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Original Research Report

Experimental evaluation of hybrid concrete produced from recycled concrete aggregates and alkali-activated fly ash for sustainable construction

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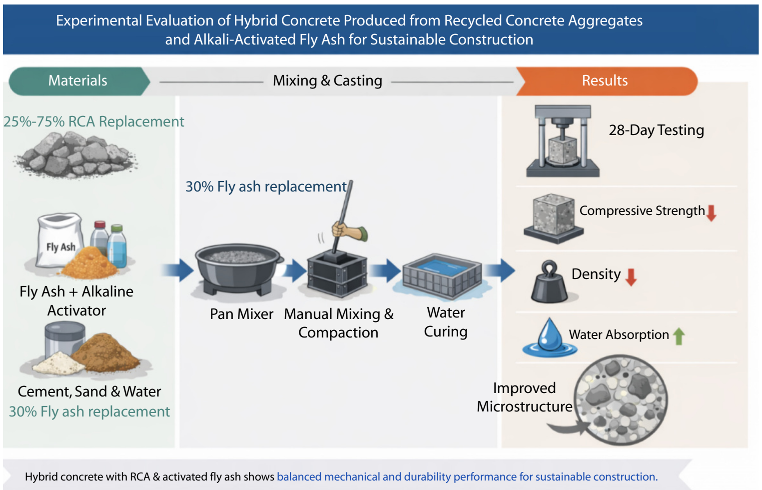
Abstract: The growing demand for sustainable construction materials has intensified interest in hybrid concrete systems incorporating recycled aggregates and industrial by-products. This study investigates durability-related properties, specifically water absorption and density characteristics of hybrid concrete produced using recycled concrete aggregates (RCA) and alkali-activated fly ash as partial binder replacements. Concrete mixtures were prepared with RCA replacement levels of 0%, 25%, 50%, 75%, and 100%, while maintaining consistent mix proportions. A total of six specimens (150 mm) were tested for each mixture to evaluate compressive strength development at 7, 14, and 28 d, alongside density and water absorption characteristics. Results revealed that compressive strength increased with curing age for all mixtures but decreased progressively with higher RCA incorporation. The 28-day compressive strength ranged from 42.8 MPa for the control mix to 28.9 MPa at full RCA replacement. Density values decreased, and water absorption increased with RCA replacement, reflecting increased pore connectivity and moisture transport pathways. The findings showed that hybrid concrete with up to 50% RCA can achieve balanced durability-related behaviour based on water absorption characteristics while significantly reducing dependence on natural aggregates and conventional cement, indicating the beneficial role of alkali-activated fly ash in enhancing matrix densification and interfacial bonding.



Keywords: hybrid concrete, recycled concrete aggregate, alkali-activated fly ash, durability performance, sustainable construction, circular economy

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1. Introduction

Concrete is the largest construction material used in the world because of its versatile benefits over other construction materials[1]. Even with all of its desirable qualities, however, the production of conventional concrete creates a lot of concern for sustainability due to its negative effects on the environment. For instance, cement contributes roughly 7%–8% of the world's anthropogenic CO_2 emissions, and the constant extraction of natural aggregates is putting an acute strain on finite natural resources[2,3]. Due to these environmental challenges, there has been much research within the construction industry to improve efficiency by developing sustainable forms of concrete that utilize by-product materials from industry and recycled materials from construction.

Fly ash, a by-product from burning coal, is an important component of developing alternatives to conventional concrete because it provides supplementary cementitious properties due to its pozzolanic behaviour, thus positively affecting the long-term properties of concrete. Further, fly ash is also an extremely reactive material when it is activated in an alkaline environment, which leads to its incorporation into geopolymeric or alkali-activated binder systems, both of which produce improved micro-structural properties and durability than conventional concrete[4,5]. Consequently, alkali-activated fly ash binders represent an opportunity to reduce the reliance on Portland cement while exhibiting satisfactory performance in terms of mechanical performance and durability.

