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SDA and laterite applications in concrete: Prospects and effects of elevated temperature

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Abstract: This research supports green eco-friendly construction through utilization of laterite and sawdust ash as fine aggregate and supplementary cementitious material in concrete. Critical literature review revealed that at fine aggregate replacement by laterite ≤50, 50–75 and 100%, mix ratios 1:2:4:0.56, 1:1.5:3:0.65 and 2:3:6:0.65 respectively are preferable for structural applications. Higher compressive strength losses of 32.81, 28.23 and 32.59% were recorded at elevated temperatures of 200, 400 and 600°C for SDA-modified laterized concrete while lower strength losses of 8.58, 7.91 and 3.74% were recorded for conventional laterized concrete. However, strength gain of 15.9% was recorded at 25°C ambient temperature for SDA-modified laterized concrete. Based on elevated temperature results, 10% SDA-modified laterized concrete at 45% optimum laterite content can only be used for production of load-bearing bricks and blocks and other non-structural applications. Further research efforts on green construction are required.

Subjects: Materials Science; Technology; Civil, Environmental and Geotechnical Engineering

Keywords: compressive strength; elevated temperature; green construction; mix ratio; laterite; laterized concrete; saw dust ash

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The group research activities include promoting sustainable, green and eco-friendly construction utilizing locally available materials and waste products and development of indigenous local technologies for use in the construction industry.

PUBLIC INTEREST STATEMENT
Laterite and sawdust wastes can be used as partial replacements for sand and cement in concrete. The concrete produced has improved strength, reduced shrinkage, last longer, reduced cracks and can withstand high temperature. In addition, the concrete produced with laterite and sawdust wastes can be used in producing high-quality bricks and blocks and mass concrete, which can be used to construct low-cost houses. For such applications, the maximum laterite content recommended is 45% while the sawdust content is 10% and can be heated to 400°C to achieve high strength and stability. Where sawdust is not available, the laterite alone can also be used to replace sand. In order to meet construction standards, the best mix proportions by volume for 0–50%, 50–75% and 75–100% replacements of sand with laterite are 1:2:4:0.56, 1:1.5:3:0.65 and 2:3:6:0.65 respectively [cement: fine aggregate (sand): coarse aggregate (granite): water/cement ratio].
1. Introduction

1.1. Green materials in concrete and construction

The importance of concrete to the construction industry cannot be overemphasized. Concrete finds usage in the construction of buildings be it residential, public, private or industrial, construction of roads, drainages and bridges to mention a few. As a composite material, concrete comprises cement, aggregate (fine and coarse), water and sometimes some admixtures. The cement and aggregates required for concrete production is of great interest to researchers all over the world, with attempted effort at reducing production cost, preserving the earth natural resources as well as increasing the performance and durability of concrete structures.

Globally, in order to achieve these lofty goals, several research efforts have been focused on the utilization of industrial, agricultural and municipal wastes in concrete mostly as supplementary cementitious materials (SCM) and fine aggregates (FA) (Liew, Sojobi & Zhang, 2017; Sojobi, 2016). Some of the waste materials investigated include sawdust ash, ordinary sawdust, rice husk ash, fly ash, waste glass and plastics to mention a few (Ajiwe, Okeke, & Akigwe, 2000; Ogundiran & Kumar, 2016; Raheem, Olasunkanmi, & Folorunso, 2012; Sojobi, 2016; Sojobi, Nwobodo, & Aladegboye, 2016; Sojobi & Owamah, 2014)

In addition, utilization of available local construction materials, either as fine or coarse aggregates, in concrete are also encouraged to reduce costs, encourage the growth of the local construction industries or improve concrete properties (Balogun & Adepegba, 1982; Ephraim, Adoga, & Rowland-Lato, 2016; Falade, 1994; Ikponmwosa & Salau, 2010; Rahman, 1987; Sojobi, 2016).

Utilization of such wastes along with the available construction materials portends enormous technical, economic and environmental benefits (Sojobi, 2016). These benefits include sustainable development and greening of the local construction industry, reduction of environmental pollution and landfill requirements, development of local construction expertise, improved durability of concrete structures and reduction of maintenance costs. Other benefits include production of commercially viable products for use by the local construction industry, development of the local construction cottage industry, cost reduction, reduction of housing deficits as well as creation of employment opportunities.

Despite these potential benefits and enormous researches that have been done on those materials, there is paucity of utilization of those materials in real-life construction projects. A variety of technical, market, regulatory, legal, and policy barriers continue to limit their deployment (Wescott, McNulty, VanGeem, & Gajda, 2010). Therefore, deliberate, co-ordinated and concerted efforts are expedient to remove those obstacles and leverage market-based incentives to encourage their implementation in the construction industry value chain.

1.2. Sawdust ash in concrete

Sawdust ash (SDA) is obtained by incineration of sawdust wastes obtained from saw milling industry, in either controlled or uncontrolled conditions. Several researches have investigated the properties of SDA in concrete cubes and hollow blocks (Elinwa & Mahmood, 2002; Madrid, Orbe, Rojí, & Cuadrado, 2017; Popoola, Ayegbokiki, & Gambo, 2015; Raheem, Akinteye, & Lasisi, 2014). Their chemical compositions are shown in Table 1.

The benefits derived from utilization of SDA in concrete include reduction of drying shrinkage, reduction of porosity and setting time, shrinkage reduction and improved CS at elevated temperature (Duan, Yan, Zhou, & Luo, 2016; Elinwa, 2006). Others include increased concrete stiffness, optimal microstructure formation, reduction in ASR expansion, improved mechanical properties, improved energy absorption capacity and enhanced durability (Duan et al., 2016; Ramos, Matos, & Sousa-Coutinho, 2013; Turgut, 2007).
SDA can also be utilized to delay setting of laterized concrete and improve workability of laterized through reduction of water demand (Falade, 1994). The high demand for water in SDAC is due to high silica content of SDA, which has a high propensity for water.

