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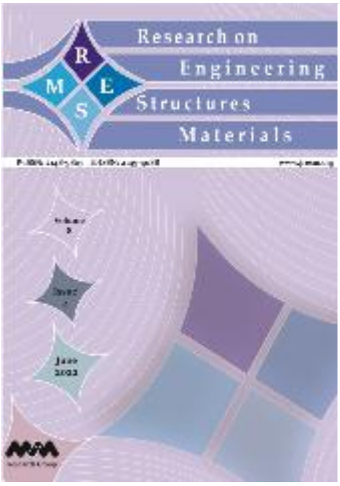

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Research Article

Strength and durability assessment of laterized concrete made with recycled aggregates: A performance index approach

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Abstract

The use of recycled aggregates (RAs) for concrete promotes circular construction while the introduction of lateritic soil (LS) seeks cost reduction in concrete production. This study reports the results of experiments on partial replacement of (i) Akure-pit sand (APS) with recycled fine aggregate (RFA); (ii) RFA with LS; (iii) APS with LS; and (iv) crushed granite (CG) with recycled coarse aggregate (RCA). Replacement levels were from 0% to 70% in steps of 10%. Major tests were compressive strength and sorptivity. The performance index approach was employed to obtain the best performance indices for various material combinations. The results revealed that at 28 days of curing, concretes attained optimum compressive strengths of 15 N/mm^2, 15.1 N/mm^2, 13.1 N/mm^2, and 16.8 N/mm^2, respectively for mixtures produced by partially substituting APS with 70%RFA; RFA with 40%LS; APS with 50%LS; and CG with 50%RCA. The sorptivity was optimal at 2.69×10^{-4} $mm/min^{0.5}$; 3.58×10^{-4} $mm/min^{0.5}$; 3.16×10^{-4} $mm/min^{0.5}$; and 2.86×10^{-4} $mm/min^{0.5}$, respectively for mixtures with partial replacement of APS with 30%RFA; RFA with 40%LS; APS with 40%LS; and CG with 10%RCA. This research will find practical application in construction works utilizing LS and RAs when optimal replacement levels of the conventional aggregates are required, in order to achieve predetermined performance criteria.

1. Introduction

The environmental impact of mining fine and coarse aggregates used in making concrete and the sustainability of the same for concrete production have been called into question in recent times [1]. Therefore, many researchers have begun to investigate the use of construction and industrial waste and by-product materials for concrete production [2-6]. Studies by Ke *et al.* [7] have shown that certain high-quality wastes reduce the cost of producing concrete, improve its durability, as well as mitigate alkali-silica interaction, cracking in mass concrete, and shrinkage-induced cracking. Some of these wastes may chemically react with calcium hydroxide when finely ground and in the presence of water to create compounds that have cementing capabilities comparable to those created during the cement hydration process. Some others are used as alternatives (in full or partial substitution) to the conventional aggregates used in concrete [8]. Some of the wastes used as alternative aggregates include recycled concrete aggregate (RCA) and lateritic soil (LS) [9-12].

Laterite has been identified as a viable supplementary material or alternative to conventional sand [13-14]. This material is readily available in sub-Saharan Africa as a product of weathering. The most popular and widely accepted application of laterite is as bedding material in road pavement construction and brick production. These days,

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researchers are beginning to investigate more productive and effective ways of making durable concrete with laterite. According to Gowda *et al.* [15], a concrete mix where laterite has been used to partially or fully replace river sand is known as laterized concrete. Udoeyo *et al.* [16] assert that substituting sand with laterite can increase the concrete's workability. However, the workability of concrete made from unprocessed laterite is considerably lower than that made from processed laterite [15]. Ettu*et al.* [17], after conducting compressive strength tests on a total of 120 standard 150 mm concrete cubes, concluded that laterite could be used as the sole fine aggregate in structural concrete, entirely replacing sand in each concrete mix. This conflicts with the results of many other researchers who, after their independent experimental-based research, concluded that laterite only has a positive influence on concrete compressive strength up to a certain level [16, 18]. According to Mathew *et al.* [18], laterite can replace 20-40% of sand without affecting the concrete's strength. Balogun and Adepegba [19] as cited by Awoyera *et al.* [20] postulated that the ideal mix (batching by weight) for laterized concrete was 1:1.5:3, provided that the laterite is kept below 50% of the total aggregate content. Laterite is composed mostly of sand, clay, and silt, and its redness in colour is caused by the presence of iron oxide [21-22]. The presence of clay and silt in the laterite particles may make it fall short in the production of high-quality concrete requirements as laid out in BS 882 (1992). Consequently, the clay and silt particles are usually washed off during processing [17]. Onakunle *et al.* [23] corroborated this inference by stating that the strength and stability of lateritic soil cannot be guaranteed under high load and moisture when it has a lot of clay constituents. The suitability or otherwise of laterite as the sole fine aggregate in concrete would depend on the amount of fine particles present in the laterite [17]. According to Osunade [13], as cited by Joshua *et al.* [24], the fineness of the grain size positively correlates with the compressive strength of concrete samples made from laterite. They also opined that the compressive strength of lateritic soil might be hugely related to where the material was collected from. This is based on the premise that different formation processes must have occurred at various source sites [24]. Osadebe & Nwakonobi [25], as cited by Tijani and Mustapha [26], stated that the consistency achieved during mixing might also have a huge influence on the laterite's compressive strength. Batha *et al.* [26] studied the influence of replacing natural sand with polyethylene terephthalate waste up to 50%. It was observed that replacing natural sand generally reduces the strength properties of the concrete beam.

