Full Paper

Effect of Microstructure on the Permeability and Sorption of Wood of *Sterculia rhinopetala* and *Albizia ferruginea*

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Abstract
This paper sets to find out the effect of the microstructure of wood on the permeability and sorption of the wood of *Sterculia rhinopetala and Albizia ferruginea*. Permeability, the way of ingress of water into wood mass, is one of the most variable properties of timber and it further influences nearly all the physical properties of wood. Wood exposed to high humidity conditions or to liquid water during use may be subjected to biological deterioration which makes equilibrium moisture content of wood very important. Equilibrium moisture content is the moisture level where the wood neither gains nor loses moisture since it is at equilibrium with the relative humidity and temperature of the surrounding environment. Sixteen randomly sampled specimens of each of the wood of *Sterculia rhinopetala* and *Albizia ferruginea* species (heartwood and sapwood) with dimensions 3 cm x 3 cm x 3 cm were exposed at various relative humidity conditions of 30 %, 45 %, 60 %, 75 % and 90 % in a temperature and humidity-controlled climate chamber. The order of water uptake in terms of percentage volume is arranged from the lowest to the highest. *Sterculia rhinopetala* heartwood had the lowest uptake per volume with a value of 0.31 %. On the uptake per weight *Sterculia rhinopetala* heartwood again had the lowest uptake whilst *Albizia ferruginea* had the highest with a value of 6.77 %. The sapwood of *Sterculia rhinopetala* had a relatively higher uptake per volume value of 0.53 % and a value of uptake per weight of 0.72 % compared to the heartwood. The equilibrium moisture content values of *Sterculia rhinopetala* suggests that it can have minimal dimensional changes when used in both the Southern and the Northern parts of Ghana.

Keywords: microstructure, *Albizia ferruginea*, permeability, sorption, *Sterculia rhinopetala*

Introduction

Wood used in final form as furniture, building construction, musical instruments and other uses are generally subjected to fluctuating atmospheric humidity [1]. Timber is hygroscopic, that is it will absorb moisture depending on the atmosphere when dry and correspondingly yield moisture to the atmosphere when wet, thereby attaining moisture content which is in equilibrium with the water vapour pressure of the surrounding atmosphere. Thus, for any combination of vapour pressure and

temperature of the atmosphere, there is corresponding moisture content of the timber such that there is no inward or outward diffusion of water vapour. This moisture content is referred to as the equilibrium moisture content (EMC) [2]. The EMC is therefore constantly changing, sometimes periodically and at other times sporadically, such as when wooden decking is exposed to rain [3]. Wood exposed to high humidity conditions or to liquid water during use may be subjected to biological deterioration. The EMC of wood in use is affected most dramatically by the relative humidity of the atmosphere to which it is exposed. According to Dinwoodie [2], where timber is subjected to wide fluctuations in relative humidity, care must be exercised to select a species that has low movement values. Permeability, the way of ingress of water into wood mass, is one of the most variable properties of timber and it further influences nearly all the physical properties of wood [2,3]. In Ghana, the monthly range of equilibrium moisture content of wood exposed to normal conditions outdoors but under cover, is 4.8 – 19.3 %. The mean annual values range from 9.8 % in Navrongo to 18.3 % in Takoradi [4]. Wood in service is exposed to both long term (seasonal) and short-term (daily) changes in relative humidity and temperature of the surrounding air. Thus, wood is always undergoing at least slight changes in moisture content. These changes usually are gradual, and short-term fluctuations tend to influence only the wood surface. Wood is a hard, fibrous tissue found in many trees. It has been used for hundreds of thousands of years for fuel, construction, and industrial raw materials. It is an organic and natural composite of cellulose fibres embedded in a matrix of lignin which resists compression [5]. According to Baraúna et al [6], the study on anatomical, physical, and chemical characteristics of wood can result in knowledge about the technological behaviour of a wood species and the influence of these traits in its products. The vessels are responsible for the transportation of fluids in hardwoods [7], by which they inter-communicate through structures called perforation plates. Wood permeability is an important indication of the displacement of fluids within the plant [8]. It is affected by the proportion of heartwood and sapwood. Additionally, other anatomical factors which affect the permeability are number, amount and diameter of the vessels [9];[10]. Some of the anatomical properties of importance which will be considered are fiber length, fibre wall thickness, fibre lumen dimeter, vessel elements and parenchyma cells. In other processes of wood such as preservation and drying, the flow of liquids or gases through the wood structure is important, since these are greatly affected by the ease with which the fluids move through the internal spaces in the wood,

