PHYSICO-MECHANICAL PROPERTIES OF FURFURYLATED *PTERYGOTA MACROCARPA* (K.Shum.) WOOD

ABSTRACT

Wood is a very important structural material requiring treatments to improve its properties and resistance to biodeterioration agents; one of such is wood modification. This study assessed the effect of furfuylation treatments on the physical and mechanical properties of *Pterygota macrocarpa.* Wood samples were collected from *Pterygota macrocarpa* tree longitudinally and transversely on which modification was carried out with furfuryl alcohol and catalyst (Maleic anhydride and Tartaric acid) at different proportions using a pressure impregnating equipment at a pressure of 4 bars and later cured at 150°C for 3 hours. Results of density for untreated *P. macrocarpa* wood ranged from 464.55 Kg/m³ to 625.92 Kg/m³ while modified *P. macrocarpa* wood has weight percent gain (WPG) and density increment (DI) due to furfurylation which ranged from 8.65 to 15.34% and 1.49 to 4.94% respectively. Effect of bulking coefficient (BC) on *P. macrocarpa* wood varied among the treatments which ranged from 5.70 to 15.26%. It was observed that the dimensional stability (Anti-swelling efficiency) of the wood increased with furfurylation. Furthermore, there was increase in the mechanical properties which varied among treatments. Modulus of Elasticity ranged from 2098.27 to 3372.64 N/mm^2, Modulus of Rupture ranged from 44.82 to 64.53 N/mm^2 with 4% level of tartaric acid recorded the highest values while compression parallel to grain ranged from 25.83 to 38.89 N/mm^2 with 4% level of maleic anhydride having the highest value. For effective performance, 4% level of the catalysts can be used in the furfurylation process. The result of this research revealed that tartaric acid in the furfurylation process could serve as an alternative to maleic anhydride which is widely used.

Keywords: Furfurylation, Furfuryl alcohol, Catalyst, *Pterygota macrocarpa*, mechanical properties

Introduction

Wood is one of the earth's most versatile and probably most familiar natural raw materials. Every day, millions of people around the world derived their livelihood from working with wood (Ban, 2012). The supply of wood for construction purposes has dwindled due to over-exploitation. The resultant effect is the availability of less mature and non-durable species in the wood market (Adhikari and Ozarska, 2018). Ekundayo *et al* (2021) ascertained that Nigeria has a long history of limiting the use of timber for construction largely to sawn timber which made the demand for a few species surge to the point of over-exploitation with a decline in the quality of forest harvest. This necessitates the need for wood treatment with the use of preservatives or modification to overcome undesirable properties of wood thereby, prolonging its service life.

Pterygota macrocarpa (locally known as Oporoporo) is of the family Sterculiaceae. The wood is medium-weight, with a density of 480 – 660 Kg/m³ at 12% moisture (Ayarkwa, 1998, The Wood Database, 2022). The wood is currently available and in use for veneer, plywood, interior panelling, interior joinery, moulding, furniture, block board, fibre board, particle board and light carpentry. It is also used for staircases, light flooring, matchboxes, boxes and crates. However, the wood is less durable, being susceptible to attack by borers, termites and fungi. It is very prone to blue stains (Christian *et al.,* 2012).

Modification is applied to overcome undesirable properties of the wood material that are mainly related to moisture sensitiveness, low dimensional stability, hardness and wear resistance, low resistance to bio-deterioration against fungi, termites, marine borers, and low resistance to UV irradiation (Dick *et al.,* 2017). Due to its potential for commercial applications, wood modification with furfuryl alcohol (FA) is now attracting enhanced attention from researchers and industries. The selection of suitable catalysts to control the polymerization of furfuryl alcohol during storage and curing is the most crucial component of this technology (Wanju, *et al.,* 2015). The use of maleic anhydride as a catalyst has been widely used in the furfurylation process. Other chemicals should be investigated as a catalyst in the furfurylation process. This present study aimed to improve the properties of *Pterygota macrocarpa* wood through furfurylation treatment. Specific objectives were to 1) determine the physical and mechanical properties of the untreated and furfurylated *Pterygota macrocarpa* and 2) investigate the effect of two different catalysts and varied percentage catalysts on the furfurylation process.

Materials and Methods

Wood sampling

Test samples were taken from *Pterygota macrocarpa* tree longitudinally (top, middle and base) and transversely (outer, sapwood area, and inner, heartwood area), at 25, 50 and 75% of the total height of the log. Material preparations and testing were done according to the American Society for Testing Materials (ASTM).

Moisture content and density

Sample sizes of 20 x 20 x 60 mm *Pterygota* wood were oven dried at 103 ± 2°C according to ASTM D4052-16 (2016) until a constant weight was attained. The initial moisture content and density were determined using Equations 1 and 2.

$$\boldsymbol{Moisture\ content}(\%) \ = \ \frac{\boldsymbol{Wg-Wo}}{\boldsymbol{Wo}} \boldsymbol{X\ 100} \qquad \text{................ (Equation 1)}$$

Where:
Wg = Weight of green samples (gm),
Wo = Weight of dried samples (gm)

$$\boldsymbol{Density(kg/m^3)} \ = \ \frac{\boldsymbol{mass\ of\ ovendried\ sample}}{\boldsymbol{volume}} \qquad \text{.................... (Equation 2)}$$

Wood Treatment

Furfurylation was performed according to Wanju *et al.,* (2015). The wood modifiers were prepared by mixing furfuryl alcohol (FA) and distilled water in a ratio 1:1; two different catalysts, Maleic anhydride (MA) and Tartaric acid (TA) were used in the furfurylation process. For each catalyst, 2% and 4% of the catalyst were separately added to the already prepared furfuryl alcohol as shown in Table 1.

Table 1. Preparation of wood modifiers

	MALEIC ANHYDRIDE (MA)		TARTARIC ACID (TA)	
	TREATMENT 1	TREATMENT 2	TREATMENT 3	TREATMENT 4
FURFURYL ALCOHOL (FA) AND DISTILLED WATER (1:1)	98% FA : DW 1:1	96% FA : DW 1:1	98% FA : DW 1:1	96% FA : DW 1:1
CATALYST	2%	4%	2%	4%

The furfurylation process comprises two stages: The impregnation stage and the curing stage.

- Impregnation stage: The treatment was done using a full cell process. Impregnation of the wood samples with furfuryl alcohol was carried out using a Chemical Impregnating Equipment. Firstly, the wood samples were loaded in the impregnating chamber (Plate 1). The vacuum was created for about 5 minutes, i.e., air was removed from the chamber loaded with the wood samples, then chemical was pumped into the chamber and a reduced pressure of 4 bars was applied for 45 minutes.

Plate 1. Chemical Impregnating Equipment used.

- Curing stage: The impregnated wood samples wrapped with aluminium foils were placed in the oven at 150°C for 3 hours for polymerization (Plate 2). After this, the treated wood samples were unwrapped and further dried at 103 ± 2°C until a constant oven-dried weight was achieved.

