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Antwi-Boasiako, C, Ofosuhene, L and Boadu, KB (2018) Suitability of sawdust from three tropical timbers for wood-cement composites. Journal of Sustainable Forestry, 37 (4). pp. 414-428. ISSN 1054-9811

https://doi.org/10.1080/10549811.2018.1427112

Suitability of the sawdust from three types of wood for wood-cement composites

CHARLES ANTWI-BOASIAKO[1*], LINDA OFOSUHENE[1] and KWADWO B. BOADU[1]

[1]Department of Wood Science and Technology, Faculty of Renewable Natural Resources,
Kwame Nkrumah University of Science and Technology,
Kumasi-Ghana.

[1*]cantwiboasiako@gmail.com; c.antwiboasiako@yahoo.co.uk; Tel.: +233 (0) 243771376 [Corresponding Author]

Shortened title: **Sawdust Suitability for composite board production**

ABSTRACT

Construction material rising cost and global demand for economically-sustainable and environmentally-friendly building resources have necessitated the use of sawdust-cement composite. Wood constituents and cement incompatibility hinder its production and need careful selection of the timber. Sawdust suitability from Triplochiton scleroxylon, Entandrophragma cylindricum and Klainedoxa gabonensis for wood-cement composite was determined by identifying their chemical constituents and their composites' physico-mechanical properties. T. scleroxylon recorded the minimum total extractive (6.12%), lignin (29.89%) and holocellulose (56.38%) and K. gabonensis the maximum (9.31, 31.59 and 57.5% respectively). Ash content was higher for T. scleroxylon (7.6%) but lower for K. gabonensis (1.53%). T. scleroxylon boards were stronger [Modulus of Elasticity (MOE) = 696.1 N/m²] and more moisture-resistant [Moisture Absorption (MA) = 8.8%] than E. cylindricum (MOE = 625.9 N/m²; MA = 9.5%). K. gabonensis boards crushed after manufacturing due to its incompatibility with cement. T. scleroxylon sawdust is suitable for wood-cement composites due to its more compatible chemical constituents (i.e., lower extractive, lignin, holocellulose contents and more ash) and its boards' excellent physico-mechanical properties than those for the other timbers. Its sawdust-cement composites could be utilized for indoor applications (e.g. ceiling and walling). The use of sawdust would increase green building resource base and reduce environmental pollution.

KEY WORDS: Cement hydration, composite board, inhibitory chemical, total extractive, wood-cement compatibility.

INTRODUCTION

The growing human population coupled with rapid socio-economic development has put great pressure on traditional building materials such as timber, concrete and sandcrete (Turgut & Algin, 2007). Consequently, the global economy is facing with imbalances in the demand, supply and remarkable rise in the price of these materials, which make construction-related projects expensive. Jeddah Economic Forum (2013) noted that an average house in the Saudi Arabia cost SR700,000, nearly 10 times the mean national salary of SR72,000, while the price of a house was three times the average salary in the US. This could be partly attributed to the high costs of conventional building materials. Turgut & Algin (2007) and Adebakin, Adeyemi, Adu, Ajayi, Lawal, & Ogunrinola (2012) noted that in order to address the unaffordability of traditional construction materials, while ensuring their sustainable supply, there is the need to search for inexpensive but effective and environmentally-friendly alternative resources. For instance, wood-cement composites could substitute most of the expensive and declining resources for cladding, panelling and building due to their ease of manufacturing, dimensional stability, fire- and decay-resistance (Semple & Evans, 2004). They have high bending strength with improved insulation and sound-proof properties (Dinwoodie & Paxton, 1991). These qualities make them suitable for the construction of noise absorbers near highways and railways to offer protection against frustrating traffic noise. They also offer effective protection from over-heating during summer and warm periods in the tropics.

According to Semple & Evans (2004), the production of wood-cement composites is a sustainable enterprise since most of the raw materials are readily available and cheap. Karade (2005) explained that wood-residue (e.g. sawdust) is a major raw material for the manufacture of such composites. Architects have often been challenged to convert these industrial "wastes" into appropriate construction/building materials. Their production appears to be one of the alternative means of utilizing wood "waste" as raw materials for construction (Tagelsir, 2004). In Australia, Indonesia and Germany, the production of composite products provides value-addition to the large amount of sawdust produced mostly from the timber mills (Semple, Cunningham & Evans, 1999). In Africa, Ghana's timber industry generates large amount of wood residue (Adamafio, Afeke, Wepeba, Ali, & Quaye, 2004). Sekyere, Okyere, Darkwah, & Nketiah (2004) noted that over 55% (by volume) of log input in most of the milling industries end up as slabs, off-cuts, edgings and sawdust. According to the Millenium Cities Initiative (2003), over 100 – 150 metric tonnes of sawdust are produced daily at the Sokoban Wood Village in Kumasi, the nation's second largest city. These are dumped or burnt as waste to pose serious environmental threats. Thus, Ghana has the great potential to produce wood-cement boards from the large amount of timber residues produced by the firms. This would contribute to the reduction of the environmental hazards associated with their indiscriminate disposal.

