Evaluation of the performance of eco-friendly lightweight interlocking concrete paving units incorporating sawdust wastes and laterite

Adebayo Olatunbosun Sojobi

Abstract: This research investigates the performance of sawdust wastes and laterite as an alternative lightweight fine aggregate and cementitious material respectively in eco-friendly lightweight interlocking concrete paving units (ICPU) using a mix ratio of 1:2:4. The lightweight sawdust and laterite were studied due to their abundant availability as industrial waste and cheap local construction material. Eco-friendly ICPU is a low-strength concrete with compressive strengths of 6.02–7.57 and 3.66–4.52 N/mm² at 5 and 10% sawdust replacements with bulk density ranges of 1,756.62–1,810.9 and 1,522.89–1,532.4 kg/m³ respectively which exceeded the minimum compressive strength requirement of 3.45 N/mm² in non-load bearing concrete applications. Though air curing recorded higher compressive strengths at early curing ages, water curing was recommended to facilitate complete hydration owing to the hygroscopic nature of the sawdust. The packing and filling effects of the lightweight sawdust coupled with the combined pozzolanic properties of the sawdust waste and laterite seemed to have contributed to the slight increase in CS of the eco-friendly ICPU when heated. Effective partnerships among the State and...
Local Government Waste Management Authorities, sawmill operators and informal waste collectors were recommended for effective sawdust waste recovery, storage and usage in eco-friendly construction.

Subjects: Concrete & Cement; Pollution; Waste & Recycling

Keywords: compressive strength; concrete; construction; curing; eco-friendly; interlocking concrete paving units; laterite; lightweight; sawdust; wastes

1. Introduction

1.1. Sustainable waste materials in concrete and construction

The increasing demand for high-performance sustainable materials in the construction industry, which represents a shift towards sustainable, eco-friendly and green practices, poses a huge challenge to structural engineers, material engineers, environmental engineers and architects (D’Alessandro, Asdrubali, & Baldinelli, 2014; Mahmoud, Ibrahim, El-Chabib, & Patibandla, 2013; Sojobi, Nwobodo, & Aladegboye, 2016; Yet, Hamid, & Kasmuri, 2012).

For sustainability to be fully achieved, there must be effective collaborations among these professions and related professions that are also stakeholders in the construction industry, as advocated by Sieffert, Huygen, and Daudon (2014). In addition, further research and development on the technical, economic and environmental aspects of eco-friendly products as well as improved standardization, government policy and public education as espoused by Zhang (2013), are urgently needed.

Furthermore, to achieve environmental sustainability in the construction industry, it is imperative that the design, selection of materials, construction and maintenance of concrete, concrete products and civil engineering structures must reflect environmental friendliness (Folic’, 2009). In addition, the selection and combination of supplementary cementitious and recycled materials (SCM) must take into consideration the properties relevant to their usage and performance, durability as well as the exposure conditions (Elahi, Basheer, Nanukuttan, & Khan, 2010).

Globally, it is common knowledge that the construction industry relies heavily on conventional materials such as cement, granite and sand, which continues to pose huge economic, environmental and development costs especially to developing countries and also continues to contribute to the depletion of natural aggregates in various regions of the world.

With the emergence of sustainable technologies which is driven largely by regulations and increasing demand for innovations and cost reduction, international organizations, shortage of landfills and scarcity of natural aggregates and environmental issues, the construction industry is increasingly embracing the use of SCM and environmental wastes in concrete (Araghi, Nikbin, Reskati, Rahmani, & Allahyari, 2015; Babu, Mullick, Jain, & Singh, 2014; Dan & Fan, 2015; Eisa, 2014; Kim, Hong, Jeong, Koo, & Jeong, 2016; Mahmoud et al., 2013; Oyelami & Van Rooy, 2016; Sojobi et al., 2016).

The use of SCMs and recycling/reuse of environmental wastes helps to achieve green concrete, contributes to reduction of global warming and have been found useful in both structural and non-structural applications (Eisa, 2014; Park, 2012).

In addition, there have been concerted calls for the increased use of local materials, which are abundant, readily available and cheaper compared to the conventional materials, in construction (Al-Swaidani & Aliyan, 2015; Olutoge, 2010; Ukpata & Ephraim, 2012). Utilization of such local materials in construction will improve self-sufficiency, reduces construction costs and accelerate achievement of sustainable development especially in developing countries with abundant local materials.
According to Ghernouti and Rabehi (2012) and Le, Nguyen, and Ludwig (2014), use of locally available materials as well as industrial and agricultural wastes in construction presents both economic and environmental advantages particularly to developing countries which generate large quantities of these wastes annually. According to Oyelami and Van Rooy (2016), utilization of sustainable earth materials present advantages such as cost efficiency, material efficiency, energy efficiency and environmental friendliness.

Sadly, there is low usage of these local materials in construction which is attributed to several factors such as lack of reliable data on the engineering properties of these materials in concrete and block production (Ukpata & Ephraim, 2012).

Other responsible factors include low level of awareness about their potential in concrete and their potential to improve properties of concrete, low research and development on these materials, poor development and support of the industries which would utilize the materials in production of concrete and concrete products and widening gap between engineering researchers in the Universities and the Industry, apathy towards local materials linking it with poverty and insatiable cravings for imported concrete products.

In addition, Acheampong, Hackman, Ayarkwa, and Agyekum (2014) noted inhibitory factors such as low level of technical expertise, low level of education, high initial cost of construction, apathy towards use of local, indigenous materials, non-availability of standards for these materials, perception of low quality of indigenous materials.

Various types of wastes have been used and are being used in concrete, various concrete products and construction (Al-Adili, Al-Ameer, & Raheem, 2015; Chung, Shin, & Rupnow, 2012; Donatello & Cheeseman, 2013; Karim, Zain, Jamil, Lai, & Islam, 2011; Rashad, Seleem, & Shaheen, 2014; Sales, de Souza, dos Santos, Zimer, & do Couto Rosa Almeida, 2010; Sojobi & Owamah, 2014; Sorlini, Sanzeni, & Rondi, 2012). These wastes can be classified as industrial wastes, agricultural wastes, domestic wastes and construction wastes.

Industrial wastes include fly ash, slag, sawdust ash (SDA), ordinary wood sawdust, electric arc furnace slag, iron splinter minced rubber and ground granulated blast-furnace slag while agricultural wastes include palm oil fuel ash, rice husks and rice husk ash, corn cob, palm kernel and palm kernel fibres. Domestic wastes include organic food wastes, post-consumer plastics, sewage sludge ash and kitchen wastewater while construction wastes include recycled aggregates, recycled concretes, recycled asphaltic pavements (RAP), bamboo, wood, plastic wastes to mention a few.

Globally, sawdust waste production is approximately 24.15 million m³ per year and are either burnt or landfilled causing environmental problems such as air pollution, emission of green-house gases (GHG), and occupation of useful land (Dan & Fan, 2015).

Also, Chowdhury, Mishra, and Suganya (2015) reported that 70% of wood ash produced is landfilled while 20% is used as soil supplement which indicates gross under-utilization of wood wastes and the environmental dangers the poor disposal and incineration poses to man and the environment at large.

The use of LWA derived from wastes in concrete helps to achieve excellent segregation resistance, high flowability, improves aggregate-paste contact zone, sustains internal curing which prevents early-age cracking because they serve as internal reservoirs of water and improved hardened properties (de Sensale & Goncalves, 2014; Holm, 1994; Lotfy, Hossain, & Lachemi, 2015).

However, it has been found that concrete utilizing these waste materials are affected by percentages of cement, SCM, micro and nano materials in the concrete, curing medium and curing time, aggregate type and dosage and mixture proportioning (Najigivi, Khaloo, Iraji zad, & Rashid, 2013; Rashad et al., 2014).
1.2. Review of literature

Results from literature review likewise revealed that very few studies have been done utilizing laterite and sawdust in concrete and concrete products including interlocking concrete paving units (ICPU).

