CCLIX. THE RELATIONSHIP BETWEEN CHEMICAL COMPOSITION AND MECHANICAL STRENGTH IN THE WOOD OF ENGLISH ASH (*FRAXINUS EXCELSIOR* LINN.).

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(Received 25 July 1936.)

IN the great majority of woods which have been investigated there is a strong correlation between specific gravity and certain mechanical characteristics. As a rule the higher the specific gravity the stronger the wood, although it is known that, in any single species, wide variations in strength may occur throughout a range of matched specimens of equal specific gravity. These latter variations have been ascribed [Clarke, 1935; 1936] to concomitant variations in the chemical composition of the wood cell walls which at the present time are not fully understood. Despite its obvious importance the relationship between chemical composition and strength in woody plants has hitherto received comparatively little attention. Dadswell & Hawley [1929] observed a higher cellulose content in tough white oak than in a single brash specimen of the same species, and Uno [1932] concluded that the strength of various species of bamboo increases with increasing cellulose content. The investigation by Luxford [1931] of the influence of minor components or extractives on the strength of wood will be referred to later.

The object of the present study was in the first instance to determine whether the chemical composition of ash wood varies within a single tree as well as from tree to tree in a single locality, and in the second instance to attempt to correlate chemical composition with strength figures already obtained for the same material [Armstrong, 1936].

EXPERIMENTAL.

A 2-ft. bolt was cut at the same height from the ground from each of six representative English ash trees (*Fraxinus excelsior*) obtained from Holkham, Norfolk. Each bolt was sawn into two discs measuring 15 and 9 in. in diameter respectively and the pairs of discs were marked out on the transverse surfaces exposed by the common cross-cuts into the following concentric zones.

A. Sapwood containing starch.

B, C. Intermediate zones containing small amounts of starch decreasing from B to C.

D. Heartwood containing no starch.

The 15-in. discs being reserved for mechanical tests [Armstrong, 1936] each 9-in. disc was sawn into the respective zones which, after air-drying, were separately converted into sawdust. The 80–100 mesh material was analysed according to the method of Schorger [1926] except that the digestion with 72 % sulphuric acid in the lignin determinations was carried out at $10 \pm 0.5^\circ$ using 12.5 ml. of acid per 2 g. sample of air-dry wood flour (Table I).

Four of the trees examined contained the heartwood discoloration known as "black-heart". This has been shown by Armstrong [1936] to have no detectable effect on the mechanical strength of the wood. The results in Table I indicate that "black-heart" does not appear to be associated with any irregularities in the relative proportions of the major components present in the trees in which it occurs but rather with some constitutional peculiarity in the extractives. This view is supported by the observation that an evaporated aqueous or alcoholic extract of "black" heartwood possessed a strong phenolic odour which was not detected in extracts obtained from normal wood. This aspect of the difference between normal and "black" heartwood could not be followed up owing to lack of available material.

DISCUSSION.

The results in Table I show that the chemical composition of ash wood is not uniform throughout the cross-section of the tree. The cellulose content exhibits a consistent increase in passing from the periphery towards the pith. The extreme differences in cellulose content between heartwood and sapwood may be as great as 7% of the dry weight of the wood substance. It is further observed that the heartwood of ash contains less extractives and slightly less lignin than sapwood. Of the three major wood components the furfuraldehyde-yielding complexes exhibit the least fluctuations within individual trees and it is, therefore, obvious that the Cross and Bevan cellulose isolated from the heartwood contains a higher proportion of hexosans than that isolated from the intermediate zones and sapwood.

The results in Table I suggest the following two important conclusions for ash wood, which may conceivably be applicable to other hardwood species. (1) Because of the variations in composition within individual trees it would be difficult or impossible by means of a limited number of analyses carried out by current methods to differentiate chemically between trees of the same species. (2) The relatively high specific gravity and consequently the relatively high mechanical strength of heartwood is not solely due to the greater density of wood substance. An additional factor, namely the amount and composition of the Cross and Bevan cellulose, must be taken into account.

Statistical analysis of results.

The complete set of mechanical data obtained by Armstrong [1936] which correspond to the chemical data in Table I are not recorded here, but average figures are given in order to illustrate the degree of variation in compressive strength between the various zones in each tree. The discussion which follows is based upon a detailed consideration of all the mechanical and chemical data.

There are undoubtedly so many influences causing the strength of wood to vary that it is impossible by inspection of the results in Table I alone to allot effects to individual components. The method of approach used here was to fit successive regression equations involving an increasing number of variables, believed to be related to strength, the progressive improvement in the fit of the observations to the equations being taken as an indication of the importance of the term added. The considerable variation between zones was eliminated by confining consideration to variation from the mean of each zone. In a preliminary examination the best fit was provided by an equation involving specific gravity, hot water-soluble and alkali-soluble material, but since it is known that sodium hydroxide attacks all the major components of wood a search was made

for an equation which would involve these latter components directly. It was found that an equation involving specific gravity and percentages by weight of cellulose, lignin and pentosans not in the cellulose was not significantly different from the first in its fit. In order to examine the specific gravity term further, each strength value was corrected to read as pounds per square inch of wood substance. These corrected values were still related to specific gravity as well as to the components already mentioned. A further improvement in fit was obtained by using the degree of dispersion (i.e. weight present in unit volume of the wood-water aggregate) of the three major components instead of their percentages by weight.