Furthermore, according to Silva *et al.* [27], construction and demolition waste (C&DW) are viable alternative aggregates to conventional materials for low-cost green concrete production. One such C&DW is the recycled concrete aggregate (RCA) being explored for concrete production [28-33]. RCA collected from construction and demolition sites is a viable solution to depleting natural aggregates in various parts of the world [34]. Only aggregates collected from demolition sites and processed into coarse (>5mm) aggregates are known as recycled coarse aggregate (RCA) [35-36]. If processed into fine (<5mm) material, it is known as recycled fine aggregate (RFA) [37]. Dhir OBE *et al.* [38] provide a detailed overview of the properties and composition of recycled aggregates. The demolition quality, and how the aggregate was sorted may determine RCA properties [29, 39]. The properties of the RCA would also depend on that of the parent concrete. Proper design parameters must be adopted to make the properties of RCA comparable with what is obtainable using natural aggregates. Still, the replacement percentage should not be more than 30% to avoid adverse effects on the concrete properties [40].

Many studies have explored using different techniques to obtain RCA properties equivalent to their natural aggregate counterparts [41-43]. It has been reported that concrete containing 30% RCA could perform as well as concrete made from natural aggregates and even better [44-45].

Some researchers Mirjana *et al.* [46] as cited by Khalid *et al.* [47] obtained their recycled concrete aggregates from crushed precast concrete columns and laboratory test cubes. According to Mirjana *et al.* [46], high-quality aggregate does not affect the strength properties of concrete regardless of the replacement levels adopted. In the same vein, the curing condition does not have a considerable effect on the compressive strength of concrete (Fonseca *et al.* [48] as cited by Abdel-Hay [49]). For RCA to be considered acceptable, it must meet a list of criteria. These include an optimum water absorption not greater than 3%, an aggregate relative density of 2.3% or more, and optimum mortar content of not greater than 50% (Butler *et al.* [50] as cited by Zheng *et al*. [51]). On recycled aggregate concrete (RAC), numerous investigations have been conducted [9, 52-61]. Batha *et al*. [62] performed a thorough analysis of the physical and mechanical characteristics of concrete using a 0.1% constant dose of glass fiber and partial replacements of the cement with fly ash up to 40% and sand with pond ash up to 20%. It was determined that the addition of fly ash and pond ash to concrete could generate strong concrete that was also reusable and durable while using less sand, cement, and energy. In another study, Batha *et al*. [63] proposed a mix design method that uses the dense particle packing arrangement principle to create sustainable concrete by partially substituting fly ash and pond ash for cement and sand. It was concluded that using a method of packing density to replace natural sand with pond ash lowers material consumption and building costs while maintaining a clean, green environment without sacrificing strength and durability.

Although studies have been conducted on the utilization of laterite, RFA, RCA, and APS separately as sand and coarse substitutes in concrete, there had yet to be any published research on the combined influence of these constituents on either freshly poured or hardened concrete. On the use of materials as a partial sand replacement in concrete mixtures, there were no specifications. These replacement levels have usually been chosen to enhance concrete performance based majorly on personnel knowledge and experience with the material. It is therefore imperative to design a technique that could enable professionals to make an informed decision on the appropriate levels of replacement for desired performance. Additionally, the study sought to determine the quality of conventional concrete using a performance index (PI) approach to choose the appropriate substitution rate and maximize each mixture's unique properties. Therefore, the overall aim of this research is to obtain the optimal combinations of LS, RFA and RCA that could substitute appropriate fractions of Akure pit sand (APS) and coarse granite (CG) to obtain low-cost and durable green concrete while offering essentially the same strength as when only conventional aggregates are used. Utilizing LS, RFA, and RCA wastes would not only encourage the sustainability of building materials but also contribute to the reduction of landfill sites and environmental degradation.

2.Experimental Strategy

2.1. Materials Adopted

The coarse granite (CG), recycled coarse aggregate (RCA), recycled fine aggregate (RFA), lateritic soil (LS), Akure pit sand (APS), cement and water were the materials used. In order to produce concrete, locally purchased grade CEM 1 42.5R ordinary Portland cement (OPC) conforming to BS 12 [64] was utilized. The oxide content of the cement is displayed in Table 1. In order to assess the actual level of fineness, OPC was allowed to pass through a filter with a 90 μm opening. The CG and APS were obtained in the Akure metropolis and processed in accordance with BS EN 933-11 [65]. In order to comply with BS 882 criteria, the APS underwent a comprehensive sieving process to reduce its impurity and organic material levels [66]. The aggregates were guaranteed to meet the requirements for the medium grading zone [67]. The maximum size of the fine aggregate was 4.75 mm, while the maximum size of the coarse aggregate was 12.5 mm. The laterite was obtained from a borrow pit in Akure, Southwest Nigeria. The RCA and RFA were obtained from the demolitions of an existing building at Jibowu Crescent, Iyaganku GRA, Ibadan also in the Southwest region of Nigeria. The RCA was manually crushed to the desired particle size of the maximum aggregate size of 12.5 mm with the aid of a rubber hammer. The RFA was also carefully processed to conform with the recommendations of BS EN 933-11 [64]. The impact value and particle size distribution of laterite, RFA, and RCA are all in agreement with BS EN 933-11 [65] and BS EN 933-1 [67]. The various aggregates as well as the OPC used in the investigation are shown in Fig. 1.