The suitability of different timber species for wood-cement composites has been a major concern for the product manufacturers due to variations in their influence on cement hydration (Mohammed, 2003; Na, Zhiqiang, Haiqin, & Xiaoning, 2014). According to Vares et al. (1997), Blankehorn, Blankehorn, Silsbee & DiCola (2001) and Chowdury, Maniar & Suyanga (2014), the chemical constituents of wood (such as extractive, lignin, holocellulose and ash) are responsible for timber's compatibility or otherwise with cement. Lignin for instance strongly held wood particles together thereby making it difficult for cement paste to penetrate them easily. Frybort, Mauritz, Teischinger & Muller (2008) reported that hardwoods are less suitable for making cement-bonded composites than softwoods due to the great amount of soluble xylans present in the former. Mohammed (2003) corroborated this finding when he studied the inhibitory index for nine (9) softwood and 12 hardwood species. Jorge, Pereira & Ferreira (2004) found that Larix decidua Mill. completely stopped cement hydration and affected the physical properties of the composites. Semple & Evans (2004) observed that great amount of soluble polyphenols in Acacia mangium Wild. also hindered cement hydration and subsequently affected its wood-cement compatibility. Hydration of Cryptomeria japonica (Thunb. ex L.f.) D.Don-cement mixture was also slower than that of Chamaecyparis obtusa (Siebold & Zucc.) Endl. due to the presence of large quantities of soluble polyphenols in C. japonica (Ma et al., 2000). These inhibitory substances have detrimental effect on the mechanical strength of wood-cement composites (Frybort et al., 2008). Thus, Semple & Evans

(2004) explained that residues from certain wood species might not be appropriate for producing wood-cement composites. Therefore, manufacturers need to be guided on the selection of timbers whose sawdust could be used for such a purpose (Semple & Evans, 2004). Triplochiton scleroxylon Schumann and Entandrophragma cylindricum (Sprague) Sprague are two tropical timbers that are frequently processed for lumber (Timber Industry Development Division, 2015). Adu et al. (2014) observed that these were among the four species that generated about 61.92% residue from the total volume of logs processed by only four (4) Timber Firms in the Ashanti and Brong Ahafo Regions of Ghana. Klainedoxa gabonensis Pierre ex. Engl. (a Lesser-Utilized-Species), which occurs widely in several tropical countries, has great potential for exploitation (Boadu et al., 2017). Residues from the processing of these timbers by Wood Firms could be useful resources for the wood-cement composite industry. However, their suitability would depend on their chemical constituents, which need to be ascertained. The objective of this study therefore was to assess the appropriateness of sawdust from these three timbers for the production of wood-cement composites. The chemical compositions of each timber as well as the physical and mechanical properties (i.e., density, moisture absorption [MA] and Modulus of Elasticity [MOE]) of the wood-cement composites produced from them were characterized. The successful production of wood-cement composites from sawdust from these timbers and other wood residues would ameliorate the various environmental challenges with their disposal and reduce the over-dependence on the conventional building materials.

MATERIALS AND METHODS

Collection and preparation of sawdust

Different samples of sawdust (600g) from three timbers of various densities [i.e. T. scleroxylon (low density), E. cylindricum (medium density) and K. gabonensis (high density)] were collected from Sokoban, a Wood Processing Community in Kumasi-Ghana. The community has an estimated 8,000 wood workers with much wood residue (Ghana Statistical Service, 2012). Sawdust (100g) was air-dried for 72 h to 12% moisture content, milled to powder with the Wiley mill (Ma et al., 2000), sieved with a mesh (size = 850 micron) (ISO 3310-2, 2013) and stored in air-tight plastic containers.

Chemical constituents of sawdust

Total extractive

Air-dried wood powder (5g) was extracted in a Soxhlet apparatus with ethanol-acetone mixture (1:2 v/v) for 4 h followed by 95% ethanol for 4h and finally with hot distilled water, which was changed every 1 h for 4 h. The filtrate was kept in a beaker and left on a water bath until all the solvent evaporated. The beaker with its content was placed in an oven (105 ºC) for 24 h, cooled to room temperature in a desiccator and weighed. The total extractive in each timber was determined (American Society for Testing Materials, 1994):

$$\text{Total extractive content (\%)} = \frac{\text{Weight of beaker plus extractives} - \text{Weight of beaker}}{\text{Weight of air-dried wood meal}} \times 100$$

The test was replicated four times.

Lignin content

Oven-dried, extractive-free sawdust (5g) of each wood species was mixed with 15 ml of cold 72% sulphuric acid, stirred and left to stand for 2 h (TAPPI, 2006). The mixture was transferred into a conical flask and diluted with distilled water (560 ml). It was boiled for 4 h, while hot water was frequently added. The insoluble material was allowed to settle and filtered. The residue was washed, dried in an oven (at 103±2°C) for 2 h, left to cool and its weight determined. The lignin content of each timber was calculated:

$$\text{Lignin content (\%)} = \frac{\text{Weight of oven-dried residue}}{\text{Weight of oven-dried extractive-Free sawdust}} \times 100$$

Holocellulose content

In accordance with ASTM 1104-56 (1978), 180ml of distilled water, 8.6g sodium chlorite and 6.0ml ethanoic acid were added to 2 g of oven-dried extractive-free material of each wood species. The mixture was digested in a 250 ml conical flask under reflux at 70°C for 3h, cooled and filtered. The residue was washed with five (5) 20 ml portions of 100 ml distilled water and oven-dried at 103±2°C for 2 h to attain constant weight. Holocellulose content was then determined as:

$$\text{Holocellulose content (\%)} = \frac{Weight\ of\ oven\text{-}dried\ residue}{Weight\ of oven\text{-}dried\ \ extractive\text{-}Free\ material} \times 100$$

Ash content

Oven-dry sawdust of each timber (1g) was placed into a dry porcelain crucible and heated (at 600°C) in a muffle furnace for 3h to remove completely all the carbon (ASTM D1102-84, 2013). The crucible was placed into a dessicator to cool and then weighed. Ash content of each timber was determined:

$$\text{Ash content (\%)} = \frac{Weight\ of\ ash}{Weight\ of\ \ oven\text{-}dried\ sample} \times 100$$

Where: weight of ash = Weight of crucible plus ash – Weight of crucible

Manufacturing of wood-cement composites

Portland cement, sawdust and deionised water were mixed in a weight ratio of 2:1:2 [Evans, 2000; Karade, 2005). The wood-cement mixture/composite was moulded in wooden deckle boxes and hydraulically pressed at 80kPa at the Civil Engineering Department, Kwame Nkrumah University of Science and Technology. The wood-cement boards produced for Modulus of Elasticity (MOE) test were moulded into 2 × 2 × 30 cm (BS EN 310, 1993) and those for density and moisture absorption (MA) into 5 × 5 × 5 cm (BS EN 323, 1993; BS EN 317, 1993). All the boards were conditioned at 25 °C and 65% relative humidity (RH) for a month until their moisture contents reached 14%. Five replicate boards made from sawdust from each timber were tested for their densities, MAs and MOEs.

