

## PHYSICAL AND MOISTURE SORPTION PROPERTIES OF THERMALLY- MODIFIED GMELINA ARBOREA WOOD

**Maxidite Amankwaah MINKAH\***

Department of Wood Science and Technology, Kwame Nkrumah University of Science and Technology  
Address: P. O. Box PMB KNUST, Kumasi, Ghana  
E-mail: [minkahmaxidite@yahoo.com](mailto:minkahmaxidite@yahoo.com)

**Kojo Agyapong AFRIFAH**

Department of Wood Science and Technology, Kwame Nkrumah University of Science and Technology  
Address: P. O. Box PMB KNUST, Kumasi, Ghana  
E-mail: [kagyapong@gmail.com](mailto:kagyapong@gmail.com)

**Charles ANTWI-BOASIAKO**

Department of Wood Science and Technology, Kwame Nkrumah University of Science and Technology  
Address: P. O. Box PMB KNUST, Kumasi, Ghana  
E-mail: [cantwiboasiako@gmail.com](mailto:cantwiboasiako@gmail.com)

**Maximilian WENTZEL**

Department of Wood Biology and Wood Products, University of Göttingen  
Address: Büsgenweg 4, D-37077, Göttingen, Germany  
E-mail: [maximilian.wentzel@yahoo.com](mailto:maximilian.wentzel@yahoo.com)

**Djeison Cesar BATISTA**

Department of Forest and Wood Sciences, Federal University of Espírito Santo  
Address: Avenida Governador Carlos, Lindenberg 316, Postal Code 29550-000, Jerônimo  
Monteiro, Espírito Santo, Brazil  
E-mail: [djeison.batista@ufes.br](mailto:djeison.batista@ufes.br)

**Holger MILITZ**

Department of Wood Biology and Wood Products, University of Göttingen  
Address: Büsgenweg 4, D-37077, Göttingen, Germany  
E-mail: [hmilitz@gwdg.de](mailto:hmilitz@gwdg.de)

### **Abstract:**

*This study investigated the impact of thermal modification on the physical and moisture sorption properties of Gmelina arborea Roxb. ex. Sm. Standard thermal modification was carried out at temperatures of 180°C, 200°C and 220°C for 3 hours at atmospheric pressure. Thermally modified wood samples were assessed for mass loss (ML), oven-dry density, moisture content, fiber saturation point (FSP), water absorption, water repellence effectiveness, volumetric swelling, anti-swell effectiveness (ASE) and moisture sorption properties. Regression analyses between ML and ASE resulted in very strong correlation implying improved dimensional stability. Generally, the results showed that, thermal modification conferred improved dimensional stability, reduced equilibrium moisture content (EMC) and narrowed the difference between adsorption and desorption EMCs as modification temperature increased. Thermally modified Gmelina arborea wood is therefore recommended for applications that are exposed to the weather and humidity variations such as, garden furniture, decorative panels, kitchen furniture, windows, saunas and cladding. Its use in persistent exposure to water or rain is discouraged to prevent loss of water repellence effectiveness and reduce susceptibility to decay.*

**Key words:** adsorption; swelling; desorption; isotherm; thermal modification.

### **INTRODUCTION**

Wood has excellent physical and aesthetic properties, including thermal resistance, good relationship between weight and strength and it can easily be processed. Together with its renewable and eco-friendly nature, it has been used widely for many applications including light and heavy weight constructions (Aydin and Colakoglu 2005). In spite of these, wood is dimensionally unstable on adsorption of water and may not naturally resist insects and fungi (Juodeikienė and Minelga 2003).

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\* Corresponding author

Durability and stability of wood can be enhanced by chemicals. However, this approach faces increasing environmental and public pressure, especially in Europe and North America (Sandberg and Kutnar 2015). Wood product manufacturers worldwide are therefore looking for alternative but effective methods to enhance wood properties (Ahmed and Moren 2012).

Heat treatments above 150°C can be used to modify properties of wood by causing changes in its chemical and physical properties. For instance, the wood colour tends to get darker, swelling and shrinkage are significantly reduced and the equilibrium moisture content (EMC) is improved (Korkut 2008). Higher modification temperatures also result in better biological resistance of wood (Syrjanen and Oy 2001).

Adeyemi *et al.* (2017) reported that thermal modification was effective to improve dimensional stability of *Anthiacleistha djalonesis* A. Chev. wood. Improved dimensional stability associated with thermally modified wood, overcomes the challenge of reducing wood moisture content and its associated volumetric swelling encountered in wood chemical modification (Hill 2006). The drawback of thermal modification of wood is significant mass loss and changes in mechanical properties (Yildiz *et al.* 2006). The higher the temperature, the greater the extent of decrease of mechanical properties and increase of mass loss. For instance, higher temperature of thermal modification, led to significant changes in mass, volume and density of Oak, Lime and Birch woods (Navickas and Albrektas 2013).

