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Effect of sawdust ash and laterite on the electrical resistivity of concrete

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Abstract. This study is an experimental research aimed at evaluating the electrical resistivity of concrete containing laterite and sawdust ash (SDA). Laterite was used to partially replace the sand in concrete while SDA partially replaced cement as a supplementary cementitious material. Cylindrical samples of Ø100 by 200 mm were used to evaluate the singular and combined influences of water-binder ratio, SDA and laterite on the electrical resistivity of concrete as a measure of durability. The sawdust ash content of 0, 10, 20 and 30% by weight of cement was considered while an optimum 30 % laterite content was examined and water-binder ratios of 0.35, 0.50 and 0.65. Additionally, some samples were cured in 1 %, 3 % and 5 % of sodium chloride salt (NaCl) to simulate the marine environment. The electrical resistivity test was conducted using the four-electrode method (Wenner's Method) in accordance with ASTM C1202. The results of the investigations revealed that the resistivity of concrete generally increases with age at all replacement levels with optimum performance at a water-binder ratio of 0.50. Also, the results show that an increase in the sawdust ash content reduces the resistivity of concrete while the addition of laterite at 30% increases the electrical resistivity of concrete at increased water content. Chloride ion exposure generally reduces the ER of concrete while laterite reduces the impact of the chloride ion.

1. Introduction

Concrete is a widely used construction material in the construction industry, hence making it one of the intensely researched materials in civil engineering [1]. However, concrete is a porous material, and the durability of concrete hangs on the properties of its microstructure such as the pore network, size, and interconnections. A finer pore network with less connectivity leads to lower penetrability. On the other hand, a porous microstructure with more degree of interconnections results in higher penetrability and reduced durability in general [2].

According to Baroghel-Bouny et al. [3], the long-term durability of reinforced concrete (RC) structures is a major concern for safety, economic and environmental reasons. There is an increasing number of RC structures and components of infrastructure that are not durable and are failing to realise their design service life [4]. Extensive experience has confirmed that the lack of concrete durability could often be related to a lack of proper quality control and problems during RC structure construction. Therefore, to ensure better construction quality and durability, there has been an increasing focus on the development of performance-based quality control techniques for concrete durability [5], [6]. One of the Non-Destructive

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Test (NDT) commonly suggested in performance-based quality control programme is electrical resistivity [7], [8].

Electrical resistivity (ER) is a non-destructive assessment technology that is related to how easily ions can move inside the concrete, that is, it is a measure of the diffusion of ions in the concrete through the pore solution. Hope et al. [9] and Hunkeler [10] posited that the electrical resistivity of a concrete sample is related to several factors which include paste microstructure, moisture content and temperature, and it is also affected by the presence of contaminants like chloride and sulphate ions [11]. The presence of chloride ion in concrete's pore liquid can induce corrosion of reinforcing bars [12] which can originate from sea water or marine atmosphere [13]. This has made some studies [13]–[15] to suggest the use of ER to measure chloride diffusion in concrete. As proposed by Tuutti [16], electrical resistivity can be principally classified into two stages of durability which are before and after steel corrosion. Thus, it can be used as the barometer of durability during latent period relating to microstructure of concrete as well as corrosion progress period [9], [17], [18] where the corrosion contaminant affects ion diffusion. These can be idealised in the laboratory with long term water curing and chloride ion exposure after initial 28 days water curing.

The rate of corrosion of steel reinforcement embedded in concrete is governed by the magnitude of the ionic corrosion current which flows in the concrete between the anodic and cathodic areas on the reinforcement. The magnitude of this current is dependent on the potential difference between the anode and the cathode, and the electrical resistance of the concrete. The electrical resistivity measurements can help to quantify these but can be significantly affected by the porosity of concrete [19]. A porous concrete would permit more space for ionic movement which can make way for chemical agents to penetrate concrete. Densifying the microstructure of concrete would reduce pores, thereby limiting ionic movements. Efforts to densify the microstructure of concrete, leading to improved durability has led to the use of supplementary cementitious materials (SCMs) and natural fillers in concrete production [20], [21].

By now, SCMs have proven to be effective in meeting most of the requirements for durable concrete and blended cements are now used in many parts of the world [20]. However, to achieve workability in most blended cement concrete, the water to binder ratio would be increased where a superplasticizer is not available. The increase in the water to binder ratio will reduce the strength of the blended cement concrete since concrete strength is related to this ratio. One such material that has the potential, on a large scale to be used as SCM is sawdust ash (SDA). Many researchers have particularly found SDA a suitable agricultural by-product for use in formulating binary blended cements with ordinary Portland cement (OPC) [21], [22]. As the call for the use of alternative materials which the environment can afford continues to rise, laterite has a potential to serve as a cheap filler or sand replacement in concrete that can improve concrete's resistance to corrosion. In the tropics such as Nigeria, laterite is available in abundance almost from any borrow pit [23]. Laterized concrete is concrete containing some percentages of laterite as replacement for sand and some studies have successfully shown that laterized concrete can achieve similar mechanical properties and sulphate attack resistance with normal concrete [24]–[27]. This experimental study on electrical resistivity of laterized concrete attempts to advance this frontier of research.

Even though many works have shown that electrical resistivity of conventional concrete is affected by factors such as moisture content, sample geometry, chloride ion and temperature of the sample [28]–[32], such investigation is yet to be performed on laterized concrete. Hence, this study also investigates some ER influencing factors such as water-binder ratio, chloride ion exposure and its concentration; these were coupled with the effects of SDA at varying contents as a SCM, yielding a total of about 24 mixes. Four forms of concrete were formulated: normal concrete, SDA blended cement concrete, laterized concrete, and SDA blended cement laterized concrete.

2. Materials and Methods

2.1. Materials

Ordinary Portland cement (CEM II 42.5 N), sand, granite chippings, laterite, sawdust ash, portable water and superplasticizer were the materials used to prepare the test specimens. The coarse aggregate, granite had a maximum size of 19 mm. The grading curve of the sand, granite and laterite is shown in Figure 1; this test was performed according to BS EN 933-1 [33]. Table 1 shows the physical properties of the sand, laterite and granite. Standards procedures have been followed to obtain the physical properties of the materials and binders.

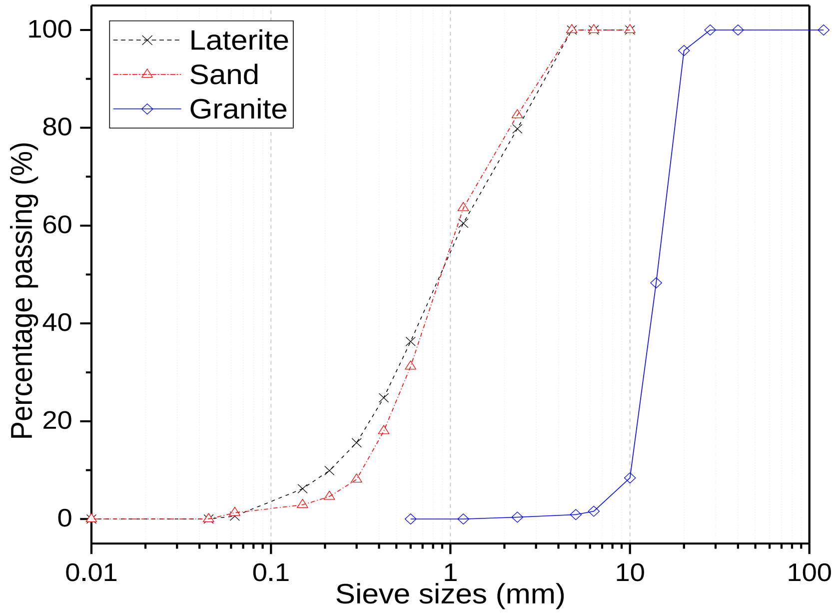

Figure 1. Grading curve of sand, laterite and granite.

Table 1. Physical properties of sand, laterite and granite.