Physical and mechanical properties of wood-cement composites

Density

Each wood-cement board (5 × 5 × 5 cm) was weighed (g) and its thickness (mm) measured with a micrometer (to an accuracy of ±0.01mm) at the point of intersection of two diagonal lines drawn from their corners. The height and width (mm) of the boards were measured at points parallel to the edges of the test piece and their densities (kg m^{-3}) calculated (BS EN 323, 1993):

$$\rho = \frac{m}{h \times d \times t} \times 10^6$$

Where: ρ = density; h= height of board; d = width of board; m = weight of board; t = thickness of board

Moisture absorption

The manufactured wood-cement boards (5 × 5 × 5 cm) were oven-dried (in a Universal oven, Model: BS 2205F) at 103 ± 2 °C for 24 h. Their weights and thicknesses were measured and they were immersed in deionised water under room conditions. Excess water was drained from the boards with boardwalk paper towels (SKU: BWK6272) and their weights and thicknesses re-measured. Moisture absorption (%) was calculated (BS EN 317, 1993):

$$MA = \frac{W(t) - Wo}{Wo} \times 100$$

Where: MA = Moisture absorption (%) after 24 h; Wo = Oven-dried weight; and W(t) = Weight after 24 h immersion

Modulus of Elasticity (MOE)

The MOE of each board was determined using an Instron-4482 Universal Testing Machine (BS EN 310, 1993). Successive loads were applied to the board at a rate of 0.1 mm/sec until it ruptured and the maximum load that caused the rupture recorded. The Instron had a computer attachment that recorded the mechanical property of the board being tested.

Data Analysis

The data were subjected to ANOVA and Fisher's Least Significant Difference (LSD) test at 95% Confidence Level using the SAS Statistical Software (Version 9.1.3).

RESULTS

Chemical Constituents of the three Timbers

The holocellulose content was greater in all the timbers (i.e., K. gabonensis = 57.5%; E. cylindricum = 59.26%; T. scleroxylon = 56.4%) than lignin (K. gabonensis = 31.59%; E. cylindricum = 31.4%; T. scleroxylon = 29.9%), total extractive (K. gabonensis = 9.3%; E. cylindricum = 7.7%; T. scleroxylon = 6.1%) and ash (K. gabonensis = 1.5%; E. cylindricum = 1.6%; T. scleroxylon = 7.6%). The differences between the quantities of these chemicals for each timber were significant ($p<0.05$) (Fig. 1).

K. gabonensis had the greatest amount of total extractives (9.31%), followed by E. cylindricum (7.675%) and T. scleroxylon (6.116%) (Fig. 1). The differences between the means were significant (F-ratio = 33.78 ≥ F-crit = 4.26) (Table 1).

Table 1: ANOVA for total extractive content among three wood species

Source of Variation	SS	df	MS	F	P-value	F crit
Wood species	20.40712	2	10.20356	33.77852	6.55E-05	4.256495
Error	2.718652	9	0.302072			
Total	23.12577	11				

Similarly, the lignin content rated as: K. gabonensis (31.59%) > E. cylindricum (31.4%) > T. scleroxylon (29.89%) (Fig. 1). The differences between the means of lignin content between the timbers were significant except between K. gabonensis and E. cylindricum (Table 2).

Table 2: ANOVA for lignin content among three wood species

Source of Variation	SS	df	MS	F	P-value	F crit
Wood species	6.886317	2	3.443158	5.806147	0.024017	4.256495
Error	5.337175	9	0.593019			
Total	12.22349	11				

For holocellulose, E. cylindricum had the greatest (59.26%), followed by K. gabonensis (57.5%) and then T. scleroxylon (56.38%); the differences were significant (F-ratio = 8.99 ≥ F-crit = 4.26) (Table 3). Ash content was lower for K. gabonensis (1.5%) than for E. cylindricum (1.65%) and T. scleroxylon (7.6%); the differences were significant (F-ratio = 1348.066 ≥ F-crit = 4.26) (Table 4) except between those for K. gabonensis and E. cylindricum.

Table 3: ANOVA for holocellulose content among three wood species

Source of Variation	SS	df	MS	F	P-value	F crit
Wood species	16.80432	2	8.402158	8.999152	0.00713	4.256495
Error	8.40295	9	0.933661			
Total	25.20727	11				

Table 4: ANOVA for ash content among three wood species

Source of Variation	SS	df	MS	F	P-value	F crit
Wood species	96.43167	2	48.21583	1348.066	7.07E-12	4.256495
Within Groups	0.3219	9	0.035767			
Total	96.75357	11				