Plate 2. Treated wood wrapped with aluminium.

The following tests were carried out after wood treatment.

Weight Percent Gain (WPG): This was to the chemical bond formed with the wood cell wall polymer, calculated according to Hill, (2006) using Equation 3.

$$\boldsymbol{WPG}(\%) = \frac{\boldsymbol{Wm-Wo}}{\boldsymbol{Wo}}\boldsymbol{X100} \quad \text{……………………………} \quad \text{(Equation 3)}$$

Where: Wm = Weight of oven-dried sample after furfurylation (g).

Wo = Weight of oven-dried sample before furfurylation (g).

Bulking Efficiency (BE): The bulking efficiency (BE) of the samples was calculated according to Bartkowiak *et al.* (2015) using Equation 4.

$$\boldsymbol{BE}(\%) = \frac{\boldsymbol{Vm-Vo}}{\boldsymbol{Vo}}\boldsymbol{X100} \quad \text{……………………………} \quad \text{(Equation 4)}$$

Where: Vo = Volume of wood samples before furfurylation (mm^3)

Vm = Volume of wood samples after furfurylation (mm^3).

Density Increment (DE): The density increment of *Pterygota macrocarpa* wood was calculated using Equation 5.

$$DI(\%) = \frac{Dm-Do}{Do}X100 \quad \text{................................ (Equation 5)}$$

Where DI = Increment in density;

Do = Density of wood samples before furfurylation;

Dm = Density of wood samples after furfurylation.

Volumetric Swelling (S): Treated and untreated samples were conditioned at about 65% relative humidity and 25^{o}C. The samples are immersed in distilled water for a period of 24 hours. The volumetric swelling was calculated according to Youming *et al.*, (2016) using Equation 6.

$$S(\%) = \frac{V3-V2}{V2}x100 \quad \text{................................ (Equation 6)}$$

Where V2 = Volume of wood samples after furfurylation (mm^3)/volume of oven-dried untreated samples

V3 = Volume of samples after immersion in distilled water (mm^3).

Dimensional Stability: The dimensional stability of the treated and untreated *Pterygota macrocarpa* wood samples were evaluated in terms of anti-swelling efficiency (ASE). The anti-swelling efficiency (ASE) was calculated using Equation 7 according to Youming *et al.*, (2016).

$$ASE(\%) = \frac{Su-Sm}{Su}X100 \quad \text{................................ (Equation 7)}$$

Where Su = Swelling coefficient of untreated sample and Sm = Swelling coefficient of treated sample.

Mechanical Properties

The mechanical properties were done according to ASTM D143-09. (2009).

Modulus of elasticity (MOE): This was calculated using Equation 8.

$$MOE = \left(\frac{PL^3}{4 \text{ x } \Delta \text{ x b x } d^3}\right) \quad \text{... (Equation 8)}$$

Where P = Maximum load (KN), L = Span of the test specimen (mm), Δ = Increment in deflection (mm) corresponding to maximum load (P), b = breadth of the test specimen (mm), and d = depth or thickness of the test specimen (mm).

Modulus of Rupture: Modulus of rupture (MOR was calculated using Equation 9.

$$MOR = \left(\frac{3PL}{2XbXd^2}\right) \quad \text{... (Equation 9)}$$

Where P = Maximum load (KN), L = Span of the test specimen (mm), b = breadth of the test specimen (mm), and d = depth or thickness of the test specimen (mm).

Compression parallel to grain: The Maximum Compressive Strength (MCS) was determined in accordance with ASTM 143 standard (2009) using Equation 10.

$$\boldsymbol{MCS = \frac{P}{bd}} \qquad (\mathrm{N/mm^2}) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(Equation 10)}$$

Where MCS = the Maximum Compressive Strength in $\mathrm{N/mm^2}$, P = the load in Newton, b = the width in mm and d = the depth in mm.

The data obtained were analysed using Statistical Package for Social Science (SPSS). Descriptive statistics of the properties measured will be generated. The data were subjected to Analysis of Variance (ANOVA) and Duncan Multiple Range Test (DMRT) to determine the significant difference between various treatment and their interactions at 0.05 level of significance.

Results

Percentage Moisture Content of *Pterygota macrocarpa*

The mean values of percentage moisture content of *Pterygota macrocarpa* ranged from 12.75 to 58.69% (Fig. 1). The base has the lowest moisture content with 12.75 and 42.27% for the inner and outer portions respectively. The middle has percentage moisture content of 14.79% for the inner portion and 45.08% for the outer portion while the top position of the tree has the highest moisture content with 36.67 and 58.69% for the inner and outer portions respectively.

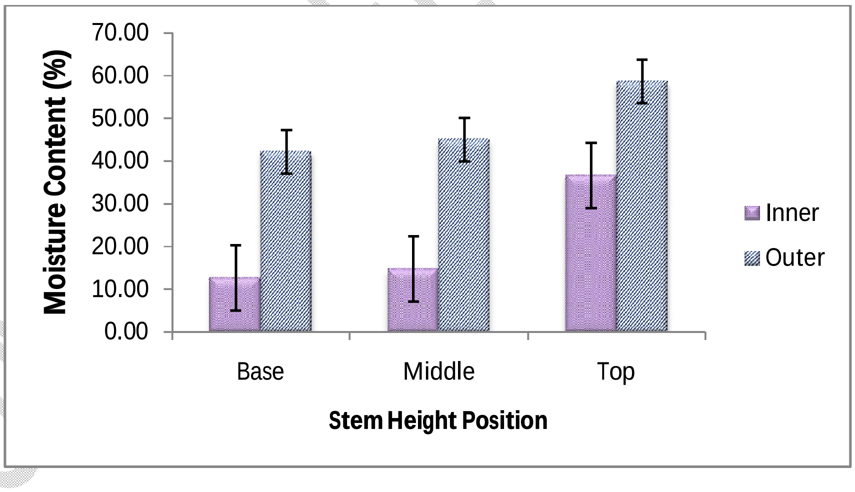

Fig.1. Moisture content of *Pterygota macrocarpa* in the longitudinal and radial directions.

The density of *Pterygota macrocarpa*

The mean values of density for *Pterygota macrocarpa* in the longitudinal and transverse direction ranged from 464.55±56.27 kg/m³ to 625.92±74.45 kg/m³ with wood samples from the base (inner portion) having the highest density value of 625.92±74.45 kg/m³ while the top (outer portion) has the lowest density value with 464.55±56.27 kg/m³ (Fig. 2).

