PROPERTIES OF TABLE 1

If the averages of any property of two species (Table 1) differ by an amount equal to the probable variation of the difference,[14] there is one chance in four that

[13] Estimated for each component property by combining the corrected probable variation of a tree, and the probable variation of an individual specimen from the tree, according to the usual method. The probable variation of composite figures was calculated by combining the probable variation of component properties, assuming first, complete independence of properties, and second, complete correlation of properties. The correlation coefficient of component properties was found to approach unity (0.90 between fiber stress at elastic limit in compression parallel to grain and maximum crushing strength; 0.92 between fiber stress at elastic limit in impact bending and modulus of rupture in static bending). Values of probable variation for composite figures presented in Table 1 are estimated from calculations just referred to, and those of the last line, Table 1 further compared with calculations of probable variation of an individual piece from the species averages for a limited number of species. It is hoped that ultimately such calculations will be made with the data on all species.

[14] The probable variation of the difference of two average figures is the square root of the sum of the squares of the probable variations of the averages. The probable variation of the average of any property may be estimated from the figures in Table 6. For an example, see page 37.

the true average for the species which is lower in that property on the basis of present data equals or exceeds the true average of the other. There is also one chance in four that the true average for the higher species exceeds that of the lower one by as much as twice the observed difference. When the averages differ by amounts which are 1, 2, 3, 4, or 5 times the probable variation of their difference, the chances of the true average of the lower species equaling or exceeding the true average of the higher, or of the observed difference being at least doubled are as follows:

TABLE 7.—*Chance that if the true average were available the order would be reversed, or the true difference found to be at least twice as great as the observed, when the observed difference is 1, 2, 3, 4, or 5 multiples of the probable variation of the difference*

Multiples	Chance	Multiples	Chance
1	1 in 4.	4	1 in 285.
2	1 in 11.	5	1 in 2,850.
3	1 in 40.		

As an example, consider the figures for bending strength of 60 and 62 for black and eastern cottonwood, respectively (Table 1). These figures are based on five trees of each species. From Table 6 or the next to the last line of Table 1, the probable variation of the species when based on five trees is 2.5 per cent of the bending strength. Two and five-tenths per cent of 60 equals 1.50, and 2.5 per cent of 62 equals 1.55, the probable variations of these averages. The probable variation of the difference between the averages is then $\sqrt{(1.50)^2 + (1.55)^2}$ or 2.16; the observed difference in the average figures for bending strength (60 and 62) is 2, which is less than its probable variation, 2.16. The chance that the true average bending strength for black cottonwood equals or exceeds that for eastern cottonwood is approximately one in four. There is the same chance that the true average of eastern cottonwood exceeds that for black cottonwood by at least 4 (twice the difference in present average figures as shown in Table 1). Hence, the difference between the figures for black and eastern cottonwood with respect to bending strength is not important for most practical purposes.

As a second example, consider the figures for bending strength of 117 and 106 for sweet birch and yellow birch, respectively. (Table 1.) The figures for sweet birch are based on 10 trees, those for yellow birch on 17. From Table 6 the probable variation of the species average when based on 10 trees is 1.7 per cent and when based on 17 trees it is 1.3 per cent. (The figure for 17 trees is taken as midway between that given for 15 trees and 20 trees.) The probable variation in bending strength of sweet birch is 1.7 per cent of 117, or 1.99; of yellow birch is 1.3 per cent of 106, or 1.38. The probable variation of the difference between the averages is $\sqrt{(1.99)^2+(1.38)^2}$ or 2.42. The difference between the observed averages (117 and 106) is 11, which is about four and one-half times its probable variation of 2.42. From Table 7 it may be estimated that the chances are only one in more than 285 that the true average for bending strength of yellow birch would equal or excel that for sweet birch. The importance of such differences will depend on the use to be made of the wood.

Calculations of probable variation as suggested above should not be taken too literally but should rather be regarded as estimates.

LITERATURE CITED

(1) American Society for Testing Materials.
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U. S. GOVERNMENT PRINTING OFFICE: 1930

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