SDA has been recommended for use in lightweight and economic bricks and self-compacting concrete (Elinwa, Ejeh, & Mamuda, 2008; Turgut, 2007). Sawdust is non-harmful in concrete (Sales, de Souza, dos Santos, Zimer, & Almeida, 2010).

1.3. Laterite in concrete
Laterite is a tropical soil that is present in parts of Africa, Asia and America (Adepegba, 1975). Its neglect as an engineering material is linked to uncertainty in its strength and other structural characteristics such as creep, shrinkage and long-term durability (Salau & Balogun, 1998).

Several researches on laterite had been done to encourage its application in concrete and are summarized in Table 2. These researches encouraged the applications of laterized concrete in hollow blocks and solid bricks, sandcrete bricks, structural and non-structural members such as beams, columns and slabs (Balogun & Adepegba, 1982; Emmanuel & Allan, 2014; Ikponmwosa & Salau, 2010; Okafor & Egbe, 2017; Olutoge, Adeniran, & Oyegbile, 2013).

The potential benefits derivable from application of laterite in concrete are improved residual CS, reduced construction costs, improved resistance to cracking and spalling; superior post-yielding and post-cracking behaviour (Mathew & Paul, 2012; Salau & Balogun, 1990; Sojobi, 2016).

Therefore, the aim of this study is to evaluate the effect of elevated temperature on laterized concrete admixed with waste sawdust ash as partial replacement of cement. The objectives of this study are:

(i) Critically evaluate the effects of sawdust ash and laterite in concrete based on literature review
(ii) Evaluate the effects of elevated temperature on the SDA-modified and normal laterized concrete at elevated temperatures of 200, 400 and 600°C respectively

| Chemical constituents | Raheem et al. (2012) | Kumar (2015) | Elinwa and Mahmood (2002) | Tyagher, Utsev, and Adagba (2011) | Ramos et al. (2013) | Chowdhury, Maniar, and Suganya (2015) (WWA) | Sojobi (2016) (Dangote cement) | Sojobi (2016) (Laterite) |
|-----------------------|----------------------|--------------|---------------------------|-----------------------------|--------------------|--------------------------------|-----------------------------|-------------------------|
| SiO₂                  | 65.75                | 62.87        | 67.20                     | 67.95                      | 73.01              | 65.3                           | 16.56-22                    | 0.11-10.93               |
| Al₂O₃                 | 5.23                 | 9.85         | 4.09                      | 4.29                       | 11.93              | 4.25                           | 1.25-6.01                   | 34.40-54.81              |
| Fe₂O₃                 | 2.09                 | 4.45         | 2.26                      | 2.15                       | 3.38               | 2.24                           | 2.86-10.5                  | 10.28-17.11              |
| CaO                   | 9.62                 | 10.35        | 9.98                      | 9.47                       | 2.64               | 9.98                           | 51.67-64                   | 11.06-27                |
| MgO                   | 4.09                 | 4.18         | 5.80                      | 5.84                       | 1.03               | 5.32                           | 0.58-3.65                  | 0-6.13                  |
| SO₃                   | 1.09                 | 0.04         | 0.56                      | <0.05                      | 1.40              | 2.46                           | 0.06-2.41                  |                        |
| Na₂O                  | 0.06                 | 0.035        | 0.08                      | 0.06                       | 3.81              | 2.6                            | 0.06-2.41                  |                        |
| K₂O                   | 2.43                 | 1.71         | 18.75                     | 0.11                       | 4.14              | 1.9                            | 0.74-10.15                 |                        |
| LOI                   | 4.89                 | 5.85         | 4.67                      | 1.47                       | 4.67              | 2.49-11.32                     |                            |                        |
| Total (SiO₂ + Al₂O₃ + Fe₂O₃) | 73.07               | 77.17        | 73.55                     | 74.39                      | 88.32              | 71.79                           | 20.67-38.51                | 44.79-82.85             |
| Authors                  | R (%) | w/c  | Sieve size | Mix ratio | Products          | CS (N/mm²) | Physical props. | Remarks                                                                 |
|-------------------------|-------|------|------------|-----------|-------------------|------------|-----------------|--------------------------------------------------------------------------|
| Raheem et al. (2014)    | 5–25  | 0.5–0.65 | 425 µm    | 1:2:4     | 150 mm cubes      | CS₂₈: 7.48–20.52 Optimum: 5% | Sump: 100–95 CF = 0.94–0.91 | • Workability reduced with SDA content  
  • Up to 10% can be used as SCM in RC |
| Obilade (2014)          | 5–30  | 600 µm  | 1:2:4      | 150 mm cubes | CS₂₈: 10.19–21.02 Optimum: 5% SDA | CF: 0.89–0.85 | • Increased concrete stiffness as SDA content increases  
  • Up to 10% can be used as SCM in RC |
| Popoola et al. (2015)   | 5–20  | 300 µm  | 1:6        | Hollow blocks (450 × 225 × 150 mm) | CS₂₈: 2.35–2.92 > 2 N/mm² | BD: 3062 Kgm⁻³ > min. NIS 1500 Kgm⁻³ | Up to 10% can be used as SCM in hollow blocks |
| Kumar (2015)            | 5–20  | 600 µm  | 150 mm cubes | CS₂₈: 35.6–29.11 | Sump: 25–107 | SDA is suitable for economical geopolymer concrete at 60°C > 20% SDA can replace fly ash |
| Elinwa & Mahmood (2002) | 5–30  | 0.32–0.42 | 212 µm    | 150 mm cubes | CS₂₈: 21.6–8.76 Optimum: 5% SDA | Slump: 75–40 mm CF: 0.94–0.92 | • Up to 5% can be used in RC  
  • w/c increased with ash content |
| Tyagher et al. (2011)   | 10–40 | 150 µm  | 1:8        | Sandcrete hollow block | CS₂₈: 0.58–0.28 | Slump: 50–85 | Did not meet minimum requirement of 2 N/mm² |
| Ettu et al. (2013)      | 5–25  | 0.6    | 600 µm     | 1:2:4     | 150 mm cubes      | CS₂₈: 25.10–6.90 CS₂₉: 29.3–22.70 | Slump: 50–85 | Up to 25% RHA-SDA (50:50) can be used as SCM in RC  
  • Optimization recommended |
| Ramos et al. (2013)     | 10–20% | 0.5     | 212 µm     | Mortar specimens | CS₂₈: 42.2–53.8 CS₂₉: 60.2–61 | Slump: 50–85 | Up to 60% reduction in ASR expansion  
  • Enhanced durability |
| Cheah, Part, & Ramli (2017) | 2–10 | 0.32 (w/b) | 50 mm mortar cubes | CS₂₈: 71.30–58.33 Optimum: 6–8% WWA | Slump: 50–85 | Slump: 50–85 | Improved bond between mortar matrix and steel reinforcements  
  • Improved flexural stiffness, crack resistance & load capacity with SF, HCWA & Steel fibres |
| Chowdhury et al. (2015) | 5–20  | 0.4–0.45 | 100 mm cubes | CS₂₈: 35.3–31.7 (0.4) CS₂₉: 33.3–29 (0.45) | Slump: 50–85 | Setting time: 570–425 min | Reduction in CS with WA decrease attributed to poor bonding & high surface area of WA |
| Duan et al. (2016)      | 5–20% | 40 mm SD-reinforced geopolymer cube | CS₂₈: 62–68 Optimum CS: 20% SD | Slump: 50–85 | Setting time: 570–425 min | Workability loss  
  • Reduction of drying shrinkage, porosity & setting time |
| Elinwa (2006)           | 10–40 | 76.2 µm | 260 mm cubes | CS₂₈: 2.6–7 Optimum: 10% SD, @ 600°C, cured for 1 day. | Slump: 50–85 | Slump: 50–85 | Shrinkage reduction  
  • Improved CS at firing temperature of 600°C |
2. Materials and methodology
Extensive literature review was carried out to critically evaluate the trends and important factors in past researches on SDA and laterite in concrete.