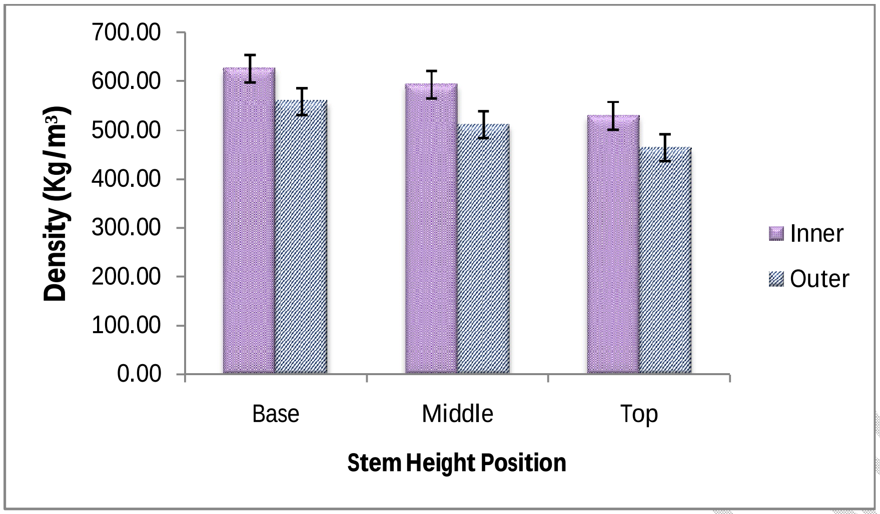

Fig.2. Density of *Pterygota macrocarpa* wood longitudinally and radially.

Weight Percentage Gain (WPG) of *Pterygota macrocarpa* due to Furfurylation

The mean values of weight percent gain as a result of furfurylation is presented in Fig. 3 which shows that the mean values for WPG due to furfurylation ranged from 8.65 to 15.34%. The highest mean value of WPG with 15.34% was achieved with Treatment 4 (FA with 4% of TA) at the inner portion of the base of the tree while the lowest mean value of WPG due to furfurylation with 8.65% was obtained with Treatment 1 (FA with 2% of MA) (FA with 2% of MA) at the inner portion of the top of the tree.

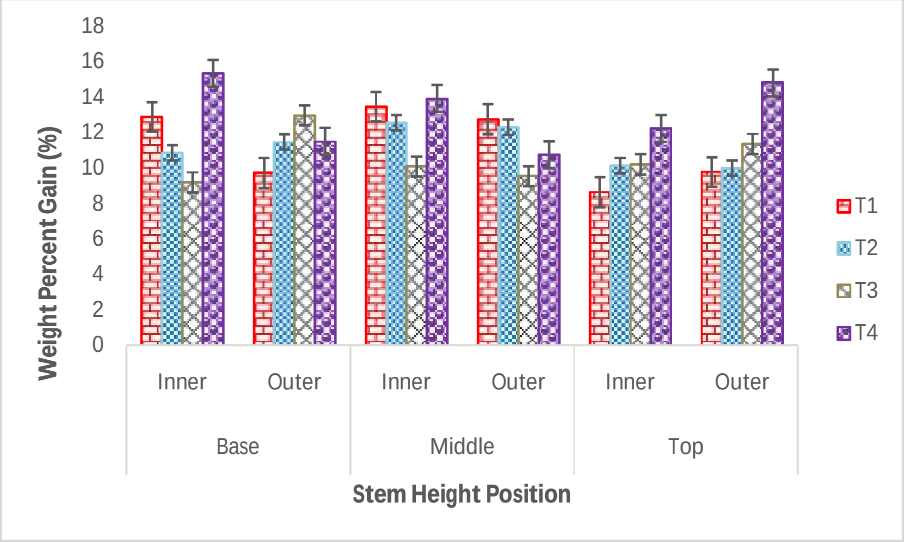

Fig.3. Mean values for weight percent gain of *Pterygota macrocarpa* due to furfurylation

The Analysis of Variance (Table 2) for the weight percent gain due to furfurylation showed that there was significant difference at *P* = .05 in the treatments and the interaction between the treatment and the longitudinal direction.

Table 2. Analysis of variance of WPG, DI, BE, MOE, MOR and compression.

		F-values					
Sources of Variation	**df**	**WPG**	**DI**	**BE**	**MOE**	**MOR**	**Compression**
Treatment	3	6.331*	1.851^{ns}	1.719^{ns}	9.545*	8.543*	4.740*
Longitudinal direction	2	1.971^{ns}	2.170^{ns}	6.555*	5.054*	1.983^{ns}	3.630*
Radial direction	1	0.191^{ns}	0.725^{ns}	2.079^{ns}	0.858^{ns}	0.991^{ns}	3.316^{ns}
Treatment * Longitudinal direction	6	2.842*	4.454*	3.526*	0.093^{ns}	0.152^{ns}	0.186^{ns}
Treatment * Radial direction	3	1.801^{ns}	6.394*	1.943^{ns}	0.014^{ns}	0.019^{ns}	0.110^{ns}
Longitudinal direction * Radial position	2	2.555^{ns}	0.055^{ns}	1.630^{ns}	0.015^{ns}	0.098^{ns}	0.112^{ns}
Treatment * Longitudinal direction * Radial direction	6	1.779^{ns}	0.971^{ns}	1.167^{ns}	0.036^{ns}	0.005^{ns}	0.077^{ns}
Error	120						
Total	143						

*significant (*P* = .05)
^{ns} not significant (p> 0.05)

Density Increment (DI) of *Pterygota macrocarpa* due to furfurylation.

The mean values for the density increment of *Pterygota macrocarpa* ranged from 1.49 to 4.94%. Treatment 4 (FA with 4% of TA) has the highest density increment with 4.94% at the outer portion of the top position of the tree while Treatment 2 (FA with 4% of MA) has the lowest density increment with 1.49% at the outer portion of the top position of the tree. These were presented on Fig. 4.

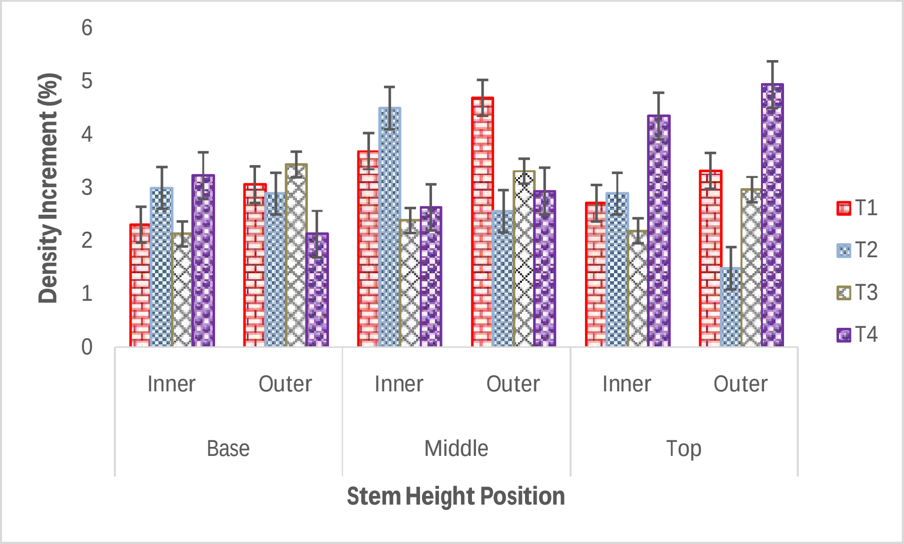

Fig. 4. Mean table for Density Increment of *Pterygota macrocarpa* due to furfurylation

The Analysis of Variance for the density increment due to furfurylation presented in Table 2 revealed that there was no significance difference at *P* = .05 in the treatment, longitudinal direction, radial direction, interaction between the longitudinal and radial position as well as the interaction between the treatment, the longitudinal and radial position.

