Performance And Packing Properties Of Silt-Aggregate In Concrete And Mortar

Murtala Yakubu Gulma*
Department of Civil Engineering
Abdullahi Fodio University of Sci. and Tech., Aliero
Birnin-Kebbi, Nigeria

*murtalayakubug@gmail.com

Bashar Sani Liman
Department of Civil Engineering
Abdullahi Fodio University of Sci. and Tech., Aliero
Birnin-Kebbi, Nigeria

mubeenu2006@gmail.com

Kamoru Ademola Ibrahim
Department of Civil Engineering
Abdullahi Fodio University of Sci. and Tech., Aliero
Birnin-Kebbi, Nigeria

ibrahimk.ademola@ksusta.edu.ng

***Abstract*—The majority of structural concrete and mortar mixtures described in the literature and employed in the construction industry are characterized by a high aggregate content. This practice accelerates the depletion of natural resources by causing extraction rates to surpass natural regeneration rates. This study develops a modified silt-aggregate composite for concrete and mortar productions, by introducing particle packing theory. Interactions between particle packing density of optimum percentage of silt, fine aggregate and binder, fresh and hardened mechanical properties, and durability performance of concrete and mortar were synergistically investigated. The experimental results revealed that the inclusion of silt generally reduced the workability of the mixtures, while the densities of silt-aggregate concrete (SAC) and silt-aggregate mortar (SAM) remained consistent across all replacement levels (0%, 5%, 10%, and 20%), indicating their suitability as alternative fine aggregates. The compressive strength of the control mixtures (0-SAC and 0-SAM) was comparable to that of specimens containing 10% silt (10-SAC and 10-SAM), with differences of approximately 19.1% and 20.9%, respectively; higher replacement levels resulted in lower strengths. This trend is attributed to variations in mixture composition and the packing characteristics of the silt–aggregate system. Flexural performance exhibited a marked reduction with increasing silt content. Conversely, the durability performance, particularly water absorption and related physical characteristics, were improved in the sustainable SAC and SAM mixtures. Overall, the findings suggest that the aggregate packing approach is effective for producing optimized and sustainable SAC and SAM. Moreover, a 10% replacement of fine aggregate with silt was found to enhance the mechanical performance of structural concrete and mortar while meeting the requirements for optimum strength and normal-weight concrete.**

Keywords—Silt-aggregate concrete; silt-aggregate mortar; packing density; mechanical properties; durability performance

I. INTRODUCTION

Concrete is the most widely used construction material globally [1], produced through a proportional combination of aggregates, water, and a binder. Upon casting, demoulding, and subsequent curing, the mixture undergoes a chemical reaction between the binder and water, resulting in the formation of a hardened, rock-like material. Mortar, on the other hand, is primarily a mixture of two components, namely paste (binder and water) and fine aggregate as a mineral filler [2]. The versatility of concrete and mortar, coupled with their adaptability to diverse environmental conditions, renders them highly suitable for application in nearly all civil engineering and building structures. Thus, they are essential to the development of the world's infrastructure and economy [3]. Aggregates, which typically occupy 60 – 80% of the total volume, are meant to enhance the workability, stiffness, and dimensional stability of concrete, including the control of creep and shrinkage properties [4, 5]. They are one of the basic components of concrete and mortar that must meet certain requirements before being recommended to be used. According to all construction regulations, the aggregates must be cleaned before use. Similarly, several factors can adversely affect the durability of concrete and mortar structures, among which are poor design, poor supervision, aggregate's impurities (such as clay/silt and debris) etc. [6, 4, 7].

In Nigeria, utilization of locally sourced aggregates (washed and unwashed gravels and river sand) for construction is a popular practice. This makes it crucial to look at the integrity of these aggregates in order to determine how well they perform in structural members [8]. The mineral makeup of the rock material that the coarse aggregate was produced of is taken into account in addition to the size, shape, and surface conditions of the aggregate [9]. Fine aggregates, usually derived from natural river sand or crushed stone, are expected to conform to strict gradation and cleanliness requirements to ensure optimal performance. However, the unsustainable extraction of natural aggregates has led to severe environmental degradation, including riverbed depletion, biodiversity loss, and land subsidence [10]. Consequently, attention has shifted toward alternative and marginal materials, such as quarry fines, industrial by-products, and silt, to address the challenges of sustainability and resource scarcity in the construction sector [11].