2.1. Materials and mix composition
Furthermore, 42.5 kg Dangote brand of ordinary portland cement (OPC) was obtained from Omu Aran local market in Kwara State, Nigeria and was used for this study. The sawdust waste was obtained from a logging industry within Omu Aran in Kwara State, Nigeria. It was observed that the OPC is dark grey in colour while the SDA is light grey in colour as depicted in Figure 1 while their microscopic images are displayed in Figure 2. The fine aggregates used were sharp sand and laterite and their particle size distributions are displayed in Figure 3. The specific gravity and fineness modulus for sharp sand were 2.67 and 2.39 respectively while laterite had a specific gravity of 2.71 and fineness modulus of 2.35.

Comparison of the fineness modulus implies that laterite is finer compared to sharp sand. This was also corroborated by the particle size distribution in Figure 3.

The chemical composition of SDA utilized was displayed in Table 3 while Table 4 shows the concrete mix proportion used for the conventional and SDA-modified laterized concrete production.

2.2. Specimen preparation and test procedure
The SDA was introduced into the concrete by weight of cement (0 and 10%) respectively. According to Obilade (2014), the use of 10% SDA achieved good strength and keeps the quantity of water required for mix adequate. The proportions of the concrete mix materials was given in Table 4 and each mix was identified with a series of numbers and letter as specified in the Table. LA15SDA10 implies concrete mix with 15% laterite replacement of sand and 10% SDA replacement of cement (Table 5).
Figure 2. Microscopic images of (a) OPC and (b) SDA at ×40 magnification.

Figure 3. Particle size distribution of sand and laterite.

Table 3. Chemical composition of SDA

| Element | CaO  | SiO\textsubscript{2} | Al\textsubscript{2}O\textsubscript{3} | Fe\textsubscript{2}O\textsubscript{3} | SO\textsubscript{3} | MgO  | Na\textsubscript{2}O | K\textsubscript{2}O | LOI  |
|---------|------|-----------------|----------------|----------------|----------------|------|----------------|----------------|------|
| SDA     | 9.72 | 65.05           | 4.68           | 2.23           | 1.01           | 3.89 | 0.05           | 2.12           | 4.05 |

Table 4. Concrete mix proportion of Laterized concrete with and without saw dust ash

| Mix      | Binder (kg) | Fine aggregate (kg) | Gravel (kg) | Water (kg) | W/C |
|----------|-------------|---------------------|-------------|------------|-----|
|          | Cement | SDA  | Sand | Laterite | 55.56 | 9.03 | 0.65 |
| LA15SDA0 | 13.89 | 0    | 23.61 | 2.08     | 55.56 | 9.03 | 0.65 |
| LA30SDA0 | 13.89 | 0    | 19.45 | 8.33     | 55.56 | 9.03 | 0.65 |
| LA45SDA0 | 13.89 | 0    | 15.28 | 12.50    | 55.56 | 9.03 | 0.65 |
| LA15SDA10| 12.49 | 1.39 | 23.61 | 2.08     | 55.56 | 9.03 | 0.65 |
| LA30SDA10| 12.49 | 1.39 | 19.45 | 8.33     | 55.56 | 9.03 | 0.65 |
| LA45SDA10| 12.49 | 1.39 | 15.28 | 12.50    | 55.56 | 9.03 | 0.65 |
### Table 5. Effects of laterite on concrete properties