Bulking Efficiency (BE) of Furfurylated *Pterygota macrocarpa*

The mean values for bulking coefficient of furfurylated wood presented on Fig. 5 revealed that the effect of furfurylation on bulking coefficient on *Pterygota macrocarpa* wood varied among the treatments which ranged from 5.70 to 15.26%. Treatment 1 (FA with 2% of MA) at the Top inner has the lowest bulking coefficient with 5.70% while Treatment 4 (FA with 4% of TA) at the Middle inner has the highest bulking coefficient with 11.62%.

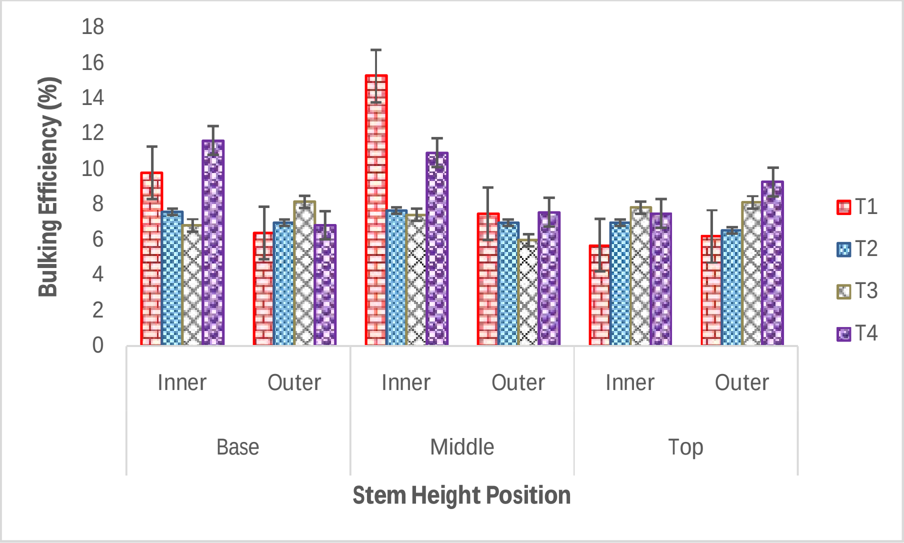

Fig.5. Mean table for bulking coefficient of furfurylated *Pterygota macrocarpa* wood

The Analysis of Variance (ANOVA) for the Bulking Efficiency presented in Table 2 revealed that there was significant difference at $P = .05$ in the longitudinal direction, and the interaction between the treatment and longitudinal direction.

Volumetric Swelling (VS) of Treated and Untreated *Pterygota macrocarpa*

The mean values for volumetric swelling of untreated and treated *Pterygota macrocarpa* wood are illustrated in Fig.6. It was observed that volumetric swelling for *Pterygota macrocarpa* wood varied with treatment, wood position, and time.

At the Top, for 24, 48 and 72 hours, Treatment 2 (FA with 4% of MA) has the highest average volumetric swelling with 20.79%, At the Middle, for 24, 48 and 72 hours, Treatment 1 (FA with 2% of MA) has the height volumetric swelling with 12.92%, and at the Base, Treatment 2 (FA with 4% of MA) has the highest average volumetric swelling with 9.74%.

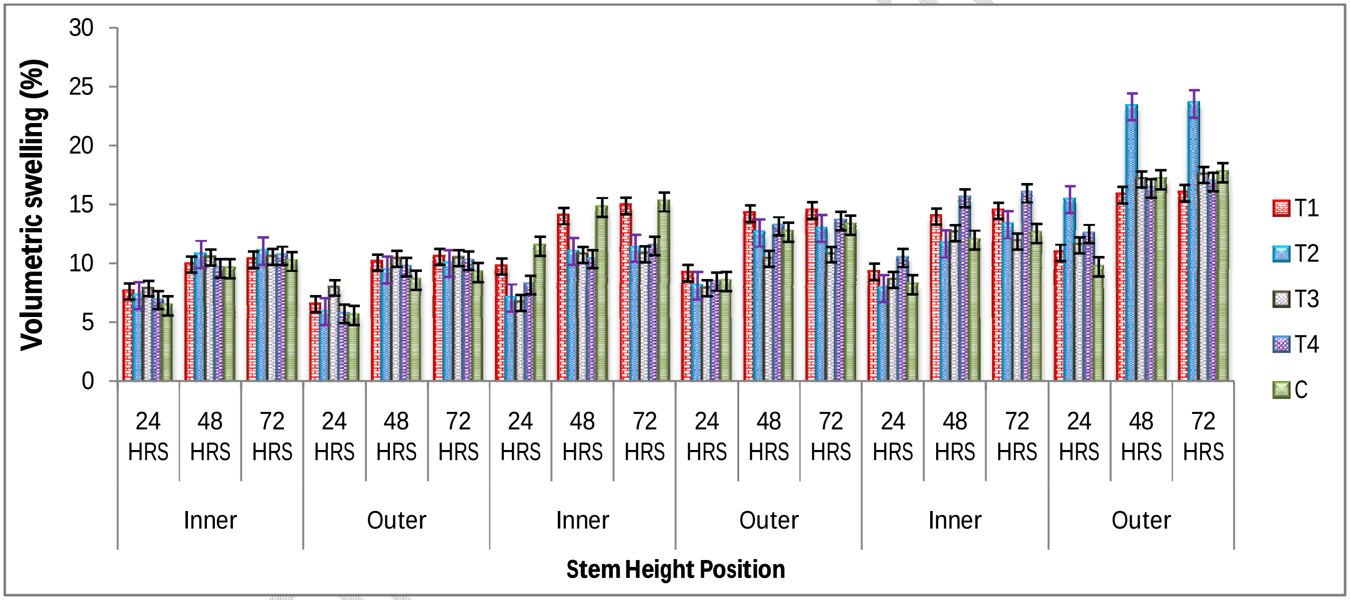

Fig.6. Mean values for volumetric swelling of treated and untreated *Pterygota macrocarpa* wood at 24, 48, and 72 hours.

The Analysis of Variance (ANOVA) for volumetric swelling presented in Table 3 revealed that at $P = .05$, there was significant difference in the longitudinal direction, radial direction, soaking time, the interaction between treatment and longitudinal direction, interaction between the longitudinal direction and radial position as well as the interaction between the treatment, longitudinal direction and radial position.