Table 1. Chemical composition of the cement

Oxide composition	CaO	SiO_2	Fe_2O_3	Al_2O_3	SO_3	Na_2O	MgO
Cement (%)	61.52	21.02	3.28	5.78	2.04	0.78	2.08

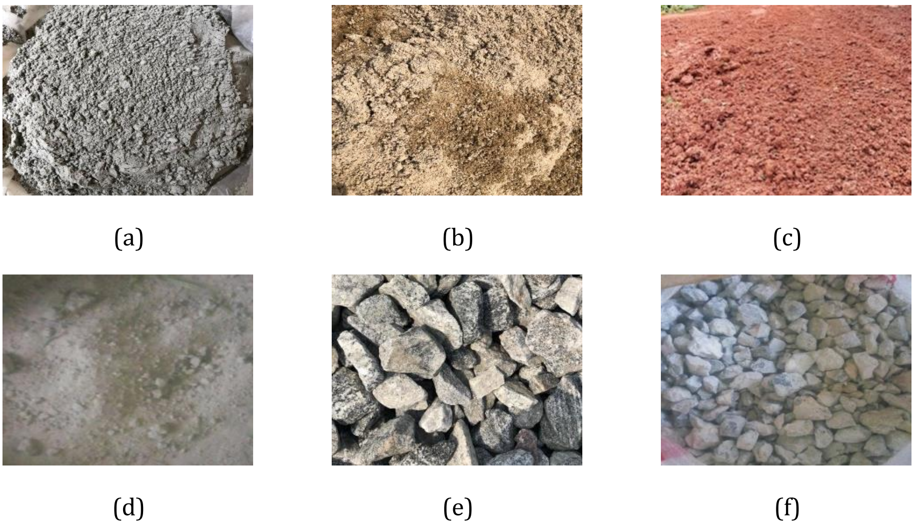

Fig. 1. (a) Cement (b) APS (c) LS (d) RFA (e) CG) (f) RCA

Aggregates' specific gravity should be between 2.30 and 2.90, according to ACI [68]. Therefore, laterite, RCA, and RFA all have specific gravity values that are within the acceptable range, making them acceptable for use in concrete. Table 2 presents some calculated properties of aggregates used while the gradation of the aggregates curves and BS EN 933-1 [67] classification are shown in Fig. 2. The aggregates used were found to satisfy the BS requirements. Furthermore, RCA and CG showed similar particle grading in much the same way as the particle gradings of RFA, LS and APS were similar. Both mixing and curing water adhere to BS 3148 [69]. It was determined that there were no sulfate, ferric, alkaline soils, vegetation, or salt present that would have an impact on the qualities of fresh or solidified concrete.

2.2. Proportioning of Concrete Mixtures

The performance of concrete was investigated using four distinct mixtures. The first mix was created by partially replacing APS with RFA at proportion rates of 0% to 70% in steps of 10%; the second combination was made by completely replacing APS with RFA and then partially replacing RFA with LS from 0% to 70% in steps of 10%; the third concrete specimens were formed by partially replacing APS from 0% to 70% in steps of

10%, with lateritic soil; and the final concrete mixture was created by partially replacing coarse granite with RCA at proportion levels of 0% to 70% in steps of 10%. Table 3 lists the precise material proportioning for the concrete mixture utilized in this study. Thirty (30) mixtures in total were prepared, as depicted in Table 3, and their workability, compressive strength and sorptivity were evaluated.

Table 2. Physical properties of aggregates and binders

Physical properties	Binder	Fine aggregate			Coarse aggregate	
	OPC	APS	RFA	LS	CG	RCA
C_u	-	2.18	2.45	2.95	2.50	4.36
C_c	-	1.88	1.67	2.25	1.60	1.91
Specific gravity	3.09	2.70	2.62	2.65	2.70	2.63
Shape	-	-	-	-	Angular	Angular
ACV (%)	-	-	-	-	21.02	20.3
AIV (%)	-	-	-	-	19.85	19.85
Moisture content (%)	-	7.20	5.16	12.5	2.12	3.16
Maximum aggregate size(mm)	-	4.75	4.75	4.75	12.75	19.00
Bulk density (kg/m^3)	-	2682	2138	1630	-	-
Liquid limit (%)	-	-	-	28.20	-	-
Plastic limit (%)	-	-	-	12.10	-	-
Shrinkage limit (mm)	-	-	-	3.00	-	-