Properties	Laterite	Sand	Granite
Fineness modulus	3.03	3.12	6.95
Coefficient of uniformity (C_u)	5.57	3.47	1.55
Coefficient of curvature (C_c)	1.00	1.00	1.00
Specific gravity	2.53	2.62	2.80
Water absorption (%)	7.33	5.17	0.88
Liquid limit (%)	37.0	-	-
Plastic limit (%)	17.0	-	-
Plasticity index (%)	20.0	-	-

The sawdust was collected from a sawmill and thereafter burnt in the open-air to reduce the bulk of the sawdust. It was then transferred to a temperature-controlled kiln for calcination at 650 °C, the resulting ash was sieved for use as SDA. It should be noted that the sawdust was fillings from different woods in the Sawmill. Table 2 shows the physical and chemical properties of the cement and the SDA. X-ray fluorescent (XRF) analyzer was used in determining the oxide composition of the SDA according to the requirements of BS ISO 29581-2 [34]; the mineralogy of the SDA and laterite was determined by X-ray diffraction according to BS EN 13925-2 [35] while their morphology was investigated by scanning electronic microscopy (SEM+EDX) in accordance to BS ISO 16700 [36]. The SDA particles that passed through sieve aperture 75 µm was used to replace the OPC at 0, 10, 20 and 30%.

The fineness of the OPC was obtained by the percentage of mass retained on 75 µm sieves as 20.96% while 20.86% was obtained for SDA. This shows that the OPC is almost of the same fineness as SDA. According to ASTM C618 [37], a limit of 34% is set which is met by the materials. The specific gravity of cement is higher than of SDA (3.14 and 2.08, respectively). The lower values obtained for the specific gravity of the SDA implies that a larger quantity of SDA will be required for batching in relation to OPC.

Table 2. Properties of cement and sawdust ash.

Properties/constituents	OPC	SDA
Fineness (% residue on 75 µm sieve)	20.96	20.86
Consistency (%)	28	52
Initial setting time (min)	110	-
Final setting Time (min)	210	-
Soundness (mm)	0.00	-1.00
Specific gravity	3.14	2.08

Properties/constituents	OPC	SDA
SiO_2	16.82	66.96
Al_2O_3	4.35	5.29
Fe_2O_3	2.43	2.65
CaO	60.39	9.53
MgO	1.43	5.48
SO_3	1.64	0.68
K2O	0.16	0.15
Na_2O	0.02	0.06
MnO	0.04	0.01
P_2O_5	0.21	0.48
TiO_2	0.24	0.00
LOI	9.84	4.85
Free Lime	0.36	0.00
$SiO_2 + Al_2O_3 + Fe_2O_3$	23.60	74.94
C_3S	85.25	
C_2S	16.15	
C_3A	7.42	
C_4AF	7.39	

2.2. Concrete mixture of SDA blended cement laterized concrete

Twenty-four different mix proportions involving cement, SDA and lateritic soil were prepared as shown in Table 3. The cement was replaced with SDA at 0, 10, 20 and 30% while the laterite was kept constant at 30% as a replacement for sand. The water-to-binder ratios (w/b) of 0.35, 0.50 and 0.65 were used.

The concrete ingredients were batched by weight and mixed manually on a neat impermeable platform with a predetermined amount of water. The cement and SDA were first thoroughly mixed manually to obtain a uniform mixture. The blended cement was then spread over the already mixed aggregate and remixed before water was added to the dry mix. Afterwards, the required dosage of superplasticizer (Mapefluid – N200) was added to obtain a medium slump, Class S2 (50 – 90 mm) for all mixes. The concrete was then thoroughly mixed for additional two minutes. Mixing was concluded when the concrete showed a uniform blend. Slump test was thereafter carried out to determine the workability of each mix. The tests were conducted out by the requirements of BS EN 12350-2 [38].

Table 3. Mix proportion for each replacement levels.

w/b ratio	Replacement levels (%) OPC:SDA:LAT*	Labels	Cement (kg/m^3)	SDA (kg/m^3)	Sand (kg/m^3)	Laterite (kg/m^3)	Granite (kg/m^3)	Water (kg/m^3)	SP* (kg/m^3)
0.65	100:0:0	1C	350	0	900	0	1200	227.5	3.80
	90:10:0	1CS1	315	35	900	0	1200	227.5	4.20
	80:20:0	1CS2	280	70	900	0	1200	227.5	6.30
	70:30:0	1CS3	245	105	900	0	1200	227.5	5.60
	100:0:30	1CL	350	0	630	270	1200	227.5	5.20
	90:10:30	1CLS1	315	35	630	270	1200	227.5	9.70
	80:20:30	1CLS2	280	70	630	270	1200	227.5	16.2
	70:30:30	1CLS3	245	105	630	270	1200	227.5	8.35
0.5	100:0:0	2C	350	0	900	0	1200	175.0	4.87
	90:10:0	2CS1	315	35	900	0	1200	175.0	5.63
	80:20:0	2CS2	280	70	900	0	1200	175.0	6.95
	70:30:0	2CS3	245	105	900	0	1200	175.0	6.05
	100:0:30	2CL	350	0	630	270	1200	175.0	9.97

w/b ratio	Replacement levels (%) OPC:SDA:LAT*	Labels	Cement (kg/m^3)	SDA (kg/m^3)	Sand (kg/m^3)	Laterite (kg/m^3)	Granite (kg/m^3)	Water (kg/m^3)	SP* (kg/m^3)
	90:10:30	2CLS1	315	35	630	270	1200	175.0	6.40
	80:20:30	2CLS2	280	70	630	270	1200	175.0	8.97
	70:30:30	2CLS3	245	105	630	270	1200	175.0	9.82
0.35	100:0:0	3C	350	0	900	0	1200	122.5	5.05
	90:10:0	3CS1	315	35	900	0	1200	122.5	6.43
	80:20:0	3CS2	280	70	900	0	1200	122.5	8.23
	70:30:0	3CS3	245	105	900	0	1200	122.5	9.27
	100:0:30	3CL	350	0	630	270	1200	122.5	6.15
	90:10:30	3CLS1	315	35	630	270	1200	122.5	7.50
	80:20:30	3CLS2	280	70	630	270	1200	122.5	8.45
	70:30:30	3CLS3	245	105	630	270	1200	122.5	11.59

* OPC – Ordinary Portland cement, SDA – saw dust ash, LAT – Laterite, SP – Superplasticizer

2.3. Sample preparation

Cylindrical moulds of Ø100×200 mm was used for casting the test specimen. The moulds were thoroughly cleaned and coated with mould oil before casting to ensure easy de-moulding. The casting was done in accordance with ASTM C192/C192M [39]. After casting, sackcloth was placed over the moulds to avoid evaporation of mix water from the concrete cylinder samples.

De-moulding of the specimens took place after 24 hours of casting, and then was kept in an area free from vibration, dehydration and direct rays of sunlight and other sources of heat. After 28 days of water curing, specimens were transferred to various concentrations of sodium chloride (NaCl) for a maximum period of 60 days. Control specimens were also cured in the water alongside those cured in NaCl for a maximum of 88 days, NaCl concentrations of 1%, 3%, and 5% were used for the investigation. This represents the extreme forms of concrete exposure of typical ocean salt concentration with an average of 3.5% [40] that can penetrate/diffuse into the concrete as contaminants. 1% and 5% concentrations were also selected to represent possible lower and higher concentrations that can occur due to probable variation of salt concentration in the ocean.