Mathusamy and Kamaruzaman (2012) and Muthusamy et al. (2015) recommended the use of laterite aggregate as a partial replacement for granite to produce lateritic concrete in order to conserve natural granite and avoid ecological imbalance.

Also, Mathusamy and Kamaruzaman (2012), Muthusamy et al. (2015) and Salau and Busari (2015) recommended laterite replacement levels of 20–30% to achieve acceptable compressive and flexural strengths and resistance to acid attack.

Ocholi and Joel (2014) advocated stabilization of lateritic interlocking bricks with 8% cement content while Ogunbibi, Akinola, Oginni, and Akerele (2014) advocated the use of 1:8 or 1:7 mix ratios in the production of cement-stabilized lateritic clay bricks and sandcrete hollow blocks.

Bose and Das (2015) recommended the use of sawdust screened through 355 μm as a pore-former for the fabrication of ceramic membrane while Sales et al. (2010) also advocated the use of sawdust as lightweight aggregate to produce lightweight concrete which can be used in pre-moulded non-structural elements. Also, Aigbomian and Fan (2014) recommended the use of alkali-treated sawdust in production of non-load bearing applications such as woodcrete while Eliche-Quesada, Corpas-Iglesias, Pérez-Villarejo, and Iglesias-Godino (2012) suggested an optimum amount of 5% sawdust in production of lightweight brick manufacturing.

Sawdust is also recommended for use in the manufacturing of lightweight bio-composite and products such as interior wall and ceiling panels and thermos-insulating blocks (Dan & Fan, 2015; Kanatautas & Vaickelionis, 2000; Zziwa et al., 2006).

Olutoge (2010) recommended utilization of sawdust (SD) and palm kernel shell (PKS) as partial replacement for fine and coarse aggregates in production of lightweight reinforced concrete slabs while Nahak and Dash (2015) recommended the use of SDA as partial cement replacement and Moreira, Macedo, and Souza (2012) recommended sulphate treatment for sawdust composite to be used in manufacturing of building blocks.

Chowdhury, Maniar, and Suganya (2015) advocated a 10% maximum replacement of cement with WWA which can be utilized in low and medium-strength concrete, road base and roller-compacted concrete pavements.

1.3. Environmental benefits and significance of study

Owing to the lack of effective solid waste management which is pervasive in the developing world (Paul, Arce-Jaque, Ravena, & Villamor, 2012), especially in the rural areas, most of the sawdust wastes are disposed onsite, along banks of streams, rivers, along road sides or incinerated onsite and become breeding spaces for germs and worms, releasing obnoxious, pungent and foul odours and gases such as carbon dioxide (CO₂) and carbon monoxide (CO).

This poor disposal constitutes environmental and occupational health hazards to the workers, their customers and the environment (Lasode, Balogun, & Aremu, 2011; Oluoti, Megwai, Petterson, & Richards, 2015; Sanchez, Pasache, & Garcia, 2014).

In addition, it is estimated that between 1.8 and 5.2 million tonnes of sawdust wastes are generated annually in Nigeria (Oluoti et al., 2015). With low economic and effective utilization of the sawdust wastes which is <10% (Onchieku, Chikamai, & Rao, 2013), this translates to production of between 220.32 and 636.48 million tonnes of CO₂ when the sawdust wastes are incinerated.
The huge sawdust wastes generated in Nigeria and in Kwara State in particular are due to increase in sawmilling industries, poor material efficiency which is <45%, increased demand for forest-based products by construction industry, furniture/joinery industries spurred by infrastructural development and industrial growth and poor economic utilization which is <10% (Olufemi, Akindeni, & Olaniran, 2012; Onchieku et al., 2013; Parikka, 2004).

Other recommended usages of sawdust wastes such as production of briquette for cooking and bio-ethanol production to mention a few face scale-up challenges such as inadequate funding, poor policy support, lack of technological track record which limits targeted research and innovation funding (Hirschnitz-Garbers & Gosens, 2015).

Recycling of the sawdust wastes either in ordinary form or in ash form in concrete and concrete products such as interlocking paving units will significantly mop up these wastes from the solid waste stream, curbs the menace arising from the poor discharge of sawdust wastes and reduces the environmental impact of such wastes (Pargana, Pinheiro, Silvestre, & de Brito, 2014; Sojobi & Owamah, 2014).

Recycling of the sawdust wastes contributes to greening our construction industry, and will assure significant improvement in the operations and working conditions of the sawmill industries, and protection of our surface and groundwater from leachate pollutants from the sawdust wastes and also averts air pollution.

Also, considering global cement consumption of 3,220 metric tonnes per year (Mt/yr) in 2010 which is expected to increase to 4,200 Mt/yr in 2050, with corresponding emission of 3,050 in 2010, 3,450 Mt CO₂/yr in 2020 and 2,900 Mt CO₂/yr in 2050 (van Ruijven, Van Vuven, Boskaljon, & Patel, 2016), the potential savings in cement range between 32.20 and 42 Mt/yr and a corresponding reduction of 29–30.5 Mt CO₂/yr within the same period when laterite is utilized as SCM in concrete.

Furthermore, utilization of environmental wastes including sawdust in structural and non-structural applications in construction of buildings, roads and cool pavements contributes to sustainable construction and reduction of urban heat islands which contribute to urban climate (Oyedepo, Oluwajana, & Akande, 2014; Pacheco-Torgal, 2015; Raut, Ralegaonkar, & Mandavgane, 2011; Santamouris, 2013).

Likewise, utilization of locally-sourced materials such laterite as aggregate contributes to preserving our natural sand resources for future uses and future generations (Sabarish, Ratnam, Prasad, & Raju, 2015; Varghese, Paul, & Manjummekudiyil, 2013; Vesuvadapateran, 2013).

Such eco-friendly construction will aid reduction of the environmental effects of sand mining and dredging such as coastal land recession, destruction of coastal ecosystem services, resuspension and dispersion of fine sand sediments and diminishing sand for exploitation (Jonah, Agbo, Agbeti, Adjei-Boateng, & Shimbo, 2015; Kim, 2009; Kim & Lim, 2009; Lai, Chau, & Lorne, 2016; Liu et al., 2016; Tang, Zhang, & Xing, 2011; Thornton et al., 2006).

Utilization of these wastes in concrete also help in conserving energy, maximizing structural efficiency, increases the service lives of structural lightweight concrete and also contribute to projects becoming leadership in energy and environmental design (LEED) certified (Lotfy et al., 2015).

Based on review of past literature, there appears to be limited or no research available on the combined use of laterite and sawdust as cement and fine aggregate replacements respectively in the production of ICPU utilized in construction of non-traffic pedestrian walkways, sidewalks and landscapes.
Therefore, the objectives of this study are to:

(1) Evaluate the effects of sawdust content on the properties of ICPU.
(2) Evaluate the effects of the curing regime on the properties of ICPU.
(3) Assess the durability of ICPU produced utilizing both sawdust and laterite.
(4) Compare results obtained with similar waste materials.

2. Experimental program

2.1. Mix proportion and concrete material proportioning
Concrete mix ratio of 1:2:4 (cement: sand: granite) was used for the production of the LWC because it exhibited a higher compressive strength compared to mix ratio 1:3:6 as reported by Usman, Idusuyi, Ojo, and Simon (2012). Likewise, the concrete mix ratio 1:2:4 was also recommended for use by Ganiron (2014) and Udoeyo, Alu, and Sulaiman (2000).

Volumetric ratio method was utilized in proportioning the various concrete components. The quantity of each component calculated using the volumetric ratio method is displayed in Table 1. Sand, laterite and sawdust were sieved with sieve No. 10 to obtain their corresponding fine particles. For the control, laterite and sawdust were not included.

