Characteristics of Archaeological Waterlogged Wood

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1. Changes through Deterioration in the Constituent Components of Cell Walls

The cell walls of wood are composed mainly of cellulose, hemicelluloses and lignins. In addition to those three main components, several percent of ash and extractives are included. Among those components, cellulose and hemicelluloses are polysaccharides, which are easily decomposed and metabolized by wood-rot fungi. In the constituent analysis of wood, when lignin is selectively removed, what is obtained is holocellulose. Holocellulose can be thought of as the total of cellulose and all hemicelluloses.

Table 1 shows the main constituents of the cell walls of archaeological waterlogged wood. For simplified comparison purposes, the components have been reduced to holocellulose and lignin.

In recent wood, holocellulose content is about 70% and lignin content is about 30%. In excavated wood, the holocellulose content drops to about 20% while lignin increases relatively to about 80%. Holocellulose is the polysaccharide fraction that is easily decomposed by wood-rot fungi. While the wood is buried under the ground, the holocellulose is considerably decomposed and tends to disappear. In contrast to the polysaccharides, the quantitative decomposition and disappearance of lignin is substantially less, and as a result its content increases relatively. Although the quantitative decrease is small, it is clear that lignin actually decomposes and decreases under the ground. Archaeological waterlogged wood is regarded as wood, but it is actually in a completely different state than recent wood.

Table 1. Chemical composition of waterlogged woods

Wood Species	Content, %		
	Cellulose	Hemicelluloses	Lignin
Chemacyparis Obtusa (S. and Z.) Endl.	47.7	21.3	31.0
Pinus densiflora S. and Z. or P. *Thunbergii* Parl.	11.2	16.0	72.8
Cryptomeria japnica D. Don	40.8	17.8	41.4
Quercus glauca Thunb.	9.8	13.6	76.6
Quercus sessilifolia Blume	10.4	12.2	77.4
Quercus myrsinaefolia Blume	9.5	11.8	78.7
Quercus gilva Blume	10.3	13.0	76.7
Castanopsis cuspidate Schottky var. *sieboldii* Nakai	11.0	11.9	77.1
Neolitsea sericea (Blume) Koidz.	12.1	11.9	76.0
Vaccinium bracteatum Thunb.	18.3	12.3	69.4

2.2 Increase in Maximum Moisture Content and Reduction in Basic specific gravity

When the structure of waterlogged wood is observed under a microscope, it can be seen to be surprisingly well preserved. As noted above, regardless of the substantial decomposition and disappearance of constituents of the cell walls, the structural characteristics are well enough preserved that the type of wood can be identified. This reflects the fact that components of the cell wall have decomposed and lost without changing the size of the cell wall itself. New voids have formed in the parts of the cell wall where components have disappeared. Disregarding pieces found in deserts, glaciers or permafrost, archaeological wood is usually discovered in humid soil. It may therefore be assumed that the reason that the size of the cell walls does not change is that the new voids opened up by the decomposition and disappearance of constituent of the cell walls are immediately filled by water.

Maximum moisture content is often used as an indicator of the scale of deterioration of archaeological waterlogged wood. The maximum moisture content is the ratio of the weight of water included in the wood to the wood weight when completely dry (weight of wood substance), expressed as a percentage.

$$u = \frac{m_w - m_0}{m_0} \times 100$$

u: maximum moisture content, m_w: water saturated weight, m_0: weight of wood substance

As noted above, the constituents of the cell wall decrease along with the deterioration of the wood, and since water increases by that amount, naturally the maximum moisture content increases. Therefore, by determining the maximum moisture content of archaeological waterlogged wood, the degree of deterioration of the wood can be estimated. To put it simply, the higher the maximum moisture content, the greater the deterioration. However, since the maximum moisture content generally differs by species or specimen even for recent wood, in order to gauge the level of deterioration with some degree of accuracy, it is desirable at the least to compare the figure with the average value for recent wood of the same species.

Basic specific gravity is the weight of wood substance per cubic centimeter in the state of maximum swelling.

$$D = \frac{m_0}{V}$$

D: basic specific gravity, V: volume of maximum swelling

For archaeological waterlogged wood, since the wood substance is reduced even though the outward size is unchanged, its basic specific gravity may decrease along with the progress of deterioration (Figure 2).