Wood property changes that accompany thermal modification depend mainly on the wood species (quality, properties, initial moisture content, sample dimensions) and the process variables (temperature, duration, type of system, use of catalysts) (Hill 2006; Korkut *et al.* 2009). For instance, poplar (*Populus x euroamericana* I-214) and oriental plane (*Platanus orientalis* L.) woods were thermally modified by exposing samples to temperatures of 150°C and 200°C for 3h in atmospheric pressure. This study revealed that, Thermal modification at 200°C had significant effect on density, mass loss and volumetric swelling of both wood species. However, the process had less effect on the swelling and fiber saturation point (FSP) of poplar wood than on properties of oriental plane wood, a clear indication of species effect (Bal 2013).

Modification temperature has been observed to have considerably greater influence on wood properties than the heating duration. Noticeable differences exist between thermally modified wood at lower temperature that lasts for longer period of time and process that takes place at higher temperature lasting for a shorter period of time (Alkyidiz and Ates 2008). In spite of the drawbacks, thermally modifying wood is a viable and eco-friendly alternative to improve wood properties (Ahmed and Moren 2012).

*Gmelina arborea* is a lesser used species (LUS) in Ghana. To promote its acceptance on the timber market, Mitchual *et al.* (2018) and Mitchual *et al.* (2019) researched on the “planing, turning, sanding and shaping characteristics of *Gmelina arborea* wood”. It was concluded that, the wood showed good machining properties. To further establish the properties of *Gmelina arborea*, this study therefore investigated the impact of thermal modification on some physical properties of *Gmelina arborea* wood. It aimed at assessing the possibility of improving its properties in order to make it attractive and promote its exploitation and utilization potential.

## **MATERIALS AND METHODS**

### **Source of material and preparation**

Four *Gmelina arborea* trees with diameter at breast height (DBH, 1.3m above ground) of 35 – 55cm were obtained from 40-year old plantation of Centre for Scientific and Industrial Research – Forestry Research Institute of Ghana (CSIR – FORIG) Research Plot at Abofour, Offinso district in the Ashanti region of Ghana. Abofour is located within the moist Semi-Deciduous Forest Zone with average annual rainfall of 1400mm. It lies 7°8'0" N and 1°45'0" W and it is about 60 km from the Ashanti regional capital, Kumasi.

Trees were bucked into 2.5m length bolts with a chainsaw. Resulting bolts were further processed using a portable Wood - Mizer (LT 30) into boards of 25mm thickness at the CSIR – FORIG wood workshop at Fumesua, Kumasi. The boards were air-dried for at least 12 months until MC below 20% was achieved. Randomly selected boards were obtained within 15cm radius from the pith to assure the use of heartwood. These boards were further processed into test slats of dimension 20x50x650mm<sup>3</sup>. The study used only the slats ranging from 300 to 400g. This pre-sorting was necessary for the homogenization of the lot and to minimize the effect of the initial density on the results.

### **Thermal modification**

The thermal modification test was undertaken at the Department of Wood Biology and Wood Products of the Georg-August University, Germany, using a Laboratory Scale Reactor 65L Capacity (WTT, Jyllandsvej, Denmark). The slats were thermally modified using three schedules under accurate conditions of temperature and time, adopting the open system (non-pressurized process). Steam was used to prevent wood from burning and influence chemical changes taking place. The modification schedules were similar to the ThermoWood® process (Mayes and Oksanen 2002).

Firstly, the temperature in the vessel was raised at 12°C/h to 100°C and then 4°C/h to 130°C to allow high temperature drying of slats to nearly 0% MC. Secondly, the temperature was again increased at 12°C/h until reaching peak temperatures (180°C, 200°C and 220°C). Each peak temperature was held for 3h. Finally, the temperature was decreased at 20°C/h until reaching 65°C, at which the vessel was opened and the slats removed.

### Mass loss

The mass loss of each slat after the thermal modification process was calculated as described by Metsä-Kortelainen *et al.* (2006). Each air-dried slat was weighed before and after the thermal modification process. Moisture contents were then determined for the slats before and after the thermal modification process. The obtained moisture contents were used to reduce the masses of the slats respectively, to determine their oven-dry masses for the computation of the mass loss. Mass loss % (ML %), was thus calculated as in Equation 1.

$$ML = \frac{(m_1 - m_2) \times 100}{m_1} \quad [\%] \quad (1)$$

where:  $m_1$  is the dry mass of the sample before the thermal modification, in g;  
 $m_2$  - dry mass of the sample after the thermal modification, in g.