Silt is a fine soil fraction, typically defined as particles ranging from 0.002 mm to 0.063 mm in size, and is often considered a deleterious component in concrete and mortar due to its tendency to retain water, increase shrinkage, and reduce bond strength between the aggregate and cement paste [12, 13, 14]. Silt transported by surface runoff is commonly deposited as sediment in lowlands, rivers, and ponds. While such deposition contributes to environmental processes, the excessive accumulation of silt poses challenges, including reduced waterway capacity and sedimentation of reservoirs. Nevertheless, the abundance of silt in these natural deposits highlights its potential as an alternative fine aggregate in construction materials, thereby offering a sustainable solution for resource conservation and waste management [15]. Previous studies have shown that the utilization of modified silt-aggregates can affect the workability, strength, and durability of concrete and mortar [13, 16]. As a result, construction specifications typically limit the allowable silt content in aggregates to less than 3 – 5% by weight. However, in many regions especially where high-quality sand is scarce, natural aggregates often contain higher proportions of silt, either due to poor washing processes or the geological nature of the deposit. Discarding such silt-rich materials not only contributes to waste accumulation but also increases material costs and logistical burdens [17].

In addition, contrary to the conventional views, recent studies have begun to re-evaluate the role of silt in concrete and mortar mixtures. Controlled incorporation of silt (sourced from quarry fines or natural deposits), particularly when it is characterized and blended with aggregates, may enhance packing density and reduce the void ratio in granular assemblies. The principle of particle packing is not new. In 1907, Fuller and Thompson [18] investigated the relationship between aggregate size distribution and concrete properties, focusing on how the constituent materials pack together. Their research led to the development of the Fuller curve, which indicates the aggregate composition that theoretically provides the densest packing, given certain assumptions about the behaviour of material. Optimizing particle packing, through precise control of cement and aggregate size distribution, is crucial for creating dense, strong, and durable cement-based materials by minimizing voids, increasing density, and reducing binder requirements [19, 20]. This potentially improves mechanical interlocking when optimized properly and lowering cement paste demand [21, 22]. The packing density of granular materials has been shown to influence a variety of properties, including compressive strength, workability, and permeability. A denser packing arrangement leads to a reduction in the interstitial volume filled by the cement paste, resulting in more economical and potentially more durable mixtures [23, 24].

Moreover, the fresh/rheological behaviour and strength development of cementitious systems are closely linked to the particle size distribution and shape characteristics of the aggregates used. Silt particles, due to their fineness and surface texture, may alter the flow characteristics of fresh mixtures and accelerate hydration kinetics when present in suitable proportions [25, 26, 26]. However, the packing behaviour and the threshold beyond which silt content begins to impair mechanical performance and durability remain poorly defined, necessitating further experimental investigation. This study aims to investigate the performance and packing properties of silt-aggregate when used in concrete and mortar mixtures. It explores the characterization of materials to obtain their physical and chemical properties. The influence of varying silt content in concrete and mortar on fresh properties, mechanical behaviour, and durability performance was assessed. The packing characteristics of binder and optimally proportioned silt-aggregate, serving as a sustainable partial replacement for fine aggregate with the intention of offering both environmental and performance benefits for construction works was analyzed and presented.

II. MATERIALS AND METHODS

A. Materials

The materials used for the production of silt-aggregates concrete and mortar were Portland-limestone cement (PLC) 42.5 N conforming to BS EN 197-1 [28], well-graded river sand and gravel of maximum nominal sizes 4.75 mm and 37.5 mm, respectively. These obtained commercially from the main suppliers of cement and aggregates (fine and coarse) for construction projects in Kebbi, Nigeria. The silt content of 0.002 to 0.075 mm collected from Dukku River was used in replacing 0%, 5%, 10%, 15%, and 20% mass ratio of fine aggregate. Water/cement ratios of 0.55 and 0.45 were kept at constant values for concrete and mortar mixtures, respectively, to achieve adequate fresh and mechanical characterization. The physical and chemical properties of PLC obtained from specific gravity, standard consistency, soundness, fineness, heat of hydration, setting time, and X-ray fluorescence spectrometry (XRF) tests are presented in Table 1. The physical properties of the aggregates conducted in compliance with the BS 812 [29] and their particle grading analysis obtained from sieve analysis are shown and illustrated in Table 2 and Fig. 1, respectively. The control and the silt-aggregate mixes of concrete and mortar were proportioned adhering to the conventional and simplified mix design approach [30] are presented in Table 3. Then, the optimum particle packing density was determined through particle grading analysis of PLC and 10% silt-containing aggregates, resulting in improved fresh properties and reduced segregation, a result consistent with Fuller-Thompson's theory and the curve in Fig. 2. This align with the findings reported by [31, 32, 10].

