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Thermal Treatment Impact on Kusia (*Nauclea diderrichii*) Dimensional Changes

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ABSTRACT

Thermal treatment of wood has grown significantly in recent decades as a method to enhance wood qualities. Wood is widely used in construction, but its tendency to swell and shrink poses challenges. High-temperature heating reduces these dimensional changes without using chemicals, making it an eco-friendly alternative to chemical modifications. This study examined the effects of thermal treatment on the dimensional stability of Kusia (*Nauclea diderrichii*) at various temperatures. Results showed that increasing the temperature from 150°C to 240°C improved stability, with anti-shrink efficiency rising from 36.62 to 52.11.

Keywords: Anti-shrink efficiency, Dimensional Stability, Kusia, Thermal Treatment, Volumetric Swelling Coefficient.

INTRODUCTION

Wood can be used for construction, but it presents challenges such as dimensional changes when exposed to natural environments (Hill, 2006). Due to wood's swelling and shrinking, wood-based materials undergo dimensional changes. The available hydroxyl groups in the polymers lead to water absorption through hydrogen bonding with the hydroxyl groups (OH), making wood dimensionally unstable (Kocaefe & Kocaefe, 2015). Thermal treatment of wood is a modification technique that reduces swelling and shrinkage and produces a material that does not pose greater environmental risks than untreated wood when discarded (Hill, 2006; Esteves et al., 2009).

Thermally unstable polymeric wood components, including hemicellulose, cellulose, and lignin, are degraded by heat modification. The degree of property change in wood due to thermal treatment depends on parameters such as temperature, duration of treatment, and wood species (Anonymous, 2003). Thermally treated wood exhibits decreased liquid water absorption (Militz, 2002; Tjeerdsma *et al*., 1998; Zikovi'c, 2008; Herrera *et al*., 2016; Zhang *et al*., 2017). When wood is thermally treated, hemicellulose degrades first inside the cell wall, followed by cellulose, producing furan compounds such as furfural and hydroxymethylfurfural (Rowell *et al*., 2009). Lignin complexes are also damaged when the treatment temperature exceeds 250°C (Tjeerdsma *et al*., 2005). According to Weiland & Guyonnet (2003), the decrease in swelling and shrinkage of thermally treated wood results from the elimination of several hydroxyl groups, leading to decreased water attraction.

When wood is heated above 150°C, its physical and chemical characteristics change irreversibly, and tangential and radial swelling is significantly reduced. As the temperature increases incrementally, the swelling and shrinkage continue to vary (Yildiz, 2006). The OH groups present in hemicellulose influence the physical properties of wood. When wood is subjected to high temperatures above 250°C, its characteristics alter due to the breakdown of hemicelluloses and the reduction of hydroxyl groups, resulting in decreased hygroscopicity (Inoue, 1993).

A measure of ASE (Anti-shrinking efficiency) can be used to determine the changes in dimensional stability after treating wood (Esteves & Pereira, *2009). ASE repre*sents the differential in swelling between modified and unmodified wood. According to Yildiz (2002a), the heat treatment of beech wood (Fagus orientalis) at varied temperatures and times resulted in an improved ASE by 65%, showing that ASE increased as the temperature and treatment time increased.

Recently, there has been increased attention towards thermal treatment procedures (Sahin, 2017) due to the limited supply of durable lumber, the growing demand for sustainable construction materials, the destruction of subtropical forests, and the greater implementation of government legislation limiting the use of harmful chemicals (Boonstra, 2008).

There is an abundance of lesser-utilized wood species in the forests of Ghana. Some of these lesser-utilized wood species have low dimensional stability. Some of the les*ser-used species co*uld be modified to improve dimensional changes. Wood hygroscopicity limits the outdoor utilization of wood (Wang et al., 2018). Wood moisture may appear in four forms: (i) as water of constitution, (ii) as surface-bound water or water in an adsorbed monolayer with a high density (1.3 gcm^{-3}), (iii) as water adsorbed in multimolecular layers with a decreasing order of dipoles, and (iv) as capillary-condensed water. Constitutional water is due to the organic nature of cell walls. It cannot be removed without altering the chemical composition of the walls. Surface-bound water differs from the water of constitution and can be removed without altering the wood chemically. Since water is a polar liquid consisting of a negative hydroxyl $(OH)^-$ and a positive hydrogen fraction, it is assumed that hydroxyl groups are attached by Valence bonds. Capillary-condensed water, as surface-bound water, can be freely evolved from wood. According to research, the accessible OH groups are responsible for hygroscopicity (*Hosseinaei et al.,* 2012; özlem et al., 2017).