For all the other concrete specimens, cement was replaced with 10% laterite. In addition, sand was increasingly replaced with 5, 10 and 15% of sawdust to obtain the optimum percentage replacement. These cement replacements levels used was in line with recommendations by Oyedepo et al. (2014) that sawdust replacement of fine sand should not exceed 25%, 10% optimum replacement of fine sand with sawdust obtained by Abdullahi, Abubakar, and Afolayan (2013), 15% replacement of fine sand with sawdust obtained by Boob (2014) and 5% optimum replacement of sand with sawdust reported by Cheng, You, Zhang, Li, and Hu (2013) and Udoeyo et al. (2000).

2.2. Mixing procedure and test procedures
The mixing of the LWA concrete and the production of the ICPU were done in the Concrete Laboratory of Civil Engineering Department, Landmark University in Kwara State, Nigeria.

Laterite, cement, sand, sawdust, granite and water were all weighed using a weighing balance. The required quantities of the various concrete components displayed in Table 1 were obtained using the volumetric method of concrete proportioning in accordance with ACI 211-2 (American Concrete Institute, 1998) and the concrete mix ratio and were weighed and poured into separate containers (buckets). Manual mixing process was utilized for improved controllability of the concrete mixing process. For the non-control samples, sand was first poured on the mixing floor that has been swept clean, followed by laterite and sawdust and were mixed thoroughly with the aid of a shovel.

Cement was then added and mixed thoroughly before granite was added and then mixed thoroughly. In order to ensure a consistent and well-mixed concrete and owing to the huge quantity of the materials to be mixed, the entire mixed materials, were then divided into two parts. Water was poured, with aid of a weighed and water-filled bucket, into each concrete part and thoroughly mixed.

<table>
<thead>
<tr>
<th>% replacement of sand with sawdust</th>
<th>Materials (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cement</td>
</tr>
<tr>
<td>0</td>
<td>17.86</td>
</tr>
<tr>
<td>5</td>
<td>16.07</td>
</tr>
<tr>
<td>10</td>
<td>17.64</td>
</tr>
<tr>
<td>15</td>
<td>16.07</td>
</tr>
</tbody>
</table>
with the shovel. Weighed amount of water was continuously poured in three parts until a workable, well-mixed concrete was produced.

Figure 1. Flow chart for production of ICPU.
The two concrete parts were then mixed together with aid of a shovel to obtain a homogeneous concrete. While the mixing was on-going, the plastic ICPU moulds were lubricated with engine oil to enhance easy removal of the ICPU units when dried. The homogenised concrete was poured into the well-arranged ICPU moulds in two layers. Each layer was compacted manually twenty-five times with a 25 mm rod. After each mould has been completely filled with concrete, it was levelled off with the aid of a trowel. The ICPU units were demoulded after 2–3 days in accordance to BS EN 12390-2 (British Standard Institution, 2000) to ensure some level of curing which would have improved the strength of the ICPU units, enhance easy removal of the ICPU units and reduce the number of ICPU breakages. The plastic...
ICPU moulds were found to have cross-sectional area of 0.034 m$^2$ and thickness of 0.06 m resulting in a volume of 0.00204 m$^3$. The flow chart for the production of the ICPU is displayed in Figure 1.

Some of the demoulded ICPU samples were completely submerged in water in a water curing tank for water curing purposes in accordance with BS 1881 (British Standard Institution, 1983) while some were left well arranged on a table in the laboratory for air curing purposes.

After the ICPU samples were cured in water and air for 7, 14, 21, 28, 60 and 90 days, they were sun-dried and weighed using a weighing machine as shown in Figure 2 and their respective weights were recorded. The weight of each ICPU divided by the known volume of the ICPU, which correspond to the volume of the ICPU moulds, gave the bulk density at that curing age. Three representative samples of the ICPU were tested for bulk density at each curing age and the average value gave the average bulk density for the respective curing age.

Also, three representative samples of the dried ICPU were tested for compressive strength at each curing age according to ASTM C140 (2015) and BS EN 12390-3 standard (British Standard Institution, 2009). Three representative samples were also utilized for each sampling points by Abalaka (2013) and Akindahunsi and Uzoegbo (2015).

Each of the ICPU was carefully, manually and centrally placed in an automated UTM machine as depicted in Figure 3. Loads were applied gradually with the rate of travel of machine equivalent to 240 ± 35 kN/m$^2$/s. The applied load was stopped once the concrete specimen was observed to have failed and there was no increment in the readings of the UTM machine.

The average crushing load for the three ICPU samples measured in KN divided by the cross-sectional area of the specimen gave the compressive strength for the ICPU at that curing age. The resulting wastes from the crushing were safely disposed in a waste bin. The bulk density and compressive strength results obtained were plotted against the respective curing ages.

2.3. Curing regime
It was reported by Najigivi et al. (2013) and Rashad et al. (2014) that concrete properties are affected by curing conditions. This was corroborated by Zziwa et al. (2006) who worked on sawdust-modified bricks, Ikponmwosa, Falade, and Fapohunda (2014) who researched on foamed aerated concrete.
and El-Nouhy and Zeedan (2012) who investigated paving units, cured with both water and air. Therefore in this study, two curing regimes were investigated namely water curing and air curing in order to compare their effects on the properties of the ICPU. Water-curing was done in a steel water tank while air-curing was done at normal room temperature (25–30°C) in the concrete laboratory in Civil Engineering Department of Landmark University as shown in Figure 4.

### 2.4. Concrete paving unit tests and standards

Tests carried out on the ICPU were bulk density, compressive strength, fire-residual bulk density and fire-residual compressive strength and they are listed in Table 2 while their standard requirements are listed in Table 3. A minimum of three samples were tested for each test at each sampling point in compliance with ASTM C140 (2015). Three representative samples were also used by Olowu, Raheem, Awe, and Bamigboye (2014), Raheem, Bello, and Makinde (2010), Raheem, Olasunkanmi, and Folorunsho (2012) and Sadek and El Nouhy (2014) for each testing point.

### 2.5. Materials

#### 2.5.1. Cement

The cement used was Dangote brand of Ordinary Portland Cement which was obtained from Omu Aran local market in Kwara State, Nigeria. The particle distribution of the cement is displayed in Table 4 while its physical properties and chemical composition are displayed in Tables 5–7.

#### Table 2. Tests carried out on ICPU

<table>
<thead>
<tr>
<th>S/N</th>
<th>Test</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bulk density</td>
<td>NIS 87 (Nigerian Industrial Standard, 2004), EN 12390-7 (2009), Sojobi and Owamah (2014)</td>
</tr>
<tr>
<td>3</td>
<td>Fire-residual tests</td>
<td>EN 1365-2 (1999), Sojobi and Owamah (2014)</td>
</tr>
</tbody>
</table>

#### Table 3. Standard requirements for ICPU

<table>
<thead>
<tr>
<th>Concrete paving units parameters</th>
<th>Standards</th>
<th>Values</th>
<th>Traffic category</th>
<th>Interlocking bricks parameters</th>
<th>Standards</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive strength (CS₂₈)</td>
<td>BS 15658 (2006)</td>
<td>C30</td>
<td>Non-traffic</td>
<td>Compressive strength (CS₂₈)</td>
<td>NBRRRI (2006)</td>
<td>2 N/mm²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C35</td>
<td>Light traffic</td>
<td>7-day compressive strength (CS7)</td>
<td>National Building Code (2006)</td>
<td>1.60 N/mm²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C40</td>
<td>Medium traffic</td>
<td>Bulk density (BD₂₈)</td>
<td>NBRRRI</td>
<td>1,810 kg/m³</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C50</td>
<td>Heavy traffic</td>
<td>Maximum water absorption</td>
<td>NIS (2004)</td>
<td>12%</td>
</tr>
<tr>
<td>Abrasion</td>
<td>ESS 4382 (2004)</td>
<td>≤8%</td>
<td>Normal duty</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>≤6%</td>
<td>Medium duty</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>
|                                 |           | ≤5%    | Heavy duty       | – | – | –

Page 10 of 27
2.5.2. Laterite
Laterite used was obtained from Omu Aran Community in Kwara State, Nigeria. The particle size distribution is displayed in Table 4 while the physical and chemical properties of the laterite are displayed in Tables 5–7. The reddish-brown laterite was used because it is abundant, cheap and readily available in Omu Aran community (Alao, 1987; Omoniyi, Olufemi, & Abdulwahid, 2014; Omotoso, Ojo, & Adetolaju, 2012) and can be improved (Mama & Osadebe, 2011; Millogo, Morel, Traoré, & Ouedraogo, 2012).