Table 1: Physical and chemical properties of Portland-limestone cement

Physical properties		Chemical composition (%)	
Specific gravity	3.15	Al_2O_3	5.93
Standard consistency (%)	30	SiO_2	21.05
Soundness (mm)	3.3	Fe_2O_3	2.96
Fineness (%)	2.9	CaO	64.57
Heat of hydration (J/g)	243	MgO	1.51
Initial setting time (min)	44	SO_3	1.92
Final setting time (min)	275	K_2O	0.51
Grade (N)	42.5	Na_2O	0.19
		LoI	1.13
		Others	0.23

Table 2: Physical properties of the aggregates used for the research work

Aggregate	Specific Gravity	Moisture Content (%)	Permeability (m/s)	Fineness modulus
Silt	2.75	–	1.95×10^{-5}	–
River sand	2.53	3.54	2.46×10^{-3}	4.77
Gravel	2.60	1.70	–	7.33

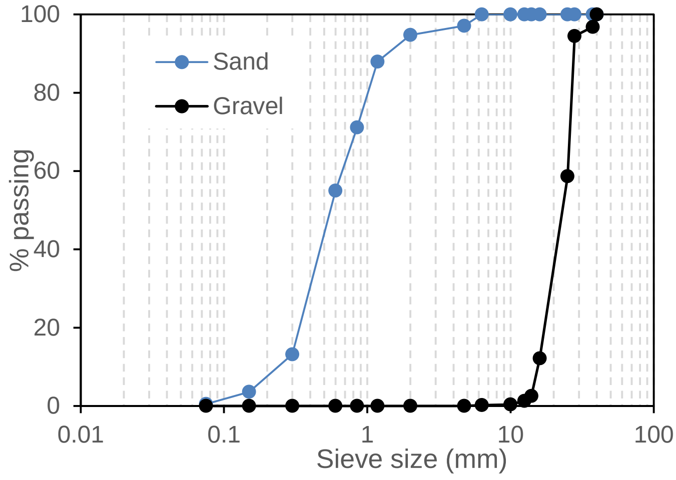

Fig. 1. Particle grading analysis of the aggregates used

Table 3: Material mix proportioning for concrete and mortar mixtures developed for the study (kg)

Mix ID	Cement	Sand	Silt	Gravel	Water
Concrete					
0 - SAC	375.0	600.0	0.0	1206.4	206.0
5 - SAC	375.0	570.0	30.0	1206.4	206.0
10 - SAC	375.0	540.0	60.0	1206.4	206.0
15 - SAC	375.0	510.0	90.0	1206.4	206.0
20 - SAC	375.0	480.0	120.0	1206.4	206.0
Mortar					
0 - SAM	410.1	1802.4	0.0	–	184.5
5 - SAM	410.1	1712.2	90.1	–	184.5
10 - SAM	410.1	1622.1	180.2	–	184.5
15 - SAM	410.1	1532.0	270.4	–	184.5
20 - SAM	410.1	1441.9	360.5	–	184.5