Recycled concrete aggregates (RCA), which are produced from demolished buildings and roads, are becoming more widely accepted as an environmentally-friendly option to replace virgin aggregate[6]. The use of recycled aggregate helps to further support the circular economy strategy by reducing landfill disposal of material as well as preserving virgin aggregate resources[7]. However, due to the way recycled aggregates are produced, they typically have adhered mortar that creates porous surfaces and increases both their ability to absorb water and their density of micro-cracks. These properties generally lead to lower strength and durability than natural aggregate concrete[6,8].

The development of hybrid concrete systems that include alkali-activated binders along with recycled aggregates has emerged as a feasible option not only to reduce their environmental impact but also to maintain their engineering performance. Research has shown that the enhanced bonding ability of activated fly ash can alleviate the inherent weaknesses of recycled aggregates by improving the properties of their interfacial transition zone and refining their pore structures[9-12].

Research on the mechanical strength of hybrid concrete systems has been extensive. However, there are fewer studies on the durability of their concrete-like products and their performance characteristics such as water absorption behaviour, permeability characteristics, and moisture transport behaviour[13,14]. These performance characteristics are very important in determining the long-term reliability of a structure. Permeability and the entry of moisture into a structure can lead to increased deterioration of the structure, including corrosion of the reinforcement, damage from freezing and thawing, and chemical attack[15].

Importantly, the interaction between the incorporation of recycled aggregates into the hybrid concrete system and alkali-activated fly ash affects the development of pore structure and transport properties in the hybrid concrete matrices. An understanding of how the incorporation of these two materials can affect the development of the pore structure would be beneficial from both structural performance and environmental sustainability perspectives.

The current study investigates, through experimental testing, durability-related behaviour based on water absorption characteristics of hybrid concrete using recycled concrete aggregates and alkali-activated fly ash. The durability-related performance characteristics investigated include water absorption behaviour, density characteristics of the hybrid concrete system, and the development of compressive strength, so we can understand the best combinations of materials for creating sustainable hybrid concrete.

2. Materials and methods

2.1. Materials

2.1.1. Cement

Portland limestone cement (Dangote 42.5 grade) conforming to ASTM C150/C150M Type I specifications[16] was used as the primary hydraulic binder. The cement possessed a specific gravity of 3.15 and was stored in moisture-free conditions prior to use.

2.1.2. Fly ash and preparation of alkali-activated binder

The Class F fly ash collected from a coal-fired electric plant was used as the additional binder material. The chemical compositions of the cement and fly ash were determined using X-ray fluorescence (XRF) analysis, and the results are presented in Table 1. The fly ash contained very little calcium, and its composition was mostly silica (SiO_2) and alumina (Al_2O_3). Before use, the fly ash was dried in an oven at (105 ± 5) °C for 24 h to remove moisture and ensure each particle reacted uniformly when activated. Two types of activators were used at a mass ratio of 1:2.5 for activating the fly ash: sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). Sodium hydroxide was prepared at 10 M by dissolving analyti-

Table 1. Chemical composition of fly ash and cement (%).

Oxide component	Fly ash (%)	Cement (%)
SiO_2	56.32	20.85
Al_2O_3	25.14	5.42
Fe_2O_3	8.67	3.21
CaO	3.85	62.76
MgO	1.72	2.18
SO_3	0.54	2.65
Na_2O	0.62	0.28
K_2O	1.15	0.47
TiO_2	0.98	0.31
P_2O_5	0.21	0.12
Mn_2O_3	0.18	0.09
Loss on ignition (LOI)	0.62	1.68

cal-grade solid pellets in distilled water and allowing it to stabilize for 24 h prior to use. The sodium silicate solution supplied by the manufacturer contained a silica modulus (SiO_2/Na_2O) of approximately 2.5 and a solid content between 40% and 45%.

Based on the contribution from each activator solution component (NaOH and the sum of both Na_2SiO_3), the total amount of water in the mixture (both added externally and contained within the sodium silicate solution) was used to account for all sources of water in the system to calculate the effective water-to-binder ratio, providing a level of consistency within mix design and the potential for repeatability.