2.5.3. Sand
The natural sand used as fine aggregate was obtained from Omu Aran community in Kwara State, Nigeria. The particle size distribution is displayed in Table 4 while the physical properties of the natural sand are displayed in Table 5 while. Sand recorded water absorption of 26.92%. The grading of the fine aggregates (sand and sawdust) compared with grading requirements for fine aggregates is displayed in Table 8.

2.5.4. Sawdust
Sawdust used, as a replacement for sand (fine aggregate), was obtained as an industrial by-product from a local sawmill industry in Omu Aran within Kwara State, Nigeria. The particle size distribution is displayed in Table 4 while the physical properties of the sawdust are displayed in Table 5. The sawdust used was unburnt to avoid air pollution and release of hazardous substances such as chromium, arsenic, iron, copper and zinc which would have been released to the atmosphere when incinerated (Udoeyo, Inyang, Young, & Oparadu, 2006). Sawdust waste recorded very high water absorption of 377.4% when soaked for twenty-four hours due to its hygroscopic nature.

2.5.5. Granite
Granite utilized as coarse aggregate was obtained from a local quarry within Omu Aran community.

Table 4. Particle size distribution of Dangote cement, sieved laterite, sand and sawdust

<table>
<thead>
<tr>
<th>Sieve sizes (mm)</th>
<th>Dangote cement</th>
<th>Sieved laterite</th>
<th>Sand</th>
<th>Sawdust</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>98.8</td>
<td>99.8</td>
<td>86.5</td>
<td>93.3</td>
</tr>
<tr>
<td>1.18</td>
<td>98</td>
<td>88.4</td>
<td>73</td>
<td>81.9</td>
</tr>
<tr>
<td>0.6</td>
<td>94.9</td>
<td>66.3</td>
<td>46.6</td>
<td>43</td>
</tr>
<tr>
<td>0.425</td>
<td>76</td>
<td>52.9</td>
<td>32.6</td>
<td>29.2</td>
</tr>
<tr>
<td>0.3</td>
<td>38.6</td>
<td>34.8</td>
<td>20.2</td>
<td>18.5</td>
</tr>
<tr>
<td>0.15</td>
<td>3.99</td>
<td>13.5</td>
<td>5.9</td>
<td>6.4</td>
</tr>
<tr>
<td>0.075</td>
<td>0.40</td>
<td>4.3</td>
<td>1.3</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Table 5. Physical properties of concrete components

<table>
<thead>
<tr>
<th>Properties</th>
<th>Sawdust</th>
<th>Sand</th>
<th>Laterite</th>
<th>Cement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loose bulk density (kg/m³)</td>
<td>185.98</td>
<td>1,445.12</td>
<td>1,064.02</td>
<td>1,125</td>
</tr>
<tr>
<td>Fineness modulus</td>
<td>2.00</td>
<td>0.94</td>
<td>0.87</td>
<td>0.63</td>
</tr>
<tr>
<td>Coefficient of uniformity (Cu)</td>
<td>3.48</td>
<td>3.04</td>
<td>3.92</td>
<td>–</td>
</tr>
<tr>
<td>Coefficient of curvature (Cc)</td>
<td>1.00</td>
<td>1.10</td>
<td>1.18</td>
<td>–</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>1.00</td>
<td>2.40</td>
<td>–</td>
<td>3.05</td>
</tr>
<tr>
<td>Water absorption (%)</td>
<td>377.4</td>
<td>26.92</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>
Table 6. Other physical properties of Cement and Laterite (Omoniyi et al., 2014)

<table>
<thead>
<tr>
<th>Physical Parameter</th>
<th>Cement</th>
<th>Laterite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consistency (%)</td>
<td>25.75–31.25</td>
<td>LL (Liquid limit) 46</td>
</tr>
<tr>
<td>Initial setting time (min)</td>
<td>11.34–approx.30</td>
<td>PL (Plastic limit) 20.9</td>
</tr>
<tr>
<td>Final setting time (min)</td>
<td>Approx. 598</td>
<td>PI (Plasticity index) 25.1</td>
</tr>
<tr>
<td>Soundness (min)</td>
<td>1.17</td>
<td>Sand (%) 54</td>
</tr>
<tr>
<td>Compressive strength (N/mm²)</td>
<td>19.5–22</td>
<td>Silt (%) 25.5</td>
</tr>
<tr>
<td>Specific surface area (m²/kg)</td>
<td>3.58</td>
<td>Clay (%) 20.5</td>
</tr>
</tbody>
</table>

Table 7. Chemical properties of Dangote cement and laterite (Alao, 1982/83; Akanni, Awofadeju, & Adeyemo, 2014; Faleye, Ogunnubi, & Olaofe, 2009; Nwankwojike, Onwuka, & Ndukwe, 2014; Omoniyi et al., 2014; Omoniyi & Okunola, 2015; Yahaya, 2009)

<table>
<thead>
<tr>
<th>Chemical Parameter</th>
<th>Cement</th>
<th>Laterite</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO (%)</td>
<td>51.67–64</td>
<td>CaO 0.11–10.93</td>
</tr>
<tr>
<td>SiO₂ (%)</td>
<td>16.56–22</td>
<td>SiO₂ 34.40–54.81</td>
</tr>
<tr>
<td>Al₂O₃ (%)</td>
<td>1.25–6.01</td>
<td>Al₂O₃ 10.28–17.11</td>
</tr>
<tr>
<td>Fe₂O₃ (%)</td>
<td>2.86–10.5</td>
<td>Fe₂O₃ 11.06–27</td>
</tr>
<tr>
<td>LOI (%)</td>
<td>2.49–11.32</td>
<td>MgO 0–6.13</td>
</tr>
<tr>
<td>IR (%)</td>
<td>2.03–4.7</td>
<td>Na₂O 0.06–2.41</td>
</tr>
<tr>
<td>Free CaO (%)</td>
<td>0.95–2.36</td>
<td>TiO₂ 0.66–1.02</td>
</tr>
<tr>
<td>SO₃ (%)</td>
<td>1.40–2.46</td>
<td>PO₄ 0.06–0.3</td>
</tr>
<tr>
<td>MgO (%)</td>
<td>0.58–3.65</td>
<td>K₂O 0.74–10.15</td>
</tr>
<tr>
<td>C₃S (%)</td>
<td>33.33–99.04</td>
<td></td>
</tr>
<tr>
<td>C₃S (%)</td>
<td>26.45–26.47</td>
<td></td>
</tr>
<tr>
<td>C₄A (%)</td>
<td>7.98–14.33</td>
<td></td>
</tr>
<tr>
<td>C₄AF (%)</td>
<td>4.77–9.17</td>
<td></td>
</tr>
</tbody>
</table>

Table 8. Comparison of grading of sand and sawdust with grading requirements [EN 13055-1 (2002)]

<table>
<thead>
<tr>
<th>Sieve size (mm)</th>
<th>Overall limits</th>
<th>% by mass passing test sieve</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coarse (C)</td>
<td>Medium (M)</td>
</tr>
<tr>
<td>10</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>89–100</td>
<td>-</td>
</tr>
<tr>
<td>2.36</td>
<td>60–100</td>
<td>60–100</td>
</tr>
<tr>
<td>1.18</td>
<td>30–100</td>
<td>30–90</td>
</tr>
<tr>
<td>0.60</td>
<td>15–100</td>
<td>15–54</td>
</tr>
<tr>
<td>0.30</td>
<td>5–70</td>
<td>5–40</td>
</tr>
<tr>
<td>0.15</td>
<td>0–20</td>
<td>-</td>
</tr>
</tbody>
</table>

Page 12 of 27
Sojobi, Cogent Engineering (2016), 3: 1255168
http://dx.doi.org/10.1080/23311916.2016.1255168

2.5.6. Water
Tap water obtained from concrete laboratory within Landmark University was used for mixing the various components to produce lightweight concrete used in moulding the ICPU. The tap water was derived from a borehole within Landmark University.