| Author(s)                        | Sand replacement (%) | Mix ratio | Product | Results | Remarks |
|---------------------------------|----------------------|-----------|---------|---------|---------|
| Adepegba (1975)                 | 15.24 cm cubes       | 1:2:4; 1:1.4:2.9 | CS<sub>50</sub> = 27.65 MPa (1:2:4); CS<sub>50</sub> = 24.22 MPa (1:1.4:2.9) | Retained 40–60% of ambient CS @ 500°C elevated temperature for agg/cement ratio ≥10 | Achieved 83.4% and 81.4% of the ultimate moments & moments of onset of failure of normal concrete respectively |
| Apeh and Ogunbode (2012)        | 150 mm cubes         | 1:2:4:0.65 | Optimum CS = 24 @ 30:70 (lat: sand); CS (water cooled): 20.7–23.6 MPa (200-600°C), 10% lat; CS (air cooled): 14.6–16.20 MPa | Water cooled recorded higher CS but higher CS losses at elevated temperature | Optimized curing/cooling recommended |
| Awoyera, Akinmusuru, and Ndambuki (2016) | 150 mm cubes | 1:1.5:3:0.6 | Optimum CS<sub>30</sub> = 26.54 MPa; Slump: 50–90 mm | CS and STS increased with curing age |
| Balogun and Adepegba (1982)     | 15.24 cm cubes       | 1:2:4; 1:1.5:3; 1:1.2 | Optimum CS<sub>50</sub> of 26.54 MPa@ 0.65 w/c, 25–50% laterite-Max CA : 19 mm | 1:1.5:3 recommended as the best mix for structural laterized concrete | Up to 50% laterite can be used |
| Balogun (1986)                  | 100 mm cubes         | 1:1.5:3:0.6 | Optimum CS<sub>28</sub> of 33.8 N/mm<sup>2</sup> at 75% laterite | Initial gain in strength up to 200°C depends on sand content | Up to 50–75% can be used as fine aggregate in laterized concrete |
| Emmanuel and Allan (2014)       | Lateritic sandcrete bricks | 1:6:0.5 | Dry CS<sub>28</sub>: 4.17–5.72 MPa; WetCS<sub>28</sub>: 3.65–5.1 MPa | Limit laterite content to 30% owing to hygroscopic nature of laterite | Requires proper rendering to prevent moisture ingress |
| Folade (1991)                   | 100 mm cubes         | 1:1.5:3; 1:2:4; 1:3:6 (w/c: 0.62, 0.75 & 1.02) | Optimum CS<sub>28</sub>: 28.2 N/mm<sup>2</sup> (1:1.5:3); Maximum CS<sub>28</sub> = 23.9 (1:2:4); Maximum CS<sub>28</sub> = 17.4 (1:3:6) | Combined water/air curing performed best compared to air, water, jute, air/water | Strength increased with cement/agg. ratio |
| Mathew and Paul (2012)          | 150 mm cubes         | 1:0.96:3.23:0.34 (cm) | Air-cooled CS: 30.9–33.2; Water-cooled CS: 30.1–32.4 | Aggregate type & fly ash improved resistance to cracking & spalling | Improved residual CS |
| Ipinnmwosa and Salau (2010)     | 150 mm cubes         | 2:3:6:0.65 | Optimum CS<sub>30</sub>: 30.44 @ 25% & 500°C | Up to 75% laterite fine aggregate burnt @ 500°C can be used for non-structural purposes | For structural purposes, limit lateral fine aggregate to 25% |
| Okar for and Egbe (2017)         | Hollow block (450 × 225 × 225) | 70: 30 (quarry dust; laterite), w/c: 0.58 | Optimum CS: 2.56 MPa | Quarry dust can replace laterite up to 70% |
| Okunade (2008)                  | Solid brick (225 × 150 × 150) | 90: 10 (laterite: SCM) | Optimum mixture: 90 lat: 2.5 sawdust: 7.5 wood ash; Wet CS<sub>4</sub>:88–17.34 MPa; Dry CS<sub>4</sub>:10.26–19.15 MPa fired for 48 h to 21,000°C | Wood ash contributed to higher and lower water absorption |