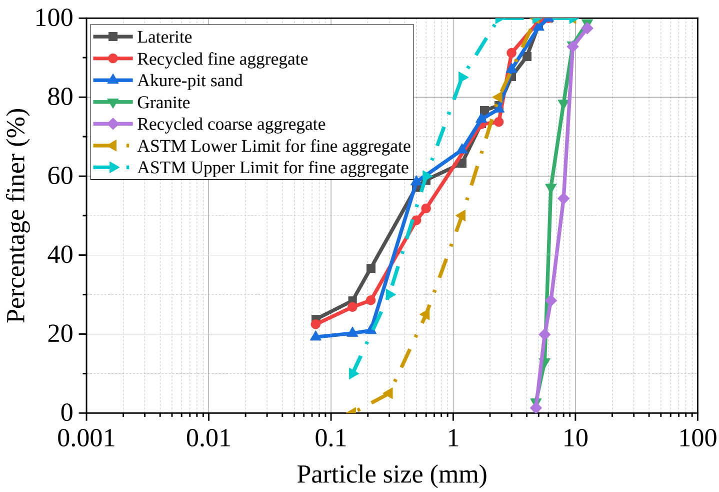

Fig. 2. The grain size distribution of aggregates

2.3. Testing of Concrete Samples

With a water-to-cement ratio (w/c) of 0.53, cement, fine aggregate, and coarse aggregate were all mixed by weight. In order to achieve the desired strength class C15/20, concrete with cement grade 42.5 was employed. The fine and coarse aggregates were first mixed for about five minutes. For roughly 3 to 6 minutes, the cement was vigorously dry-mixed after being added gradually. For about 8 minutes, the mixture was slowly stirred after the addition of the mixing water, until a homogeneous composition became apparent. Before being placed in the necessary moulds in accordance with BS EN, 12350-2 [70], the fresh property of the concrete, such as slump, was tested in accordance with 1881: Part 102 [71]. The fresh concrete was poured into the 150 mm standard concrete cubic moulds, which had been lubricated with used engine oil to ensure easy demoulding and smooth surface before pouring. The compaction was done manually in about three equal layers for the cube specimens at an average depth of 50 mm and at each layer 25 blows was given using standard rod. The casting was carried out as per the requirements of BS EN, 12390-2 [70]. After 24 hours, the concrete was removed from the moulds and cured in the curing tank, following BS 12390 [72]. At each hydration time at 7 days, 14 days, 28 days, and 56 days, three specimens of concrete cubes produced from each of the concrete mixes were removed from the curing tank, weighed, tested, and recorded for compressive strength. The ELE 2000 compressive strength machine with a loading rate of 6800 N/s was employed. To measure concrete resistance to exposure to aggressive environments, the sorptivity test is adopted. The recommendation of ASTM C1585-13 [73] standard was followed to conduct the sorptivity test. After 7, 14, 28, and 56 days of curing, standard test samples of 100 mm diameter disc with a height of 50 mm were prepared. The samples were immersed in water with a water level not more than 3 mm above the base of the specimen. By appropriately sealing the peripheral surface with a non-absorbent coating, the flow from the peripheral surface is stopped. The amount of water absorbed over 30 minutes was determined by weighing the specimen on a top pan balance. Each weighted operation was finished in 30 seconds after surface water on the specimen was wiped away using a dampened cloth.

2.4. Performance Assessment of Concrete Mix Properties

It is frequently important to show data from different experimental schedules at the same time, as well as a statistical assessment of how concrete performance evolves. That is exactly what the performance index strategy accomplishes. It is a management tool that enables the compilation of multiple pieces of data into a single overall metric. This section explains how to use this technique to create a concrete mixture performance index. The performance indexes work on a simple principle: it condenses a large amount of data into a single number. When working with a small number of indicators, it is known that performance indicator (*PI*) relates data in an easy-to-comprehend format [74-75].

Therefore, the performance index technique is adopted as the improved model for the current study to assess the behaviour of concrete with a portion of Akure-pit sand (APS) and crushed granite (CG) replaced with lateritic soil (LS) and recycled aggregates (RAs) respectively. The details of concrete mixture proportions are given in section 2.2. Moreover, the suitable replacement level is selected using the performance index method. In this study, three performance indicators were selected which are compressive strength and sorptivity. The first step of this approach is to determine the weight rating for each performance indicator (θ_i) using Eq. (1). The highest individual performance indicator (e.g., compressive strength) has a 1.00 weight rating and other compressive strengths are rated relative to the highest compressive strength [74].

$$\theta_i = \frac{p_o}{p_h} \tag{1}$$

where p_o and p_h are respectively, the observed performance (i.e., performance indicator such as compressive strength, and sorptivity) for each concrete mixture and the highest observed performance.

The numeric index (ψ_i) is then determined using Eq. (2), such that the highest numeric index is set to be 5. Therefore, each weight rating of the individual performance indicator is multiplied by the highest numeric rating [75].

$$\psi_i = 5\theta_i \tag{2}$$

Table 3. Concrete mixture proportions per cubic metre (kg/m[3])

Percentage replacement			Fine aggregate			Coarse aggregate		Cement	Water
RFA (%)	LS (%)	RCA (%)	APS	RFA	LS	CG	RCA		
0	-	-	498.80	-	-	1220	-	425	225
10	-	-	448.92	49.88	-	1220	-	425	225
20	-	-	399.04	99.76	-	1220	-	425	225
30	-	-	349.16	149.64	-	1220	-	425	225
40	-	-	299.28	199.52	-	1220	-	425	225
50	-	-	249.40	249.40	-	1220	-	425	225
60		-	199.52	299.28		1220	-	425	225
70		-	149.64	349.16		1220	-	425	225
	0	-	-	498.80	-	1220	-	425	225
-	10	-	-	448.92	49.88	1220	-	425	225
-	20	-	-	399.04	99.76	1220	-	425	225
-	30	-	-	349.16	149.64	1220	-	425	225
-	40	-	-	299.28	199.52	1220	-	425	225
-	50	-	-	249.40	249.40	1220	-	425	225
-	60	-	-	199.52	299.28	1220	-	425	225
	70	-	-	149.64	349.16	1220	-	425	225
-	10	-	448.92	-	49.88	1220	-	425	225
-	20	-	399.04	-	99.76	1220	-	425	225
-	30	-	349.16	-	149.64	1220	-	425	225
-	40	-	299.28	-	199.52	1220	-	425	225
-	50	-	249.40	-	249.40	1220	-	425	225
-	60	-	199.52	-	299.28	1220	-	425	225
-	70	-	149.64	-	349.16	1220	-	425	225
-	-	10	-	-	-	1098	122	425	225
-	-	20	-	-	-	976	244	425	225
-	-	30	-	-	-	854	366	425	225
-	-	40	-	-	-	732	488	425	225
-	-	50	-	-	-	610	610	425	225
-	-	60	-	-	-	488	732	425	225
-	-	70	-	-	-	366	854	425	225

Based on the essential performance indicators (*j* indicators), the associated ψ_i are multiplied to obtain a mixture score, (*PI)*ij as specified in Eq. (3).

$$(PI)_{ij} = \psi_{i1} \times \psi_{i2} \times \dots \psi_{ij} \tag{3}$$

The inference from Eq. (3) is that the strength of weighted combinations can help in deciding how to distribute scarce resources. In terms of the relevant necessary numerous indicators, the combination receiving the highest score is the best acceptable mixture. The technique for selecting the right replacement amount to optimize the mixture's unique features to obtain the target performance indicator is briefly represented in the flowchart in Figure 3.