2.4. Experimental tests

Electrical resistivity (ER) of the concrete specimens after various curing ages was determined. The test was carried out using the four-electrode method (Wenner's Method) in accordance with AASHTO T 358 [41]. Studies such as Azarsa and Gupta [42] and Lencioni and Lima [43] rated Wenner's method an easily deployable approach to determining electrical resistivity and better than the two-point method. 360 cylindrical specimens were used to determine the effect of SDA and water/cement ratio on the electrical resistivity of laterized concrete at curing ages of 7, 14, 28, 58 and 88 days in water; 216 cylinder specimens were also used to determine the effect of 1, 3 and 5% NaCl concentration on the electrical resistivity of blended cement laterized concrete at 30 and 60 days after water curing for 28 days. Four data points were taken per sample and at least three samples were tested for the ER, and the average reported. The schematic diagram of the test equipment is shown in Figure 2. For qualitative purposes AASHTO T 358 [41] classifies the ER values into high (< 12 kΩ.cm), moderate (12–21 kΩ.cm), low (21–37 kΩ.cm), very low (37–254 kΩ.cm) and negligible (> 254 kΩ.cm) potentials for chloride ion penetration based on established correlations. According to AASHTO T 358 [41], curing in lime solution reduces the ER by 10% and should be factored into the ER values. In the case of this study, no correction factors were applied on the ER of the specimens cured in NaCl since they were initially cured in water for 28 days.

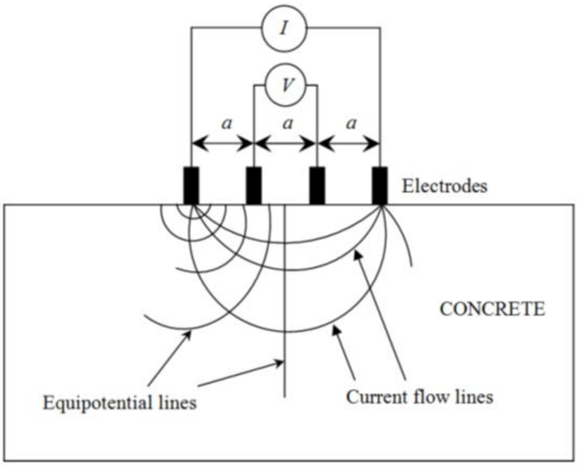

Figure 2. Schematic representation for measurement of electrical resistivity.

3. Results and Discussion

3.1. Mineralogy and morphology of the SDA and laterite

Figure 3 shows the mineralogy of both the saw dust ash (SDA) and laterite. The peaks in the XRD results depict crystalline phases with position and intensity proportional to crystalline compounds [44]. The intensity peaks in Figure 3 shows that the laterite has more crystalline structures than the SDA. This is in order of their use since amorphous compounds (less crystalline) is more reactive with hydrated lime ($Ca(OH)_2$) as a supplementary cementitious material (SCM) while the more stable crystalline nature of the laterite suits its use as a filler and replacement of sand.

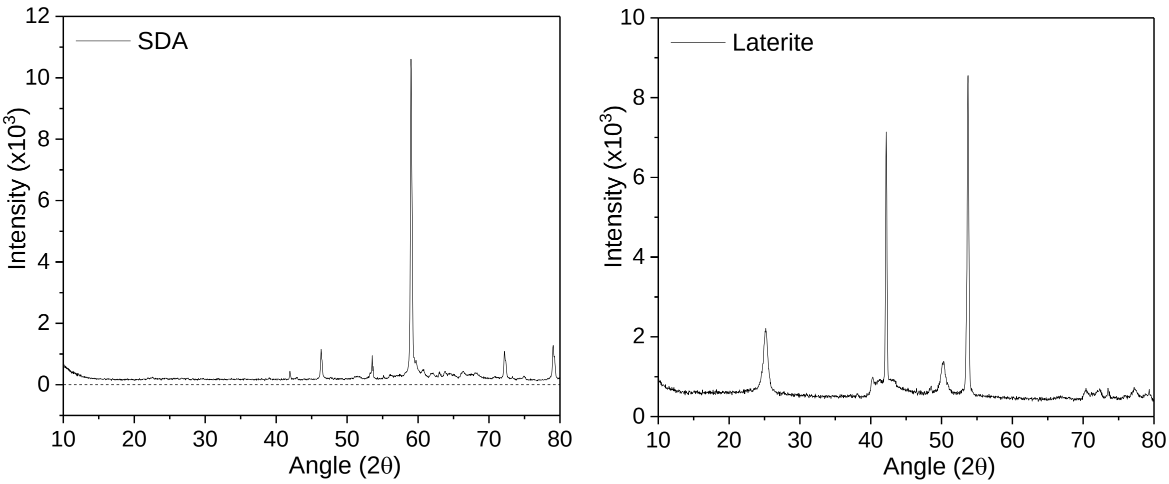

Figure 3. XRD pattern of (a) saw dust ash (SDA) and (b) laterite.

Figure 4 show the morphology of the SDA and laterite. The images were obtained using a Zeiss MERLIN high-resolution Scanning Electron Microscopy (SEM). The samples were scanned on a coated carbon tape. The results show that the SDA particles tend to be flat with more regularity and less sperity while the laterite is fairly flat but more rounded. This shape is envisaged to require more water for lubrication, hence workability, as compared to more rounded shapes. This was observed in the next section on the concrete's workability. Since both Figure 4a and b are of the same magnification (200 nm), it can be said that the SDA particles are more bigger than that of the laterite, though the laterite particles seem to agglomerate into bigger particles (lumps). The shape and form of SDA is probably due to its burning that turns it into ash as compared to laterite in its natural form. The energy dispersive X-ray analysis (EDX) shown in Figure 5 helps to quantify the elemental analysis of the material which is shown in Table 4. The richness of the laterite in silica and alumina explains the additional crystalline phases detected as peaks in Figure 3. That is, laterite is known to have phases of quartz (crystalline SiO_2), gibbsite [$Al(OH)_3$], kaolinite [$Al_2Si_2O_5(OH)_4$] and hematite (Fe_2O_3) [45], [46] which coincides with the detected substantial elemental content (Si, Al, Fe) of the laterite in Table 4.

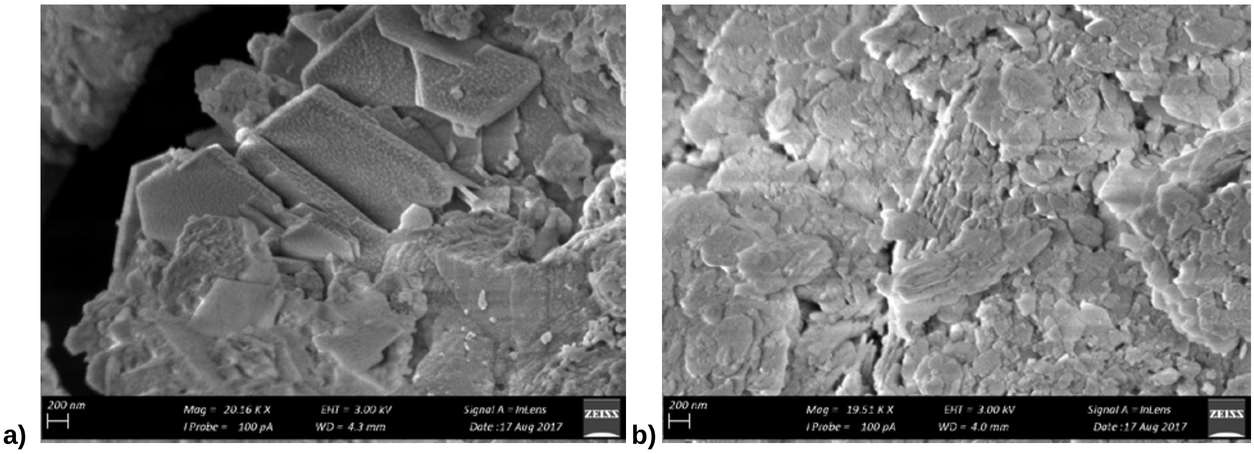

Figure 4. SEM images of (a) saw dust ash and (b) laterite at 200 nm magnification.