Dry mass (g),  $mdry$ , was calculated as follows (Equation 2).

$$mdry = \frac{100 \times m_u}{u + 100} \quad [g] \quad (2)$$

where:  $m_u$  is the mass of the sample at moisture content  $u$ , in g;  
 $u$  - moisture content of the sample, %.

### Moisture content

The MC ( $u$ ), was measured before and immediately after the thermal modification process on small samples of dimension  $20 \times 50 \times 20 \text{ mm}^3$  taken from each slat. The masses of the small samples from air-dried unmodified slats and thermally modified slats were initially determined. Subsequently, the samples were oven-dried at 103°C for 48h to their respective constant masses. The moisture content (%),  $u$ , was calculated using Equation 3.

$$u = \frac{(m_u - mdry)}{mdry} \times 100 \quad [\%] \quad (3)$$

where:  $m_u$  is the mass of the sample at moisture content  $u$ , in g;  
 $mdry$  - oven-dry mass of the sample, g.

### Oven-dry density

Oven-dry density was determined in accordance with ISO 3131 (1975). Twenty samples of unmodified and each thermally modified group, with dimensions of  $10 \times 10 \times 10 \text{ mm}^3$  were tested. The samples were obtained from four randomly selected slats. Samples were oven - dried at  $103 \pm 2$  °C until attaining constant masses, weighed to the nearest 0.001g, and their volumes measured to the nearest  $0.001 \text{ mm}^3$ . The oven-dry density was then calculated as in Equation 4.

$$OD = \frac{M_o}{V_o} \quad [g/cm^3] \quad (4)$$

where:  $M_o$  is the oven-dry mass, g;  
 $V_o$  - oven-dry volume,  $\text{cm}^3$ .

### Volumetric swelling

The volumetric swelling was determined with 20 samples of dimensions  $10 \times 10 \times 10 \text{ mm}^3$  obtained from four slats per treatment. The samples were firstly conditioned at 20°C/65% relative humidity until constant mass (nearest 0.001g). Subsequently, they were oven-dried at  $103 \pm 2$ °C for 24h and their volumes (nearest  $0.001 \text{ mm}^3$ ) and weights determined. The samples were immersed in water for 10 days to ensure complete saturation of the wood cells. The mass and saturated volume of each sample was determined. The volumetric swelling was then calculated with Equation 5.

$$Sw = \frac{V_2 - V_1}{V_1} \times 100 \quad [\%] \quad (5)$$

where:  $V_2$  is saturated volume,  $\text{cm}^3$ ;  
 $V_1$  - oven-dried volume,  $\text{cm}^3$ .

#### **Fiber Saturation Point, Anti-Swell Effectiveness, Water Absorption and Water Repellent Effectiveness**

Fiber saturation point (FSP), anti-swell effectiveness (ASE), water absorption (WA) and water repellent effectiveness (WRE) for each sample was calculated with Equations. 6, 7, 8, and 9, respectively.

$$Fsp = \frac{Sws}{Do} \quad [\%] \quad (6)$$

where: Sws is the volumetric swelling at saturation with water, %;  
Do - oven-dry density,  $\text{g}/\text{cm}^3$ .

Anti-Swell Effectiveness (ASE) was calculated based on the volumetric swelling (Sw) of the samples (Equation 7).

$$ASE = \frac{(Sw \text{ of unmodified specimen} - Sw \text{ of modified specimen})}{Sw \text{ of unmodified specimen}} \times 100 \quad [\%] \quad (7)$$

Water absorption (WA) was determined as in Equation 8.

$$WA = \frac{(mf - mi)}{mi} \times 100 \quad [\%] \quad (8)$$

where:  $m_f$  is the final mass of conditioned samples, g;  
 $m_i$  - oven-dry mass, g.

Water Repellent Effectiveness (WRE) was determined for each sample as follows (Equation 9).

$$WRE = \frac{(WA \text{ of the unmodified specimen} - WA \text{ of modified specimen})}{WA \text{ of unmodified specimen}} \times 100 \quad [\%] \quad (9)$$

Equations 4 – 9 were obtained from Rowel and Young (1981).