Table 3. Analysis of Variance (ANOVA) for Mean values of volumetric swelling and anti-swelling efficiency of treated and untreated *Pterygota macrocarpa* wood

		F-values	
Sources of Variation	**df**	**VS**	**ASE**
Treatment	4	1.116^{ns}	13.4208*
Longitudinal direction	2	9.980*	2.897^{ns}
Radial direction	1	96.974*	1.235^{ns}
Soaking Time	2	79.208*	6.852*
Treatment * Longitudinal direction	8	2.517*	2.219*
Treatment * Radial direction	4	1.913^{ns}	2.074^{ns}
Treatment * Soaking Time	8	0.179^{ns}	0.440^{ns}
Longitudinal direction * Radial direction	2	34.238*	1.898^{ns}
Longitudinal direction * Soaking Time	4	0.234^{ns}	0.189^{ns}
Radial direction * Soaking Time	2	0.669^{ns}	0.031^{ns}
Treatment * Longitudinal direction * Radial direction	8	2.694*	0.871^{ns}
Treatment * Longitudinal direction * Soaking Time	16	0.076^{ns}	0.066^{ns}
Treatment * Radial direction * Soaking Time	8	0.066^{ns}	0.391^{ns}
Longitudinal direction * Radial direction * Soaking Time	4	0.041^{ns}	0.092^{ns}
Treatment * Longitudinal direction * Radial direction * Soaking Time	16	0.182^{ns}	0.116^{ns}
Error	450		
Total	539		

*significant (*P* = .05)

^{ns} not significant (p > .05)

Anti-Swelling Efficiency (ASE) of treated and untreated *Pterygota macrocarpa*

The mean values for anti-swelling efficiency for fufurylated *Pterygota macrocarpa* wood illustrated in Fig.7 showed that the mean values for ASE varied among the treatments, the stem positions and time. For Top Outer, Treatment 4 (FA with 4% of TA) has the highest average ASE values for 24, 48 and 72 hours with 87.18%, for the Middle, Treatment 2 (FA with 4% of MA) has the highest average ASE values for 24, 48 and 72 hours with 78.40%

while at the base, Treatment 3 (FA with 2% TA) has the highest average ASE values for 24, 48 and 72 hours with 87.18%.

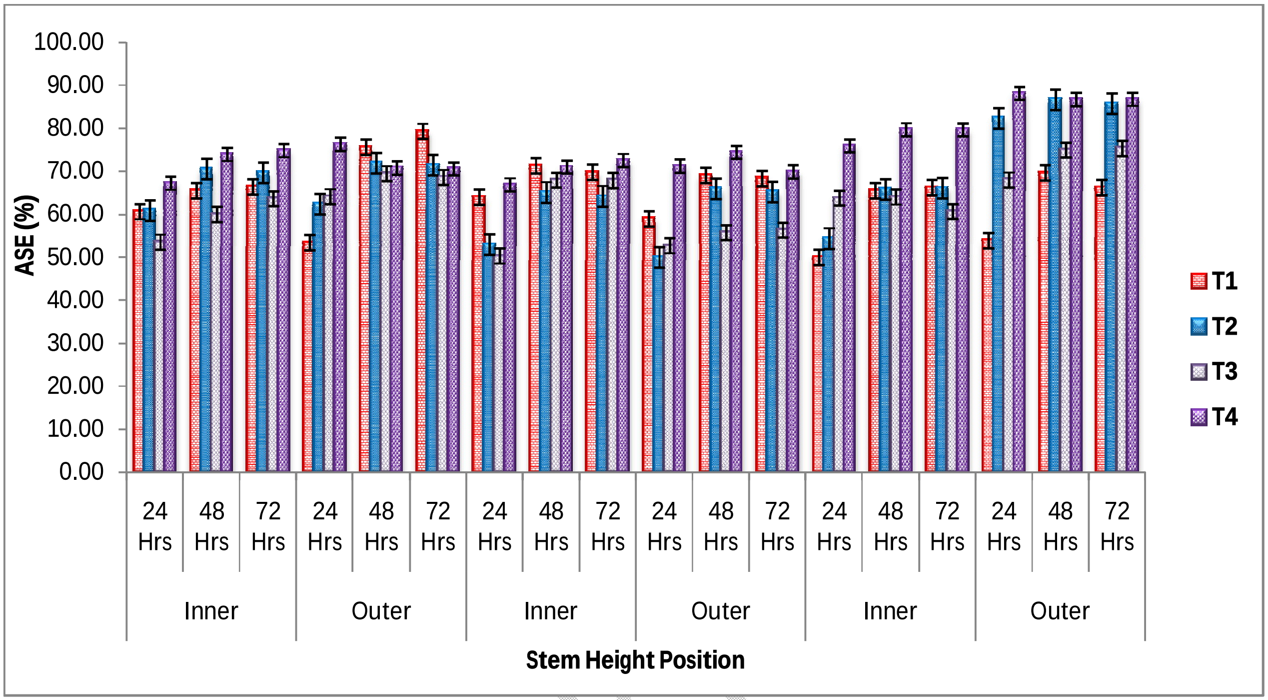

Fig.7. Mean values for anti-swelling efficiency for furfurylated *Pterygota macrocarpa* wood.

The Analysis of Variance (ANOVA) for anti-swelling efficiency presented in Table 3 revealed that there was significant difference at *P* = .05 in the treatments, soaking time and the interaction between the treatment and longitudinal direction.

Modulus of Elasticity (MOE) of treated and untreated *Pterygota macrocarpa*

The mean values for the modulus of elasticity (MOE) ranged from 2098.27 to 3372.64 N/mm^2 (Fig.8). The control of untreated samples has the lowest MOE at all the stem height position. At the base position of the tree, Treatment 4 (FA with 4% of TA) has the highest MOE with 3372.64 N/mm^2, while treatment 1 has the lowest MOE with 2558.34 N/mm^2. At the middle position of the tree, Treatment 4 (FA with 4% of TA) has the highest MOE with 3104.65 N/mm^2 also, Treatment 4 (FA with 4% of TA) has the highest MOE with 3005.56 N/mm^2. Finally, at the top position of the tree, Treatment 4 (FA with 4% of TA) has the highest MOE with 2933.11 N/mm^2 and 2822.03 N/mm^2 for the inner and outer portion respectively.