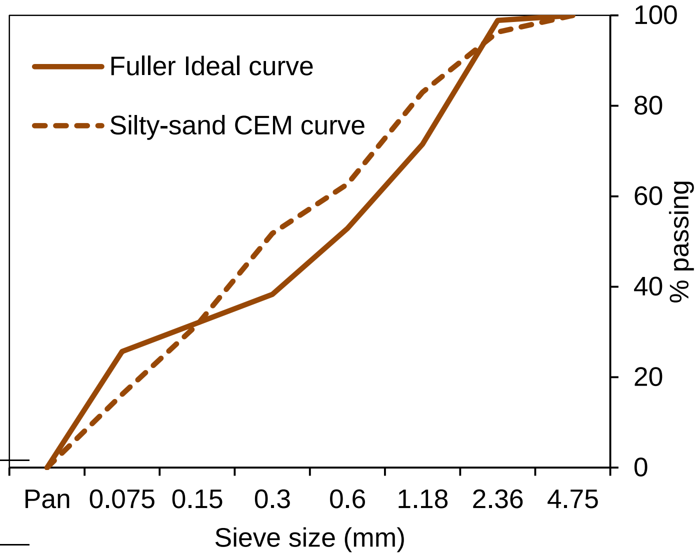

Fig. 2. Fuller Ideal grading curve compared to optimum silty-sand cement mixture

B. Methods

Test on Freshly Mixed Concrete

Slump: Slump test was conducted on fresh mixture of silt-aggregate concrete using slump cone in adherence to ASTM C143 [33]. The workability and consistency was measured by determining the differential deformation of fresh compacted concrete comparing to the total vertical height of the cone used. A visual assessment of the mixes was performed to evaluate their susceptibility to bleeding and segregation.

Test on Hardened Concrete and Mortar

Compressive strength: The silt-aggregate concrete (SAC) and silt-aggregate mortar (SAM) specimens of 150x150x150 mm^3 and 100x100x100 mm^3, respectively, were prepared, cured at a temperature of 23 ^oC ($\pm$ 3), and tested for compressive strength analysis at an early and later strengths using a compression testing machine in accordance with BS 1881: 116 [34]. Minimum of three specimens were tested for every mixes to obtain the average values. The compressive strength (f_{cu}) was calculated by the equation 1.

$$f_{cu} = \frac{Maximum\ force}{Cross-sectioal\ Area} \quad (N/mm^2) \qquad (1)$$

. *Density:* The average densities of SAC and SAM specimens were obtained prior the crushing of the specimens. This directly impact the strength, durability, and the structural integrity of concrete and mortar structures. The density (ρ) was computed by the equation 2.

$$\rho = \frac{Mass}{Volume} \quad (kg/m^3) \qquad (2)$$

Flexural strength: SAC and SAM beam specimens were produced using 150x150x500 mm^3 and 100x100x500 mm^3 moulds, respectively, in good environmental condition. They were tested at 28 and 90 days of curing with four-point bending on a loading frame to evaluate flexural strength adhering to BS 1881: 118 [35]. Minimum of three specimens were tested for every mixes to obtain the average values. The flexural strength (f_f) was calculated by the equation 3.

$$f_f = \frac{Maximum\ moment}{Section\ modulus} \quad (N/mm^2) \qquad (3)$$

Water absorption: This correlates with the durability of materials and resistance of concrete and mortar to environmental damage. High water absorption (W_a) indicates a porous structure, allowing aggressive substances like chlorides and sulphates to penetrate and cause deterioration. The percentage of water absorbed in SAC and SAM specimens were determined after 28 and 90 days of curing by the equation 4.

$$W_a = \frac{Initial\ weight - Final\ weight}{Initial\ weight} \text{ X } 100 \quad (\%) \qquad (4)$$

Carbonation test: The depth of carbonation was determined on freshly cut SAC and SAM specimens using phenolphthalein. This is done on a destructive specimen by the compression testing machine conforming to ASTM C 856. The indicator would turned purple in uncarbonated areas, indicating a high pH (pH > 9.0) and remained colourless in carbonated areas, which signifies a low pH (pH < 9.0) [36].

III. Results and Discussion

Slump: The results from the slump are depicted in Fig. 3 to conceptualize and quantify the workability and consistency of fresh mixtures of SAC. A reduction in the workability of concrete was observed with an increase in the percentage of silt content in the mixes compared to 0-SAC, i.e. 11%, 21.3%, 31.4%, and 40.8% for 5-SAC, 10-SAC, 15-SAC, and 20-SAC, respectively, which concurred with the results presented by Mohammed et al. [11] and ACI [37]. This trend was noted despite the slump measurements remaining within the specified tolerance values for moderate slumps of between 50 mm and 100 mm for concrete mixes containing up to 10% silt content, implying adequate workability and suitable for normal reinforced flexural members and columns. However, the slump values for all mixes fell within the range required for the workability of various concrete applications in building and civil engineering works [38].