#### **Moisture sorption**

The sorption test was determined using 20 samples from each treatment group, with dimensions  $10 \times 10 \times 10 \text{ mm}^3$ . Samples were obtained from 4 different slats per treatment. The samples were initially conditioned at  $20^\circ\text{C}/65\%$  relative humidity until constant mass (nearest  $0.001\text{g}$ ) using a climate chamber of 115 L capacity (Binder, model KBF 115, Tuttlingen, Germany). Subsequently, the samples were oven-dried at  $103 \pm 2^\circ\text{C}$  for 48h and the oven-dried masses were determined to the nearest  $0.001\text{g}$  ( $m_0$ ). The samples were exposed to an adsorption isotherm ( $20^\circ\text{C}$ ) at crescent relative humidity of 35%, 50%, 65%, 80% and 90%. The samples were weighed until a constant mass ( $m_i$ ) (nearest  $0.001\text{g}$ ) or equilibrium was attained. The RH was changed when they reached equilibrium ( $m_i$ ). Finally, they were exposed to a desorption isotherm, using the same conditions and method. The equilibrium moisture content (EMC) at every step 'i' was calculated (Equation 10).

$$EMC = \frac{m_i - m_0}{m_0} \times 100 \quad [\%] \quad (10)$$

#### **Data analysis**

Descriptive statistics comprising mean percent with standard deviation was used to assess sample values for each treatment. Comparison of the properties determined from the samples (unmodified,  $180^\circ\text{C}$ ,  $200^\circ\text{C}$  and  $220^\circ\text{C}$ ) was assessed using Analysis of Variance (ANOVA). Least Square Deviation was used to compare differences between samples when ANOVA revealed significant differences at  $\alpha = 0.05$ . Statistical Package for Social Sciences (IBM Statistics) version 26 was used to do the analyses.

## RESULTS AND DISCUSSION

### Mass loss

Table 1 presents the mass loss of wood at three different modification temperatures. The appropriateness and suitability of any thermal modification depends largely on resulting mass loss (Bal 2013). Table 1 reveals significant increase in mass loss as modification temperature rises. Mass loss of 5.44% was recorded at 180°C and 15.13% at 220°C. High mass loss implies more pronounced changes in wood properties, for example, density, chemical and strength properties (Militz 2002, Hill 2006; Esteves and Pereira 2009). Thermal degradation of hemicelluloses and volatilization of some extractives increases with increase in modification temperature and may have accounted for the significant increases in mass loss from a lowest value recorded at 180°C and the highest at 220°C (Table 1).

Table 1

**The effect of thermal modification on mass loss, oven-dried density, moisture content, fiber saturation point and water absorption at 3 hours holding time**

	ML	ODD	MC	FSP	WA <sub>20/65%</sub>	WA <sub>10days</sub>
<b>Unmodified</b>	0.00 (0.00)	0.51 <sup>a</sup> (0.03)	10.46 <sup>a</sup> (0.74)	20.24 <sup>a</sup> (2.09)	13.08 <sup>a</sup> (0.62)	102.27 <sup>a</sup> (8.26)
<b>180</b>	5.44 <sup>a</sup> (0.86)	0.49 <sup>ab</sup> (0.04)	2.71 <sup>b</sup> (0.49)	11.09 <sup>b</sup> (2.53)	4.55 <sup>b</sup> (0.77)	108.74 <sup>a</sup> (21.30)
<b>200</b>	10.08 <sup>b</sup> (0.95)	0.48 <sup>b</sup> (0.03)	1.73 <sup>c</sup> (0.46)	8.07 <sup>c</sup> (1.54)	3.77 <sup>c</sup> (0.25)	107.40 <sup>a</sup> (11.04)
<b>220</b>	15.13 <sup>c</sup> (2.17)	0.41 <sup>c</sup> (0.04)	1.36 <sup>d</sup> (0.19)	7.11 <sup>c</sup> (0.85)	3.11 <sup>d</sup> (0.37)	91.82 <sup>b</sup> (16.46)
<b>Significance level</b>	***	***	***	***	***	***

<sup>1</sup>Means followed by the same letter are not significantly different.

<sup>2</sup>Standard deviation are shown in parentheses; \*\*\*, 0.05

ML: Mass loss (%); ODD: Oven-dry Density (g/cm<sup>3</sup>); MC: Moisture Content (%); FSP: Fiber Saturation Point (%); WA<sub>20/65%</sub>: WA (20/65%); WA<sub>10days</sub>: WA 10 days (%).

### Oven-dry density

Density of wood is a very important property since it is closely connected to most mechanical and physical properties (Korkut and Aydin 2015). Table 1 shows oven – dry densities (ODD) at three heat treatment levels. Significant differences in ODD were recorded between unmodified and modified wood. The ODD decreased significantly with increasing modification temperature (Table 1). Treatment temperature 180°C recorded ODD value of 0.49g/cm<sup>3</sup> with 220°C showing the least of 0.41g/cm<sup>3</sup>. Density reduction in thermally modified wood is due to the occurrence of depolymerization reaction of wood polymers. Wood component depolymerization takes place above the following thresholds: 127 – 235°C for hemicelluloses, 167 - 217°C for lignin and 231 – 253°C for cellulose. This results in changes in the mechanical and physical properties of wood (Boonstra *et al.* 2007). Reports indicate that, the hemicelluloses are less stable to heat effect than cellulose and lignin and accounts for the decrease in density at high temperatures (Hillis 1984; Fengel 1989). Esteves and Pereira (2009) also associated the degradation of hemicelluloses into volatile products and the evaporation of extractives as the main causes of lowered density, increasing as modification temperature increased.