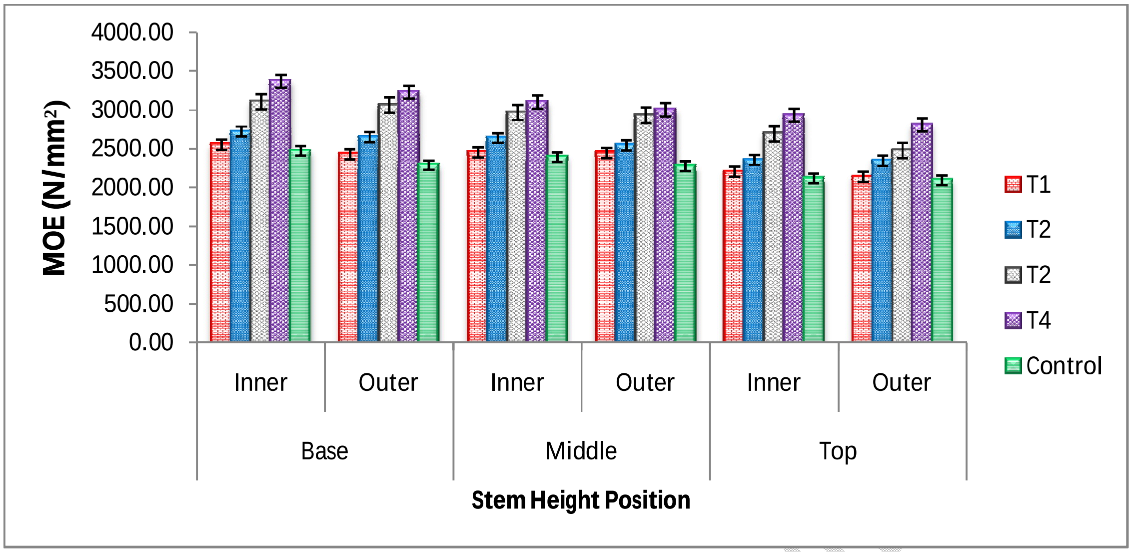

Fig.8. Modulus of Elasticity (MOE) of treated and untreated *Pterygota macrocarpa*

The Analysis of Variance (ANOVA) presented in Table 2 showed that there was significant difference at *P* = .05 in the treatment and the longitudinal direction. It further revealed that there was no significant difference in the radial position, the interaction between the treatment and longitudinal direction, the interaction between treatment and radial direction, the interaction between the longitudinal and radial direction as well as the interaction between the treatment, longitudinal and radial direction.

Modulus of Rupture (MOR) of untreated and treated *Pterygota macrocarpa*

The mean values of Modulus of Rupture (MOR) ranged from 44.82 to 64.53 N/mm^2. The untreated wood samples (control) from the all the stem height positions have lower MOR compared to the treated samples. At the Top, Middle and Base position, Treatment 4 (FA with 4% of TA) has the highest MOR with 60.48 N/mm^2, 62.51 N/mm^2, and 64.53 N/mm^2 respectively (Fig. 9).

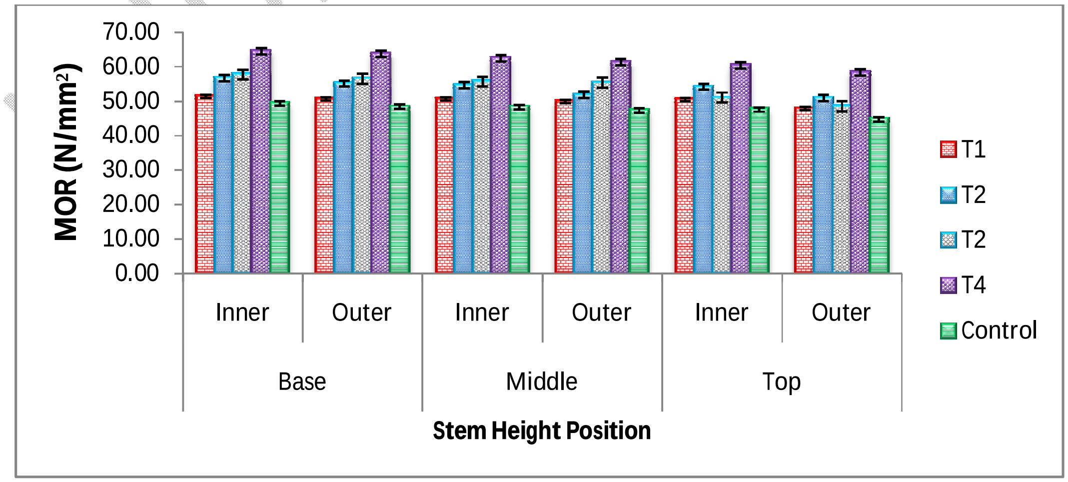

Fig. 9. Modulus of Rupture (MOR) for the treated and untreated *Pterygota macrocarpa*

The Analysis of Variance (ANOVA) for the Modulus of Rupture as presented on Table 2 revealed that there was significant difference at *P* = .05 in the treatment while there was no significant difference in the longitudinal direction and radial direction.

Compression parallel to grain of treated and untreated *Pterygota macrocarpa*

The mean values for compression parallel to grain for the treated and untreated *Pterygota macrocarpa* ranged from 25.83 to 38.89 N/mm^2. The untreated samples have the lowest compressive value at all the stem height positions. For the base position, the inner portion with Treatment 2 (FA with 4% of MA) has the highest compressive strength with 38.89 and Treatment 4 (FA with 4% of TA) has the highest compression value with 36.32 N/mm^2 at the outer portion. Furthermore, at the middle position of the tree, the inner portion of the wood with Treatment 2 (FA with 4% of MA) has the highest compressive strength with 37.50 N/mm^2 while at the outer portion, Treatment 4 (FA with 4% of TA) has the highest compression value with 36.31 N/mm^2. Lastly, at the top position of the tree, Treatment 4 (FA with 4% of TA) has the highest value at the inner and outer portion with 36.21 N/mm^2 and 33.54 N/mm^2 respectively (Fig.10).

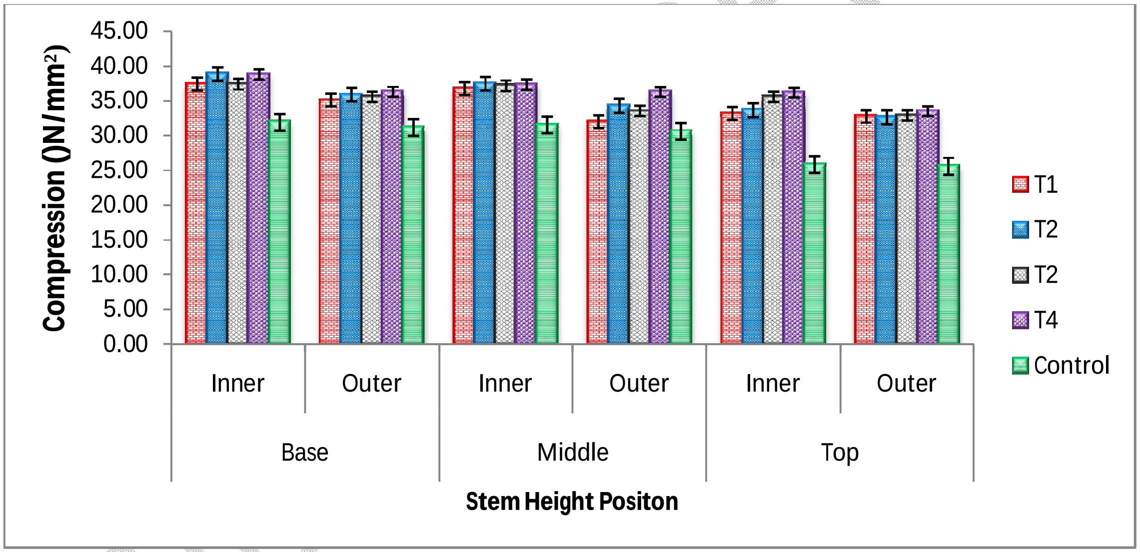

Fig.10. Compression parallel to grain for the treated and untreated *Pterygota macrocarpa* wood.