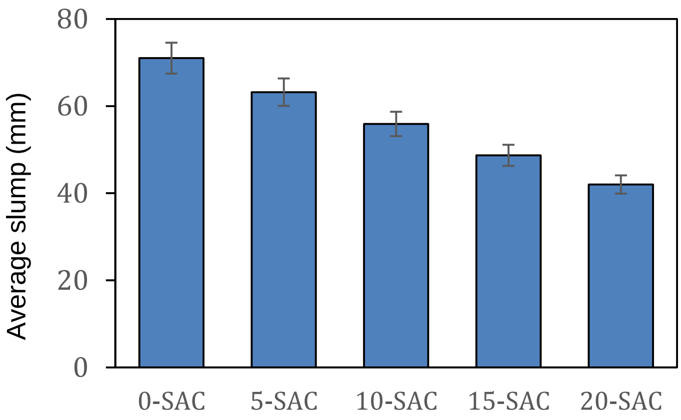

Fig. 3. Slump results of concrete cubes

Compressive strength: The results of compression tests on hardened concrete and mortar mixtures with up to 20% silt content are depicted in Figs 4 and 5, respectively, with average densities ranging from 2020 kg/m^3 to 2503 kg/m^3. The control specimens (0-SAC) exhibited higher early-age compressive strength, exceeding those of 5-SAC and 10-SAC by approximately 21% and 27%, respectively. At 90 days of curing, 0-SAC attained a maximum strength of 40.5 N/mm², representing reductions of 5.6% and 19.1% relative to 5-SAC and 10-SAC, respectively. These variations can be attributed to differences in mixture composition and the packing characteristics of the silt–aggregate system, and are consistent with the findings presented by Adegoke and Ikumapayi [39] and Mohammed et al. [11]. The compressive strength development of the 10-SAC mix at both 28 and 90 days satisfied the requirements for grade 30 concrete, indicating that a 10% silt content represents the optimum level for structural applications. In contrast, the 15-SAC and 20-SAC mixes did not achieve the 30 N/mm² threshold and are therefore unsuitable for normal-strength concrete. Similar to strengths of SAC, SAM strengths show linear increase up to 7 days, followed by a slower rate of increase, as illustrated in Fig. 5. The strength ratios between 7 and 28 days for all SAM mixtures exceeded 70%. Beyond 28 days of curing, most specimens exhibited further strength development, with increases ranging from 1.5% to 15.3%. This continued gain can be attributed to the ongoing hydration of cementitious materials and the progressive enhancement of the interfacial bond between the matrix and the silt-aggregate. Notably, the replacement of 10% of the fine aggregate with silt improved the mechanical performance of the mortar and satisfied the requirements for optimum strength as well as for normal-weight mortar.