### Moisture content and fiber saturation

Wood is a hygroscopic material that absorbs water (Dinwoodie 2004). Table 1 presents the moisture content (MC) and fiber saturation point (FSP) at various modification temperatures. Moisture content of wood after thermal modification decreased significantly with increasing modification temperature. Unmodified wood recorded the highest MC of 10.46%, while the least MC of 1.37% was observed for wood modified at 220°C. Differences in MC of modified wood at the three modification temperatures were significant (Table 1). Wood shows reduced hygroscopicity when thermally modified due to reduced number of –OH groups which reduces its ability to absorb and retain moisture (Boonstra and Tjeerdma 2006; Jimenez *et al.* 2011). FSP refers to the MC of wood at which “free water” has been removed from cell cavities and the cell wall is completely filled with ‘bound water’ (Dinwoodie 2004). Unmodified wood gave significantly higher FSP (of 20.24%) than their thermally-modified counterparts (Table 1). Generally, FSP decreased significantly as the modification temperature increased with the lowest value recorded at 220°C (Table 1). Thermal modification of wood initially results in degradation of hemicelluloses decreasing their number of hydroxyl groups (-OH). The -OH groups within the cellulose are also replaced by O-acetyl groups resulting in increased cellulose

crystallinity, with the wood subsequently becoming less hygroscopic (Kocafe *et al.* 2008). The reduced number of -OH groups lowers the FSP. Boonstra and Tjeerdsma (2006) indicated that, a polycondensation reaction resulting in cross-linking of lignin in thermally-modified wood could also be responsible for reduced FSP. These effects became greater as modification temperature was increased, accounting for the significant reduction of FSP as modification temperature increased.

### Water absorption

Table 1 presents the water absorption of thermally-modified wood under standard conditions of 20°C/65%RH and complete immersion in water. Use of wood as components in residential and industrial buildings/applications requires that its behavior on exposure to moisture/water is studied. *G. arborea* wood in standard conditions of 20°C/65 %RH indicated reduced water absorption (WA) as modification temperature increased (Table 1). The unmodified wood recorded 13.08% WA reducing significantly to the least of 3.11% at 220°C. Sundquist (2004) and Nuopponen (2005) explained that, the reduction in water absorption, as a result of reduced hygroscopicity of thermally-modified wood, could be attributed to reduction in hydroxyl groups bonding sites for water in celluloses and hemicelluloses, due to thermal degradation of wood. Generally, the reduced amount of free hydroxyl groups, results in decreased interactions between wood and water. In the course of the thermal modification process, hydrophilic oxygen-acetyl groups replace the hydroxyl groups in wood (Tjeerdsma and Militz 2005). Additionally, the increased hydrophobicity of thermally modified wood was associated with cross-linking of lignin, resulting in limited sorption sites for water (Sundquist 2004; Nuopponen 2005; Tjeerdsma and Militz 2005). However, in conditions of complete saturation by water (immersion in water), modification temperatures of 180°C and 200°C recorded WA of 108.74% and 107.40%, respectively, indicating that, higher water immersion time lowers the impact of thermal modification on WA (Dünder *et al.* 2012). These were greater than the unmodified group (102.27%) (Table 1). However, the increase was not significant at  $\alpha=0.05$ . This could be due to similarity of wood-water interaction of unmodified and thermally modified wood (180°C and 200°C) when completely saturated with water. By contrast, at 220°C, a significant reduction in WA was observed compared to the control group. This could be due to the effect of much pronounced hydrophobicity at high temperatures (Jimenez *et al.* 2011).

### Water repellence effectiveness

From Table 2, water repellence effectiveness (WRE) at various modification temperatures significantly increased as modification temperature was increased under standard conditions of 20°C/65% RH. Modification temperature of 220°C gave the highest WRE of 76.22% under standard condition. Thermally-modified wood tends to repel water due to degradation of hemicelluloses, reduced number of OH groups and increased crystallinity of cellulose (Wikberg 2004). In complete water saturation, WRE was lowered at modification temperatures 180°C (-6.11%) and 200°C (-5.66%) compared to the unmodified wood. By contrast, modification temperature of 220°C recorded WRE of 10.05% under complete saturation. Comparing with WRE values in standard conditions, it could be concluded that, the ability of thermally-modified wood (180°C, 200°C and 220°C) to repel water, is highly compromised when completely saturated with water.