The Analysis of variance (ANOVA) for the compression parallel to grain revealed that there was significant difference at *P* = .05 in the treatment and the longitudinal position. It also showed that there was no significant difference in the radial direction. These were presented in Table 2.

Discussion

Moisture Content Variations in *Pterygota macrocarpa* Wood

Wood is hygroscopic in nature, that is, it has the affinity to absorbs water and release moisture until it reaches equilibrium with its surrounding environment. Water gets into wood in three ways: as a fluid through the cell lumens through capillary tension, as vapour through the cell lumens, and as molecular diffusion through the cell walls. In normal use, the moisture content of wood varies between 8% and 25% by weight, depending on the relative humidity of the air (Tom, 2018). An excess of moisture in wood can cause problems in application such as preventing adhesives from making a secure bond, promoting the growth of mold in wood and shrinkage as the excess moisture leaves the wood (Denig *et al.,* 2000). The moisture content of *Pterygota macrocarpa* wood varied from top to the base and from the outer portion to the inner portion. At the longitudinal direction of the tree, the top has the highest percentage moisture while the middle has the medium average moisture content, and the base has the lowest average percentage moisture content. Radially, the outer portion has the highest moisture content when compared with the moisture content at the inner position. This agrees with the work of Nageeb and Dev-Prasad, (2010) which state that there are variations in percentage moisture content of wood samples.

Variation in Density of *Pterygota macrocarpa* Wood

Wood density is considered as an important criterion of quality because of its high correlation to other physical properties, mechanical strength and performance in use (Sofia *et al.,* 2008). Wood density is determined by multiple growth and physiological factors compounded into fairly easily measured wood characteristic. Variation in wood density in individual trees is often as great as that between different trees (Wood densities, 2012). There are variations in the density of *Pterygota macrocarpa* wood from the base to the top, and from inner to outer. The density variation is high at the base, medium at the middle and low at the top, while the density variation is low at the outer portion and high at the inner portion of the wood. In summary, *Pterygota macrocarpa* wood has average density value of 547.32 kg/m^3 which fall within the wood density classification of medium density according to density classification of Owoyemi and Olaniran (2014). This corroborates with the research of Peter *et al*., (2015) and Owoyemi *et al.,* (2020), where the values of wood density obtained for *Pterygota macrocarpa* falls within medium density classification. Wood within this classification is mostly used for lumber, plywood, furniture and finger jointed products (Peter *et al.,* 2015).

Effect of Furfurylation on Weight Percent Gain (WPG) of *Pterygota macrocarpa* Wood

WPG was to determine if a chemical load or chemical bond has been formed with the wood cell wall polymer (Hill, 2006). In this study, WPG was achieved due to the fact that furfurylation bulked the wood as a result of the grafting of the furfuryl alcohol polymers with the lignin polymers (Youming *et al.,* 2016), and this varied with treatments and stem height positions which indicates that irrespective of the percentage of catalyst used and the location of the *Pterygota macrocarpa* wood, furfurylation increase the WPG of the wood. However, furfurylation with the inclusion of tartaric acid has higher WPG when compared to maleic anhydride. This implies that tartaric acid can be used as maleic anhydride which is currently widely acceptable. This corroborated with the work of Prabu *et al.,* (2017) where it was stated that furfurylation catalysed with tartaric acid performed excellently on WPG of beech wood. It is noteworthy that the highest percentage of catalyst (4%) has a higher WPG for most of the position of the wood (longitudinally and radially). This indicates for an effective performance, there should be inclusion of higher concentration of catalyst during furfurylation process. In summary, modification of wood through furfurylation has considerable WPG on *Pterygota macrocarpa* wood, and this correlates with the works of Bartkowiak *et al.,* (2015), Wanju *et al.,* (2015) and Monika *et al.,* (2015) where they affirmed that furfurylation led to WPG of wood as a result of cell wall bulking.

Effect of Furfurylation on Density Increment (DI) of *Pterygota macrocarpa* Wood

Increase in density was determined to know if modification of wood using furfuryl alcohol contributes to density increase of *Pterygota macrocarpa* wood. It was noted that there was no significant difference in all the treatments which indicates that irrespective of the concentration of catalyst and the type of catalyst used, furfurylation results in DI of *Pterygota macrocarpa* wood. It was observed that DI is greater at the outer portion when compared to the inner portion; this may be due to the lower density of the wood at the outer portion which leads to considerable increment in its density after furfurylation. Also, DI is higher at the top and middle of the tree than the base, this can be as a result of variations in the density of the wood longitudinally, where the density at the top and middle is lower than the density at the base which leads to considerable increment at the top and the middle portion of the wood. Increment in density shows that there is some increase in cell wall volume leading to wood swelling (Bruno *et al.,* 2011). This agrees with the work of Epmeier *et al.,* (2007) and Bruno e*t al.,* (2011) which affirmed that furfurylation contributes to density increment of wood.

Effect of Furfurylation on Bulking Coefficient (BC) of *Pterygota macrocarpa* Wood

Furfurylation tends to permanently increase the volume of the wood i.e. furfurylation bulked the cell wall of the wood causing a permanent swelling which in turn reduce the swelling and shrinkage of wood. In this research, furfurylation leads to the bulking of *Pterygota macrocarpa* wood which varied among the treatments and the positions in the wood. Furfurylation with the inclusion of tartaric acid has higher bulking coefficient at almost all the stem height positions. It was observed that higher concentration of tartaric acid (Treatment 4 with 4% tartaric acid) has higher bulking coefficient of *Pterygota macrocarpa* wood when compared to maleic anhydride which implies that furfurylation process with inclusion of higher level of catalyst has an increasing bulking coefficient. This was in line with the work of Youming *et al.,* (2016) where it was reported that there was increase in bulking coefficient of furfurylated eucalyptus wood. Also, Bartkowiak *et al.,* (2015) reported that furfurylation catalysed by maleic anhydride influenced the bulking coeffient pine wood. Polymerization between furfuryl alcohol molecules and wood polymers can cause wood to permanently swell (bulking), thereby increasing the dimensional stability of the wood (Kocaefe *et al.,* 2015).