As basic specific gravity also varies according to the wood species or the specimen, as with maximum moisture content, it is desirable at the least to compare the figure with the average value for recent wood of the same species.

Maximum moisture content and basic specific gravity vary according to the decrease of constituents, and hence there is a very close relationship between these two characteristics that is approximately expressed by the following equation (Figure 3).

$$D = \frac{R\delta}{\delta + 0.01u}$$

R: density of cell wall, ™: density of water

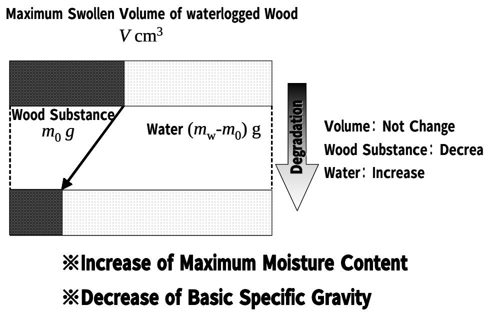


Figure 1. Degradation of buried woods

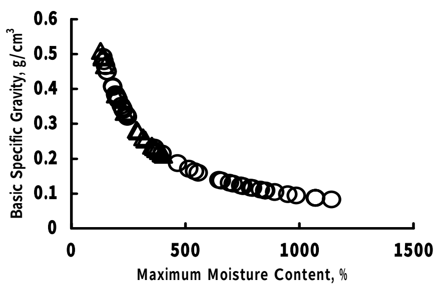
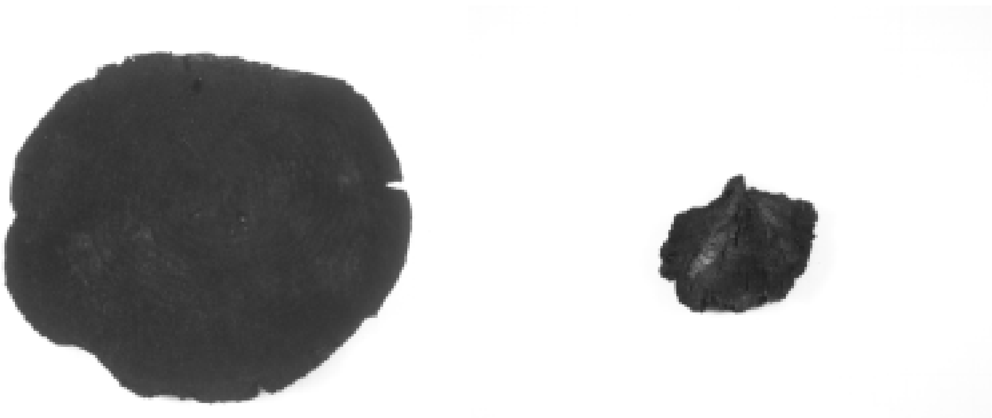


Figure 2. A relationship between maximum moisture content and basic specific gravity



Before drying

After drying

Figure 3. Deformation of an archeological waterlogged wood

2.3 Shrinkage through Drying

Trees grow in thickness as they grow in length, and there is often some degree of difference in the physical properties of a piece of wood according to the direction of measurement. In wood science, three basic directions are defined. Such a difference in properties according to direction is called anisotropy, and the shrinkage of wood through drying is a physical property that shows striking anisotropy.

Drying archaeological waterlogged wood often leads to drastic shrinkage and deformation (Figure 4). Once such shrinkage and deformation has occurred it is difficult to return the wood to its previous size and shape even by reimmersion in water. With recent wood, thorough drying does not result in such extensive shrinkage, and reimmersion in water will restore it to almost the original size.