(Continued)
| Author(s)                  | Sand replacement (%) | Mix ratio | Product                                      | Results                                                                 | Remarks                                                                                      |
|---------------------------|----------------------|-----------|----------------------------------------------|--------------------------------------------------------------------------|----------------------------------------------------------------------------------------------|
| Olutoge et al. (2013)     | 10–40                | 1:2:4:0.55| Laterite beam (800 × 225 × 112.5)           | Optimum CS: 35.6 MPa @ 10% laterite replacement                          | • Laterite content limited to 10–20%  
• CS increased with number of rebars but decreased from laterite content > 20% |
| Rahman (1987)             | 20–40%               |           | 5 cm cubical specimen                       | Optimum CS: 22.78 N/mm² @ 4 h soaking @ 1000°C                         | • Firing should not exceed 4 h to gain strength  
• Combination of laterite-clay & clay-sand recommended for good quality bricks |
| Salau and Balogun (1998)  | 25–100%              | 2:3:6:0.65| Concrete column                             | Shear resistance of 25S laterized concrete comparable to normal concrete | • Laterized concrete with 25% laterite recommended for low-cost housing                        |
| Salau and Balogun (1990)  | 2:3:6:0.65           |           | Rectangular reinforced concrete beams       | Shear resistance of 25S laterized concrete comparable to normal concrete | • Laterized concrete exhibited superior post-yielding and post-cracking behaviour              |
| Salau (2003)              | 1:2:4; 2:3:6          |           | Short columns (100 × 100 × 40)              | Basic creep sealed laterized concrete: 511 x 10⁻⁶; Basic creep sealed normal concrete: 500 x 10⁻⁶ | • Unsealed laterized and normal concretes have comparable creep deformation  
• Protection against humidity & temperature changes required |
| Sabarish et al. (2015)    | 1:2:4:0.56           | 150 mm cubes |                                              | CS: 40.58–40.35 N/mm²; CS: 50.87–50.47 N/mm²; CS: 61.15–60.45 N/mm²; All at 1–5% H₂SO₄ | • Highly durable & stable                                                                        |
| Osadebe, Mbajiorgu, and Nwakonobi (2007) | 1:1:2:0.65 | 150 mm cubes |                                              | CS: 7.3–27 N/mm²                                                      | • Optimization of laterized concrete constituents reduces facilitate prediction & reduces laboratory experiments |
| Ephraim et al. (2016)     | Laterite as coarse aggregate | 1:2:4; 1:1:5:3 | 150 mm cubes                              | Optimum CS, STS & FS: 1:1:5:3; Optimum CS: 25.2 MPa                   | • 1:1:5:3 performed better than 1:2:4  
• Applicable in floors subjected to impact loading  
• Lower static MOE, higher impact energy & higher impact strength |

Table 5. (Continued)
The saw dust wastes were burnt into ash by open burning in a metal container. After burning and cooling, the residue was ground mechanically using an electric-powered grinding machine in order to increase the fineness of the sample which is shown in Figure 1. The specific gravity of SDA is 2.21 and the chemical composition is presented in Table 1. In order to ascertain compatibility of SDA as a suitable replacement for cement in producing laterized concrete, an electron microscope (EM) image was taken. The SEM image revealed higher interspatial distances between SDA particles compared to cement particles, which look more compact as revealed by Figure 2.

The mix ratio and water to binder ratio were kept constant at 1:2:4 and 0.63 respectively for all the concrete mixes. The interior of the mix drum was initially wetted with water to minimize the absorption of water added as a part of concrete mixture. All the concrete constituents were measured using an automated weighing balance manufactured by Control with model number D0630/30. The coarse aggregate was placed into the mixer with the mixer in motion, the fine aggregate (sand and laterite) and cement mixed with/without SDA as applicable were poured into the drum and then water was added. The concrete mixer manufactured by Control of model number 55-C01968/14001178 displayed in Figure 4(a) was operated for about 10 min and the concrete consistency was measured using slump test. 150 × 150 × 150 mm cubes were used for casting test specimens.

For each concrete cube specimen, concrete was poured into the steel moulds and were compacted in three layers of approximately 50 mm with each layer receiving 35 stroke of the tamping rod. The concrete cubes were marked after some few hours for easy identification. Also, the concrete specimens were covered with polyethylene to prevent evaporation from the concrete surface. The specimen were kept in the moulds for 24 h, then de-moulded and cured for 28 days in a plastic water-curing tank manufactured by Control as displayed in Figure 4(b).

Afterwards, the concrete cubes were removed from water after 28 days of water curing and allowed to dry at room temperature for 24 h after which they were then subjected to heat pre-treatment for one hour at 200, 400 and 600°C in an electric oven manufactured by Control with model number 10-D1390/25 as displayed in Figure 5(a). With the aid of a thermostat, the temperature of the oven was controlled with the aid of a control and it can attain a maximum temperature of 800°C.

The internal dimension of the oven is 520 × 520 × 300 mm, provided with insulator material and the outer body is stiff steel. Specimens were fed into the oven through the front door opening. Twelve cubes from each batch were left in the laboratory to cool down naturally at normal room temperature before testing. The unheated cubes were also crushed at room temperature. In each test the measured value represents the average of three specimens.
Each of the concrete specimens was carefully and centrally placed in the automated UTM machine of model number C3422 displayed in Figure 5(b) and loads were applied gradually with the rate of travel of machine equivalent to 240 ± 35 kN/m²/s. The applied load was stopped once the concrete specimen was observed to have failed. The average maximum crushing load for three concrete specimen divided by the cross-sectional area of the specimen gives the compressive strength for the concrete at that concrete mix ratio.

3. Results and discussion

3.1. Sawdust ash in concrete

The SDA found in literature, with total pozzolanic content range of 73.07–88.32 %, met the 70% minimum pozzolanic content (SiO₂ + Al₂O₃ + Fe₂O₃) required to be classified as supplementary cementitious material (SCM) and can be utilized as potential cement replacement (ASTM, 2015). The SiO₂ content of SDA is about 2.8–4.4 times that of Dangote Cement. On the other hand, the CaO (Calcium Oxide) content of Dangote Cement is about 5.37–6.65 times that of SDA. These two compounds play crucial complementary roles in the hydration properties of SDA-modified laterized concrete. Similar trend of pozzolanic content was also observed in wood waste ash (WWA) as shown in Table 1.

The SDA used in our experiment has a total pozzolanic content of 71.96% which met the minimum requirement of 70% to be utilized as SCM to replace cement. Likewise, its SiO₂ content is about 3.71–4.93 times that of Dangote Cement, which is similar to the ratio of 2.8–4.4 for SDA obtained in past researches in literature. In addition, the ratio of the CaO of Dangote Cement to that of the SDA which is 5.32–6.58 is similar to that the 5.37–6.65 earlier obtained for previous SDA researches in literature. This may imply that the SDA utilized in our study has similar composition to past SDAs used in literature as shown in Tables 2 and 3.