The regression equation giving the best fit to the variations within zones of the corrected strength was:

$$y - \bar{y} = 102 (m - \bar{m}) + 965 (x - \bar{x}) + 45 \frac{c - \bar{c}}{\bar{V}m} + 69 \frac{l - \bar{l}}{\bar{V}m} + 21 \frac{p - \bar{p}}{\bar{V}m} \dots A,$$

where y is the maximum crushing strength in lb./sq. in. of wood substance; m is the moisture content at time of test as percentage of dry weight; x is the specific gravity of the wood block at time of test; c is the weight of cellulose per 100 g. of oven-dry (105°) wood substance; l is the weight of lignin per 100 g. of oven-dry (105°) wood substance; p is the weight of pentosans not in the cellulose per 100 g. of oven-dry (105°) wood substance; $\bar{V}m$ is the volume occupied by a wood-water; aggregate consisting of 1 g. oven-dry wood and $m/100$ g. water. Symbols with bar indicate mean values for one zone.

No great importance can be attached to the values of the coefficients since these would no doubt be altered as a result of a more extensive investigation. It is significant, however, that each term was proved to represent an important source of variation in strength and the most important, as tested by the omission of each in turn from the equation, was found to be the cellulose term.

Finally, the observed variation in corrected strength was analysed according to the scheme set out in Table II by the methods laid down by Fisher [1935]. This type of analysis is important, firstly in dividing an observed variation into parts whose sources can be recognized (named in column 1) and secondly in enabling a test to be made of the significance of each of these sources when compared with the "residual" or "unexplained" variation (item iv).

Table II. *Analysis of variance of strength values corrected for porosity of wood.*

Variation attributed to	Sum of squares	Degrees of freedom	Mean square
(i) A regression with same coefficients as A but passing through the general mean	1,369,118	5	273,824
(ii) Deviation of zone means from this regression	263,308	2	131,654
(iii) Differences between zone regressions	129,889	10	12,989
(iv) Deviations from zone regressions, residual variation	333,838	84	3,974
Total	2,096,153	101	—

Co-variation of strength and chemical composition.

The fact that the percentage amounts of all the chemical components determined in Table I vary in a regular gradation across each disc does not simplify the task of explaining the strength variations, which undergo a similar regular change. The chief evidence for any one component being the cause of variations

in strength would be an observed change in such component which was not reflected in changes in the other components. In the mathematical methods employed full advantage was taken of such cases where they existed. The prominence of the specific gravity term in this type of analysis is in accord with much other published work. After due allowance is made for the direct effect of bearing-area in the test piece the remaining effect must be ascribed to some of the properties which run parallel with specific gravity. Specific gravity and cellulose content both increase from the periphery towards the heart of the tree but cellulose is already a term in the equation, so that it may well be that those regions which are high in cellulose have the higher proportion of strength-giving cellulose. In this connexion it has already been noted that the Cross and Bevan cellulose of the heartwood zones (Table I) is relatively high in hexosans and low in pentosans. It is evident, however, that structural features such as ring width, proportion of summer wood etc. account for a part of the variations in strength as distinct from variations ascribed to purely chemical causes. No measurements from which it might have been possible to assess the separate effect of structural features were made in this study.

The strong relation found here between strength, specific gravity and extractives is worthy of note. It is highly probable that the so-called extractives of wood are not confined to the cell cavities, so that they may influence strength to some extent by dispersion of the cell wall substance. Luxford [1931] claims to have shown that the presence of extractives increases the compressive strength of wood, but before such a conclusion can be accepted the following point must be considered. In all the woods used by Luxford the extractives increased in amount from the sapwood towards the heartwood, whereas in the material of the present study the extractives decreased in amount in the same direction. Yet in both cases specific gravity and mechanical strength were greater towards the heartwood. It is therefore indicated that, where a measured variable is only one of a highly related group, the properties of which change regularly in passing from sapwood towards heartwood, there is a real danger in assuming cause from the existence of a single apparent relation. The results of the present study tend to weaken Luxford's [1931] conclusions, although this author made subsidiary observations of an increase in strength after the artificial addition of extractives to wood and a decrease on leaching them out. Had these latter observations been as definite as those in the main experiment, they might have made Luxford's conclusions more acceptable.

SUMMARY.

1. Analytical data are given for comparable cross-sectional discs from six English ash trees (*Fraxinus excelsior* Linn.) taken from the same site.

2. It is shown that in ash wood the percentage amount of Cross and Bevan cellulose increases in passing from the periphery towards the pith. The percentage amounts of lignin and extractives tend to decrease in the same direction while the furfuraldehyde-yielding complexes remain virtually constant in amount throughout a cross-sectional disc of any one tree.

3. The Cross and Bevan cellulose of ash heartwood contains proportionately less furfuraldehyde-yielding material and more hexosans than the corresponding component of sapwood.

4. The commercial defect known as "black-heart" in ash wood is not associated with any irregularities in the proportions of the three major components present in wood in which it occurs, but rather with a change in some minor constituent.

5. A statistical analysis is given of the effect of chemical composition on the compressive strength of ash wood, from which it is concluded that the most important component responsible for variations in crushing strength in pounds per square inch of wood substance is the Cross and Bevan cellulose. In all the material examined, specific gravity, cellulose content and strength increased in a direction from the periphery towards the pith.

The authors are indebted to Mr W. G. Campbell of this Laboratory for advice and assistance during the work and in the preparation of the paper, to Mr F. H. Armstrong for the strength data, to Prof. R. A. Fisher for advice on the statistical analysis, and to Mr W. A. Robertson, Director of Forest Products Research (Department of Scientific and Industrial Research) for permission to communicate these results.

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