2.1.3. Aggregate

According to ASTM C33/C33M specifications[17], river sand was the fine aggregate material used in this experiment, which was washed and dried in air before being processed through a series of sieves to remove contaminants and obtain a consistent gradation. The natural coarse aggregate material used for control was crushed granite with an approximate maximum diameter of 20 mm. Recycled concrete aggregates (RCAs) were recovered from concrete debris that was mechanically separated at construction and demolition sites. After the RCA was crushed and sieved to achieve particle size distributions matching those typically found in virgin natural aggregates, it was then thoroughly cleaned to remove residual mortar and dust. Before mixing, this material was also thoroughly washed and then dried in an oven. Both types of coarse aggregate (natural and recycled) were found to conform to the standard grading specifications; however, the recycled aggregate displayed somewhat finer gradation than an equivalent-sized sample prepared using virgin aggregate due to the residual mortar (Fig. 1). The physical properties of the aggregate, such as saturated surface dry (SSD) specific gravity, bulk density, and aggregate crushing index, were measured and are listed in Table 2.

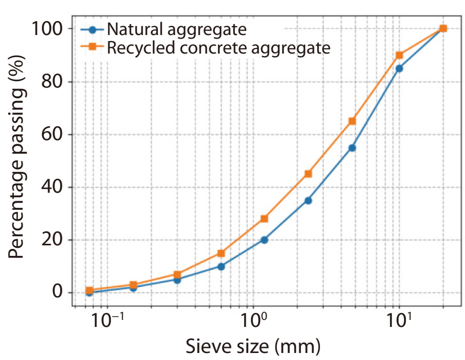

Fig. 1. Grading curve of natural and recycled aggregates.

Table 2. Physical properties of aggregates.

Property	Natural aggregate	Recycled concrete aggregates
SSD water absorption (%)	0.8	4.5
Apparent density (kg m^{-3})	2650	2400
Crushing index (%)	18	28
Bulk density (kg m^{-3})	1580	1450
Specific gravity	2.65	2.40

2.1.4. Mixing water

Potable water free from contaminants was used for mixing and curing all concrete specimens.

2.2. Mix proportioning

Fly ash was used to replace a portion of Portland limestone cement to create a new type of binder that utilizes traditional cement hydration and alkali-activated binders. The amount of fly ash used for this study was fixed at 30%. When calculating the proportions of cementitious material for each mixture, 70% of the total amount was Portland limestone cement, and 30% was fly ash. Thus, it was ensured that the only variable affecting performance was the percentage of RCA used in the mixtures, rather than variations in binder chemistry or method of activation.

The five mixtures developed in this study had different levels of recycled concrete aggregate, including 0%, 25%, 50%, 75%, and 100%, and the 0% RCA mixture served as the control (baseline). All five mixtures were mixed with a water/binder ratio of 0.45 to ensure uniformity, which allows for a direct comparison of results. Detailed mixing proportions for the five hybrid concrete mixtures are provided in Table 3.

2.3. Specimen preparation

Concrete was mixed manually to replicate realistic site-based construction scenarios. Coarse aggregate, fine aggregate, cement, and fly ash were dry-mixed for about 2 min to achieve an even combination of all ingredients. Afterward, water containing an alkaline activator solution was gradually added to the dry-mixed materials and then wet-mixed manually for about 3 min to ensure a homogeneous mixture.

The freshly prepared concrete was then placed in steel moulds to produce 150 mm cube samples. Each mould was filled in two equal layers and manually compacted using a tamping rod to eliminate entrapped air and achieve proper compaction. Following casting, the specimens were covered with plastic sheets to minimise moisture loss and prevent premature drying. The specimens were then allowed to set and were carefully demoulded 24 h prior to curing. Demoulded

Table 3. Mix proportions of hybrid concrete.