Critical evaluation of the compressive strength (CS) results of SDA-modified concrete in literature listed in Table 2 revealed the existence of size effects of the SDA particles utilized in such concretes.
SDA particles sieved with 600 µm recorded the highest CS$_{28}$ (Ettu, Ezeh, Anya, Nwachukwu, & Njoku, 2013; Kumar, 2015) compared to those sieved with 212 and 425 µm sieves (Elinwa & Mahmood, 2002; Raheem et al., 2014) as displayed in Figure 6. This may imply that a good spread of the SDA particles (that is a well-graded particle size) rather than a narrow-range, very fine particle sizes is required to obtain a high CS$_{28}$ that meets the minimum requirements of 20 MPa for use in reinforced concrete as specified in BS8110 (British Standard Institution, 1997). Therefore, careful consideration should be given to size effects of SDA in the production of SDAC in order to obtain maximum CS. The size effects may affect the optimum SDA content to be utilized in sawdust-ash concrete (SDAC).

Furthermore, the highest CS$_{28}$ of sawdust-ash concrete (SDAC) ranging from 35.6–29.11 N/mm$^2$ was obtained using fly-ash based geopolymer binders comprising sodium hydroxide and sodium silicate. This imply that fly-ash based geopolymer concrete is preferable for the production of SDA-modified laterized concrete in terms of CS development. In addition, the second highest CS$_{28}$ was obtained with a 50:50 combination of RHA and SDA (Ettu et al., 2013). Compared to SDA, wood waste ash (WWA) also exhibited comparably higher CS$_{28}$ and can also be utilized in concrete even though it contains lesser pozzolanic content as displayed in Table 1.

In addition, mix ratio 1:6 is preferable to 1:8 for the production of SDA-modified hollow blocks. The SDA-modified hollow blocks (Popoola et al., 2015) produced with a mix ratio of 1:6 recorded CS$_{28}$ range of 2.35–2.92 N/mm$^2$ which met the minimum CS$_{28}$ of 2 N/mm$^2$ for hollow block of the National Building Code (Ministry of Housing & Urban Development [MHUD], 2006) for non-load bearing walls. With incessant building collapse in some developing countries and the scarcity of quality sandcrete blocks in those nations, upgrade of the minimum CS$_{28}$ N/mm$^2$ requirements to 5 N/mm$^2$ is recommended in line with the Spanish Building Technical Code (Spanish Ministry of Public Service [SMPS], 2013) and British Building Regulations of England (BR, 1976) for load-bearing walls. This may help reduce the menace of building collapse in developing countries.

### 3.2 Laterite in concrete

Laterite is rich in aluminium oxide and compliments cement which is rich in calcium oxide. In terms of chemical composition, shown in Table 2, the order of ranking of the chemical compounds in laterite is Al$_2$O$_3$ > CaO > Fe$_2$O$_3$ > SiO$_2$ while the order of ranking for cement is CaO > SiO$_2$ > Fe$_2$O$_3$ > Al$_2$O$_3$. This result indicates that laterite has complimentary chemical composition that augments deficiencies in OPC (Dangote Cement).
Even though laterite was utilized as fine aggregates in laterized concrete, technically, it performs dual functions of SCM and fine aggregates and thus has the potential to yield improved mechanical properties at optimum fine aggregate replacement and with appropriate production method.

Furthermore, literature review revealed varied mix ratio used in laterized concrete. The common mix ratios used were 1:1.5:3, 1:2:4, 2:3:6, 1:1.2, 1:0.96:3.23, 1:1.4:2.9 for concrete cubes; 1:6, 70:30 and 90:10 for bricks, hollow block and solid brick respectively. Also, the common water-cement ratios utilized varied from 0.34–1.02.

Based on the experimental results of Balogun and Adepegba (1982), mix ratio 1:2:4 gave higher CS28 for fine aggregate replacement ratio >25% at w/c ratio of 0.55 while mix ratio 1:1.5:3 recorded higher CS28 for fine aggregate replacement ratio ≥50%. Also, for both mix ratios, it was observed at FAR (fine aggregate replacement ratio) ≤50%, 0.55 w/c ratio gave higher CS28 while at ≥50% FAR, 0.65 w/c achieved higher CS28. This was because higher FAR requires more water for complete hydration and contains higher pozzolanic contents. For mix ratio 1:1.5:3, the FAR should be limited to 50% using 0.55 w/c ratio while for 0.65 w/c ratio, FAR must be limited to 75% to achieve minimum CS28 of 20 N/mm² for structural applications. On the other hand, for mix ratio 1:2:4, for 0.55 w/c ratio, FAR should be limited to 25% while for 0.65 w/c ratio FAR must be limited to 75% to meet the minimum CS28 of 20 N/mm² for structural applications.

Based on experimental results from available literatures displayed in Figure 7, mix ratio 1:2:4:0.56 achieved the highest CS28 up to 50% FAR at 0.56 w/c ratio (Sabarish, Ratnam, Prasad, & Raju, 2015). This corroborates our earlier findings that at FAR ≤ 50%, mix ratio 1:2:4:0.56 is preferable because it achieved higher CS28 compared to 1:1.5:3. Our result and observation was also corroborated by another researcher (Awolusi, Akinkurolere, Oke, & Adetifa, 2013) who reported optimum CS28 at 20% laterite content using mix ratio of 1:2:4:0.50 for the production of microbial laterized concrete. The preferred order of ranking of the various mix ratios obtained from literature are summarized in Table 6. It was also observed that only mix ratio 2:3:6 met the minimum CS28 at 100% FAR at 0.65 w/c ratio (Salau & Balogun, 1998).