under static or dynamic pressure gradient [11]. Thus, this study `investigates the effect of anatomical and chemical structure on the sorption of water in *Sterculia rhinopetala* and *Albizia ferruginea* to aid in their utilisation.

Methodology

Wood samples were obtained from three *Sterculia rhinopetala* and *Albizia ferruginea* trees from a natural forest located at Fenaso Nkwanta in Ghana. Fenaso Nkwanta is situated nearby to Sefwikura (5' 23.1" N 1° 46' 55" W). Two-meter-long logs were removed from 40 meters high trees. The logs were sent to the Forest Research Institute of Ghana's workshop where three planks 2000 mm long, 650 mm wide and 30 mm thick, of each tree, were cut for this study.

Absorption Test

The standard used was a modification of ISO 15148 [12]. The experimental set up adopted the set up by Markus Jakob in his diploma research work at the ETH Zürich [13] where a basin made of stainless steel was filled with conditioned water (23°C). The water was untreated and had a pH of 6.98. It was pigmented with standard blue ink (Pelikan 4001, 1:20 - ink: water) to make water uptake visible. The water level was held constant at +/- 2 mm by an installation: A bottle filled with the same water was held upside down over the basin with its opening exactly 45 degrees at the ideal water level. As soon as water was lost during the testing and it causes a level decrease, the bottle takes up air and water flows into the basin until the level was stable at the correct level again. The parameter measured was the weight change and thus water uptake of the samples when in direct contact with water for a short time (in this experiment 5 minutes). Thirty (30) samples at a time were placed on the grid and immersed by 5 mm into the water. They were held in position by a heavy plastic board. The grid helps to move all samples at the same time in and out of the water.

Test Procedure

The conditions in the laboratory were kept constant as stated in Deutsches Institut für Normung (DIN) [14]: 23 °C and 50 % relative humidity. All wood specimens were conditioned until the daily weight changes were less than by 0.1 %. The air was circulated inside the laboratory to maintain this condition. The samples were conditioned under standard climate of ISO [15] for 3 weeks. They were weighed and then placed on the grid. They were immersed 5 mm below the surface of water in the basin. After 5 minutes they were taken out, cleaned of adhering water and weighed

again. Afterwards they were reconditioned under standard climate of ISO [15] for 3 weeks for density measurement.

Water uptake: To compare the uptake by the different species, the amount of water taken up was calculated as weight change:

$M_{change} = M_{test} - M_{cond}$

Where M_{test} = weight of sample after the test

$M_{cond.}$ = conditioned weight of the sample before the test.

M_{change} = weight change, which is the amount of water taken up by the sample

Relative water uptake is given as M_{change} in relation to M_{cond}.

$$\text{Rel. Change} = \frac{M_{change}}{M_{cond.}} \times 100\,\%$$

Uptake in relation to volume:

Rel. Change/vol. = rel. Change * ϱu

Where ϱu = green density at standardised climate

Density calculated as defined in German Standard [15] for oven dry density:

$\varrho o \sim 0 = M o / V o$

and according to [16] for green density as:

$\varrho u = M u / V u$...(Equation 1)

Where Mo = oven dry weight of samples

Mu = weight of samples at moisture content u

Vo = volume at oven dry (volume determined after the samples have been oven-dried)

 Vu = volume at moisture content u

Mu is measured after acclimatization in standard climate (50/23) until the weight is constant. Measurements were taken every 24 hours.