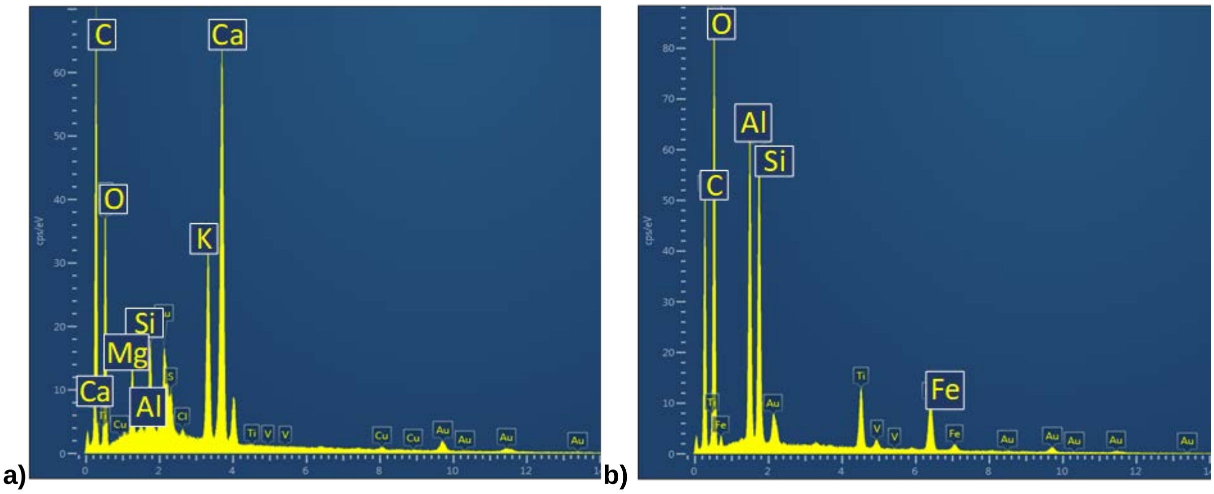

Figure 5. EDX microanalysis of the (a) saw dust ash and (b) laterite.

Table 4. Elemental composition of the SDA and laterite.

	O	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Fe	Cu
Laterite	65.88	0	14.81	14.86	0	0	0.03	0.03	0	0.55	3.55	0.28
SDA	64.83	2.68	0.77	2.61	0.70	0.96	0.30	7.79	18.34	0.06	0.40	0.59

3.2. Workability of the concrete

The slump of every wet concrete mix was carried out as a measure of the workability, and the result is shown in Figure 6. The labels on top of the columns represent the ratio of the superplasticizer (SP) of each mix as a ratio of the control mix; this ratio is normalized by the value of the slump. The result reveals that as the percentage of SDA content increases, the superplasticizer required for mixing to achieve a slump of Class S2 also increases at all w/b ratio. All slump values were within the range of 55–65 mm, this was done to ensure that the concrete's compaction does not influence the microstructure differently; hence, allowing for ER results limited to the concrete's material variation. With the addition of laterite at a constant amount of 30% to all these mixes, the demand for the superplasticizer increases to keep the mix at a medium workability. It can be said that the addition of SDA to laterized concrete makes it stiffer than just adding SDA to normal concrete. For example, addition of 30% SDA to normal concrete required 1.2 times more SP at 0.5 w/b ratio while addition of 30% SDA to laterized concrete required 2 times more SP. This trend is similar at all SDA contents and w/b ratios. It can, therefore, be concluded that the SDA blended cement laterized concrete becomes stiffer and less workable as the content of the SDA increases and much more with the addition of laterite. The flat nature of the SDA and laterite particles from the SEM images in Section 3.1 explains the observed reduction of workability (and increased superplasticizer requirement) due to their inclusion in concrete because more water is needed to lubricate their particles than rounder particles.

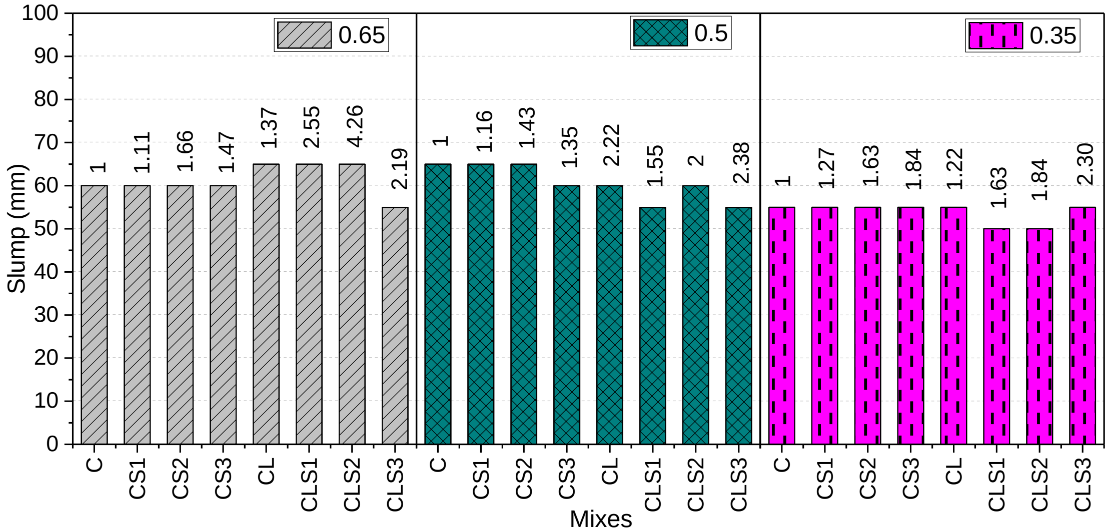

Figure 6. Slump values of SDA blended cement laterized concrete.

3.3. Electrical resistivity (ER) of the concrete

3.3.1. Effect of water-binder ratio: normal and laterized concrete

The effect of the water-binder ratio on the electrical resistivity (ER) of the normal concrete (Mix C) and laterized concrete (Mix CL), at curing ages of 7, 14, 28, 58 and 88 days is shown in Figure 7. The results presented are the average values of three samples taken when the concrete is in the moist state (30 minutes after removal from the curing tank). The specimens were surface dried before the readings were taken. From the result, it is evident that the resistivity of the concrete is a function of age; it increases with curing age irrespective of the w/b ratio and material content. The increase in resistivity with age is due to further hydration as a function of age which improves microstructure against the movement of ions through the pore structure. It should be noted that this was also observed for other mixes (containing SDA with/without laterite) with the curing age. The increase in resistivity of concrete with curing age has been confirmed by previous researchers [47], [48]. However, unlike this study, some studies [47], [49] showed that the ER stabilized at about 14 days at 0.5 w-b ratio.

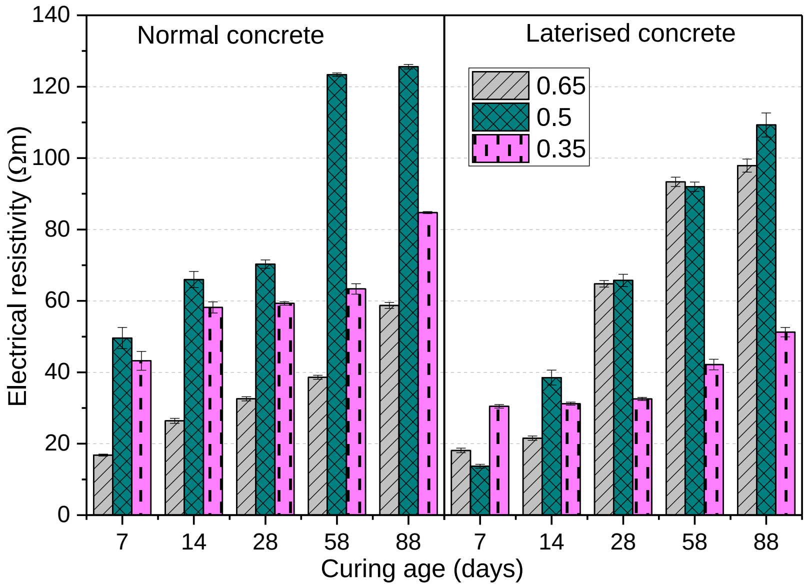

Figure 7. Electrical resistivity of the control concrete at different w/b ratio and curing age.