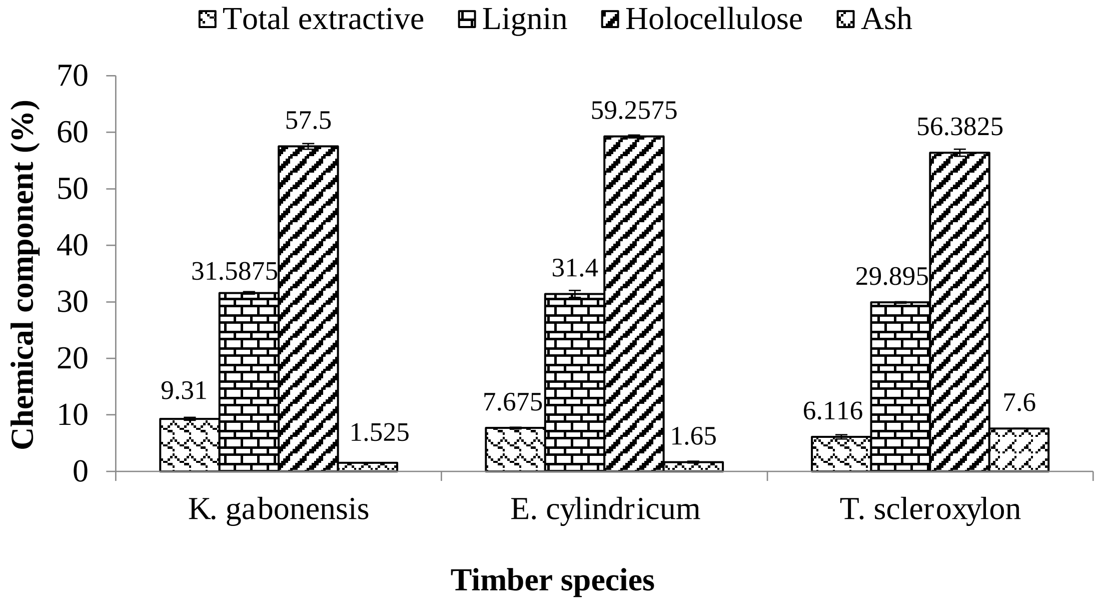

Fig. 1: Chemical constituents of three tropical timbers

Physical and mechanical properties of wood-cement composites

Density and moisture absorption

All the wood-cement composites produced from K. gabonensis sawdust crumbled into pieces upon removal from the wooden deckle boxes (Fig. 2). Therefore, their physical properties could not be determined. Wood-cement composites made from the sawdust of T. scleroxylon, had higher density (630.97 kg m^{-3}) than those from E. cylindricum (572.98 kg m^{-3}) (Fig. 3). The difference between the densities of the composites from the two timbers was significant (F-ratio = 1349.439 ≥ F-crit = 3.885) (Table 5).

Table 5: ANOVA for density of wood-cement composites from three wood species

Source of Variation	SS	df	MS	F	P-value	F crit
Wood species	1216315	2	608157.6	1349.439	7.52E-15	3.885294
Error	5408.094	12	450.6745			
Total	1221723	14				

Similarly, T. scleroxylon composites had lower moisture absorption (8.82%) than E. cylindricum (9.52%) (Fig. 4); the difference was also significant (F-ratio = 395.2588 ≥ F-crit = 3.885) (Table 6).

Table 6: ANOVA for moisture absorption of wood-cement composites from three wood species

Source of Variation	SS	df	MS	F	P-value	F crit
Wood species	281.576	2	140.788	395.2587	1.12E-11	3.885294
Error	4.274305	12	0.356192			
Total	285.8504	14				

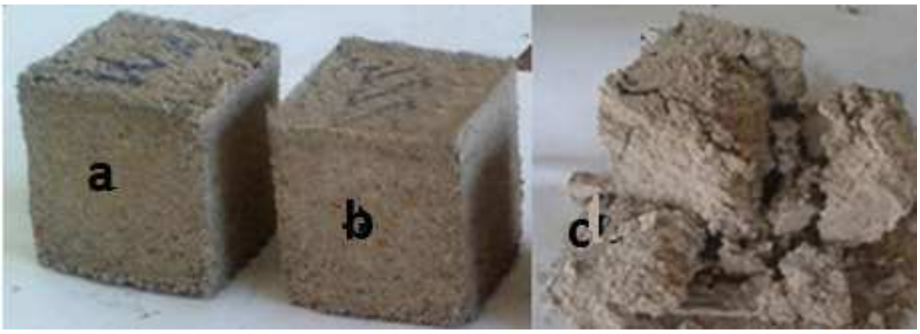

Fig. 2: Wood-cement composites made from cement and sawdust from T. scleroxylon (a), E. cylindricum (b) and K. gabonensis (crumbled) (c).

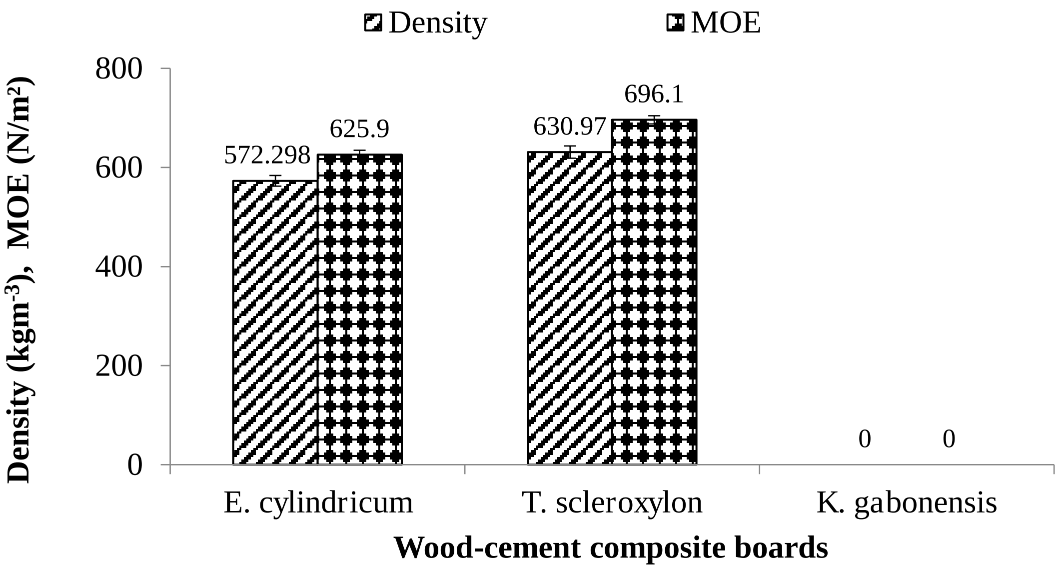

Fig. 3: Density and MOE of composite boards made from cement and sawdust from three timbers