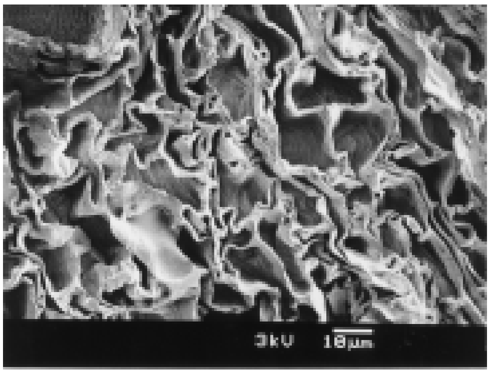


Figure 4. Deformation of cell walls

The degree of shrinking in wood is expressed as the shrinkage. When a wet wood is shrank by drying, the shrinkage of the wood is the ratio of the dimensional change to the original dimensions, expressed as a percentage. The shrinkage when wood is dried completely from a state of maximum swelling is called the maximum shrinkage.

$$S = \frac{L_w - L_0}{L_w} \times 100$$

S: maximum shrinkage, L_w: maximum length, L_0: oven-drying length

The anisotropy of wood shrinking tends to follow the approximate ratio of 1 for longitudinal shrinkage to 5 for radial shrinkage to 10 for tangential shrinkage. Since water soaks into archaeological waterlogged wood in an amount equal to the disappearance of constituent components of the cell walls, archaeological waterlogged wood shrinks drastically with drying. While tangential shrinkage amounts to 7~8% in recent wood, in archaeological waterlogged wood it often exceeds 60%. In other words, a 10 cm object shrinks to about 4 cm. The more deteriorated the object, the greater the shrinkage. Shrinkage anisotropy in archaeological waterlogged wood is most pronounced in the tangential, then in the radial, then in the longitudinal direction. In recent wood the order is the same, but the ratios are not necessarily the same.

For wood in general, shrinkage occurs in the range of moisture content below 30%, which is the fiber saturation point. When archaeological waterlogged wood is dried, shrinking and deformation begin to occur over a much higher range of moisture content. That shrinking and deformation does not result from water escaping from the cell walls, but rather from the evaporation of water from lumina and other macro-spaces. Water is a liquid with very high surface tension. When a liquid with such high surface tension starts to evaporate via one of the extremely small pits that connect one cell to another, the interior of the cell is decompressed and a strong attractive force is generated. This tends to attract an influx of outside air to the interior of the cell, but that influx is blocked by the surface tension of the water that is in the pit, causing the cell to buckle and deform along with the reduction in water (Figure 5). This phenomenon is known as collapse. Hence in archaeological waterlogged wood, the fact that shrinking and deformation occurs in a range of moisture content that is much higher than the fiber saturation point may be regarded as being caused by the cell wall having lost the strength to bear the surface tension generated by the evaporation of water.

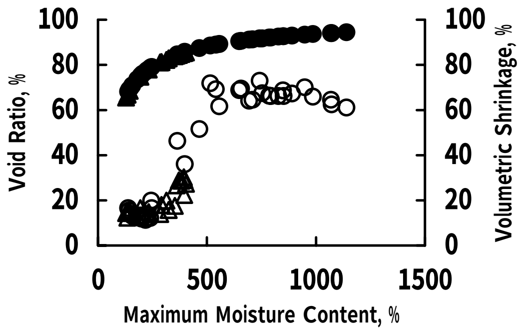


Figure 5. Changes of void ratio and volumetric shrinkage of buried woods

The fragility of the cell walls results from decomposition and leaching of components of the cell wall structure, and also depends on the increase in the voids inside the wood. Consequently the shrinkage due to drying of a piece of excavated wood may be expected to escalate suddenly at the point where the amount of air space inside the wood increases to a certain level. In Figure 6, the overall porosity and the maximum volumetric shrinkage are plotted against the maximum moisture content or a wood sample. This shows that the overall void ratio increases sharply in the range of the maximum moisture content. Meanwhile, assuming that the fiber saturation point is unaffected by the degree of deterioration and remains virtually unchanged at 0.3, the temporary void ratio will gradually decrease.

That indicates that as recovery occurs through moisture absorption and the amount of temporary void decreases, collapse will be caused and the amount of permanent void will rapidly increase. The rise of the maximum moisture content to the 200% level indicates a maximum bulk shrinkage that follows the line of the temporary void ratio. In this range, rather than being associated with the collapse of permanent void, the shrinkage from drying appears to depend rather closely on the blockage of temporary void due to desorption of moisture. If similar correlations can be derived for many kinds of wood, the data may well be useful in the selection of appropriate methods of conservation treatment.