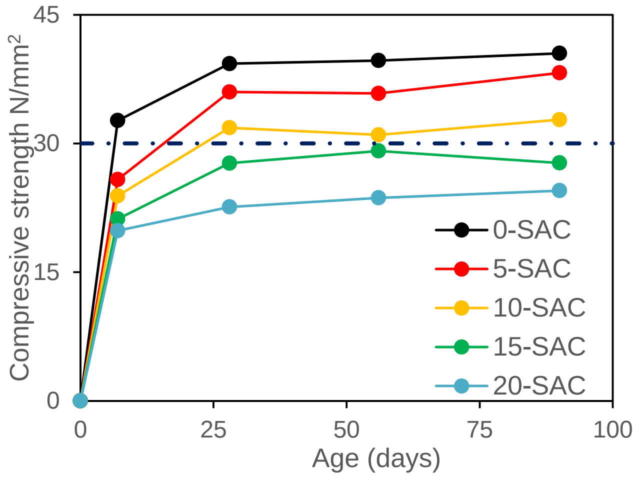

Fig. 4. Compressive strength results of normal and SA concrete mixtures

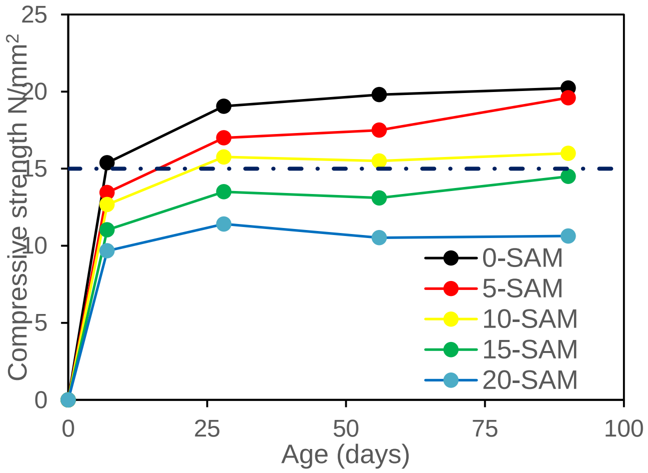

Fig. 5. Compressive strength results of normal and SA mortar mixtures

Flexural Strength: Figs 6 and 7 present the flexural strength results of SAC and SAM mixtures, respectively. In both cases, the specimens exhibited a steady increase in strength with curing age, accompanied by appreciable coefficients of variation (CoV) and strength ratios (28/90). Across all mixtures, the flexural strength followed a consistent trend – increasing silt content in the fine aggregate led to a reduction in strength. This corroborates earlier findings reported in the literature [13, 14]. At 90 days of curing, the strengths of 0-SAC and 5-SAC differed by only 3.4%, while those of 5-SAM and 10-SAM were comparable within 3.7%. Beyond a 10% silt replacement, however, both SAC and SAM mixtures demonstrated a marked decline in flexural strengths.

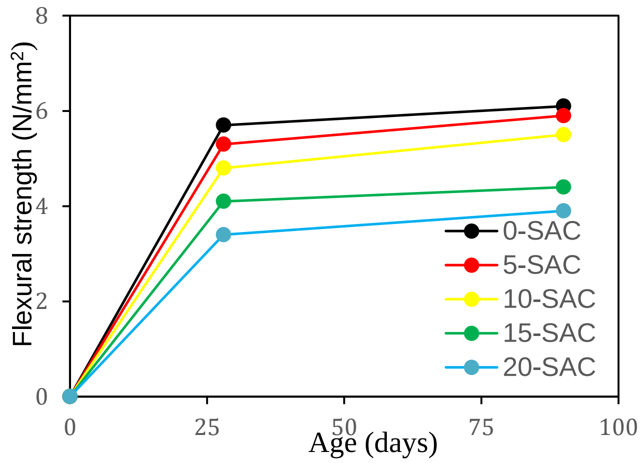

Fig. 6. Flexural strength development of normal and SA concrete mixtures

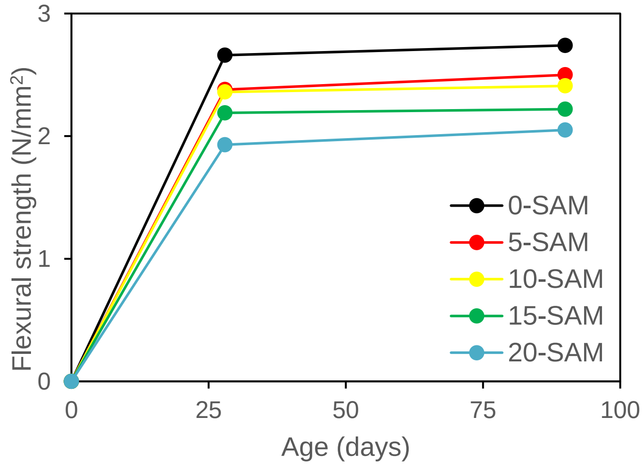

Fig. 7. Flexural strength development of normal and SA mortar mixtures

Water absorptions: Figs 8 and 9 present the water absorption results of the SAC and SAM mixtures. Water absorption is indicative of pore presence within the microstructure and serves as a key parameter in evaluating the durability of concrete and mortar. The results show that partial replacement of sand with 5%, 10%, and 15% silt content in SAC mixtures increased water absorption by 16.7%, 3.5%, and 21.0%, respectively, relative to the control mixture (0-SAC). Conversely, the 20-SAC specimens exhibited water absorption values comparable to 0-SAC, suggesting reduced capillary porosity and the formation of a denser matrix. For SAM specimens, water absorption values were generally consistent across all replacement levels and testing ages, with the exception of 5-SAM, which recorded a notably lower absorption at 28 days. These observations may be attributed to variations in the mechanisms influencing degradation in SAC and SAM, which differ from those governing their permeability. Importantly, all mixtures recorded low water absorption values (below 6%), aligning with findings reported by other researchers who demonstrated that water absorption tends to decrease with increasing concrete grade [40, 41].