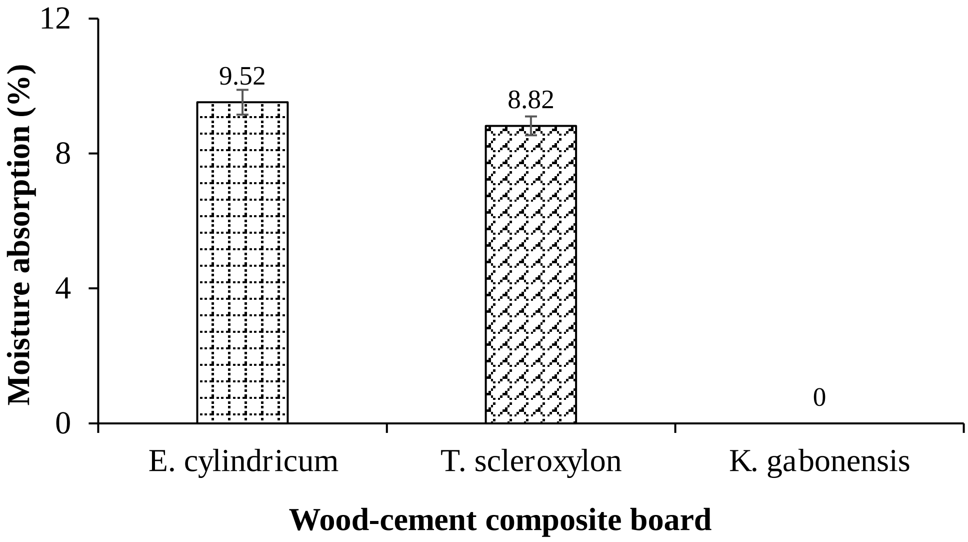

Fig. 4: Moisture absorption capacity of composite boards made from cement and sawdust from three timbers

MOE of wood-cement composites

MOE was greater for T. scleroxylon boards (696.1 N/m²) than those from E. cylindricum (625.9 N/m²) (Fig. 3). The difference between their MOEs was significant (F-ratio = 3028.876 ≥ F-crit = 3.885). Since composite boards from K. gabonensis crushed after manufacturing, their MOEs could not be determined.

Table 7: ANOVA for MOE of wood-cement composites from three wood species

Source of Variation	SS	df	MS	F	P-value	F crit
Wood species	1468810	2	734404.8	3028.876	5.97E-17	3.885294
Error	2909.613	12	242.4677			
Total	1471719	14				

DISCUSSION

Chemical constituents of sawdust

According to Dong, Yu, Song, Ma & Lu (2016) variations in chemical constituents could determine the appropriateness of timber for manufacturing wood-cement composites. While some of these components (e.g. holocellulose, lignin and total extractive) impede bonding between wood and cement particles, others (e.g. ash) enhance the compatibility between these particles. Sanaev, Zaprudnov, Gorbacheva, & Oblivin (2016) recommended that in order to ensure the successful production of wood-cement composites, the chemical components of the timbers must be determined so that those with the lowest amount of holocellulose, lignin and total extractive would be selected. Thus, the suitability of sawdust from these timbers for wood-cement board manufacturing was assessed by comparing their chemical constituents.

Fan, Ndikontar, Zhou & Ngamveng (2012) mentioned that wood generally contains more holocellulose than lignin, total extractive and ash. Similarly, for all the three timbers examined (i.e., K. gabonensis, E. cylindricum and T. scleroxylon), holocellulose was greater in quantity (i.e., 57.5, 59.26 and 56.4 % respectively) than lignin (i.e., 31.59, 31.4 and 29.9 % respectively), total extractive (i.e., 9.3, 7.7 and 6.1 % respectively) and ash (i.e., 1.5, 1.6 and 7.6 % respectively). The total extractive, lignin and holocellulose contents of the timbers also compare well with those previously reported for hardwoods (i.e., 2-10%, 20-40% and 50 - 70% respectively) (Xanthos, 2006; Pawlicka & Waliszewska, 2011). Extractives are the main cause of incompatibility between wood and cement (Frybort et al., 2008; Na et al., 2014). Na et al. (2014) noted that wood species with low amount of extractives are generally preferred for wood-cement composites because they have no adverse or minimal effect on the compatibility of wood and cement. Extractives contain hydroxyl and carboxylic functional groups, which inhibit wood-cement compatibility by interrupting with the crystallization reaction of cement and prevent it from solidifying (Frybort et al., 2008). According to Ma et al. (2000), extractives are also composed of several organic compounds that form complexes with metallic ions, which are present in cement solution. They reduce the concentration of calcium ions (Ca_{2+}) in cement and disrupt the equilibrium of the solution, which delays the start of nucleation of $Ca(OH)_2$ and Calcium-Silicate-Hydrate (C-S-H) gel. As extractive content increases, the percentage of non-hydrated cement clinker also rises, which leads to strength decrease of the wood-cement composites (Frybort et al., 2008). Espinoza-Herrera & Cloutier (2008) found that Pinus banksiana Lamb, Abies balsamea (L.) Mill, Populus tremuloides Michx. and Betula papyrifera Marsh. were potential timbers for the production of cement-bonded composites due to their low extractive contents (i.e., 3.4, 2.9, 2.2 and 2% respectively). They explained that wood species, which contain more than 7% of extractives were not suitable for composite manufacturing. The present results indicate that T. scleroxylon has lower amount of extractives (6.116%) than K. gabonensis (9.31%) as well as E. cylindricum (7.675%). T. scleroxylon extractive content meets the acceptable threshold (i.e., ≤7%) proposed by Espinoza-Herrera & Cloutier (2008) for timbers for wood-cement composite making. Thus, sawdust from T. scleroxylon would be a better raw material for the production of sturdy wood-cement boards than those from the other two timbers. Expectedly, the great amount of extractives in K. gabonensis and E. cylindricum interfered with cement setting and prevented their sawdust from binding well with the cement.