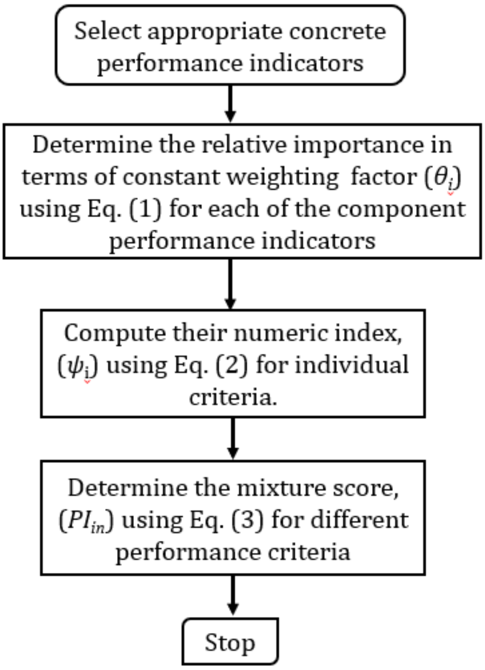

Fig. 3 Optimum concrete mixture based on specific performance criteria

3. Results and Discussion

3.1. Workability of the Concrete

In order to assess how easily and uniformly newly prepared concrete can be poured, compacted, and finished, the concrete's workability was determined. The slump test was used to evaluate flowability. The slump results for each blend are shown in Fig. 4. It was noted that for all the mixtures, the relative value of the slump often increases as the proportion of replacement increases. The moisture content in the aggregate may be the reason for this. Additionally, it was shown that concrete samples made when APS was partially replaced with LS had slump values that were higher than the control mix. This suggests that adding LS alters the cohesiveness of the mixtures, which in turn influences how well they flow. This finding agrees with research findings by Gowda *et al*. [15] and Udoeyo *et al.* [16].

From Fig. 4, the slump values for concrete with LS replacing APS and RFA are generally lower compared to other mixtures. This could be due to the dry surface of RFA and the fact that the presence of kaolinites and illites in LS requires more water to increase the plasticity [22] and workability. The slump value of the concrete mixture when APS is partially substituted with RFA, ranges from 75 mm to 75.5 mm. The slump value of the concrete mixture when APS is partially replaced with LS ranges from 75 mm to 90 mm. The slump value of the concrete mixture when RFA is partially replaced with LS ranges from 74 mm to 75 mm. A relatively lower value was observed in this particular concrete mixture due to the potential of RFA to soak up more water. The slump value of the concrete mixture when CG is partially replaced with RCA ranges from 75 mm to 76 mm. This suggests that all of the mixtures have a medium slump, which was designated by British standards as the most practical and often prescribed consistency. The findings of this research indicate that the optimum percentage replacement of APS with RFA; APS with LS; RFA with LS; and CG with RCA were 20%, 40%, 40%, and 50% respectively.

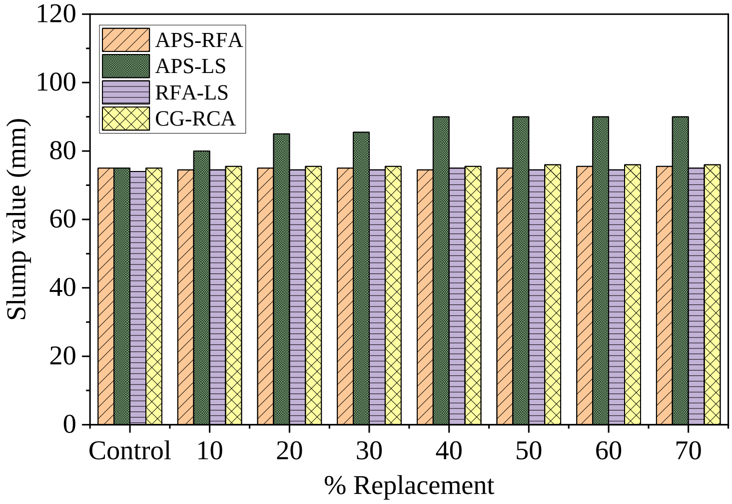

Fig. 4. Slump values of different fresh concrete mixes with varying replacement levels.