Kusia (*Nauclea diderrichii*) is a tropical plant prevalent in Ghana's forests. It is a high-density wood species suitable for building construction in Ghana. It is also used for structural work, marine defense and dock construction, paneling, flooring, and boat building. Its heartwood is moderately resistant to termites. Shrinkage from green to oven-dry includes radial 4.5%; tangential 8.4%; volumetric 12.6%. According to Ofori *et al*. (2009), although it has a tangential to radial ratio greater than 1.5, it is prone to large cracks, checks, and distortions, if kiln drying procedures are not observed. Movement in service is rated as small (https://timberteam.com/wp-content/uploads/2014/07/badi-bilinga-kusia-O4GJ6L-H5VLS0-OW3PCP.pdf). Its treatability is moderate, and it has low moisture movement. This study aimed to assess the influence of thermal treatment on the dimensional changes of Kusia (*Nauclea diderrichii*) treated at varying temperatures. Kusia was thermally treated at different temperatures at various times to analyze variations in dimensional stability between thermally treated and untreated materials.

MATERIALS AND METHODS

Source of Wood Samples

The logs were obtained from the Western north in Ghana and were processed into lumber at John Bitar Company in Takoradi. The average density at was 630 kg/m^3 at the moisture content of 12 %.

Sample Preparation of Wood

The lumber was kiln dried for two weeks. Samples devoid of defect were extracted from the heartwood. The dimensions of the samples were 20 mm by 20 mm by 20 mm. Five sets with each set containing 10 replicates, were produced.

Thermal Process

One set of ten repetitions served as the control (untreated), whereas four sets were heated in an oven with poor oxygen using nitrogen as inert gas for six hours at varying temperatures of 150^{o}C, 180^{o}C, 210^{o}C, and 240^{o}C in the absence of oxygen. The thermal treatment was performed at the Department of Chemical Material Engineering at Kwame Nkrumah University of Science and Technology in Kumasi, Ghana.

Analysis of Dimensional Stability

Volumes of the oven dried wood samples were calculated as V_o. The samples were then immersed for five days in distilled water, and the saturated volumes V_s, were also calculated. The oven dry-water soak cycles were done five times, and the average volumes of ten replicates were calculated for each of the five cycles. On the untreated samples, identical oven dry-water soak cycles were carried out.

Average volumetric swelling coefficient (S %) and anti-shrink efficiency (ASE %) were determined using equations 1 and 2, respectively.

$$S\% = (V_s - V_o)/V_o \text{ X } 100 \qquad \text{equation (1)}$$

Where:

- V_s = volume of water saturated wood

- V_o = volume of oven-dried wood.

From the volumetric swelling coefficient (S %) in equation 1, the anti-shrink efficiency was calculated as in equation 2.

$$ASE\% = (S_u - S_m)/S_u \qquad \text{equation (2)}$$

Where:
- ASE = anti-shrink efficiency
- S_u = volumetric swelling coefficient of unmodified
- S_m = volumetric swelling coefficient of modified.

Analytical Statistics
Genstart 12th edition was used for dimensional stability analysis and Analysis of Variance (ANOVA) determination.

RESULTS AND DISCUSSIONS

Use of Volumetric Swelling Coefficient to Evaluate Dimensional Stability

Table 1 shows the results of average S_t% from five water soak – oven dry cycles of untreated at 28^{o}C and treated samples at 150^{o}C, 180^{o}C, 210^{o}C, and 240^{o}C.

Table 1: Average S% and standard deviation (st) from Five Water- soak oven – dry cycles

Samples	Treatment Temperature (^{o}C)				
	28^{o}C	150	180	210	240
S_u (Untreated Sample)	7.10	-	-	-	-
S_m (Treated Sample)	-	4.50^a	4.45^a	3.82^b	3.40^c
Standard Deviation	0.1	0.08	0.11	0.30	0.09

*Means with the same letters are not significantly different at $P < 0.05$.