Mix ID	RCA replacement (%)	Cement (kg m^{-3})	Fly ash (kg m^{-3})	Fine aggregate (kg m^{-3})	NCA (kg m^{-3})	RCA (kg m^{-3})	Water (kg m^{-3})	Activator (kg m^{-3})
M0	0	280	120	720	1050	0	180	60
M25	25	280	120	720	788	262	180	60
M50	50	280	120	720	525	525	180	60
M75	75	280	120	720	262	788	180	60
M100	100	280	120	720	0	1050	180	60

specimens were cured in a water tank maintained at (23 ± 2) °C until the designated testing ages of 7, 14, and 28 d. Continuous water curing was adopted to ensure adequate hydration and alkali activation reactions.

2.4. Testing methods

2.4.1. Compressive strength test

Tests were conducted by following ASTM C39/C39M methods for compressive strength[18]. Cured samples were removed, their surfaces were dried, and then they were tested using a calibrated compression machine with loads applied at a rate of 0.25 MPa s^{-1}. The average result of six specimens from each mixture and curing age was recorded.

2.4.2. Density measurement

The density of hardened concrete specimens was determined by measuring dry mass and geometric volume. Specimens were oven-dried at (105 ± 5) °C until constant mass was achieved prior to density calculation.

2.4.3. Water absorption test

Saturated surface-dry mass was determined after subjecting oven-dried concrete to 24 h of water immersion, according to ASTM C642[19]. The resulting increase in weight, with respect to the original oven-dry weight, was used to calculate the amount of water absorbed by the concrete.

3. Results and discussion

3.1. Density variation with RCA replacement

The results, as seen in Fig. 2, demonstrate a progressive drop in the density of concrete as the amount of recycled concrete aggregate (RCA) increases. The density of the control concrete mixture was found to be 2435 kg m^{-3} and gradually decreased to 2215 kg m^{-3} when using 100% RCA, representing approximately a 9% reduction relative to the initial density. This decrease in density is due to the lower specific gravity of RCA versus natural aggregate. The internal voids provided by the adhered mortar attached to the RCA particles also decrease the bulk density. Limbachiya et al.[20] provided similar findings by indicating that RCA generally contains greater porosity and lower particle density when compared to natural aggregate.

Using lower-density concrete can be advantageous because it results in reduced self-weight. However, due to the relationship with decreased mechanical performance and increased permeability, a decrease in density would have negative implications. Tam et al.[21] have provided evidence suggesting that there is a strong link between decreased density in RCA concrete and increased capillary porosity and water transport pathways.

The relatively small decrease in density found in this research suggests that the use of activated fly ash aided in densification of the concrete matrix and thus partially compensated for the increased porosity resulting from the addition of RCA[10,11].

3.2. Water absorption behaviour of hybrid concrete

The results from the investigation into the water absorption of the hybrid mixtures of concrete are shown in Fig. 3. As can be seen, the percentage of absorbed water in the various mixtures increases from a value of 5.1 to a maximum value of 8.1 for the control mixture when fully replacing the RCA. Recycled concrete aggregates (RCA) are typically more porous than natural aggregates, and their absorption characteristics reflect this difference. Poon et al.[22] further stated that the presence of adhered mortar and microdeformations in the surrounding mortar that binds the RCA contributes to a greater absorption capacity of RCA than natural aggregates.

Higher absorption values are often correlated with higher capillary porosity and greater interconnectedness of the pore structure in concrete, thereby creating greater potential for liquid ingress into concrete due to the increased potential for liquid intrusion through the pore structure[13]. However, water absorption does not solely determine the long-term durability of concrete; many other factors contribute to concrete durability (e.g., permeability, chloride ions, sulphate ions, carbonation, and chemical attack). Thus, the increased capillary suction of concrete containing RCA will likely increase the penetration of aggressive agents, such as chloride and sulphate ions, into the concrete matrix, affecting the long-term performance of the concrete. This is consistent with the work of Katz[23], who showed that while water absorption does affect the durability of recycled aggregate concrete, it is not the sole factor that defines durability performance.