Determination of Density

For the volume determination water would have been a very convenient liquid to use but pre-tests showed that the samples absorbed the water so quickly, that it was not possible to measure their volume. Sunflower oil proved to be a suitable alternative. It was not that quickly absorbed by wood. The density of the oil had to be determined

with a pyknometer. It was conditioned under standard climate and the weight of 100 cm³ was taken. The density of the oil under laboratory conditions was 0.9165 g/cm³. The set up (Figure 1) was used to determine the volume of the samples.
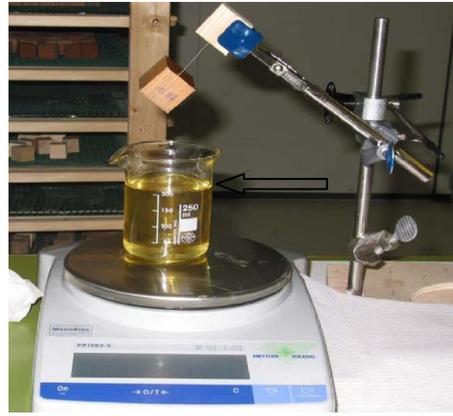
Figure 1. Set up for volume measurement by displacement method using sunflower oil

The formula used was:

Flift = Vbody * ϱliquid

Vbody = m/ϱliquid...(Equation 2)

Where Flift = weight change through immersion of the sample

Vbody = volume of the sample

ϱliquid = density of liquid

m = mass of wood

Air Dry Density

The samples were conditioned under laboratory conditions (23 °C and 50 % relative humidity). Their weights were taken. The samples were pinned to the holding device and immersed into the liquid. The balance shows the weight of the displaced volume of the sample. The air-dry density determined under laboratory conditions (23 °C and 50 % relative humidity) was then calculated with the formula in equation 1.

Oven Dry Density

The samples were dried in the oven at 103 °C. Their weights were taken. Volumes were determined as given in equation 2.

Determining Water Sorption Capacity

Adsorption of the wood species was determined. Sixteen randomly sampled specimens of each of the two species (heartwood and sapwood) with dimensions 3 cm x 3 cm x 3 cm were exposed at various relative humidity conditions of 30 %, 45 %, 60 %, 75 % and 90 % in a temperature and humidity-controlled climate chamber at a temperature of 25 ºC according to German standard [17]. Internal wood temperature and humidity were measured with datalogger. Samples were considered to have reached equilibrium at any given humidity when the daily weight changes were less than 0.1 mg according to German Standard [16]. Weight measurements were carried out after 1, 2, 4, 8, 24, 48 and 72 hours to measure the water uptake. After the last measurements of the weight changes the samples were dried at 103 °C until there was a constant weight. The equilibrium moisture contents (EMC) were calculated based on the oven-dried weight of the samples: The formula used was:

$$MC = \frac{Initial \ Weight \ - \ Oven\text{-}dry}{Oven\text{-}dry \ weight} \ X \ 100\%$$

Where MC= moisture content of the wood

Determination of Anatomical features

As reported by Quartey [18], Discs 10 cm thick were cut from a height of 1.30 m from the butt of the tree. From each disc samples of 1 cm × 3 cm were taken from the heartwood portion. They were weighed and their densities determined by the oven dry method. The samples were then softened by first saturating with water and later soaking them in ethanol and glycerol (1:1) in labelled containers for an average period of about 21 days. Thin sections, 20 - 30 μm thick produced on a Leica sliding microtome were first washed in water and then in 1% safranin in 50% ethanol solution for about 15 minutes. After staining they were washed in water and dehydrated in increasing concentrations of ethanol: 30 %, 50 %, 70%, 85 %, 90 % and 100 %. After dehydration, they were permanently mounted in Canada balsam. Slides were examined using a Leica DMLM light microscope, and photographs taken using a Leica DFC 320 digital camera. Photomicrographs were then analysed with software Leica 1M 1000 Version 4.0 Release 132. Vessel diameter was obtained by measuring 30 randomly selected pore, then taking the average. The frequency of vessels per mm^2 was calculated by counting the number