3.2. Compressive Strength

Figs. 5 to 8 for the various concrete mixtures illustrate the impact of LS, RFA, and RCA as partial substitutes of APS and CG, on the progression of compressive strength at 7, 14, 28, and 56 curing days. The impact of curing period on concrete compressive strength is typically shown by a steady rise in compressive strength as the curing period increases. From Fig. 5, at maturity ages of 7, 14, 28, and 56 days, the compressive strength of concrete mixtures with RFA replacing APS up to 70% was lower than the control. The reduction ranged from 5.05% with 70%RFA at 14 days to 40.43% with 10%RFA at 7 days when compared with the control mixture (i.e., without RFA). The optimum mix proportion of 70%RFA, which is greater than control mixture by 7.12% at 28 days, can be recommended. According to Fig. 6, the compressive strength of concrete mixtures with LS replacing RFA up to 70% was lower than the control (i.e., the reduction ranges from 3.94% with 40%LS at 14 days to 46.20% with 50%LS at 28 days) at 7, 14, 28, 56 days. When contrasted to the control mixture, at 28 days maturity, the optimum mix proportion of 40%LS is greater by 4.43% and therefore, can be recommended. According to Fig. 7, the compressive strength of concrete mixtures with LS substituting APS up to 70% was lower than that of the control mixture (i.e., without LS) at 7, 14, 28, 56 days (i.e., the loss ranged from 3.45% with 10% LS at 56 days to 39.72% with 70% LS at 7 days). With a difference of 18.89% as contrasted to the control mixture, the optimum mixture percentage of 50%LS can be proposed at 28 days. The high silt/clay proportion observed in Laterite and APS (Fanijo *et al*. [22] and Olanitori and Afolayan [76]), as seen in Fig. 7, may be the cause of the weakening of all concrete compositions. The maximum silt/clay content recommended by ASTM C33 is given to be 10%; meanwhile, for the fine aggregates used, the silt/clay content ranges between 20.20% to 28.48%. This type of fine aggregate is commonly used in most building constructions within the metropolis. This could result in poor adhesion between the concrete composites. However, in a concrete mixture where LS partially replaced RFA; a reduction in compressive strength was observed as laterite content increases up to 10% in the composite matrix, and thereafter a sudden increase in strength was observed, followed by a gradual reduction. A similar trend was noticed in the concrete mixture in which LS partially replaced APS; the reduction in compressive strength was observed as laterite content increased up to 40% in the composite matrix, after which a sudden rise in strength was observed, before a gradual reduction in strength. This behaviour could be attributed to the poor workability of concrete produced with laterite and RFA. Poor workability makes compaction more difficult, which could have resulted in larger voids and a drop in compressive strength. This result is also consistent with the studies by Ettu *et al.* [17] and Muthusamy and Kamaruzaman [77]. Furthermore, the larger replacement levels of sand with laterite result in lower density than natural sand, resulting in reduced strength. Also, from Fig. 8, at 7, 14, 28, and 56 days of age, the compressive strength of concrete mixtures with RCA replacing CG up to 70% was significantly high only at the replacement level of 50%RCA for all curing ages. However, a relative reduction in strength (i.e., a reduction ranging from 6.96% to 34.03%) when compared with the control mixture (i.e., without RCA) was noticeable in other concrete mixtures. The variation in the water absorption capacity of the aggregates used could potentially be a factor in the loss of compressive strength. A drop in strength could be because of the amount of the adhered mortar on the RCA and poor compaction. The optimum mix proportion of 50%RCA can be recommended at 28 days with an increase in strength of 6.39% when contrasted with the control mixture.

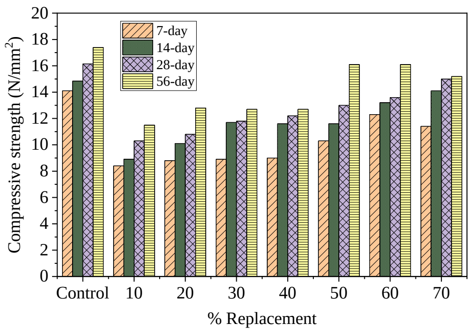

Fig. 5. Compressive strength development of concrete for partial substitution of APS with RFA.

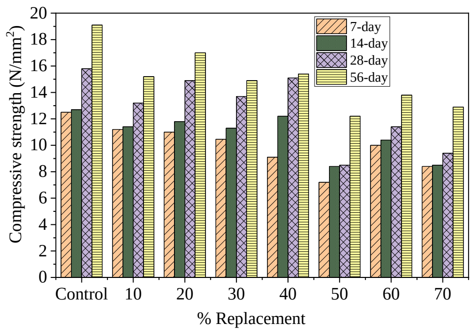

Fig. 6. Compressive strength development of concrete for partial substitution of RFA with LS.

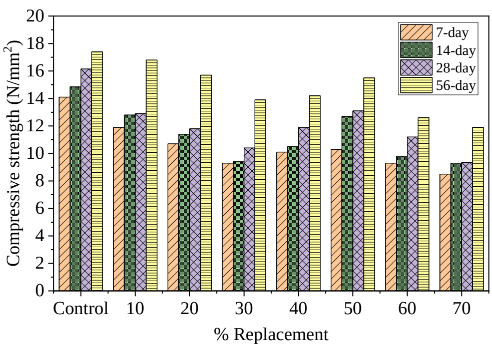

Fig. 7. Compressive strength development of concrete for partial substitution of APS with LS.

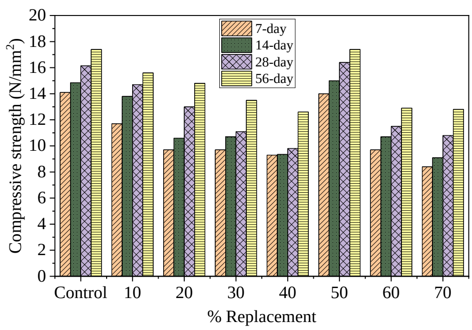

Fig. 8. Compressive strength development of concrete for partial substitution of CG with RCA.