Even though the water absorption of the mixtures followed this trend, the use of activated fly ash may moderate the increase in water absorption by refining the pore structure via pozzolanic reactions and reducing the connectivity of capillary pores.

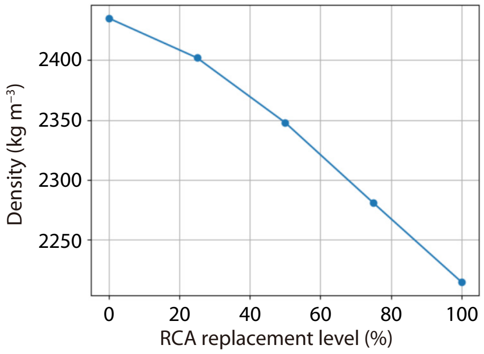

Fig. 2. Density variation with RCA replacement.

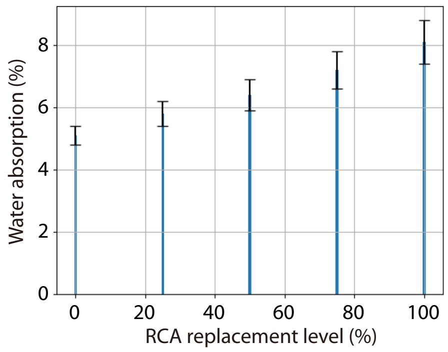

Fig. 3. Water absorption behaviour of hybrid concrete.

3.3. Compressive strength development of hybrid concrete

Fig. 4 illustrates the compressive strength of hybrid concretes with a combination of recycled concrete aggregates (RCA) and activated fly ash cured for 7, 14, and 28 d. The data consistently exhibits an increase in compressive strength with increasing curing time, but a decrease in strength was found as the amount of RCA increased. Compressive strengths of 31.6, 37.9, and 42.8 MPa were measured for the control mixture at 7, 14, and 28 d, respectively. The compressive strength was only marginally reduced by around 8.6% at 28 d with 25% substitution of RCA compared to the control mixture. Once RCA substitution exceeds 25%, the reduction in strength becomes more severe. At 100% substitution, the compressive strength is reduced by 32.5% when compared to the control at 28 d.

A primary cause of the decrease in strength with increasing amounts of RCA is the adhered mortar on the recycled aggregates. The adhered mortar creates a more porous aggregate and reduces the stiffness of the aggregates, thus resulting in a weakened interfacial transition zone (ITZ) between the aggregate and cement matrix. Silva et al.[8] found that the presence of the residual mortar layer created microstructural defects that reduced the efficiency of the load transfer. As Evangelista and Brito[24] showed, the use of RCA will generally result in the reduction of strength due to the increased water absorption and the development of a weak bond.

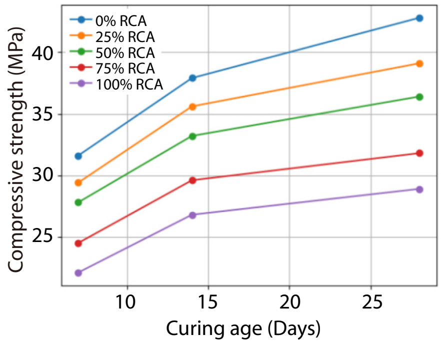

Fig. 4. Compressive strength development of hybrid concrete.

While there is a drop in compressive strength with increased usage of RCA, significant strength development was observed for all of the mixtures at both 7 and 28 d, showing evidence of pozzolanic activity of the activated fly ash. Continued hydration of the activated fly ash (along with the associated formation of secondary calcium silicate hydrates (C-S-H)) contributed to an increase in density for the cementitious matrix. This finding is supported by Thomas[25], who found that activated fly ash exhibits improved long-term strength due to continued pozzolanic activity over time.