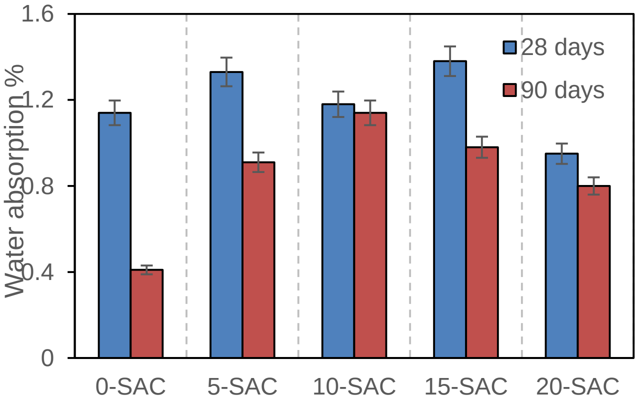

Fig. 8. Water absorption results of normal and SA concrete mixtures

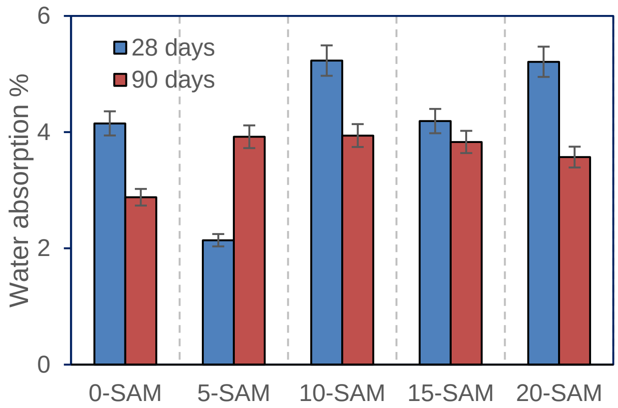

Fig. 9. Water absorption results of normal and SA mortar mixtures

Carbonation resistance: The durability performance of SAM and SAC specimens obtained from carbonation test are shown in Figs 10 and 11, respectively. The carbonation depth was assessed by applying a phenolphthalein indicator solution to the freshly broken surfaces of SAM and SAC specimens. It was applied to the central cross-sections of the specimens, where the least amount of carbonation was expected. The indicator turned purple at the centre of all the specimens, confirming that the pH remained highly alkalinity (> 9.0) in those areas and indicating that the carbonation front had not yet reached the core of the specimens.

Fig. 10. Carbonation resistance results of normal and SA mortar mixtures

Fig. 11. Carbonation resistance results of normal and SA concrete mixtures

IV. CONCLUSIONS

In this study, experimental results were presented on the fresh properties of SAC and on the mechanical performance of SAC and SAM under compression and flexure. The findings indicate promising fresh and mechanical behaviours of silt-based construction materials, highlighting the potential of silt as a partial replacement for sand in SAC and SAM production. This approach could offer economic benefits by conserving scarce and increasingly depleted natural resources while promoting the use of waste materials. Based on the study, the following conclusions are drawn:

- The incorporation of increasing silt content and limestone addition in PLC led to higher water demand in both SAC and SAM mixtures. This adversely affected workability and contributed to variations in the mechanical performance of the concrete and mortar specimens.
- The slump values obtained for the 0-SAC, 5-SAC, and 10-SAC mixtures were within the recommended limits for moderate workability. These values indicate suitability for use in normal reinforced flexural members and columns, reflecting the influence of mixture composition and the packing characteristics of the silt–aggregate system.
- For the first time, a denser particle packing arrangement between PLC and silt–aggregate was established and systematically evaluated.

The resulting gradation curves were compared against the Fuller ideal grading model to assess the packing efficiency of the mixtures.

- The average density of SAC and SAM specimens ranged between 2020 kg/m^3 and 2503 kg/m^3, which is consistent with the classification of normal-weight Portland cement concrete. A positive correlation was observed between specimen density and compressive strength, indicating that higher density contributed to improved mechanical performance of the hardened mixtures.
- The strength development ratios between 7 and 28 days exceeded 70% across all mixtures. This suggests adequate compaction, effective bonding between the matrix and silt–aggregate, and minimal specimen preparation errors.
- The optimum silt content for structural applications was determined to be 10%, yielding compressive strengths of approximately 30 N/mm^2 for concrete (SAC) and 15 N/mm^2 for mortar (SAM), which are comparable to the control mixtures (0-SAC and 0-SAM).
- The incorporation of 20% silt in concrete and 5% silt in mortar resulted in improved water absorption performance relative to the control mixtures. This behaviour suggests that the inclusion of silt at these proportions contributes to acceptable durability characteristics in both concrete and mortar.

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