![Figure 7. Compressive strength of laterized concrete in literature.](image-url)
The above results also showed that mix ratio and w/c ratio play significant roles in the CS development in laterized concrete. Therefore, utmost care should be taken to select appropriate mix ratio along with proper w/c ratio based on envisaged FAR to achieve targeted CS for structural applications. Failure to take these precautionary measures may yield sub-optimal CS for intended structural applications. For non-structural applications such as mass concrete, mix ratios that falls below the minimum CS line may be utilized but care should be taken to ensure their CS is not below 15 N/mm².

With respect to bricks, solid bricks manufactured using 90% laterite and 10% wood ash and sawdust in 50:50 combination ratio as fine aggregates, recorded the highest CS at 10% FAR as displayed in Figure 8. The maximum CS developed was 19.15 MPa which was higher than 5.72 MPa achieved by lateritic sandcrete bricks produced using 1:6 laterite fine replacement of sand (Emmanuel & Allan, 2014) and also surpassed the requirement for both load-bearing and non-load bearing bricks. The least CS of 2.56 MPa was recorded using quarry dust for the manufacture of hollow blocks (Okafor & Egbe, 2017).

This may imply that solid bricks possess higher CS than hollow bricks and should be encouraged in building and infrastructure constructions. In addition, owing to scarcity of lateritic brick works in literature, future research efforts should be directed at the utilization and optimization of various locally available SCMs to improve the properties of lateritic bricks for building and infrastructural purposes.

Likewise, research works on laterized concrete in columns and beams are scarce and various concerns such as creep, elevated temperature effects and durability need to be addressed to encourage the utilization of laterized concrete in concrete structures.

| FAR (%) | Order of ranking |
|---------|------------------|
| 25      | 1:2:4:0.55 > 1:1.5:3:0.55 > 1:2:4:0.65 > 2:3:6:0.65 > 1:1.5:3:0.65 > 2:3:6:0.65 |
| 50      | 1:2:4:0.56 > 1:1.5:3:0.55 > 1:2:4:0.65 > 2:3:6:0.65 > 1:1.5:3:0.65 |
| 75      | 2:3:6:0.65 > 1:1.5:3:0.55 > 1:2:4:0.65 |
| 100     | 2:3:6:0.65 |

Figure 8. Compressive strength of laterized bricks in literature.
3.3. Effects of elevated temperature on the SDA-modified and normal laterized concrete

3.3.1. Effect of laterite content and different elevated temperatures on 28th-day compressive strength (CS$_{28}$) of conventional laterized concrete without SDA

For the unheated, conventional laterized concrete produced without SDA at normal room temperature, 28th-day compressive strength (CS$_{28}$) increased with increasing laterite content as displayed in Figure 9 and produced an average increase of 18.63% with CS$_{28}$ at 15% laterite content as reference point as shown in Table 4. The maximum CS$_{28}$ recorded for LA45SDA10 was 22.41 N/mm$^2$.

At elevated temperature of 200°C, increase in laterite content from 15 to 30 and 45% resulted in an average decrease of 4.37% in the CS$_{28}$ while at elevated temperature of 400°C, the reduction in CS$_{28}$ increased to 12.95%. Surprisingly, increase in lateritic content at 600°C, produced an average increase in CS$_{28}$ of 37.74%. This could imply that the effect of certain minerals in the laterite were activated at 600°C and contributed to the substantial increase in CS$_{28}$ recorded at that temperature. In addition, this implies that for conventional laterized concrete to gain the benefit of increase in CS$_{28}$ it must be subjected to a temperature ≥600°C.

Table 7 also revealed that all the elevated temperature produced different amounts of decrease in CS$_{28}$ of the concrete specimens. With reference to the CS$_{28}$ for LA15SDA10, LA30SDA10 and LA45SDA10 at normal room temperature, the corresponding average reduction in their average CS$_{28}$ at 200, 400 and 600°C were 29.07, 20.32 and 24.01%. This implies that 400°C produced the least reduction in CS$_{28}$, followed by 600°C while the highest reduction occurred at 200°C.

The compressive strengths of conventional laterite concrete without SDA modification produced at 15, 30 and 45% laterite replacement of sand meets the requirement for use in reinforced concrete (15 N/mm$^2$) and plain concrete (7 N/mm$^2$) according to BS8110 Part 1 (British Standard Institution, 1997) and American Concrete Institute (2003) respectively. In addition, the conventional concrete produced with 30 and 45% laterite replacement of sand (LA30SDA10 and LA45SDA10) can be classified as grade-20 concrete at ambient temperature.

3.3.2. Effect of laterite content and elevated temperature on 28th-day compressive strength (CS$_{28}$) of SDA-modified laterized concrete

SDA-modified laterized concrete produced under room temperature also exhibited increasing CS$_{28}$ with increasing lateritic content as depicted in Figure 8 and recorded the optimum CS$_{28}$ of 23.49 N/mm$^2$ for LA45SDA10. The average increase in CS$_{28}$ recorded at room temperature was 15.9%. With increase in laterite contents from 15 to 30 and 45, the average corresponding decrease recorded in...
the CS$_{28}$ for SDA-modified laterized concrete were 7.23 and 18.82% at 200 and 400°C while an average increase of 5.06% in CS$_{28}$ was recorded at 600°C.

Comparatively, the average increase in CS$_{28}$ related to increment in laterite content recorded for SDA-modified laterized concrete were lesser compared to those recorded for conventional laterized concrete. Likewise, the average reduction in CS$_{28}$ related to increment in laterite content recorded for SDA-modified laterized concrete were greater compared to those recorded for conventional laterized concrete. This distinct behavior could be attributed to the SDA contents of the laterized concrete.