3. Results and discussion

3.1. Grading analyses of laterized concrete materials and classification of concrete
The sieved sawdust can be classified as a medium, fine aggregate (FA) based on EN 13055-1 (European Standard, 2002), even though, it meets the requirements to be classified as both coarse and medium FA. On the other hand, the mined river sand can be categorised as fine FA as specified by EN 13055-1 (2002) as shown in Table 8. Also, the sieved sawdust can be classified as ultra-lightweight fine aggregate since its loose bulk density of 185.98 kg/m³ is <500 kg/m³ specified by Alexander and Mindess (2010). The laterite obtained from the study area can be classified as sandy laterite (Omoniyi et al., 2014) with intermediate plasticity (Omoniyi et al., 2014) since its liquid limit (LL) of 46 falls within the range of 35–50 specified for intermediate plasticity (Whitlow, 1995). The major minerals in the laterite were quartz while the minor minerals were kaolinite and feldspar (Omoniyi et al., 2014). According to Alao (1987), the silica (SiO₂)/sesquioxide (Al₂O₃) ratio of the different laterites range from 2.42 to 5.3.

Based on ASTM D2487 (American Society for Testing & Materials, 2006) Unified Soil Classification System, the river sand and sawdust used can both be classified as poorly graded aggregate since their close coefficients of uniformity (Cu) of 2.98 and 3 are <6 specified as lower limit for well-graded aggregate as shown in Table 9. Also, both the river sand and sieved sawdust were found to have similar coefficient of curvature (Cc) of 1.07 and 1.06. Comparison of D₆₀ and D₃₀ values of cement and sieved laterite indicated that the cement was finer because the D₆₀ and D₃₀ values for cement were lower. In addition, the sieved laterite can also be classified as a poorly-graded cementitious aggregate as well.

In terms of bulk density, the water-cured ICPU with 28th-day bulk density (BD₂₈) range of 1,449.51–1,945.9 kg/m³ and the air-cured ICPU with BD₂₈ range of 1,422.3–1,883.3 kg/m³ can both be classified as structural lightweight concrete since their bulk densities fell within the range of Ultra-lightweight 300–500
Lightweight 500–800
Moderate-strength lightweight 800–1350
Structural lightweight 1,350–2,000
Normal-weight 2,000–2,600
Heavyweight Moderate high-density 2,600–2,900
High-density 2,900–6,100
Ultra-high-density –

Table 9. Grading analyses of lateritic concrete materials

<table>
<thead>
<tr>
<th>Grain parameters</th>
<th>Sawdust</th>
<th>Sand</th>
<th>Laterite</th>
</tr>
</thead>
<tbody>
<tr>
<td>D₆₀</td>
<td>0.7</td>
<td>0.69</td>
<td>0.51</td>
</tr>
<tr>
<td>D₃₀</td>
<td>0.42</td>
<td>0.41</td>
<td>0.28</td>
</tr>
<tr>
<td>D₁₀</td>
<td>0.235</td>
<td>0.23</td>
<td>0.12</td>
</tr>
<tr>
<td>Cu</td>
<td>2.98</td>
<td>3.00</td>
<td>4.25</td>
</tr>
<tr>
<td>Cc</td>
<td>1.07</td>
<td>1.06</td>
<td>1.28</td>
</tr>
</tbody>
</table>

Table 10. Classification of concrete based on bulk density (Sojobi & Owamah, 2014)

<table>
<thead>
<tr>
<th>Type of concrete</th>
<th>Bulk density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultra-lightweight</td>
<td>300–500</td>
</tr>
<tr>
<td>Lightweight</td>
<td>500–800</td>
</tr>
<tr>
<td>Moderate-strength lightweight</td>
<td>800–1350</td>
</tr>
<tr>
<td>Structural lightweight</td>
<td>1,350–2,000</td>
</tr>
<tr>
<td>Normal-weight</td>
<td>2,000–2,600</td>
</tr>
<tr>
<td>Heavyweight</td>
<td>Moderate high-density 2,600–2,900</td>
</tr>
<tr>
<td></td>
<td>High-density 2,900–6,100</td>
</tr>
<tr>
<td></td>
<td>Ultra-high-density –</td>
</tr>
</tbody>
</table>
1,350–2,000 kg/m³ specified for structural lightweight concrete by Sojobi and Owamah (2014) as shown in Table 10.

Based on fineness modulus, sieved sawdust of fineness modulus (FM) of 2.0 was found to be coarser than sieved natural sand with fineness modulus of 0.94. This also applies to the sieved laterite which was found to be coarser than cement with a FM of 0.87 which is >FM of 0.63 for cement.

3.2. Effect of sawdust content on bulk density

In all the samples, a progressive decrease in bulk densities were observed with increasing sawdust contents and curing ages. The mean reduction in bulk densities were 7.16, 17.48 and 24.01% at 5, 10 and 15% replacement levels respectively while the mean reduction in bulk densities were 14.46, 16.96, 17.01 and 16.44% at 7, 28, 60 and 90 curing ages respectively.

At 28 curing age, the BD$_{28}$ of water cured samples at 0, 5, 10 and 15% replacement levels were 1,945.9, 1,764, 1,634.2 and 1,449.51 kg/m³ which reduced to 1,874.4, 1,756.62, 1,522.89 and 1,418.9 kg/m³ at 90 curing age respectively as shown in Figure 5. With reference to the control, the average reduction in bulk densities between 28 and 90 curing ages were 7.01, 18.24 and 25.15% at 5, 10 and 15% replacement levels respectively. The reduction in bulk density with increasing replacement levels can be attributed to the packing effect of sawdust which is lighter than sand, with loose bulk density of 185.98 kg/m³ compared to 1,445.1 kg/m³ for sand.

The same phenomenon was observed in the air-cured samples as depicted in Figure 6. The bulk densities at 0, 5, 10% replacement levels were 1,883.3, 1,652 and 1,422.3 kg/m³ respectively. Comparison of the BD$_{28}$ for water and air-cured samples, in Figure 7, indicated that water-cured samples recorded higher BD$_{28}$ than air-cured samples because they absorbed more water during hydration process. However, the difference in their bulk densities reduced drastically with increasing curing ages.

The same trend of reduction in CS was corroborated by Ismail and Yacoob (2011). The authors obtained BD$_{28}$ of 1,940.56 kg/m³ at 5% replacement of cement with OPEFB (oil palm empty fruit bunch) which was higher than the BD$_{28}$ of 1,764 and 1,652 kg/m³ recorded for water-cured and
air-cured laterized concrete paving units respectively in this study. This was because sawdust is lighter with a specific gravity of 1.00 compared to 1.3 reported for OPEFB. Density reduction with curing age was also reported by Oyedepo et al. (2014) from 2,582.84 kg/m³ at 7 days to 2,514.79 kg/m³ at 28 days and was attributed to the hygroscopic nature of the sawdust and the air entrainment in the concrete.