3.4. Failure characteristics of concrete specimens

The specimens failed in a typical brittle manner (Fig. 5), with vertical and diagonal cracking; this is similar to what has been observed in conventional concrete under the same loading conditions of compressive strength testing. As the recycled concrete aggregate (RCA) content of each concrete specimen increased, the failure surfaces of these specimens became more poorly defined or frayed and exhibited greater fragmentation. The consistent nature of these failure modes can be attributed to the amount of adhered mortar and the increased porosity of the RCA material, which decreases the structural integrity of the interfacial transition zone (ITZ) between the aggregate and the cementitious matrix[22,26].

3.5. Effect of RCA replacement on 28-day compressive strength

As depicted in Fig. 6, the 28-day compressive strength of RCA concrete, with varying amounts of RCA replaced, yields a linear regression line of strength loss as the percentage of RCA increases from 0% to 100% (as shown by the error bars for each value based on six individual tests). The error bars display a very slight increase in variability with the increase in RCA percentage. The standard deviation was observed to increase significantly from ±1.2 MPa (control mixture) at 0%

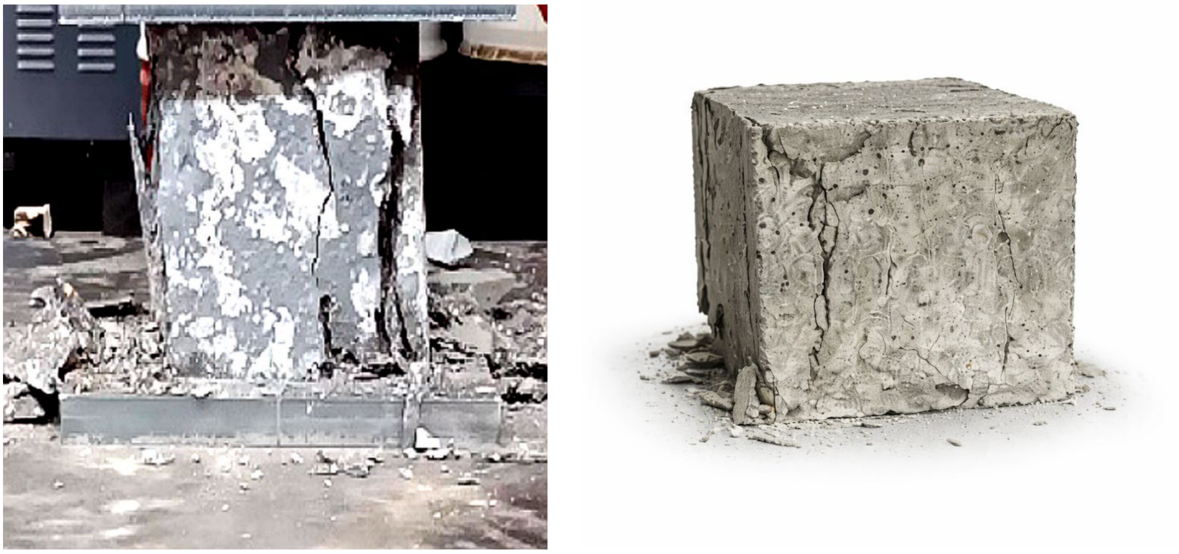

Fig. 5. Failure patterns of concrete cube specimens after compressive strength testing.

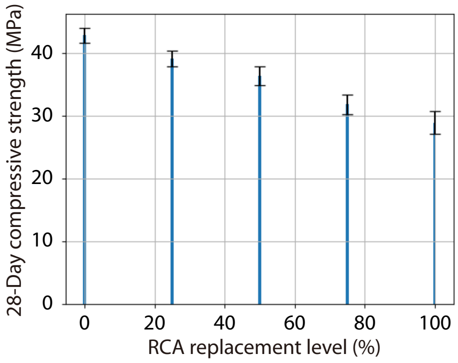

Fig. 6. Effect of RCA replacement on 28-day compressive strength.

RCA replacement to ±1.8 MPa (at 100% RCA replacement).

This disparity can be attributed to differences in the properties of recycled aggregates themselves due to the heterogeneity within the material. Many recycled aggregates contain varying levels of residual strength because they retain strength from previous structures that have been discarded, while others do not contain any remaining strength from previous structures.