From the study of Dong *et al.* [50] and Su *et al.* [51], ER resistivity is supposed to increase as w/c ratio increases; this is similar for this study except for 0.5 w/b. According to Neville [52], moist concrete acts as an electrolyte, hence, lower resistivity at higher w/b ratio. It will be observed that at all ages, the resistivity of the normal concrete was higher at a w/c of 0.50 compared to those of 0.35; this difference becomes pronounced as the curing age increased, especially above 28 days. Though considerable effort was made to ensure similar workability of the fresh concrete, the results of Figure 6 revealed that the control mix is stiffest at w/b of 0.35 (slump – 55 mm) followed by that of 0.65 (slump – 60 mm) and 0.5 (slump – 65 mm) which could influence the efficacy of the equal amount of compaction applied; hence, the pore structure (voids and its interconnectivity) and measured ER. That is, assuming equally applied compaction, 0.5 w/b has a higher chance to achieve denser microstructure for less voids and interconnectivity due to its less slump; hence, having higher ER. In the same vein, the laterized concrete also shows that w/b ratio of 0.65 and 0.5 improved the resistivity more than that of 0.35 and these improvements increases with the curing age. Possible reason for this is the increased water content that is absorbable by the laterite for microstructure densification, this is explained further in the next section.

Water-to-binder ratio as a measure of water content is a crucial factor which determines concrete resistivity because it controls the performance of the concrete. Not only does the w/b ratio has a significant effect on strength and durability of the concrete, but also plays an important role in the microstructure of the cement paste, as well as the ionic concentration of the pore solution. Therefore, an increase in w/b ratio can be concluded to cause a higher porosity and coarser pore structure of the concrete; hence, lower electrical resistivity [53]–[55]. Furthermore, a stiffer concrete can reduce the efficacy of compaction, causing lower ER (due to higher porosity and coarser pore structure). Though the AASHTO T 358 code [41] stated that the classification highlighted in Section 2.4 must be used with caution, all the mixes can be said to have high potential for chloride ion penetration. The use of laterite did not cause any significant change in the classification for chloride ion penetration; as found later, this is also the case for the SDA. Therefore, the effects of the laterite and/or SDA lies in the variation of the numeric results of the ER.

3.3.2. Effect of laterite on ER of normal concrete

As previously stated, laterite at optimum replacement level of 30% [56], [57] was introduced into the concrete mix to form what has been termed laterized concrete. The result of the impact of the laterite on the electrical resistivity of concrete mixes (Mixes CL) at the various w/b ratios and curing ages is shown in Figure 8. The general trend is that the addition of laterite in the concrete reduces the resistivity. It can, however, be observed from the figure that the higher the w/b ratio, the lesser the detrimental influence of the laterite on the concrete's resistivity. In fact, at 28 days curing age and later ages, the laterite increased the ER of concrete at w/b of 0.65 by 99%, 141% and 67%, respectively. This could be due to the fact that laterite as part of the fine aggregate absorbs more water (Table 1) to densify the microstructure and inhibit ion movement, especially along the interfacial transition zone (ITZ) [58], [59]; this absorption will be, expectedly, more pronounced at higher w/b ratio such as 0.65 and 0.5 as noted in the previous section. The recent study of Yaragal *et al.* [28] achieved similar ITZs for laterized and normal concretes at a w-b ratio of 0.5; in this case, the laterite was pre-wetted which can negatively impact the ITZ development of the laterized concrete. Furthermore, it implies that, similar to the effects of w/b ratio in the previous section, increased curing magnifies the effects of the laterite on the ER.

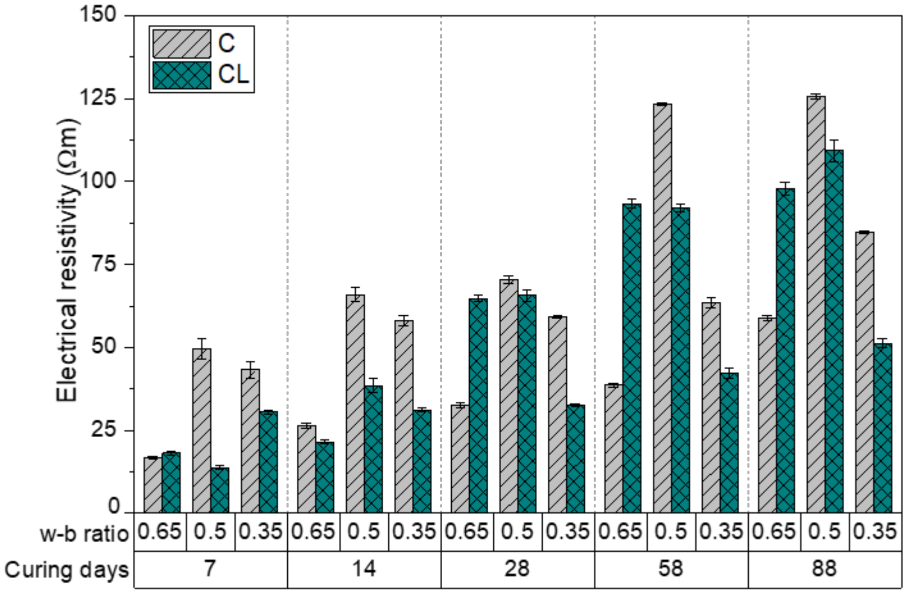

Figure 8. Effect of laterite on the electrical resistivity of concrete at various curing ages.

3.3.3. Effect of saw dust ash (SDA) on ER of normal concrete

The results shown in Figure 9 represent the impact of SDA content at various water-binder ratio and curing ages on the electrical resistivity of concrete. Similar to the normal concrete, concrete mixes containing SDA (Mixes CS1, CS2 and CS3) reveal that increased w/b ratio reduces the ER, the optimum being 0.35. This is dissimilar to the results of Rupnow et al. [60] containing slag SCM which showed increased ER values from w-b ratio of 0.35 to 0.65, which could be due to less reactivity of SDA as explained later. More importantly, w/b ratio of 0.65 and 0.35 tends to dampen the effects of the SDA on the ER of the concrete while 0.5 w/b ratio tends to magnify the influence of the SDA. That is, there is lesser difference between the ERs of the mixes at both 0.65 and 0.35 w/b ratio. For example, at 28 days curing, the difference between the ERs of Mixes C/CS2 and CS1/CS3 at 0.35 w/b ratio are 16% and 8%, respectively, while it was 61% and 55%, respectively, at 0.5 w/b ratio. Again, at the different replacement levels of cement with SDA, the resistivity of concrete mixes increases with curing ages due to further hydration. This behaviour could be due to some pozzolanic action induced by the higher content of SiO_2, Al_2O_3 and Fe_2O_3 (fallen into Class N raw and calcined natural pozzolans recommended in ASTM C618, see Table 2) in SDA, which increases the amount of secondary CSH, and at the same time continuous formation of hydration product with time (i.e., lower un-hydrated binders). It is noted that the higher content of SDA decreases the ER values; even at later ages of 58 and 88 days when blended cement concrete is expected to have improved properties [61]. This could be attributed to the higher percentage of MgO (5.48%), which could induce higher expansion (soundness, see Table 2), resulting in higher cracking and lower ER. Unlike rice husk ash with a higher reactivity as a pozzolan in concrete [62], SDA has been shown to have a rather reduced reactivity compared to control samples even at later ages [63], [64]. Figure 9 also reveals that the addition of SDA impacts more negatively on the resistivity of concrete than those of laterite. For example, at 28 days curing, laterite (Mix CL – 30% content) impacted the concrete by +50%, -7% and -45% at 0.65, 0.5 and 0.35 w/b ratio, respectively, while the SDA (Mix CS3 – 30% content) impacted the concrete by -42%, -73% and -24%, respectively.