3.3. Effect of sawdust content on compressive strength

The compressive strengths at 7, 28 and 90 curing days were 9.24, 6.8, 3.71 and 3.13; 8.65, 4.56, 3.3 and 2.28; 10.56, 7.57, 4.52 and 2.41 N/mm² at 0, 5, 10 and 15% replacement levels as shown in Figure 8. At 28 curing days, corresponding CS decline of 6.39, 32.94, 11.05 and 27.16% were recorded at 0, 5, 10 and 15% replacement levels. The same trend was also replicated at 90 days curing age with a corresponding increase of 42.32% and a decline of 11.47, 1.35 and 11.50% at 90 curing days.

It was observed that the compressive strengths of the interlocking paving units reduced with increasing replacement levels of sand with sawdust. Compared to the CS of the controls at different curing ages, the mean CS reduction were 39.06, 62.77 and 73.97% at 5, 10 and 15% replacement levels. This implies that the loss in CS increased with increasing replacement levels.

Likewise, it was also observed that the loss in CS increased from 50.80% at 7 days to 60.92% at 28 days, reduced to 54.23% at 60 days and then increased to 68.44% at 90 days curing ages.

In addition, it was also observed that all the samples experienced a decline in their CS up to 28 curing days before experiencing some increase at 60 and 90 curing days. This indicates that the pozzolanic impact of the sawdust took effect from 60 days of curing and was highest at 10% replacement level with a net increase of 21.83% followed by 5% replacement level with a net increase of 11.32% when compared to their respective controls.

In agreement with the observations of Mathusamy and Kamaruzaman (2012) who utilized lighter laterite with specific gravity (SG) of 2.49–2.54 to replace sand with SG of 2.69, increased addition of sawdust with a lower loose bulk density of 185.98 kg/m³ compared to 1,445.12 kg/m³ for sand contributed to the reduction in the CS.
This reduction in CS at increased replacement levels was also corroborated by Udoeyo and Abubakar (2003), Udoeyo and Dashibil (2002) and Udoeyo et al. (2006) with sawdust-ash (SDA) cement, maize-cob ash cement and wood-waste ash (WWA) cement, even though the compressive strengths they obtained were higher. This implies that ashing of the sawdust waste confers greater CS than ordinary sawdust which was utilized in our study.

The increase in CS at 60 days was also noted by Udoeyo and Dashibil (2002) and Udoeyo et al. (2006) with SDA cement and wood-waste ash cement within 0–10% replacement levels and was attributed to the pozzolanic activities of the SDA and WWA. The CS28 obtained at 10 and 15% for SDA were 24.25 and 18.97 N/mm², 24.61, 21.86 and 21.73 N/mm² for WWA and were found to be higher than the CS28 of 4.65, 3.3 and 2.28 obtained for 5, 10 and 15% for water-cured ordinary sawdust laterized concrete samples and 8.22, 4.67 and 2.98 N/mm² obtained for air-cured samples in our study.

Duan, Yan, Zhou, and Luo (2016) also reported appreciable increase in CS from 14 days of curing with CS gain of 9.6 and 12.1% at 28 and 90 curing days when fly ash was replaced with sawdust. CS and flexural strength gains were attributed to compacted and denser microstructure and reduction in porosity.

3.4. Effect of curing conditions

Results obtained indicated that curing conditions affect the properties of the interlocking paving units. Air-cured samples exhibited higher compressive strengths at 5, 10 and 15% replacement levels while water-cured samples recorded higher compressive strength at 0% replacement level which is the control as depicted in Figure 9. This implies that air-curing can also be used for interlocking paving units, which meets the CS requirements.

In contrast, the water-cured samples recorded higher bulk density at all percentage replacement levels when compared to air-cured samples as shown in Figure 6. This could be attributed to the high water-absorptive capacity of sawdust which resulted in the increase in their bulk densities.

3.5. Durability of lightweight interlocking paving units

The CS90 of the water-cured paving units which were 13.15, 6.02, 3.66 and 2.77 N/mm², were found to exceed the CS requirements of 2 N/mm² specified by NBRRI (2006) for interlocking paving bricks. The BD90 of the samples were 1,874.4, 1,756.62, 1,522.89 and 1,418.9 kg/m³ at 0, 5, 10 and 15% replacement levels. Compared to the BD90 for the control, the correspond ratios of BD90 for 5, 10 and 15% replacement levels were 93.72, 81.25 and 75.7% which is still acceptable.

With the exception of the control, all the other paving units containing sawdust did not meet the BD requirement of 1,810 kg/m³. This was as a result of the ultra-lightweight sawdust aggregate in their mix composition. With reference to the CS90 of the control, the corresponding ratios of BD90 for 5, 10 and 15% replacement levels were 45.78, 27.83 and 21.06%.
In terms of fire-residual compressive strength (FRCS), it was observed that the fire-resistant compressive strength at 60 days (FRCS<sub>60</sub>) of the samples decreased with increasing oven temperature and at increasing replacement levels as demonstrated in Figure 10. The FRCS obtained at 2,000, 4,000, and 6,000°C were 13.32, 8.46, 4.31; 10.79, 6.76, 4.54; 10.94, 6.98 and 4.65 N/mm² at 0, 5 and 10 replacement levels respectively. Comparison of the FRCS at 400 and 600°C indicated that the FRCS of the samples remained relatively stable after heating to 400°C. The highest FRCS of sawdust paving unit 8.46 N/mm² was obtained at 5% replacement level.

It was also observed that the control exhibited an average increase of 10% in FRCS<sub>60</sub> while 5 and 10% replacement levels recorded average losses in FRCS<sub>60</sub> of 2.24 and 0.44% respectively. On the other hand, average strength gain of 11.08% was experienced at 200°C while strength losses of 2.70 and 0.44% were recorded at 400 and 600°C respectively. These results seem to demonstrate that sawdust fibre addition reduces strength losses at increasing replacement levels and temperatures owing to reduction in micro-crack development (Duan et al., 2016).

With the exception of 600°C, the fire-residual bulk density (FRDB<sub>60</sub>) for all the samples were found to decrease with increasing elevated temperature and increasing replacement levels as depicted in Figure 11.
At 600°C, an abnormal occurrence occurred in which the FRDB_{60} at 5% of 1,692 kg/m³ was greater than 1,536 kg/m³ recorded for the control. This may be attributed to the high bonding level at such temperature and percentage replacement which reduced the amount of void and the ingress of water.

The average losses in FRDB_{60} at 0, 5, 10% replacement levels were 9.85, 8.88 and 3.78% respectively while the corresponding losses in FRDB_{60} at 200, 400, and 600°C were 5.7, 7.22 and 9.60% respectively. This implies addition of sawdust fibres seems to increase concrete fire resistance.

3.6. Statistical analyses

The correlation of the compressive strength and bulk density values of the paving units revealed linear relationships at 7 and 60 curing days with $R^2$ values of 0.9439 and 0.9547, and exponential relationships at 28 and 90 curing days with $R^2$ values of 0.9741 and 0.9547 respectively as shown in Figure 12. This connotes that the compressive strength values of the paving units are positively highly correlated to their bulk densities, which implies that low bulk density paving unit gave low CS while high BD paving unit result in low CS.

The correlation coefficients between CS and BD of the paving units for 7, 28, 60 and 90 days were 0.9862, 0.9454, 0.9846 and 0.9021 respectively and were evaluated using two-tailed t-test. The relationship between their CS and BD were found to be significant at 7 and 60 days with corresponding t-values of 11.92 and 7.96 which fall outside the range of ±4.303 (t-critical value range) obtained at significance level of 0.05 and 2 degrees of freedom (Bluman, 2013).