3.4. Outcome of Sorptivity Test

Workability, compressive strengths, durability, and other qualities of fresh and hardened concrete are all influenced by the water content in the matrix and cracking propensity. In other words, to a considerable degree, the penetrability of the pore system determines the performance of concrete in a variety of harsh situations. Figs. 9 to 12 show the variation in the sorptivity with curing age and different concrete mixture proportions. Generally, all the concrete mixtures performed well at prolonged curing age. From Fig. 9, the sorptivity was found to be decreasing at early curing ages for up to 30%RFA replacement. This could be a result of the unsaturated poor formation of the concrete pattern. However, an increase was observed at a substitution level of 30%RFA, after which, the trend continued up to 70%RFA replacement. Considering the long-term application of this type of concrete mixture, a 40%RFA was found to be capable of performing well in an aggressive environment. As seen in Fig. 10, the rate of absorption increases as the curing age increases. This could imply that the pore structure has achieved a fully saturated state. The optimum mix proportion of 30%LS for partial replacement of RFA can be recommended to withstand harsh conditions. From Fig 11, it can be seen that the lower sorptivity ability of these concrete samples may be due to the high silt/clay content preventing the absorption of the water as the laterite requires high water content to be worked upon. This is also evident in the sorptivity value of the mixture in the early curing days. The optimum mix proportion of 70%LS for partial replacement of APS can be recommended to withstand harsh conditions. From Fig. 12, it was observed that the sorptivity increases in the concrete samples as both curing age and percentage replacement increase. This implies that the dry saturation condition of the RCA may be responsible for the high sorptivity behavior when CG was replaced beyond 10%RCA. The optimum mix proportion of 10%RCA for partial replacement of CG can be recommended to withstand harsh conditions.

3.5. Performance Evaluation of Concrete Mixture

The outcomes of the application of the performance index technique are presented in Tables 4 to 11. This method was used to further assist in the selection or identification of optimum concrete mixtures with different performance indicators in the hardened state. The selected properties of the concrete used in this section are critical for particular application to meet construction and design criteria, hence the different best combination with compressive strength, and sorptivity could be chosen. For applications that require compressive strength and sorptivity, PI(1), (see Table 12), the use of 60%RFA to replace APS in the concrete mixture will best meet this performance condition. From Table 7, it can be seen that, for the best performance criteria, in the case where the application requires compressive strength and sorptivity, PI(1), the incorporation of 20%LS replacing RFA in the concrete will be suitable. In a case where the LS is replaced with APS and the compressive strength and sorptivity are required as the performance criteria as presented in Table 9, the use of 50%LS can be recommended. From Table 11, it can be seen that the use of 50%RCA to replace CG in the concrete mixture will meet performance condition PI(1) when compressive strength and sorptivity are required. According to the performance index technique, LS and RAs (i.e., RFA and RCA) can be used as a partial substitution for fine and coarse aggregates in concrete mixtures that satisfy prescribed performance requirements. The amount of the LS and RAs will vary depending on the needed performance characteristics of the blend, which will be application specific. From the foregoing discussion, the performance index approach has been suitably used as a powerful tool to combine multiple data values into a single measure while simplifying the selection procedure.

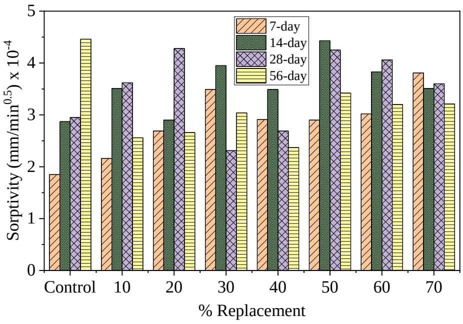

Fig. 9. Sorptivity value of concrete for partial replacement of APS with RFA

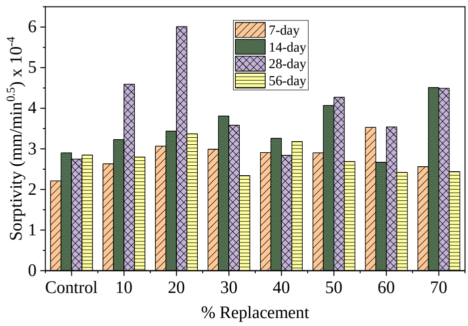

Fig. 10. Sorptivity value of concrete for partial replacement of RFA with LS

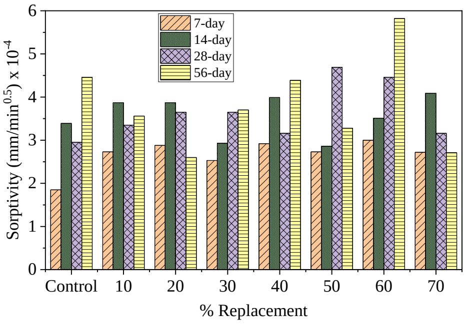

Fig. 11. Sorptivity value of concrete for partial replacement of APS with LS

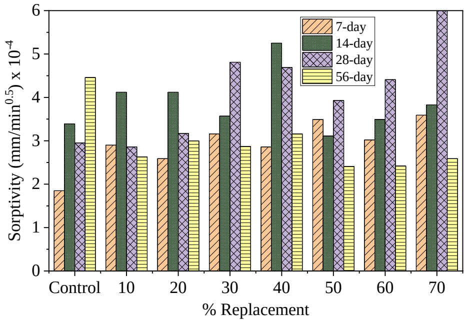

Fig. 12. Sorptivity value of concrete for partial replacement of CG with RCA

4. Concluding Remarks

This study reports the strength and durability behaviours of laterized concrete produced with recycled aggregates, RAs as a substitution for Akure-pit sand, and crushed granite using the performance index strategy. A comprehensive series of experimental tests were executed to assess its mechanical and durability performance. The results of this study led to the following conclusions:

- The flowability of the concrete made with the optimum percentage replacement of APS with RFA; APS with LS; RFA with LS; and CG with RCA at 20%, 40%, 40%, and 50% respectively were found to be satisfactory.
- The concretes made using 70%RFA to partially replace APS; 40%LS to partially substitute RFA; 50%LS to partially replace APS and 50%RCA to partially substitute CG have optimum compressive strengths of 15 N/mm^2; 15.1 N/mm^2; 13.1 N/mm^2; and 16.8 N/mm^2 at 28 days curing age, respectively. All the values satisfy the strength requirement for concrete of 15N/mm^2 characteristic strength, except for the concrete in which LS is used to partially replace APS.
- The concretes made by employing 40%RFA to partially replace APS; 30%LS to partially substitute RFA; 70%LS to partially replace APS and 10%RCA to partially substitute CG have optimum sorptivity of 2.69 x 10^{-4} mm/min$^{0.5}$; 3.58 x 10^{-4} mm/min$^{0.5}$; 3.16 x 10^{-4} mm/min$^{0.5}$; and 2.86 x 10^{-4} mm/min$^{0.5}$ at 28 days curing age, respectively.

- The performance index strategy, which was used to evaluate multiple performance requirements for site-specific application of concrete mixtures, is a helpful way to enable the concrete technologist to select the appropriate laterite and recycled aggregate replacement levels that can maximize the required performance. The findings of this investigation reveal that laterite and recycled aggregate contents may vary and that such variations are mostly determined by the performance requirements of the site-specific concrete mixtures.
- The incorporation of construction and demolition wastes with laterite in the concrete mixtures significantly reduces the amounts of fresh aggregates used for concrete and in addition, leads to cost reduction in Nigeria's cost conditions. The laterized concrete with recycled aggregates is also eco-friendly and will contribute positively to the conservation of natural resources and the overall sustainability of construction materials, a central objective of circular construction.

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Appendix

Table 4. Performance index for individual indicator

Performance indicator		Concrete mixture							
		APS	RFA10	RFA20	RFA30	RFA40	RFA50	RFA60	RFA70
Compressive strength (N/mm^2)	θ_i	1.0	0.64	0.67	0.73	0.76	0.80	0.84	0.93
	ψ_i	5.00	3.20	3.35	3.65	3.80	4.00	4.20	4.65
Sorptivity (mm/min0.5) x 10^{-4}	θ_i	0.69	0.85	1.00	0.54	0.63	0.99	0.95	0.84
	ψ_i	3.45	4.25	5.00	2.70	3.15	4.95	4.75	4.20

Table 5. Performance index for multiple performance indicators

Multiple performance indicators	Concrete mixture							
	APS	RFA10	RFA20	RFA30	RFA40	RFA50	RFA60	RFA70
PI (1)	17.25	13.60	16.75	9.86	11.97	19.80	19.95	19.53

Table 6. Performance index for individual indicator

Performance indicator		Concrete mixture							
		APS	RFA10	RFA20	RFA30	RFA40	RFA50	RFA60	RFA70
Compressive strength (N/mm^2)	θ_i	1.00	0.84	0.94	0.87	0.96	0.54	0.72	0.59
	ψ_i	5.00	4.20	4.70	4.35	4.80	2.70	3.60	2.95
Sorptivity (mm/min0.5) x 10^{-4}	θ_i	0.46	0.76	1.00	0.60	0.47	0.71	0.59	0.75
	ψ_i	2.30	3.80	5.00	3.00	2.35	3.55	2.95	3.75

Table 7. Performance index for multiple performance indicators

Multiple performance indicators	Concrete mixture							
	APS	RFA10	RFA20	RFA30	RFA40	RFA50	RFA60	RFA70
PI (1)	11.50	15.96	23.50	13.05	11.28	9.59	10.62	11.06

Table 8. Performance index for individual indicator

Performance indicator		Concrete mixture							
		APS	RFA10	RFA20	RFA30	RFA40	RFA50	RFA60	RFA70
Compressive strength (N/mm^2)	θ_i	1.00	0.80	0.73	0.64	0.74	0.81	0.69	0.58
	ψ_i	5.00	4.00	3.65	3.20	3.70	4.05	3.45	2.90
Sorptivity (mm/min0.5) x 10^{-4}	θ_i	0.63	0.71	0.78	0.78	0.67	1.00	0.95	0.67
	ψ_i	3.15	3.55	3.90	3.90	3.35	5.00	4.75	3.35

Table 9. Performance index for multiple performance indicators

Multiple performance indicators	Concrete mixture							
	APS	RFA10	RFA20	RFA30	RFA40	RFA50	RFA60	RFA70
PI (1)	15.75	14.50	14.24	12.48	12.40	20.25	16.39	9.72

Table 10. Performance index for individual indicator

Performance indicator		Concrete mixture							
		APS	RFA10	RFA20	RFA30	RFA40	RFA50	RFA60	RFA70
Compressive strength (N/mm^2)	θ_i	0.96	0.88	0.77	0.66	0.58	1.00	0.68	0.64
	ψ_i	4.80	4.40	3.85	3.30	2.90	5.00	3.40	3.20
Sorptivity (mm/min0.5) x 10^{-4}	θ_i	0.48	0.47	0.52	0.79	0.77	0.64	0.72	1.00
	ψ_i	2.40	2.25	2.60	3.95	3.85	3.20	3.60	5.00

Table 11. Performance index for multiple performance indicators

Multiple performance indicators	Concrete mixture							
	APS	RFA10	RFA20	RFA30	RFA40	RFA50	RFA60	RFA70
PI (1)	11.52	9.90	10.01	13.04	11.17	16.00	12.24	16.00

Note: In the various concrete mixture notations, the figures following the letters denote the percentage content levels of the respective aggregates.

Table 12. Required performance indicators

Performance indicator	
PI (1)	Compressive strength + sorptivity

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