Table 2

#### The effect of thermal modification on water repellent effectiveness, volume swelling and anti-swell effectiveness at 3 hours holding time

	WRE <sub>20/65%</sub>	WRE <sub>10days</sub>	VS <sub>20/65%</sub>	VS <sub>10days</sub>	ASE <sub>20/65%</sub>	ASE <sub>10days</sub>
Unmodified	0.00	0.00	5.55 <sup>a</sup>	10.43 <sup>a</sup>	0.00	<b>0.00</b>
	(0.00)	(0.00)	(1.10)	(1.00)	(0.00)	<b>(0.00)</b>
180	65.13 <sup>a</sup>	-6.11 <sup>a</sup>	1.69 <sup>b</sup>	5.43 <sup>b</sup>	68.24 <sup>a</sup>	<b>47.13<sup>a</sup></b>
	(5.92)	(22.21)	(0.44)	(1.15)	(10.74)	<b>(13.68)</b>
200	71.10 <sup>b</sup>	-5.66 <sup>a</sup>	1.36 <sup>b</sup>	3.87 <sup>c</sup>	73.78 <sup>a</sup>	<b>62.49<sup>b</sup></b>
	(2.40)	(13.82)	(0.64)	(0.80)	(15.17)	<b>(9.15)</b>
220	76.22 <sup>c</sup>	9.91 <sup>b</sup>	1.37 <sup>b</sup>	2.92 <sup>d</sup>	74.62 <sup>a</sup>	<b>71.72<sup>c</sup></b>
	(3.11)	(16.05)	(0.23)	(0.32)	(6.22)	<b>(4.93)</b>
Significance level	***	***	***	***	NS	***

<sup>1</sup>Means followed by the same letter are not significantly different.

<sup>2</sup>Standard deviation are shown in parentheses. NS; Not Significant \*\*\*; 0.05

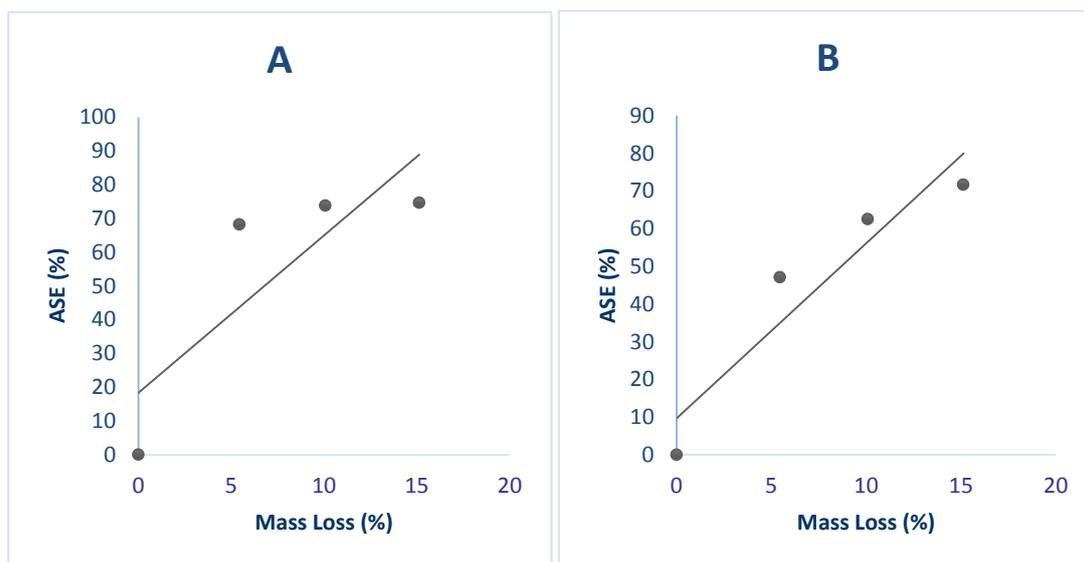
WRE<sub>20/65%</sub>: WRE(20/65%); WRE<sub>10days</sub>: WRE(10 days) (%); VS<sub>20/65%</sub>: Volume Swelling (20/65%)(%); VS<sub>10days</sub>: Volume Swelling (10 days)(%); ASE<sub>20/65%</sub>: ASE (20/65%)(%) and ASE<sub>10days</sub>: ASE (10 days)(%)