Dimensional Stability of Furfurylated *Pterygota macrocarpa* Wood

Furfurylation contributes to the dimensional stability of *Pterygota macrocarpa* wood by the reduction in the sorption site thereby increasing the anti-swelling efficiency of the wood. The volumetric swelling of furfurylated wood after 24 hours, 48 hours and 72 hours of immersion in water has higher percentage compared to the untreated samples for almost all the stem height positions which can be attributed to the fact that furfurylation has bulked the cell wall of the wood (causing the wood to permanently swell) which in turn increases the volume of the wood even before soaking in water.

The Anti-swelling efficiency (ASE) measures the resistant of furfurylated wood to water absorption. The mean values for the ASE revealed that furfurylation greatly influence the ASE of *Pterygota macrocarpa* wood with all the treatments (i.e., for maleic anhydride and tartaric acid). All samples showed increased ASE values for all the samples. It was observed that higher level of concentration (4%) of each catalyst (maleic anhydride and tartaric acid) has higher anti-swelling efficiency when compared to lower level of concentration (2% catalyst). Also, it was noted that treatment 4 (FA with 4% of TA) has higher ASE values for all the positions on longitudinal and radial directions, except for outer portion of the base after 48 hours and 72 hours. The ASE was related to the increased polymer filling as indicated by the increment in Weight Percent Gain (WPG). A higher Density Increment (DI) value indicates higher cell wall bulking and increased cell lumens, which form a barrier and reduce water absorption, resulting in enhanced dimensional stability. The result of this research corroborated with the works of Lande *et al.,* 2004 and Yourming *et al.,* 2016 where it was affirmed that modification of wood using furfuryl alcohol showed distinct increment in anti-swelling efficient of wood.

Modulus of Elasticity (MOE)

Modulus of elasticity (MOE) measures a wood’s stiffness. Technically, it’s a measure of the ratio of stress placed upon the wood compared to the strain (deformation) that wood exhibits along its length. The mean values for MOE revealed that furfurylation catalysed with maleic anhydride and tartaric acid improves the modulus of elasticity (MOE) irrespective of the stem height position of *Pterygota macrocarpa* wood. For both maleic anhydride and tartaric acid, higher level (2%) of catalyst has an increased modulus of elasticity when compared to low level of catalyst (2%). Furfurylation with the inclusion of tartaric acid i.e., Treatment 3 (FA with 2% TA) and treatment 4 (FA with 4% TA), has the highest value for Modulus of Elasticity (MOE) when compared with maleic anhydride. This indicates that furfurylation process catalysed with tartaric acid have better performance in the MOE of *Pterygota macrocarpa* wood. It was noted that MOE for the treated samples is higher at the base position compared to the top and middle. This can be attributed to the concentration of lignin at the base of the wood and furfuryl alcohol polymers reacts with lignin polymers which indicated that furfurylation reaction is more concentrated towards the base of the wood thereby causing the wood fibre to become stiffer and adding more strength to the wood which gives a rise in the modulus of elasticity. This is similar to the work of Prabu *et al.,* (2017) where there was significant increment in MOE of beech wood after furfurylation catalysed with maleic anhydride, citric acid, and itaconic. This result was confirmed by Lande *et al.,* (2004) where it was stated that the permanent bulking and grafting of furfuryl alcohol polymer to the cell structure affect the stiffness and strength of the wood. This is contrary to the research of Pfriem *et al.,* (2012) where it was deduced that there was reduction in MOE in furfurylated beech wood catalysed by maleic anhydride.

Modulus of Rupture (MOR)

Modulus of rupture (MOR) is the stress in a material just before it yields in a flexure test. It is a measure of a specimen's strength before rupture. Furfurylation increases the MOR of *Pterygota macrocarpa* wood with all the levels of catalyst and the type of catalyst when compared with the untreated wood samples. This is as a result of the grafting of furfuryl alcohol polymers with the lignin polymer which increases the stiffness/stress of the wood samples. Furfurylation with the inclusion of tartaric acid performed better than maleic anhydride, also, there was an increase in modulus of rupture (MOR) with a higher level of concentration (4%) when compared with lower level of concentration (2%). The mean values for MOR showed that high level of tartaric acid (i.e., Treatment 4 (FA with 4% of TA) has a significant increment in MOR in all the positions in the *Pterygota macrocarpa* wood when compared to the other treatment. Although there was increment in MOR with the other treatments (1, 2 and 3), but they are not significant as Treatment 4 (FA with 4% of TA). This correlates with the work of Wanju *et al.,* (2015) where it was confirmed that inclusion of higher percentage of catalyst in the furfurylation process increase Modulus of Rupture (MOR) of Masson pine. Epmeier *et al.,* (2007) and Esteves *et al.,* (2011), who also observed a slight improvement of MOE and MOR for furfurylated *Pinus sylvestris* and *Pinus pinaster* relative to untreated wood.

Effect of Furfurylation on Compression Parallel to Grain of *Pterygota macrocarpa* wood

Compressive strength is an important index for wood's mechanical properties. Furfurylation has effect on the compression parallel to grain of *Pterygota macrocarpa* wood. The mean value for compression shows that in relation to the untreated wood, all the treatments significantly increase the compression parallel to grain of *Pterygota macrocarpa* wood. For the two types of catalyst (maleic anhydride and tartaric acid), it was observed that the higher level of concentration for maleic anhydride and tartaric acid (4%) has the higher value when compared to the low level of concentration (2%). It was observed that Treatment 4 (FA with 4% of TA) has the highest values of compression at almost all the positions of the tree. It was observed that there is higher resistance to compression at the base of the wood when compared with top and middle, this is because of more reaction of furfuryl polymer with more lignin polymer at the base because lignin is more concentrated at the base of the wood (Yao *et al.,* 2017). This results in an increased stiffness of the wood samples caused by the polymer fillings of the furfuryl alcohol in the cell wall, which cause bulking (swelling) of the wood as well as the density increment. This is similar with the work of Wanju *et al.*, (2015) and Yao *et al.,* (2017) where it was reported that furfurylation increases the compressive strength of Masson pine and Chinese fir wood respectively. Also, the result of this study correlates with the work of Abdolzah *et al.,* (2014) where it was reported that furfurylation contributes to the compressive strength of wood which leads to an improvement of the joint tension performance.

Conclusion

Furfurylation process improved the physical and mechanical properties of *Pterygota macrocarpa* wood. It was observed that tartaric acid with 4% concentration greatly contributes to the Modulus of Elasticity (MOE), Modulus of Rupture (MOR) and compression parallel to grain of *Pterygota macrocarpa* wood. Furfurylation improved the physical properties of *Pterygota macrocarpa* wood by causing cell wall bulking. The two levels (2% and 4%) of catalyst can be used in the furfurylation process but for effective performance, higher level (%) of catalyst can be used. Also, the inclusion of tartaric acid in furfurylation process performed excellently, which indicated that tartaric acid can likewise be used in the furfurylation process as maleic anhydride which is currently widely accepted.

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