of vessels in thirty 1-mm^2 fields, then taking an average. The micrographs were analysed using the stereological technique for the proportion of the tissues [19] [20]. Thirty randomly selected micrographs for each tissue studied were used for study and then the averages taken. Dots grids were used to determine area fractions (P_P) of anatomical elements and oriented segments of predetermined length were used to determine the number of elements per unit length of the test line in the radial and tangential directions ($NL_R \cdot NL_T$). Standard areas were used to determine the number of elements per unit area (N_A). These basic counts were then used to derive other parameters such as proportion of elements in percentages. Splinters were also taken from the discs and macerated in a solution of equal parts of Acetic acid and hydrogen peroxide and heated in an oven at about 65 °C for 72 hours.

Results and Discussion Section

Absorption Test

The results of the absorption test are presented in **Table 1**. The order of water uptake in terms of percentage volume is arranged from the lowest to the highest. *Sterculia rhinopetala* heartwood had the lowest uptake per volume with a value of 0.31 %, the sapwood having a relatively higher uptake per volume was 0.53 % whilst *Albizia ferruginea* heartwood an uptake per volume of 1.37 % and sapwood 1.42 % respectively. On the uptake per weight *Sterculia rhinopetala* heartwood again had the lowest uptake with 0.38 % and sapwood value of 0.72 %. Figure a and b shows a sample of *Sterculia* before and after immersion. The percentage per weight of *Albizia ferruginea* was high for both its heartwood and sapwood with values of 2.49 % and 2.44 % respectively. The values presented in the absorption test of the wood species are influenced by anatomical features, which is one factor that affects the permeability of the fluid in the timber. According to Comstock [9] and Siau [10], size, distribution, and number of conductor elements and mainly the presence and intensity of obstructions of these anatomical structures act differently in the different species. Additionally, the low values of heartwood is explained by Cŏté [24] that the influence of heartwood formation on the reduction of intercell flow due to incrustation, tylosis development and extractive content which renders the heartwood less permeable than the sapwood. From Table 2, the density of vessels which is responsible for conduction of fluids or water, was more for *Albizia ferruginea* with a value of 12 vessels per mm^2 and 7 vessels per mm^2 for *Sterculia rhinopetala.* Rays and axial parenchyma which also plays roles in conduction

and storage are more in *Sterculia rhinopetala* which may impede the flow of water in the wood accounting for its low uptake of water. This is also confirmed by Cǒté [24] who stated that anatomical features have effect on permeability.

Table 1. Percentage water uptake in 5 minutes through absorption arranged by amount of uptake per volume (%) from the lowest to highest value for both heartwood and sapwood of the various species

| | Arranged by amount of uptake per volume [%]: lowest to highest
Results: capillarity 5 minutes | | | |
Species	Weight change[g]	Variation coefficient (%)	% per weight (conditioned)	% per volume (conditioned)
SRH	0.09	9.42	0.38	0.31
SRS	0.14	8.55	0.72	0.53
AFH	0.36	2.71	2.49	1.37
AFS	0.39	8.03	2.44	1.42

Legend: SRH = *Sterculia rhinopetala* heartwood, SRS = *Sterculia rhinopetala* sapwood, AFH = *Albizia ferruginea* heartwood, AFS = *Albizia ferruginea* sapwood. *Per volume- is the change in volume of the sample after immersion in water. *Per weight is the change in weight of the sample after the immersion in water

Figure 2. Sample of *Sterculia rhinopetala* before immersion
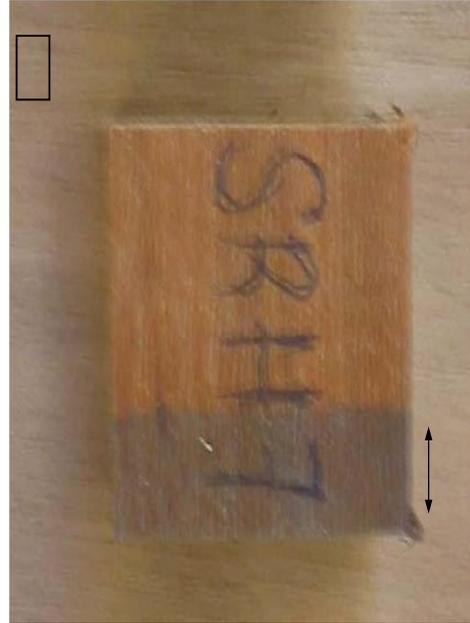
Figure 3. *Sterculia rhinopetala* after 5 minutes of immersion