Campbell & Sederoff (1996), Vares et al. (1997), Sierra (2011) and Marques et al. (2016) noted that the higher the lignin and holocellulose contents, the greater the incompatibility of the wood with cement. Lignin lowers the hydration temperature that is obtained when water is added to cement and wood mixture, which reduces the compatibility between wood and cement (Tagelsir, 2004). Holocellulose is non-crystalline, alkaline-soluble and forms complex compounds with calcium, aluminium and iron in cement, which negatively affect cement crystallization (Marques et al., 2016). Under heat and pressure treatment, they are hydrolysed and their water solubility increases (Tagelsir, 2004). This considerably affects the hydration characteristics of its solution and reduces the strength properties of the cement. Aigbomian & Fan (2013) noted that cellulose inhibits bonding of cement and wood together due to its hydrophilic nature even at a lower quantity (0.1%) and does not allow cement paste to penetrate it. Thus, although cement bonds well with other constructional materials in alkaline medium (e.g. fly ash), holocellulose in wood degrades in similar medium and stops cement from setting (Luzardo et al., 2016). Consequently, the differences in the amount of lignin and holocellulose for the three wood species [T. scleroxylon had lower amount of lignin and holocellulose (29.89% and 56.38% respectively) than E. cylindricum (31.4% and 59.26% respectively) and K. gabonensis (31.59% and 57.5% respectively)] would be expected to cause variations in their compatibility with cement. K. gabonensis and E. cylindricum wood residues would therefore form weaker bonds with cement particles and produce brittle composites than those of T. scleroxylon, which had the minimum lignin and holocellulose contents. Unsurprisingly, T. scleroxylon produced stronger wood-cement composites than K. gabonensis and E. cylindricum.

Higher amount of ash was recorded for T. scleroxylon (7.6%) than K. gabonensis (1.525%) and E. cylindricum (1.65%). The high ash content in T. scleroxylon could be attributed to its high amount of silicon compounds (Pawlicka & Waliszewska, 2011). Cement contains Silicon dioxide (SiO_2), Aluminium oxide (Al_2O_3), Iron (III) oxide (Fe_2O_3), Calcium hydroxide (CaO), Magnesium oxide (MgO), Sodium oxide (Na_2O) and Potassium oxide (K_2O) (Taylor, 1997). These chemicals are also found in large quantities in wood ash (Chowdhury et al., 2014). Therefore, Chen and Biljana (2014) noted that due to the high amount of silica in wood ash, it can replace cement in the manufacture of cement-bonded composites. In a study to determine strength development in concrete with ash-blended cement, Chowdhury et al. (2014) reported that wood ash possesses cement properties and it can augment the role cement plays in the production of wood-cement composite. Thomas (2007) explained that wood ash is a pozzolan, which reacts with water and calcium hydroxide released by the hydration of cement to produce various calcium-silicate hydrates (C-S-H) and hardened concrete. He indicated that the pozzolanic reactions increase the quantity of the cementitious binder phase (C-S-H) and improve the bonding strength of cement. Thus, wood with great amount of ash, and therefore high in silica, would be more suitable for wood-cement composite manufacturing than that with low ash content. Similarly, the greater amount of ash in T. scleroxylon than in the two timbers would improve its binding properties with cement and contribute to making its sawdust a preferred raw material for wood-cement composites.

Physical and mechanical properties of wood-cement composites

Density

Density is a significant characteristic of wood-cement boards because it influences their mechanical properties (Del Menezzi, de Castro & de Souza, 2007). For example, high density boards (density = >1300 kg m^{-3}) were stronger [Modulus of rupture (MOR) = >15.7 Nmm^{-2}] than their low density counterparts [MOR = 5.3 – 15.7 Nmm^{-2}] (Del Menezzi, de Castro & de Souza, 2007). The density of wood-cement composites could be higher when effective bonding of cement and wood particles is achieved (Zhou & Kamdem, 2002). The high density obtained for T. scleroxylon composites could be because of the great compatibility of the wood and cement due to the timber's chemical constituents. The high amount of extractives, holocellulose and lignin, and low amount of ash in K. gabonensis and E. cylindricum inhibited efficient bonding and perhaps created several free pores, which were reduced the mass of the composites and their overall densities (Ma et al., 2000). The densities of the boards currently produced from sawdust from the timbers conform to the range of densities (500 - 1000 kg m^{-3}) obtained by Forest Products Laboratory (1999) and Mahzabin et al. (2013) for low density boards used in various applications including cladding and building insulation. Based on the density of the composites from the three wood species, sawdust from T. scleroxylon could produce stronger boards than those from the other two timbers.

Moisture absorption

T. scleroxylon boards had lower moisture absorption (8.8%) than E. cylindricum (9.5%). According to Moslemi et al. (1995), wood and cement incompatibility, which leads to large amount of free internal spaces within the wood-cement matrix, could be a possible cause for great moisture absorption of composites. Mahzabin et al. (2013) further explained that, without proper encasing of wood fibres by cement particles, the hygroscopic nature of wood fibres complicates the issue of moisture absorption among poorly compacted composites. Wood-cement composites from T. scleroxylon had low moisture absorption, which could be due to the timber's improved compatibility with cement, which resulted in effective bonding of sawdust and cement. Tabarsa & Ashori (2011) found that composites with low moisture absorption were dimensionally stable. Thus, T. scleroxylon would contribute to the excellent dimensional stability of wood and cement-bonded composites, which are often used for roofing, shingles and shales (van Elten, 2006). T. scleroxylon sawdust-cement composites will offer an alternative to the frequently used constructional materials like concrete for buildings.