Compressive strength loss is also attributed to the density of RCA and its rate of water absorption, which, when used in concrete mixes, increase the effective amount of water in relation to cement ratios in the matrix. Kou and Poon[27] found that most concrete containing RCA typically had increased pore rates of connectivity, which lowered mechanical properties. Xiao et al.[28] found that recycled concrete aggregate mixtures exhibited decreased elastic modulus and compressive strength due to the presence of internal micro-chambers caused by microcracking.

3.6. Relationship between density and water absorption

Fig. 7 depicts the correlation between the hybrid concrete density and its water absorption. The data illustrated shows a strong inverse linear relationship: as the density of hybrid concrete decreases, the amount of water absorbed increases. This relationship based on the experimental results can be defined mathematically using regression analysis in Equation (1):

$$\text{Water absorption (\%)} = -0.01308 \times \text{Density (kg m}^{-3}\text{)} + 37.08, R^2 = 0.993 \quad (1)$$

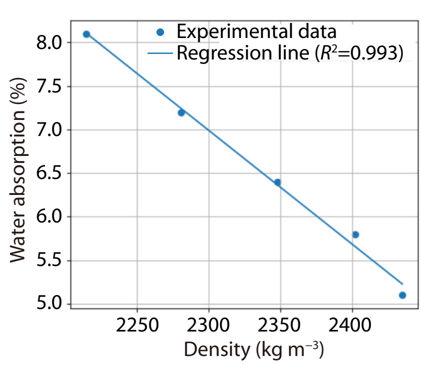

Fig. 7. Relationship between density and water absorption.

The trend indicates that the RCA content within the hybrid concrete mix influences the internal structure of the concrete matrix because lower-density mixes have a greater volume of total pore space, allowing more water to enter the mix. This finding confirms that density can be used as an accurate predictor of durability-related behaviour for hybrid concrete systems, consistent with the earlier works of Mehta and Monteiro[3] and Butler et al.[29], both noting that the incorporation of recycled aggregates reduced the density of concrete mixes, which ultimately led to an increase in porosity and permeability. A number of recent studies[11,14] have identified that both water absorption and density in RCA concrete depend on the amount of microstructural porosity and the degree of matrix refinement produced via alkali-activated fly ash.

3.7. Interaction between compressive strength and water absorption

The relationship between compressive strength and water absorption for hybrid concrete mixtures is shown in Fig. 8. A strong inverse correlation is observed, quantified by Equation (2):

$$\text{Compressive strength (MPa)} = -4.722 \times \text{Water absorption (\%)} + 66.59, R^2 = 0.992 \quad (2)$$

The results show decreased compressive strength as the percentage of water absorbed increases, which is attributed to both increased porosity and decreased microstructure integrity resulting from higher amounts of recycled aggregate materials. These results support previous work by Thomas et al.[30], which indicated that increased porosity in concrete made with recycled aggregates would both decrease strength and increase permeability. The use of alkali-activated fly ash improves the density of the concrete matrix and refines its microstructure, helping to diminish some of the effects of porosity on the overall balance between mechanical properties and durability indicators.

The results suggest that hybrid concrete incorporating recycled aggregate and fly ash will perform adequately if the proportion of each material is controlled, with water absorption serving as a key indicator of the associated strength reduction mechanisms.

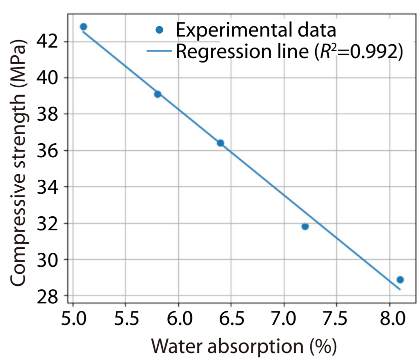

Fig. 8. Interaction between compressive strength and water absorption.