### Volumetric swelling and anti-swell effectiveness

Swelling is a dimensional increase occurring as a result of uptake of water or any liquid by wood. Table 2 indicated significant reduction of volumetric swelling between unmodified and thermally modified *G. arborea* under standard condition of 20°C/65%RH and in complete water immersion. In 20°C/65%RH, the unmodified samples had a volume swelling of approximately 5.55%, while reduced value of 1.37% was recorded for the modification temperature of 220°C. When completely saturated with water, the same trend was depicted with unmodified wood having volume swelling of 10.43% while treatment temperature of 220°C had 2.92%. This implies that, under standard condition of 20°C/65%RH, dimensional stability of the *G. arborea* improved as modification temperature was increased. Thermal modification renders wood less hygroscopic, thus, improving its dimensional stability, as temperature increases. (Gündüz *et al.* 2008; Baysal *et al.* 2014). Paul *et al.* (2007) showed that, the loss of hemicelluloses, which are hydrophilic, and contributes greatly to uptake of water, is a major contributory factor to improved dimensional stability. Inone *et al.* (1993) also indicated that, the reduction in the number of -OH groups in hemicelluloses following thermal modification makes wood absorb less water. This makes wood less hygroscopic and more dimensionally stable (Shi *et al.* 2007; Korkut and Aytin 2015).

With unmodified wood as reference, under standard condition of 20°C/65%RH, modification temperature of 220°C recorded the highest ASE of 74.62%. This high ASE was however not significantly different from those of the other treatment temperatures (Table 2). Although the ASE for complete water saturation condition was generally low compared to the standard condition, it increased significantly with an increase in modification temperature (Table 2). The highest ASE at complete saturation was observed at 220°C (i.e. 71.72%). This could be ascribed to increased cellulose crystallinity and reduced wood hygroscopicity as modification temperature is increased (Wikberg 2004; Baysal *et al.* 2014).

Fig. 1 depicts the relationship between mass loss and ASE at standard condition of 20°C/65%RH and complete water saturation. In Fig. 1A and 1B, mass loss tends to be strongly correlated with ASE at coefficients of 0.83 and 0.94, respectively. This suggests that, above the FSP, modification temperature exerts greater influence on the ASE. Improved dimensional stability of thermally modified wood even in condition of complete water saturation makes it more preferred to chemically treated wood, which commonly undergo dimensional changes (Hill 2006).