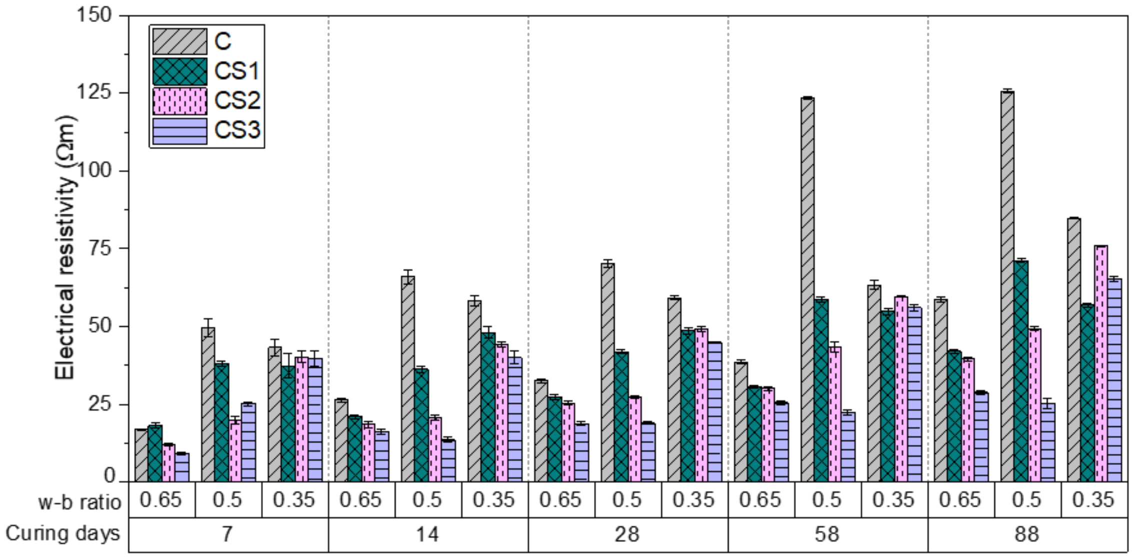

Figure 9. Effect of saw dust ash on the electrical resistivity of concrete at various curing ages.

3.3.4. Effect of saw dust ash (SDA) on ER of laterized concrete

Figure 10 shows the influence of SDA blended cement on the electrical resistivity of laterized concrete. The intention of the figure is to depict the effects of adding both laterite and SDA in concrete. The effects can be proposed to be in two parts: early age (7 and 14 days) and later age (28, 58 and 88 days) at all w/b ratios. At early age, the influence of SDA on laterized concrete tends to be minimal while at later age it tends to be pronounced. For example, at 7 days curing and 0.65 w/b ratio, 30% SDA content (Mix CLS3) impacted the ER of laterized concrete by -27% while it impacted the ER by -72% at 88 days curing. That is, similar to the effect of SDA on ER of normal concrete in the previous section, increased curing tends to magnify the effects of SDA on the ER of laterized concrete. At lower w-b ratio of 0.35, the ER increased for the laterized concrete blended with 10% and 30% SDA at later age while the ER decreased at higher w-b ratios. This behaviour could be due to some pozzolanic action (as explained earlier) which densifies the concrete matrix especially at later ages where the SDA influence became pronounced. The variation in this study has been confirmed by Singh and Singh [65] that showed that the ER of concrete is dependent on the binder combination and nature of aggregates. Singh and Singh [65] made use of silica fume/metakaolin as SCMs and reused concrete aggregates as substitute for river sand.

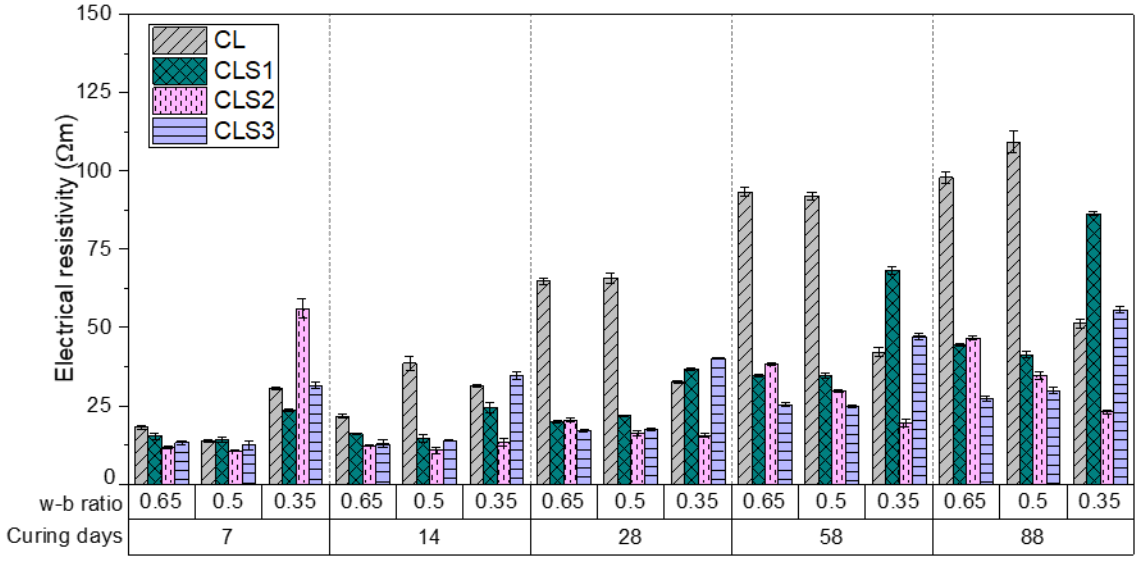

Figure 10. Effect of SDA on the electrical resistivity of laterized concrete at various curing ages.

3.3.5. Electrical resistivity of concrete containing SDA and laterite exposed to chloride ion

This section examines the electrical resistivity (ER) of SDA blended cement laterized concrete exposed to chloride solution. Chloride ion in concrete's pore solution is expected to increase the easy passage of electricity. Hence, a reduction in the ER is expected for the concrete cured in NaCl. It should be noted that the samples were initially cured in water for 28 days before exposure to NaCl for 30 and 60 days. Similar to Section 3.3, this section attempts to delineate the effects of w-b ratio, laterite and SDA, singularly and jointly, on the electrical resistivity.

Figure 11 shows the ER of Mix C and CL in 1, 3 and 5% NaCl at 0.65, 0.5 and 0.35 w-b ratio exposed to NaCl for 30 and 60 days. This figure delineates the effects of laterite, w-b ratio, NaCl concentration, and exposure time. The more the exposure period and chloride ion concentration, the less the ER of the samples; this is also evident in Figure 12 and Figure 13 that depict the effects of SDA (combined with that of w-b ratio) on normal and laterized concrete, respectively. This is because more exposure time and chloride ions would allow for additional penetration of the chloride ions that can create more routes for the passage of electric current. The inclusion of laterite in concrete tends to reduce the ER of the concrete, however, laterite greatly improved the ER at 0.65 w-b ratio. For example, at 30/60 days exposure, the laterite averagely increased the ER by 230%/61% at 0.65 w-b ratio while it reduced the ER by 34 %/31 % at 0.5 w-b ratio and 13 %/31 % at 0.35 w-b ratio, respectively. This is similar to the water curing in Section 3.3.2 where increased water content is envisaged to improve the effectiveness of laterite in mitigating durability problems. The trend in the example sentence also revealed that continued exposure to chloride ion seems to drastically reduce the effectiveness of the laterite at the increased water content. Similar to the results for water curing, 0.5 w-b ratio yielded the highest resistivity in chloride ion.