MOE

According to Pan & Watson (1998), materials used for cladding and partitioning, such as wood-cement composites, must possess sufficient stiffness to prevent buildings from flexing too much under wind loads or internal loading. Therefore, the MOE of the wood-cement composites, which is a measure of their stiffness, was determined. MOE obtained for all the wood-cement composites from sawdust from the three timbers (E. cylindricum = 625.9 Nm^{-2}; T. scleroxylon = 696.1 Nm^{-2}) compare well with those established by the Forest Products Laboratory (1999) (621 – 1,241 Nm^{-2}) for several low density wood-cement composites produced by the U.S. Department of Agriculture. However, the MOE values for the composites were lower than the required MOE (3000 Nm^{-2}) for high density boards by ISO 8335 (1987).

T. scleroxylon sawdust-cement boards had greater MOE (696.1 Nm^{-2}) than those from E. cylindricum (625.9 Nm^{-2}). Soriano et al. (1997) and Sutigno (2000) noted that the effect of extractives, lignin and holocellulose on wood-cement compatibility often contributes to the reduction of the strength properties of wood-cement composites manufactured from certain wood species. Ashori & Nourbakhsh (2010) explained that extractives, these chemicals weaken the interfacial bonding between wood fibres and cement, which leads to the production of wood-cement composites with inferior strengths (Evans, 2000; Fan et al., 2012). Thus, T. scleroxylon with low amount of extractives, lignin and holocellulose but great ash content produced stronger boards than E. cylindricum, which contains more of these inhibitory substances.

Adebakin, Adeyemi, Adu, Ajayi, Lawal, & Ogunrinola (2012) mentioned that the rising demand for housing and other related structures such as panel sheathing, has put the traditional building materials including steel, aluminium and bricks under intense pressure. Wood-cement composites are eco-friendly and sustainable resources, which could serve as alternatives to the traditional materials. The current study has established that T. scleroxylon (the light timber) sawdust is a preferable raw material for the manufacture of wood-cement boards due to its chemical composition as well as the physical and mechanical properties of its manufactured boards compared to those of E. cylindricum and K. gabonensis. Cement-bonded composites from T. scleroxylon sawdust would provide cost-effective and sustainable alternative materials for green buildings (including cladding and partitioning) due to the availability, low cost and environmentally-friendly characteristic of its sawdust (Zakaria et al., 2015). This will increase the raw material base for the production of construction materials for the housing industry.

CONCLUSION

1. Compatibility of T. scleroxylon with cement was better than those of E. cylindricum and K. gabonensis because of its lower contents of lignin, holocellulose and total extractive, and high ash content.
2. Wood-cement composites from T. scleroxylon were denser, stronger and had better moisture resistance capacity than those from E. cylindricum. Sawdust from K. gabonensis would not be appropriate for wood-cement composite manufacture due to its incompatibility with cement.
3. T. scleroxylon sawdust will be a better raw material for the manufacturing of cement-bonded composites than the two timbers.
4. The use of sawdust from T. scleroxylon for manufacturing composites would reduce environmental pollution and increase the resource base for the manufacturing of green building materials.

ACKNOWLEDGEMENT

We thank the staff of the Chemical Laboratories of the Faculty of Pharmacy and Pharmaceutical Sciences and the Department of Wood Science and Technology, Kwame Nkrumah University of Science and Technology (KNUST) for the sample preparation and the determination of the chemical constituents of the wood samples. We are grateful to the staff of the Department of Civil Engineering, KNUST, for the manufacture of wood-cement composites and Mr. Eric Owusu Danquah [Crops Research Institute of the Council for Scientific and Industrial Research (CSIR)], Kumasi- Ghana, for the statistical analyses.

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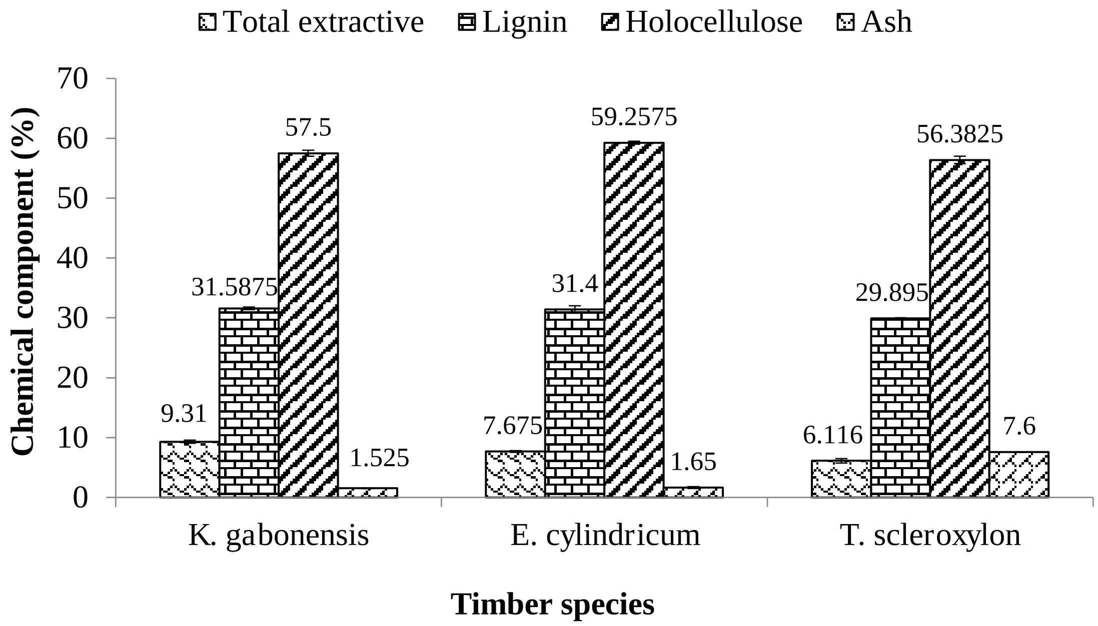