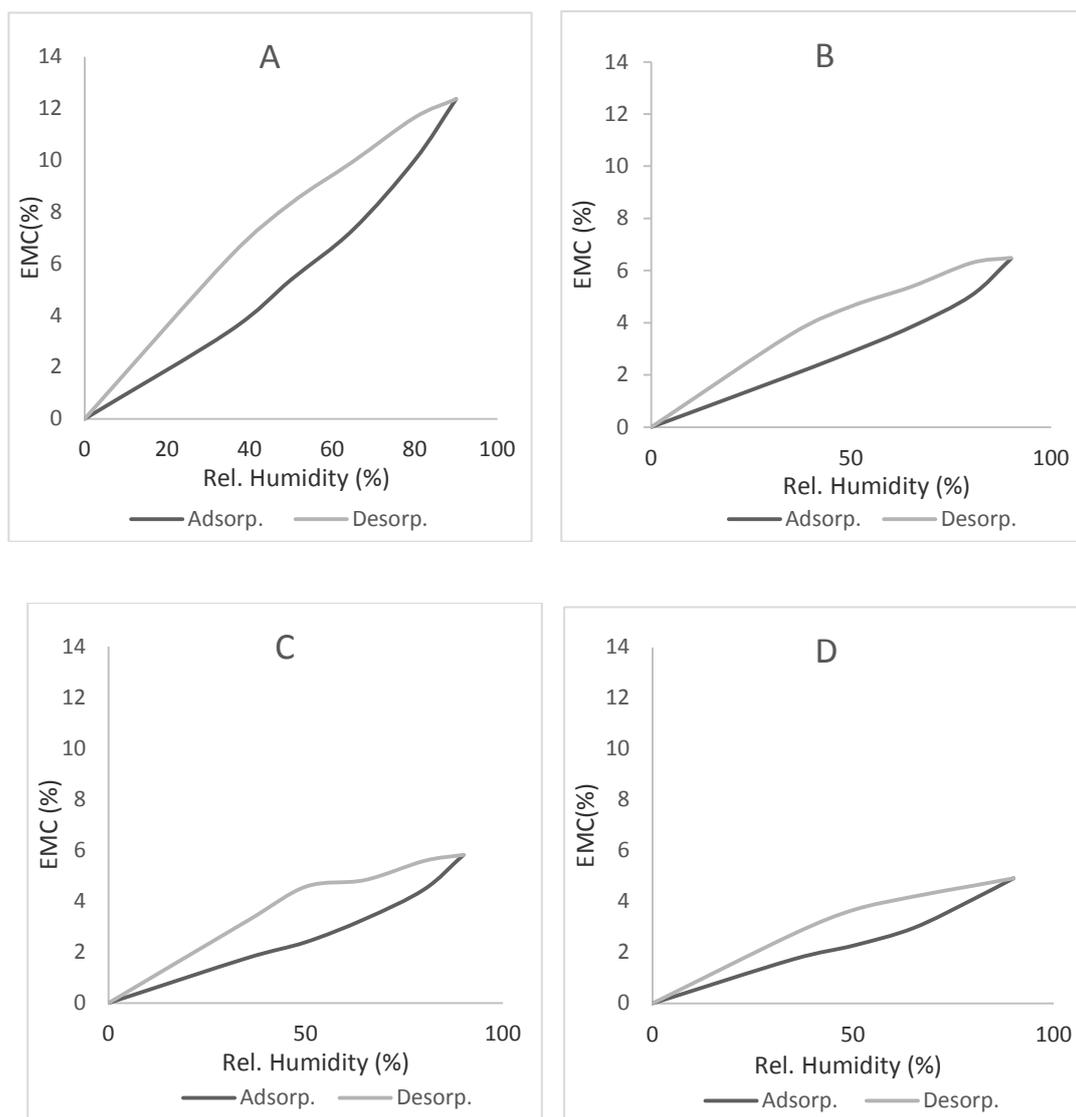


**Fig. 1.**  
**Relationships between ML and ASE in 20°C/65%RH (A) and complete water saturation (B).**

### Moisture sorption

Fig. 2A to 2D depict sorption isotherms for unmodified (Fig. A) and thermally-modified (Fig. B-D) *G. arborea* wood. These sorption isotherms show adsorption and desorption EMCs for the assessed unmodified and thermally modified wood. The shape of the isotherms of thermally modified wood differs from unmodified wood. Adsorption and desorption EMCs of unmodified and thermally modified wood differed significantly, with unmodified wood recording highest adsorption and desorption EMCs. *G. arborea* in humid air generally recorded decreases in EMC for both adsorption and desorption processes as treatment temperature increased (Fig. 2A – 2D). At 80%RH for instance, highest EMC is recorded for adsorption (10.01%) and desorption (11.66%) of unmodified samples (Fig. 2A). Contrastingly, the highest modification temperature of

220°C recorded the lowest adsorption (4.10%) and desorption (4.63%) EMCs (Fig. 2D) as wood tends to be less hygroscopic when exposed to increasing modification temperatures (Korkut and Aydin 2015; Navickas and Albrektas 2013). Differences in adsorption and desorption EMCs account for the hysteresis loop in the isotherms (Dinwoodie 2004). Generally, the hysteresis loop became narrower with increased modification temperature (Fig. 2B – 2D). Increasing the modification temperature cumulatively reduces the number of hydroxyl (-OH) groups taking part in adsorption and desorption (Sander et al. 2005). EMCs are therefore reduced as treatment temperature increased. Reduction of EMC of thermally modified wood in adsorption and desorption may also stem from accompanying changes in wood, such as irreversible aggregation of cellulose microfibrils and stiffening of the hemicellulose/lignin matrix and the creation of new hydrogen bonds in the amorphous regions of cellulose and hemicellulose (hornification) (Borrega and Kärenlampi 2007). Reduced adsorption and desorption EMCs with increased modification temperature is evidenced by the gradual shifting of the sorption isotherms (Fig. 2A – 2D) closer to the x-axis (relative humidity-axis).



**Fig. 2.**  
**Sorption Isotherms (unmodified (A), 180°C (B), 200°C (C) and 220°C (D)).**

## CONCLUSION

Thermal modification is a reliable method for improving the physical and moisture sorption properties of wood. Significant differences in physical and moisture sorption properties were recorded between unmodified and thermally-modified *G. arborea* wood. Generally, ML, WRE and ASE increased as modification temperature were increased, indicating highest values at 220°C. WRE<sub>10days</sub> decreased at 180°C and 200°C increasing only at 220°C. Oven-dried density, moisture content, fiber saturation point, water absorption, volumetric swelling and EMC were also reduced as modification temperature increased,

recording least values at 220°C. Thermally modified *G. arborea* wood has significantly improved dimensional stability, exhibiting very strong correlation between mass loss and anti-swell effectiveness when in 20°C/65 %RH and complete water saturation. Improved dimensional stability makes thermally modified wood more preferred to unmodified wood in situations where wood products would be exposed to conditions of varying temperature and humidity, such as, garden furniture, decorative panels, kitchen furniture, windows, saunas and cladding. However, its use in conditions of direct and persistent exposure to water or rain is strongly discouraged, since it could result in significant reduction in its water repellence effectiveness (WRE) and render the wood more susceptible to decay.

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