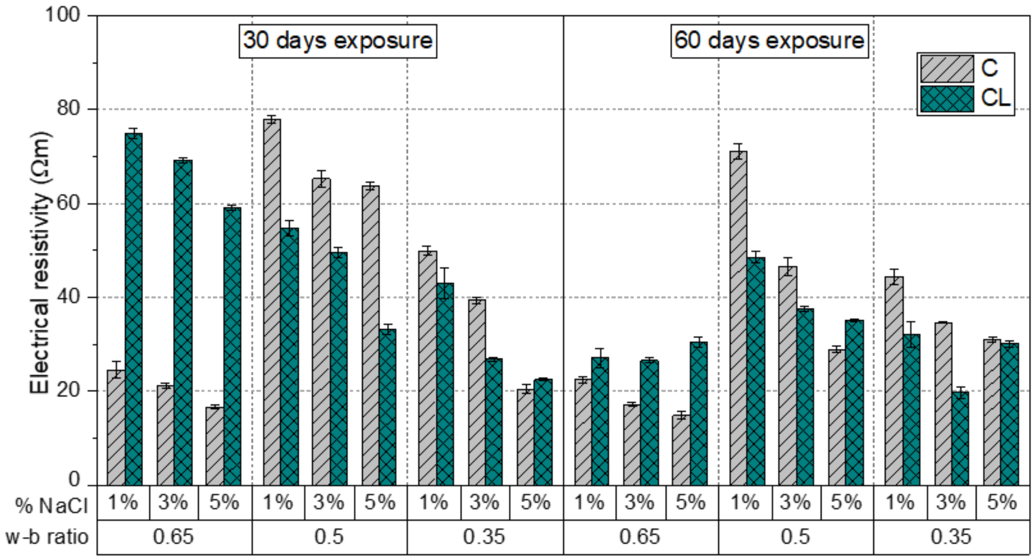

Figure 11. Impact of chloride ion exposure on the ER of normal and laterized concrete.

Figure 12 depicts the influence of SDA on the ER of concrete in the presence of chloride ion. Similar to water curing, lower w-b ratio tends to improve the effectiveness of the SDA in concrete in NaCl solution. This effectiveness being magnified due to the NaCl solution, especially at 0.35 w-b ratio. At 30/60 days of NaCl exposure at 0.35 w-b ratio, 30% inclusion of SDA in normal concrete impacted the ER by an average of +71 %/+17 %, respectively, while water cured samples had -13%/-23% decrease due to 30% SDA.

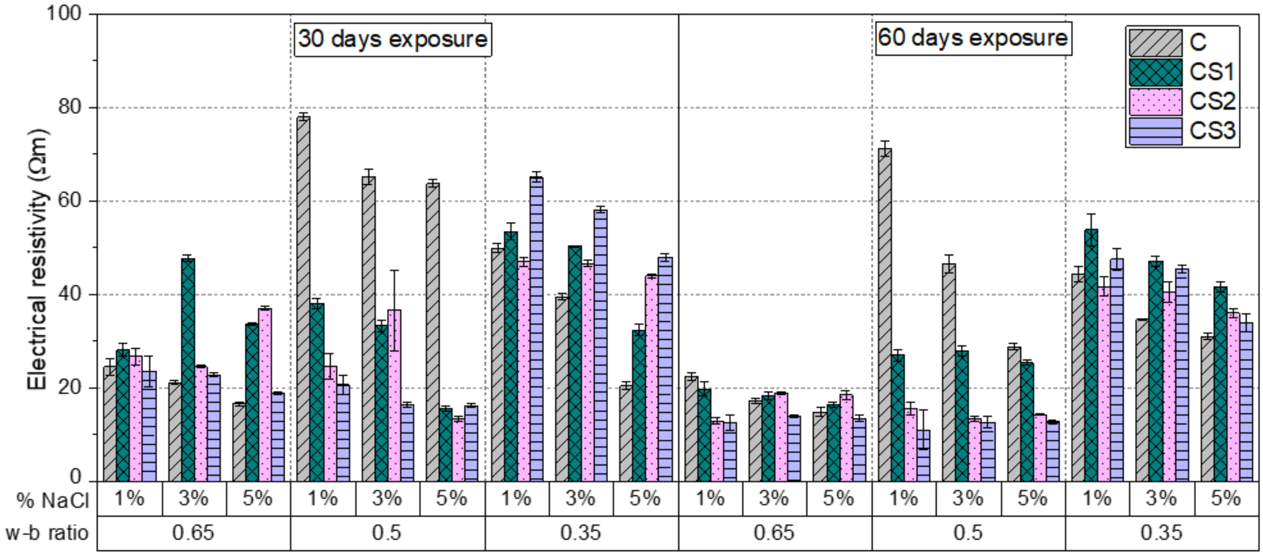

Figure 12. Effects of chloride ion exposure on the ER of normal and SDA blended cement concrete.

The impact of SDA in improving ER of concrete (Figure 13) tends to be dampened due to the presence of laterite, especially at the lower 0.35 w-b ratio identified (see previous paragraph) for SDA utmost efficiency in normal concrete. From Figure 13, 30% inclusion of SDA in laterized concrete at 0.35 w-b ratio and 30/60 days exposure impacted the ER by an average of +31%/+2% respectively which is quite low to that of normal concrete (+71%/+17%). Similar to the SDA in normal concrete, the presence of chloride ion in laterized concrete tends to improve the effectiveness of the SDA.

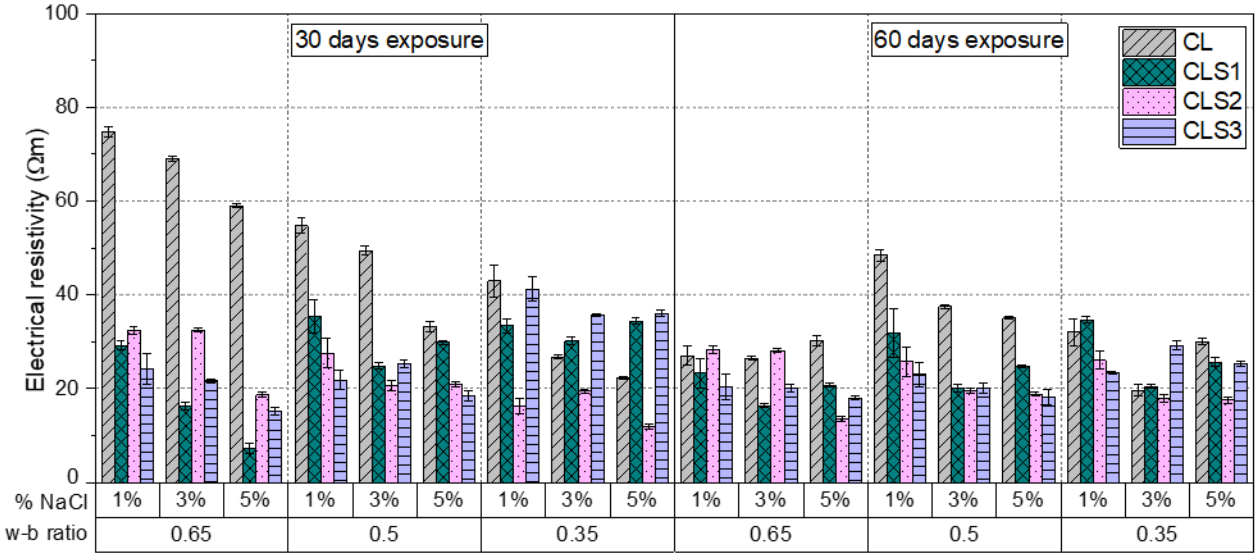

Figure 13. Effects of chloride ion exposure on the ER of normal and SDA blended cement concrete.

3.3.6. Statistical analysis of the effects of w/b ratio, SDA and laterite on the ER of concrete

The essence of the statistical analysis is to examine the kind of relationship and extent of influence of the considered parameters influencing the electrical resistivity (ER) of concrete. These parameters include w-b ratio, SDA, laterite, curing age, and chloride ion. An analysis of variance (ANOVA) showed that significant differences exist within and between the considered parameters (see Tables 5-7), implying that statistical inferences can be made to reinforce inferences made earlier from the experimental results.

Table 5. Univariate ANOVA results for blended cement normal concrete.