On the other hand, their relationships were found to be insignificant at 14 and 60 days with corresponding t-values of 4.1027 and 2.9565 respectively which were outside the t-critical value range of ±4.303 obtained at significance level of 0.05 and 2 degrees of freedom (Bluman, 2013). At each percentage replacements of 0, 5, 10 and 15, evaluation of the correlation coefficients between CS and BD of the paving units using two-tailed t-test revealed that their correlations were not significant.

In addition, evaluation of the differences of the CS and BD at different curing days using ANOVA (analyses of variance) revealed that the differences were insignificant with corresponding F-test values of 0.206 and 0.151 respectively for CS and BD, both of which were <F-critical value of 3.49 obtained at d.f.N (degree of freedom of numerator) of 3, d.f.D (degree of freedom of denominator) of 12 and 0.05 significance value (Bluman, 2013).

3.7. Microstructural properties of the lightweight lateritic interlocking paving units

The concrete mix ratio 1:2:4 is highly porous and contains a high amount of void which contributes to its lightweight. Additional increments of sawdust fibres led to reduction of compressive strength (CS) at high percentage replacements with sawdust.

The lower CS observed at 28 days curing age compared to 7 days could be attributed to the primary hydration products formed by the reaction between cement and water (Udoeyo & Dashibil, 2002) which seems to hinder formation of C–S–H gels, thereby leading to reduction in CS_{28} for control and all the sawdust-paving units. CS seems to be affected also by presence of elements such as chromium, arsenic, iron, copper and zinc released from sawdust (Udoeyo et al., 2006).

The sawdust fibres seem to have delayed the hydration process beyond 28 days which can be observed in the gradual reduction of the compressive strengths of the unfired paving units, which corroborates the observations of Elinwa and Mamuda (2014).

The hydration process seems to be noticeable from 60 days curing where all the samples experienced sharp increase in their CS as a result of the improvement in the laterized concrete internal structure which enhanced the strength performance of the paving units (Mathusamy &
Kamaruzaman, 2012). In addition, the sawdust fibres seems to trigger pozzolanic reaction with excess Ca(OH)₂ produced during cement hydration (Elinwa & Mamuda, 2014).

Owing to the hydraulic and hygroscopic nature of the sawdust fibres, the sawdust fibres not utilized in pozzolanic reactions absorbed free water in the concrete matrix and surrounding water-curing environment (Abalaka, 2013) resulting in increased water intake and corresponding decline in bulk density with increasing sawdust contents and at increased curing ages.

Owing to the packing and filler effects of the sawdust fibres (Abalaka, 2013; Elinwa & Mamuda, 2014), the capillary of the laterized concrete reduced with increasing sawdust contents resulting in the growth of more calcium-alumino-ferrous-silicate-hydrate (C-A-F-S-H) gels (binder) from the pozzolanic reactions especially when subjected to elevated temperatures.

This might have contributed to the increase in CS at elevated temperatures. The C-A-F-S-H was formed through the reaction of free lime [Ca (OH)₂] from the Dangote OPC, amorphous silica (SiO₂) content of the sawdust, the filler effect of the sawdust (Najigivi et al., 2013; Udoeyo et al., 2006) and the aluminium and ferrous oxides from the laterite.

Beyond 200°C, high amount of voids were created due to the destruction of the sawdust fibres, deterioration of the bonding interface between the sawdust fibres and the laterized concrete matrix leading to the formation of cracks along the bonding interface and pores within the concrete matrix (Li & Liu, 2016), thereby resulting in the corresponding reduction in CS at 400 and 600°C compared to CS at 200°C. Addition of lightweight polypropylene fibres was also found to significantly improve post-cracking behaviour of lightweight concrete (Li & Liu, 2016).

The presence of excessive water in the water-cured laterized concrete samples reduced the hydration rate (Embong, Kusbaintoro, Shafiq, & Nuruddin, 2015) hence producing lower strength concrete compared to the air-cured samples especially at early curing ages and at low sawdust contents.

**3.8. Comparison of results with other waste materials**

Comparison of the composite compressive strength results for other fibrous/waste/local materials as depicted in Figure 13 suggests that the performance/engineering properties of eco-friendly fibrous concrete depends on fibre material type and fibre concentration (Zollo, 1997).

In addition, CS of fibrous/waste/local materials are also affected by concrete parameters such as water-binder ratio and addition of superplasticizers (Elinwa & Mamuda, 2014), material proportioning (Arimanwa, Onwuka, Arimanwa, & Onwuka, 2012), fineness modulus of the fine and coarse
aggregates, shape and geometry of the concrete product tested, differences in chemical composition of the SCM/waste materials, firing temperature, additions of SCM as well as curing conditions.

The composite compressive strengths were obtained by multiplying each percentage cement/aggregate replacement levels with corresponding CS and divided by the sum of all the percentage cement/aggregate replacement levels used in the research. The composite CS and mean percentage cement/aggregate replacements obtained for all the researches considered gave representative value for each material and were plotted to allow for accurate and unbiased comparison of the CS values of each material.

The composite CS of 3–4.42 N/mm² for sawdust-FA obtained from this research as shown in Figure 12 was observed to be lower compared to 38.38 N/mm² for RHA-cement (Abalaka, 2013), 29.69 N/mm² obtained for fly ash (Mathew & Paul, 2014), 29.334 N/mm² obtained for oil palm empty fruit bunch fibres (OPEFB)-cement (Ismail & Yacoob, 2011), 29.01 N/mm² obtained for ground granulated blast furnace slag (GGBFS)-cement (Mathew & Paul, 2014).

The CS obtained in our study was also lower compared to 25.5 N/mm² obtained for oven-cured limestone CA (Embong et al., 2015), 17.91 N/mm² obtained for oven-cured oil palm shell (OPS)-FA (Embong et al., 2015), 16.11 N/mm² obtained for sawdust ash cement (Udoeyo & Dashibil, 2002), 14.45 N/mm² obtained for ambient-cured OPS-FA (Embong et al., 2015), 14.05 N/mm² obtained for maize-cob ash cement (Udoeyo & Abubakar, 2003) and 8.8 N/mm² obtained for Aluminium waste-cement (Arimanwa et al., 2012).

Results shown in Figure 13 indicate that different waste materials should be targeted at different applications with high-strength materials targeted at high-strength applications and low-strength materials at low-strength applications.

3.9. Suitability of the lightweight sawdust concrete in ICPU

All the samples met the minimum CS₂ and CS₂₈ required by National Building Code (2006) and NBRRI (2006) for use as interlocking paving bricks but did not meet the minimum CS requirements of 30 N/mm² recommended by BIS 15658 (Bureau of Indian Standards, 2006) and ESS 4382 (2004) for interlocking paving units for non-traffic and normal-duty applications, respectively.

This implies that the requirements of BIS 15658 (2006) and ESS 4382 (2004) are excessive for non-traffic areas such as building premises, landscapes, slopes and pedestrian sidewalks of low-traffic roads. This excessive CS requirement was also pointed out by El-Nouhy and Zeedan (2012).

Even though the lightweight interlocking paving units did not meet the BD requirement of NBRRI (2006) and the CS requirements of BIS 15658 (2006) and ESS 4382 (2004), it met the requirements for use as interlocking paving bricks. Therefore, it can be utilized for non-traffic areas and light-pedestrian traffic areas where it would have minimum load/impact on the subgrade because of its lightweight. In addition, it can be used in areas prone to flooding in which case the paving units will contribute to absorbing the excess water from the environment. Utilization of high CS requirement for non-traffic areas and light-traffic pedestrian sidewalks seems excessive and is antithetical to the principle of cost-effective environmental sustainability.

The lightweight ICPU can be used in paving areas where CS is not a major requirement such as pedestrian walkways in building environment or on low-pedestrian traffic walkways.