Water Sorption Capacity

Specimens of each of the species (heartwood and sapwood) were exposed at various relative humidity conditions of 30 %, 45 %, 60 %, 75 % and 90 % in a temperature and humidity-controlled climate chamber at a temperature of 25 °C according to Quartey [18]. The mean equilibrium moisture contents of the wood species at the different humidity's and temperature of 25 °C are presented in Table 3. The difference between the quantity of water in the sapwood and the heartwood after wetting was significant. The respective differences in the moisture content at the end of the adsorption test were nearly significant. According to Table 3, at 90 % R.H. and 25 ° C, *Sterculia rhinopetala* had the lowest EMC with sapwood value of 11.0 % and heartwood value of 9.6 % whilst *Albizia ferruginea* had a sapwood value of 20.5 % and a heartwood value of 18.1. An adsorption sorption relationship for *Sterculia rhinopetala* and *Albizia ferruginea* can be seen in Figure 4. It can be seen that the isotherm of the sorption of water vapours by the two types of wood are very close which confirms the assumption about the similar microstructure of cell walls of different wood species [21]. According to Bariska [22] and Chirkova et al [23] most of the adsorbed water vapour takes place in the cellulose region and this can be confirmed by Table 4 where *Albizia ferruginea* has more cellulose content of between 44.1 – 46.5 % as against 38.2 – 43.4 % for *Sterculia rhinopetala* and so takes up more water. Therefore, water uptake particularly relied on microstructure of the hardwood. This is because Siau [3] stated that the dimensions of the wood change with

water molecules entering/leaving the amorphous zones of cellulose which causes the separation/combination of microfibrils and swelling/shrinkage of cell walls. The EMC values of *Sterculia rhinopetala* suggests that it can have minimal dimensional changes when used in both the southern part of Ghana and the Northern part since the EMC since according to Ofori [4], in Ghana, the monthly range of equilibrium moisture content of wood exposed to normal conditions outdoors but under cover, is 4.8 – 19.3 %. The mean annual values range from 9.8 % in Navrongo (Northern part) to 18.3 % in Takoradi, (Southern part).

**Table 2.** Proportion of tissues (and standard deviation) in the three species

Species	Fibers (%)	Vessel (%) & vessel density	Axial parenchyma	Rays (%)	DFWT (μm)	Density (g/cm^3)
A. ferruginea	63.3 (2.7)	5.8 (1.5) 12 vessels/mm^2	23 (1.9)	8 (0.7)	374(0.7)	0.603
S. rhinopetala	43 (2.6)	7.3 (1.1) 7 vessels/mm^2	34.3 (1.3)	15.5 (2.3)	806(1.3)	0.945

Legend: DFWT – Double fiber wall thickness
Source: Reproduced with permission Quartey, 2015 doi: <u>10.4236/msa.2015.612110</u>

Table 3. Mean equilibrium moisture contents of the wood species at different relative humidities and at 25°C. The value in brackets against each mean is the standard deviation.