Dependent Variable: Resistivity

Source	Type III Sum of Squares	*df*	Mean Square	*F*	Sig.
Corrected Model	1003767252.861[a]	59	17013004.286	481.467	.000
Intercept	2122246356.806	1	2122246356.806	60059.449	.000
SDA	240117320.994	3	80039106.998	2265.102	.000
w-b ratio	13252728.711	2	6626364.356	187.526	.000
Curing	327062851.222	4	81765712.806	2313.965	.000
SDA * w-b ratio	148135513.822	6	24689252.304	698.704	.000
SDA * curing	124052965.533	12	10337747.128	292.558	.000
w-b ratio * curing	32224314.178	8	4028039.272	113.993	.000
SDA * w-b ratio * curing	118921558.400	24	4955064.933	140.228	.000
Error	4240291.333	120	35335.761		
Total	3130253901.000	180			
Corrected Total	1008007544.194	179			

R Squared = 0.996, adjusted R Squared = 0.99, significance level p=0.05

Table 6. Univariate ANOVA results for blended cement laterized concrete.

Dependent Variable: Resistivity

Source	Type III Sum of Squares	*df*	Mean Square	*F*	Sig.
Corrected Model	2040372430.122[a]	119	17145986.808	434.915	.000
Intercept	5320664977.878	1	5320664977.878	134960.762	.000
w-b ratio	160075425.506	2	80037712.753	2030.188	.000
Mix (SDA, laterite)	540706908.389	7	77243844.056	1959.321	.000
Curing	550901403.761	4	137725350.940	3493.458	.000
w-b ratio * mix	403022369.828	14	28787312.131	730.202	.000
w-b ratio * curing	25300341.772	8	3162542.722	80.219	.000
mix * curing	174279559.972	28	6224269.999	157.881	.000
w-b ratio * mix * curing	186086420.894	56	3322971.802	84.288	.000
Error	9461710.000	240	39423.792		
Total	7370499118.000	360			
Corrected Total	2049834140.122	359			

a. R Squared = 0.995, adjusted R Squared = 0.993, significance level p=0.05

Table 7. Univariate ANOVA results for blended cement laterized concrete exposed to chloride ions.

Dependent Variable: Resistivity

Source	Type III Sum of Squares	*df*	Mean Square	*F*	Sig.
Corrected Model	2471098784.998[a]	191	12937689.974	385.934	.000
Intercept	7322788246.671	1	7322788246.671	218440.493	.000
w-b ratio	121762700.847	2	60881350.424	1816.105	.000
Mix (SDA, laterite)	472689447.984	7	67527063.998	2014.348	.000
Chloride	606444066.769	3	202148022.256	6030.123	.000
Curing	13989781.752	1	13989781.752	417.318	.000
w-b ratio * mix	666290802.208	14	47592200.158	1419.687	.000

Dependent Variable: Resistivity

Source	Type III Sum of Squares	*df*	Mean Square	*F*	Sig.
w-b ratio * chloride	20576840.736	6	3429473.456	102.302	.000
w-b ratio * curing	6483224.222	2	3241612.111	96.698	.000
mix * chloride	204215511.523	21	9724548.168	290.086	.000
mix * curing	15837016.679	7	2262430.954	67.489	.000
chloride * curing	74549371.880	3	24849790.627	741.275	.000
w-b ratio * mix * chloride	155038680.764	42	3691397.161	110.115	.000
w-b ratio * mix * curing	53167007.389	14	3797643.385	113.285	.000
w-b ratio * chloride * curing	1949610.083	6	324935.014	9.693	.000
mix * chloride * curing	18734507.078	21	892119.385	26.612	.000
w-b ratio * mix * chloride * curing	39370215.083	42	937386.073	27.962	.000
Error	12872845.333	384	33523.035		
Total	9806759877.000	576			
Corrected Total	2483971630.332	575			

R Squared = 0.995, adjusted R Squared = 0.992, significance level p=0.05

Table 8 shows the correlation analysis which depicts the magnitude of influence of each material component on the workability. The italicized values show significant correlation. The Pearson correlation coefficients help to establish the relationship between the variables (such as slump versus SDA/laterite content, w-b ratio, SP content), that is, the strength of association between them in pairs. The laterite tends to negatively impact the slump more than the SDA and w-b ratio. This can imply that the laterite has more affinity for water than the SDA while the superplasticizer tends to positively improve the workability more than the water content. Furthermore, correlation analysis was carried between the electrical resistivity and the considered parameters (Table 9). The number of samples (N) represent specimens tested with unique values/result used in the correlation analysis. Table 9 reveals that curing age (out of all the parameters) have the highest impact on the ER except when it is exposed to chloride ion where the concentration of the ion influences more than the exposure time. Generally, SDA and laterite inclusion negatively affects the ER while the w-b ratio seems to positively influence the ER. It should, however, be noted that this positive influence is only significant for concrete containing both SDA and laterite (including exposure to chloride ion).

Table 8. Pearson correlation analysis of the parameter influencing the workability.

	SDA content	laterite content	w-b ratio	SP* content
Slump	-0.304	-0.576	+0.315	+0.651

* SP – superplasticizer, number of samples (N) = 24, significance level p=0.05

Table 9. Pearson correlation analysis of the parameter influencing the electrical resistivity.

		Mixes				
		SDA content	laterite content	w-b ratio	curing age	% NaCl
Laterized concrete	ER	–	-0.124	+0.037	+0.707	–
SDA blended concrete	ER	-0.421	–	+0.097	+0.548	–
SDA blended laterized concrete	ER	-0.364		+0.276	+0.505	–
SDA blended laterized concrete in NaCl	ER	-0.277		+0.220	-0.075	-0.457

* SP – superplasticizer; number of samples (N) = 90, 180, 360, 576 respectively; significance level p=0.05

Various Duncan multi range test results are shown in Table 10 to observe the average ER within each considered parameter. This statistics helps to reinforce the general inductions (from the previous sections) that increased curing improved the ER of the concrete, increased w-b ratio decreases the ER, increased SDA content reduces the ER; and that in the presence of chloride ion, latertie improves the ER of concrete while the further inclusion of SDA reduces the positive impact of the laterite. Furthermore, increased concentration of chloride ion reduces the ER of concrete.

Table 10. Duncan multi range test results.

Water curing						Chloride ion exposure			
Curing age		Water-binder ratio		SDA content		SDA and laterite		NaCl concentration	
N = 18		N = 30		N = 45		N = 72		N = 144	
Mean	Age	Mean	w-b	Mean	% SDA	Mean	Mixes	Mean	% NaCl
87.91	88 days	75.40	0.35	53.50	0%	50.2	CL	52.65	0%
75.47	58 days	49.64	0.5	33.05	10%	49.33	C	34.13	1%
54.20	28 days	46.88	0.65	26.88	20%	31.88	CS	30.13	3%
40.31	14 days			23.89	30%	30.00	CLS	25.68	5%
28.65	7 days								

4. Conclusion

The goal of this study is to examine the electrical resistivity (ER) of concrete. The concrete was modified with laterite as partial replacement of sand and saw dust ash (SDA) as a supplementary cementitious material (SCM). Effects of other factors such as w-b ratio, curing age, chloride ion exposure and concentrations. The following conclusions can be made from the results.

- Increased curing, hence, hydration increases the ER of concrete. The influence of w-b ratio on normal concrete, SDA blended cement concrete, laterized concrete and SDA blended cement laterized concrete were varied. A w-b ratio of 0.5 seemed favourable for normal and laterized concrete while 0.35 seemed the optimum for SDA blended cement concrete and SDA blended cement laterized concrete.
- Inclusion of laterite in concrete can improve the ER at higher water content. SDA has little or no potential to improve the ER of concrete at early age but can yield similar results at later age and reduced water content. However, inclusion of both laterite and SDA in concrete can potentially improve the ER at lower water content.
- The use of laterite in normal or blended cement concrete seems to stabilise the concrete against chloride ion exposure, especially at increased water content. That is, the laterite yielded better ER than the control in NaCl solution.
- Statistical analysis showed that, generally, the laterite tends to have more affinity for water than the SDA; increased curing increases ER, water content reduces ER, SDA reduces ER, chloride ion reduces ER while the laterite improves ER in the presence of chloride ion.

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