The CS of the normal and fired-ICPU at 5% sawdust content ranges from 6.02–7.57 N/mm² and 6.98–8.46 N/mm² respectively which exceeded the minimum CS of 3.45, 3.5 and 6 N/mm² required by NIS 444 (Nigerian Industrial Standard, 2003), RILEM (1978) and BS 5224 (1976) for non-load-bearing concrete elements, lightweight concrete and masonry works respectively.
The CS at 10% sawdust content ranges from 3.66–4.52 N/mm² and 4.31–4.65 N/mm² which only met the CS requirements of NIS 444 (2003) and RILEM (1978). This implies the sawdust concrete at 5 and 10% replacement levels can be utilized in the production of ICPU where strength is not a major requirement.

To corroborate our findings, Raheem, Olasunkanmi, et al. (2012) also recommended the use of sawdust-ash concrete in concrete applications where CS is of less importance such as mass concrete, floor screed and mortar while Sales et al. (2010) and Sales, de Souza, and Almeida (2011) also recommended the use of low-strength concrete composites in non-structural concrete elements. In addition, the sawdust concrete produced can be classified as low-strength concrete since the range of CS obtained was <15 N/mm² specified for low-strength concrete by EN 1365 (European Standard, 1999).

3.10. Economic benefits and significance
Cost savings between 19.37 and 19.52% per 1 m³ of concrete were obtained for Varghese et al. (2013) who utilized combination of laterite powder with other waste materials in eco-friendly concrete. In our research, utilization of laterite as 10% replacement for cement and sawdust as 5% replacement of sand will yield cost savings of approximately 5%.

3.11. Waste management approach
Literature review and site visits to some sawmills in Omu Aran community have demonstrated that the current sawdust waste management approach is ineffective, unsustainable and environmentally unsound (Lasode et al., 2011). Owing to the weak solid waste management in Kwara State, the Waste Management Board/Ministry in the State needs to be supported through capacity building initiatives so that they could be awakened to their duties and be informed of up-to-date, best practices to put in place to manage this toxic, hazardous waste.

Furthermore, the informal sector involved in waste recovery could be engaged formally in the sawdust waste collection as espoused by Paul et al. (2012). In addition, the Local Government Authorities should be re-awakened to their duties to monitor and enforce compliance with environmental best practices in the sawmill industries within its jurisdiction.

The State and Local Governments should engage the owners and operators of the sawmills on sustainable modalities to manage the sawdust wastes through effective and economic recovery for eco-friendly uses in interlocking paving units and other eco-friendly construction purposes. Well-constructed storage centres for the sawdust wastes should be built in strategic places within the State for easy collection by end-users. Government should encourage the utilization of sawdust wastes as fine aggregate and laterite as supplementary cementitious materials in infrastructural construction projects in the State.

4. Conclusions
Based on the results of this investigation, the following conclusions can be drawn:

(1) The sieved sawdust utilized with FM of 2 was coarser than natural sand with FM of 0.94. In addition, the sieved laterite utilized with FM of 0.87 was coarser than Dangote cement with FM of 0.63.

(2) The compressive strengths of the paving units were found to reduce with increasing sawdust replacements of sand with mean CS reductions of 39.06, 62.77 and 73.97% at 5, 10 and 15% replacement levels while the mean CS reductions were 50.80, 60.92, 54.23 and 68.44% at 7, 28, 60 and 90 days curing ages.

(3) The bulk densities of the paving units were found to decrease with increasing sawdust replacements of sand with mean bulk density reduction of 7.16, 17.48 and 24.01% at 5, 10 and
15% replacement levels respectively and mean BD reductions of 14.46, 16.96, 17.01 and 16.44% at 7, 28, 60 and 90 curing ages respectively.

(4) Addition of sawdust fibres seems to improve the laterized concrete fire-resistance bulk density with average FRDB_{60} losses of 9.85, 8.88 and 3.78% at 0, 5 and 10% replacement levels.

(5) The bulk density reduced at elevated temperatures recording average FRDB_{60} losses of 5.7, 7.22 and 9.60% at 200, 400 and 600°C, respectively.

(6) Addition of sawdust fibres seems to reduce the compressive strength of laterized concrete recording strength (FRCS_{60}) losses of 2.24 and 0.44% at 5 and 10% replacement levels while strength (FRCS_{60}) gain of 10.64% was exhibited by the control.

(7) In addition, average strength gain of 11.08% was recorded at 200°C, while average strength losses of 2.70 and 0.44% were recorded at 400 and 600°C respectively. This implies that the laterized concrete paving unit should not be heated more than 200°C to take advantage of the pozzolanic properties of the sawdust fibres and laterite.

(8) The lightweight ICPU meets the compressive strength requirement for use as interlocking paving bricks which can be utilized in non-traffic paving applications such as building premises, landscape, public parks, low-traffic pedestrian sidewalks and slope stabilization.

(9) A maximum of 5% sawdust replacement of sand is recommended where moderate compressive strength is desired while an optimum of 10% can be used where high compressive strength is not a requirement.

(10) Sawdust concrete can be utilized in non-load bearing applications where compressive strength is not a requirement such as outdoor pedestrian walkways in a building environment and low-traffic pedestrian walkways especially in rural areas.

(11) The pozzolanic contents in the laterite (SiO_2 + Al_2O_3 + Fe_2O_3) ranges from 76.17 to 98.50% which exceeded the 70% minimum requirement of ASTM C-618 (2007) for it to be used as cement replacement for construction purposes.

(12) The eco-friendly lightweight concrete produced can be classified as low-strength concrete with CS range of 6.02–8.46 and 3.66–4.65 N/mm² at 5 and 10% sawdust replacement of sand which met exceeded the minimum requirement of 3.45 N/mm² of NIS 444 (2003) for non-load concrete applications.

(13) ANOVA test revealed insignificant increases in compressive strength and bulk density losses while two-tailed t-test revealed significant relationship between CS and bulk density only at 7 and 60 curing days at 0.05 significance level.

(14) The sawdust wastes and laterite led to cost savings of approximately 7 with 10% laterite replacement of cement and 10% sawdust replacement of sand.

(15) Recycling of the sawdust wastes as fine aggregates in eco-friendly concrete such as ICPU will significantly mop up the solid waste with added benefits such as prevention of surface and groundwater pollution as well as air pollution, improved working conditions for the sawmill workers and elongation of landfills.

(16) Effective solid waste management approach recommended include capacity building of the State Waste Management Authority/Ministry, partnership with the sawmill owners and operators for effective sawdust waste recovery, monitoring and enforcement of sawmill industries by State and Local Governments, partnership with informal waste collectors and establishment of storage centres in strategic places within the State for effective sawdust waste collection and storage.

(17) In terms of high compressive strength requirements, preference is given as follows: RHA cement > Fly ash cement > OPEFB cement > GGBFS cement > Limestone CA > OPS FA oven > SDA cement > OPS FA ambient > MCA cement > Al waste cement > SD FA air cured > SD FA water cured.
Acknowledgement

The author appreciates the technical advice and support received from the Faculty and technologists within the Department of Civil Engineering, Landmark University. The author also appreciates the Proprietor and Management of Landmark University for the equipment provided in the Geotechnical/Highway Engineering Laboratory of Department of Civil Engineering, Landmark University.

Funding

The author received no direct funding for this research.

Author details

Adebayo Olatunbosun Sojobi1,2
E-mails: adebayosojobi@gmail.com, sojobi.adebayo@lmu.edu.ng
1 Department of Architecture and Civil Engineering, City University of Hong Kong, Hong Kong.
2 Department of Civil Engineering, Landmark University, P.M.B. 1001, Omu Aran, Kwaara State, Nigeria.

Citation information

Cite this article as: Evaluation of the performance of eco-friendly lightweight interlocking concrete paving units incorporating sawdust wastes and laterite, Adebayo Olatunbosun Sojobi, Cogent Engineering (2016), 3: 1255168.

References