3.8. Relationship between compressive strength and density

A strong positive correlation suggests that when concrete density increases, the compressive strength of concrete also increases. The connection between the internal pore structure and the quality of the aggregate greatly influences the mechanical performance of concrete. The relationship between compressive strength and concrete density is illustrated graphically in Fig. 9. Regression analysis of the relationship between compressive strength and density yields Equation (3):

$$\text{Compressive strength (MPa)} = 0.06172 \times \text{Density (kg m}^{-3}) - 108.38, R^2 = 0.983 \tag{3}$$

The observed positive relationship between density and compressive strength is consistent with the general understanding of the concrete microstructure: as the density of concrete increases, porosity decreases, and the mechanical integrity (strength) of the material improves. Conversely, the lower the density of concrete, the more voids or empty spaces there are in the concrete mixture, thereby decreasing the cross-sectional area of concrete that can be used to resist an applied load. This agrees with the results reported by Bu and Tian[31], who indicated that the compressive strength of concrete is significantly influenced by the pore structure of the concrete and how compact or densely packed it is. Similarly, Butler et al.[29] found that incorporating recycled aggregates into concrete leads to reductions in the overall density of the concrete mixture and, as a result, reductions in compressive strength due to increased porosity and weakened aggregate-paste bonding. Hence, the strong correlation obtained from this study further supports the use of density as an indicator of mechanical performance in hybrid concrete systems.

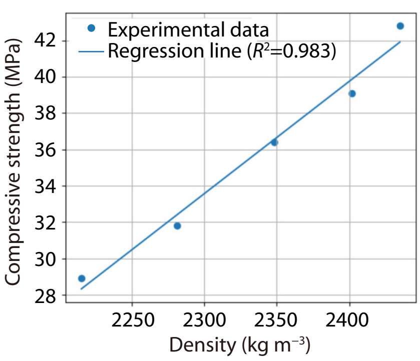

Fig. 9. Relationship between compressive strength and density.

4. Conclusions

From the experimental study of hybrid concrete using recycled concrete aggregate and alkali-activated fly ash, the following conclusions were drawn:

1) Although there was no separately measured control group for pure RCA concrete without fly ash, a comparison of the results shows that the use of alkali-activated fly ash may help counteract the reductions in compressive strength and density observed in the 0% RCA control mixture, indicating that alkali-activated fly ash plays a significant role in densifying the matrix.

2) The increased amount of RCA reduced compressive strength due to the presence of adhered mortar, increased porosity, and a weaker interfacial transition zone.

3) With increasing amounts of RCA, there was a progressive decrease in concrete density due to the lower specific gravity and higher porosity of the recycled aggregate.

4) There was an increase in water absorption with RCA replacement, indicating higher pore connectivity, but this should be viewed as a durability indicator rather than a direct measure of durability.

5) Hybrid concrete mixtures containing up to 50% RCA exhibited performance comparable to the 0% RCA in compressive strength, density, and properties related to durability.

6) The combination of RCA and alkali-activated fly ash shows promise for sustainable construction, but further studies with fully developed durability tests are necessary to understand long-term performance.

Data availability statement

All data needed to support the conclusions in the paper are presented in the manuscript. Additional data related to this paper may be requested from the corresponding author upon request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contribution statement

John Igeimokhia Braimah: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Nureni Adekunle Lamidi:** Supervision, Methodology, Validation, Project administration, Writing – review & editing. **Nafisat Motunrayo Akinniyi:** Investigation, Data curation, Validation, Methodology, Formal analysis, Resources, Writing – original draft, Writing – review & editing. **Silifat Mobisayo Adeniran-Bakare:** Investigation, Data curation, Validation, Methodology, Formal analysis, Writing – original draft, Resources, Writing – review & editing. **Robert Ojonugwa Okpanachi:** Investigation, Resources, Data curation, Validation, Writing – review & editing. **Banjo Adeola Olorunshola:** Investigation, Project administration, Data curation, Resources, Writing – Review & editing. **David Fadiran:** Investigation, Resources, Data curation, Validation, Writing – review & editing. All the authors have approved the final manuscript.

Use of AI statement

None.

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