From Table 1, the average volumetric swelling coefficient of untreated samples (S_u% = 7.10) was greater than that of treated samples (S_m% = 4.50, 4.45, 3.82, and 3.40) at temperatures of 150^{o}C, 180^{o}C, 210^{o}C, and 240^{o}C, respectively. The greater volumetric swelling coefficient of the untreated samples indicates that the treated samples had superior dimensional stability compared to the untreated samples.

There was no significant change in S_m% of the modified samples when the heating temperature was increased from 150^{o}C to 180^{o}C and S_m% values were 4.50^a to 4.45^a respectively. That indicated there was no significant change in swelling and shrinkage. However, the volumetric swelling co-efficient values decreased: 4.45^a, 3.82^b, and 3.63^c at higher temperatures of 180^{o}C, 210^{o}C, and 240^{o}C respectively. This is consistent with the study of Yildiz 2002b, which states that the degree of modification in wood properties due to heat treatment is dependent on the temperature gradient, and the duration of treatment. As temperature and duration of treatment increase, more polymers are degraded reducing the OH groups and hence absorption of water molecules by hydrogen bonding decrease, as a result, swelling and shrinkage decreased. The thermally modified samples showed less volumetric shrinkage which agreed with Militz, (2002); Tjeerdsma (1998); Zikovi'c, (2008) report, resulting in less hygroscopicity and less liquid water uptake (Hererra et al., 2016; Zhang et al., 2017). The reduction in volumetric shrinkage is as a result of reduction in OH groups caused by the heat treatment leading to degradation of hemicellulose, cellulose and lignin and thereby decreasing absorption of water molecules into the wood.

Determination of Dimensional Stability by Means of Anti-Shrink Efficiency

Table 2 shows the result of average ASE% from five water soak – oven dry cycles of untreated and treated samples at 150°C, 180°C, 210°C, and 240°C.

Table 2. Average ASE% and standard deviation from five water- soak oven – dry cycles.

Samples	**Treatment Temperature (° C)**			
	150	**180**	**210**	**240**
ASE **%**	36.62[a]	37.32[b]	46.20[c]	52.11[d]

*Means with the same letters are not significantly different at $P < 0.05$.

In Table 2, there were considerable variations in the anti-shrinkage efficiency percentages. As temperatures rose from 150°C to 240°C, the ASE increased from 36.62 % through 37.32 %, 46.20 % to 52.11 %. It is known that hemicelluloses are the first structural constituents changed by thermal treatment, even at moderate temperatures of 150°C Estives & Pereira, (2009), while lignin and cellulose are degraded at higher temperature above 210°C. Degradation of hemicelluloses begins even at 120°C Poncsák *et al*. (2007), but significant degradation with positive effects occurs above 180°C (Sivonen *et al.*, 2002; Hakkou *et al*., 2006; Wang *et al*., 2016; Özlem *et al*., 2017). According to (Weiland & Guyonnet, 2003) at low temperatures of 150°C, hemicelluloses undergo degradation processes, resulting in the loss of OH groups and a reduction in swelling and shrinkage. The result was in agreement with (Weiland & Guyonnet, 2003; Estives & Pereira, (2009). As the temperature of the treatment rise, degradation of lignin and cellulose increases, leading to a decrease in the amount of water absorbed resulting in an increase of ASE values. As heat treatment is increased, more polymeric compounds are degraded, leading to a decrease in the quantity of hydroxyl groups and a decrease in absorption of water, thus swelling and shrinkage also reduced (Yildiz *et al*., 2006). Esteves *et al*. (2008b) also observed that, relative to hemicelluloses, cellulose had a greater resilience to breakdown at lower temperatures of 150°C and since only hemicellulose are affected at temperatures below 150°C it results in less swelling and shrinkage.

CONCLUSION

Kusia samples heated at 150°C, 180°C, 210°C, and 240°C exhibited greater dimensional stability than unmodified. Thermal treatment enhances the dimensional stability of kusia, a tropical hardwood, substantially. As the heating temperature rises, the dimensional stability increases. Thermal treatment of wood between temperatures of 150°C and 240°C improved dimensional stability of kusia, a tropical hardwood species. As the temperature for the treatment increases, shrinkage and swelling of the wood species decrease. Thermal modification of wood can be used to improve dimensional changes however, to use the thermally treated wood as engineering material, there is the need to research into the effect of the treatment on the strength properties of the wood.

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