Fig. 1: Chemical constituents of three tropical timbers

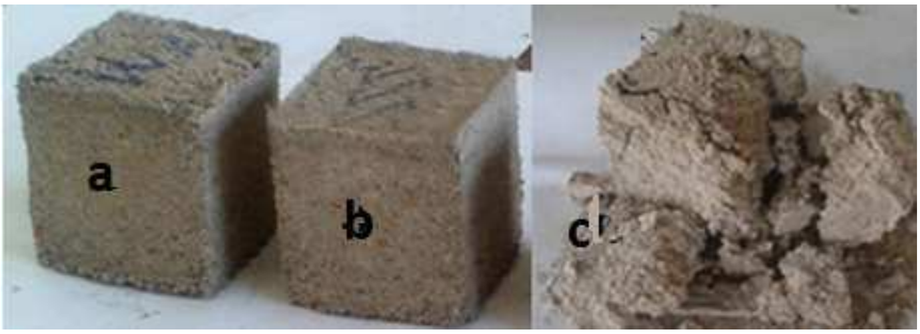

Fig. 2: Wood-cement composites made from cement and sawdust from T. scleroxylon (a), E. cylindricum (b) and K. gabonensis (crumbled) (c).

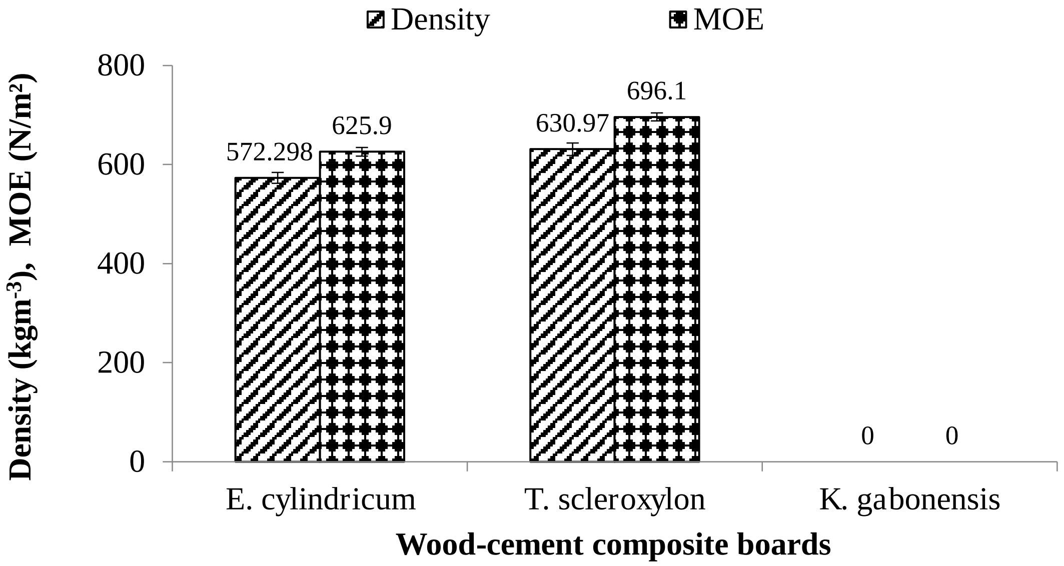

Fig. 3: Density and MOE of composite boards made from cement and sawdust from three timbers

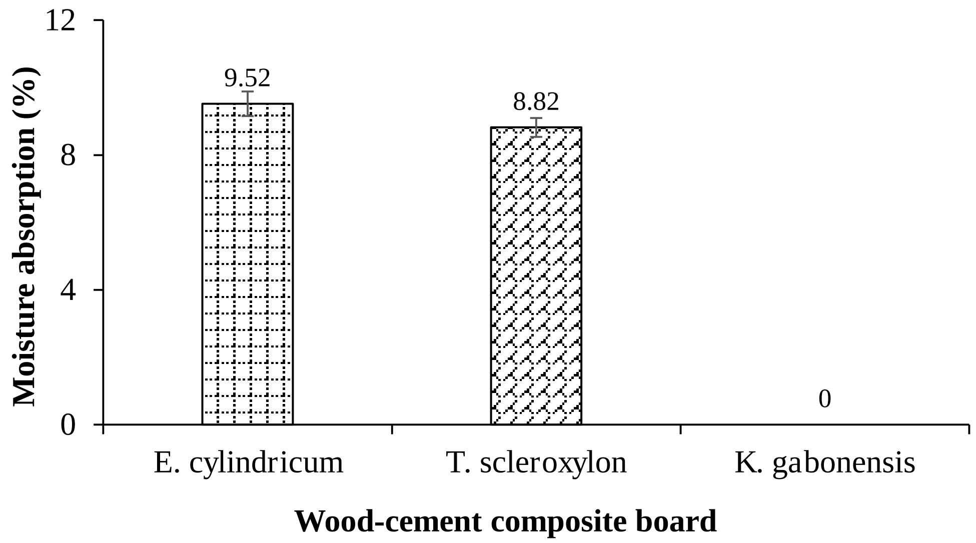

Fig. 4: Moisture absorption capacity of composite boards made from cement and sawdust from three timbers