From Table 8, it was observed that the optimum lateritic content in terms of maximum CS$_{28}$ of 23.49 N/mm$^2$ was obtained at 45% laterite content under room temperature. Also, optimum elevated temperature in terms of least reduction in CS$_{28}$ was also achieved at 400°C.
3.3.3. Effect of SDA on CS$_{28}$ of laterized concrete at normal and elevated temperatures

The effect of SDA on CS$_{28}$ of laterized concrete were obtained by comparing the CS$_{28}$ of each SDA-modified laterized concrete with that of corresponding values of conventional laterized concrete. Results displayed in Table 9 indicated that SDA replacement of cement in the laterized concrete produced at room temperature contributed an average increase of 10.69% to the CS$_{28}$ as displayed Figure 10 while at elevated temperature of 200°C, SDA replacement of cement contributed 4.76% to the CS$_{28}$. At 400 and 600°C, SDA replacement of cement in laterized concrete resulted in a decrease of 4.36% and 0.62 in CS$_{28}$.

This implies that SDA modifications contributed more to the compressive strength of laterized concrete when produced at normal room temperature. It was also observed that the optimum SDA modifications at room temperature was recorded by LA30SDA10. In addition, the highest contribution of SDA of +17.38% CS improvement took place at elevated temperature of 600°C.

Also, the compressive strengths of SDA-modified laterized concrete namely LA15SDA10, LA30SDA10 and LA45SDA10 can be classified as grade-20 concrete when produced at ambient temperature. Likewise, they all met the requirement for use in reinforced concrete (15 N/mm$^2$) and plain

| Temperature (°C) | % laterite content | Increase/decrease (%) | Average increase/decrease (%) |
|------------------|--------------------|-----------------------|-----------------------------|
| 21               | 15                 | +12.22                | +10.69                      |
|                  | 30                 | +15.04                |                             |
|                  | 45                 | +4.82                 |                             |
| 200              | 15                 | +7.01                 | +4.76                       |
|                  | 30                 | +11.25                |                             |
|                  | 45                 | −3.97                 |                             |
| 400              | 15                 | +0.11                 | −4.36                       |
|                  | 30                 | −7.33                 |                             |
|                  | 45                 | −5.85                 |                             |
| 600              | 15                 | +17.38                | −0.62                       |
|                  | 30                 | −1.11                 |                             |
|                  | 45                 | −18.13                |                             |

Figure 10. Effects of elevated temperature on laterized and SDA-modified concrete.
concrete (7 N/mm²) according to BS8110 Part 1 (British Standard Institution, 1997) and American Concrete Institute (2003) respectively.

3.3.4. Comparison of effects of elevated temperature on conventional and SDA-modified laterized concrete

Our experimental results displayed in Figure 10 revealed optimum CS at 400°C for LA15SDA10 and LA30SDA10 with CS strength losses of 33.2 and 28.23% and optimum CS at 600°C for 45% laterite content. This optimum temperature was corroborated by earlier researches which recorded optimum CS at the same temperature (Balogun, 1986). Therefore, to benefit from the strength gain caused by the pozzolanic contents of laterized and SDA-modified concrete at elevated temperature, they should not be heated beyond 400°C.

In addition, laterized concrete can be utilized in structural applications and must not be exposed to elevated temperature beyond 600°C to be able to maintain minimum CS required for structural, load-bearing applications such as columns, beams and slabs.

Our results also revealed that SDA-modified laterized concrete cannot be used for structural, load-bearing applications because it does not meet the minimum CS requirement for such applications. Therefore, the use of SDA-modified laterized concrete should be limited to load-bearing blocks/bricks and non-structural applications.

It is also important that effects of elevated temperature should be incorporated into laterized concrete researches to avoid misleading end-users about the potential applications of such important material which may lead to catastrophic consequences.

Owing to scarcity of literatures on properties of laterized concrete at elevated temperature, more research efforts should be directed to investigate their potential applicability especially in developing countries where it is abundant in supply.

4. Conclusions

Combined utilization of waste saw dust ash and laterite as SCM and fine aggregate in concrete production contributes to eco-friendly construction. Laterite as fine aggregate in laterized concrete performs dual functions of SCM alongside being a fine aggregate replacement for sand. The utilization of waste sawdust ash helps to reduce the environmental impact of the waste saw dust while at the same time improves the compressive strength of laterized concrete. Therefore, the following conclusions could be drawn:

(i) For fine aggregate replacement by laterite ≤50%, concrete mix ratio 1:2:4:0.56 is preferable.
(ii) For fine aggregate replacement by laterite ≥50% up to 75%, concrete mix ratio 1:1.5:3:0.65 is preferable.
(iii) For 100% fine aggregate replacement by laterite, concrete mix ratio 2:3:6:0.65 is preferable.
(iv) Waste saw dust ash contributed an average of 10.69 and 4.76% to the CS₂₈ of SDA-modified laterized concrete under room temperature and 200°C respectively and an average CS reduction of 4.36 and 0.62% at 400 and 600°C respectively.
(v) The optimum elevated temperature for heating laterized and SDA-modified laterized concrete and bricks for strength gain is 400°C while optimum laterite content is 45%.
(vi) Based on elevated temperature results, both conventional and SDA-modified laterized concrete meet the requirements to be used in production of load-bearing bricks and blocks as well as other non-structural applications.
6. Recommendations

Size effects should be investigated in laterized concrete works to ascertain which optimum laterite sizes to utilize as SCM and fine aggregate for laterized concrete.

More research efforts should be directed to optimize utilization of available biomass such as sawdust ash, wood ash, quarry dust, etc. as SCM and fine aggregate replacement in concrete. Such efforts will go a long way to improve the durability and cost of laterized concrete for structural and non-structural applications.

Research efforts on laterized concrete must take into consideration elevated temperature effects to avoid misleading end-users.

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