Species	relative humidity	30%	45%	60%	75%	90%
Sterculia	Sapwood	3.2(0.9)	4.3(0.6)	6.3(0.4)	8.9(0.2)	11.0(0.2)
rhinopetala	Heartwood	2.5(0.2)	3.4(0.4)	5.3(0.3)	7.9(0.2)	9.6(0.3)
Albizia	Heartwood	5.1 (0.7)	7.8 (0.5)	8.8 (0.4)	12.2(0.5)	18.1(0.4)
Ferruginea	Sapwood	5.2 (0.2)	7.5 (0.2)	8.7 (0.2)	13.8(0.1)	20.5 (0.3)
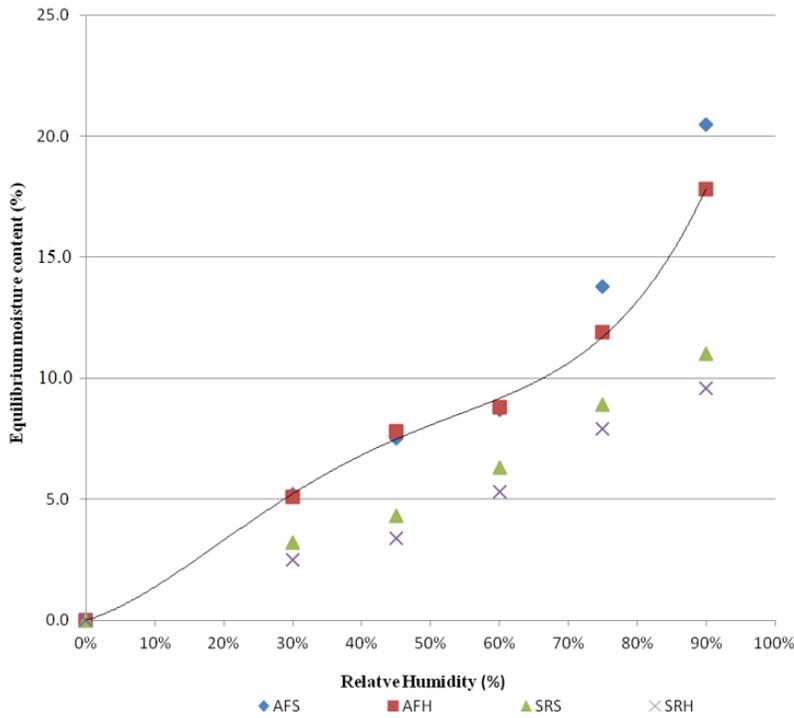
Figure 4. Relation between equilibrium moisture content and relative humidity at a temperature of 25^0C for *Albizia ferruginea* and *Sterculia rhinopetala* AFS – *Albizia ferruginea* sapwood, AFH – *Albizia ferruginea* heartwood, SRS – *Sterculia rhinopetala* sapwood, SRH – *Sterculia rhinopetala* heartwood.
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Table 4. Chemical composition of some of the wood species studied

Wood species	Cellulose %	Hemicellulose %	Lignin %	Extractives %
Sterculia rhinopetala	38.2 - 43.4	29.3 - 31.6	22.4 - 25.2	6.5 - 8.3
Albizia ferruginea	44.1 -46.5	28.3 - 31.6	25.2 - 28.4	8.3 - 9.0

Source: Reproduced with permission courtesy of Chemistry department of Forest Research Institute of Ghana, Kumasi, 2006

In use, wood is subjected to shrinkage, swelling, mould growth and rot if exposed to unfavourable environmental conditions. These phenomena are all related to moisture content and moisture conditions in a building. Rot may occur in wood which is in contact with liquid water for some time, while shrinkage, swelling and mould growth

are mainly related to hygroscopic moisture [25]. Outdoor climate changes occur throughout the day and night, and throughout the year.

Conclusion

The variability of hardwood structure causes wide differences in water absorption and adsorption ability not only among species, but permeability and water absorption behavior are widely affected by the microstructure of wood that is number of vessels that are not sealed by tyloses and their distribution within the mass, diameter of the vessel lumens, density of vessel elements among other features as seen in the behaviour of *Sterculia rhinopetala* and *Albizia ferruginea*. Even though moisture content changes can be retarded, but not prevented, by preventive coatings, such as varnish, lacquer, or paint, knowledge of the moisture content of the wood in use will be of advantage. In cases where dimensional changes could obviously cause problems, the designer or user should carefully consider the moisture content of the lumber being used, the species, the conditions of use, the amount of dimensional change that should be expected and the average relative humidity of the environment where the wood will be used.

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