CONSTRUCTION

Experimental Evaluation of Mechanical, Hydraulic and Abrasion Properties of Pervious Geopolymer Concrete Incorporating Recycled Concrete Aggregate

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Abstract

This study experimentally evaluated the influence of recycled concrete aggregate (RCA) on the mechanical, hydraulic and abrasion properties of conventional pervious geopolymer concrete produced with a ground granulated blast furnace slag (GGBS)–rice husk ash (RHA) binder. Four mixtures were prepared by replacing natural granite with RCA at 0, 25, 50 and 75% by mass. The binder comprised GGBS and RHA at a mass ratio of 60:40 and was activated with sodium hydroxide and sodium silicate solutions. Specimens were oven-cured at 60 °C for 24 h and then stored under laboratory conditions. Compressive strength was measured at 7, 14 and 28 days; splitting tensile strength, flexural strength, porosity and permeability were determined at 28 days; and abrasion loss was assessed at 56 days. The results, reported as means of three replicate specimens, showed that 28-day compressive strength decreased from 22.8 MPa in the control mixture to 16.5 MPa at 75% RCA, splitting tensile strength from 2.35 to 1.91 MPa, and flexural strength from 3.85 to 3.19 MPa. Porosity increased from 10.5 to 14.0%, whereas permeability increased from 1.2 mm/s in the control to 1.6 mm/s at 50% RCA before decreasing to 1.3 mm/s at 75% RCA. Abrasion loss increased from 12 to 19%. The results indicate a trade-off between mechanical performance and hydraulic response as RCA content increases. Within the materials and test conditions investigated, 25–50% RCA gave the most favourable compromise, although the measured permeability indicates that drainage performance requires further optimisation and field validation.

Keywords: Abrasion resistance; Permeability; Pervious geopolymer concrete; Recycled concrete aggregate; Rice husk ash

1 Introduction

Pervious concrete is a gap-graded cementitious material in which coarse aggregate particles are bonded by a thin paste coating, leaving interconnected voids through which water can drain. It is increasingly considered for permeable pavements and stormwater management because it can reduce surface runoff and promote infiltration. Its practical use requires a balance between hydraulic conductivity and mechanical capacity: a more open void structure improves water transmission but reduces the effective load-bearing area and strength [1, 2].

Geopolymer and alkali-activated binders are being investigated as alternatives to Portland cement. They are produced by reacting aluminosilicate-rich precursors with alkaline activator solutions, commonly sodium hydroxide and sodium silicate [3, 4]. Ground granulated blast furnace slag (GGBS) supplies calcium-bearing and aluminosilicate phases, while rice husk ash (RHA) is a silica-rich

agricultural residue that can serve as a precursor. The performance of a blended GGBS–RHA binder depends on precursor chemistry, fineness, activator composition and curing. Earlier work on dense geopolymer concrete has examined GGBS and RHA combinations, but the response of such a binder in a pervious aggregate skeleton requires separate evaluation [5].

Recycled concrete aggregate (RCA) offers a route to reduce the consumption of virgin aggregate and to reuse construction and demolition waste. RCA contains original aggregate particles with adhered mortar, which can increase porosity and water absorption and reduce aggregate density and strength compared with natural aggregate. In conventional pervious concrete, RCA has been associated with changes in strength, porosity and permeability, although the size and even the direction of the response depend on aggregate quality, grading, binder and mixture design [6, 7, 8].

Research on pervious geopolymer concrete containing RCA is developing, but comparison between studies is complicated by differences in binder chemistry, aggregate grading, specimen geometry, curing regime, target porosity and permeability test method. Results from channel-type concrete should not be treated as equivalent to conventional gap-graded pervious concrete because the pore-forming geometry and load-transfer mechanism differ. Even within conventional pervious geopolymer concrete, cube and cylinder strengths are not interchangeable, and constant-head and falling-head permeability measurements can give different values. These differences help to explain apparently conflicting findings in the literature [9, 10].

A further gap concerns the combined use of a GGBS–RHA binder and RCA in conventional pervious geopolymer concrete. To the best of the authors' knowledge, none of the direct experimental studies on pervious geopolymer concrete with RCA that were identified used RHA, and none was carried out in Africa. The present study addresses this gap using locally sourced precursors and aggregates. Its objective was to determine how replacing granite with RCA at 0, 25, 50 and 75% by mass affects compressive, splitting tensile and flexural strengths, porosity, laboratory permeability coefficient and abrasion loss. The observed trends are related to measured aggregate characteristics, and the limitations that should be considered before pavement application are identified.

2 Materials and methods

2.1 Materials

The binder precursors were rice husk ash (RHA) and GGBS. Rice husk was obtained from Hybrid Feeds Ltd, Ibadan, Oyo State, Nigeria, burnt in a furnace at 600 °C for 5 h, cooled and ground. GGBS was supplied by African Foundries Limited, Ogijo, Ogun State, Nigeria, and 80% of it passed a 45 μm sieve. The coarse aggregates were crushed granite of 13.2–25 mm particle size and RCA obtained by manually crushing waste concrete from the demolition of a building about 10 years old to a nominal size of 19–25 mm. The alkaline activator combined sodium hydroxide (NaOH) pellets of 99% purity, dissolved in distilled water to give a 10 M solution, with liquid sodium silicate (Na2SiO3). No fine aggregate or superplasticiser was used.

2.2 Characterisation of materials

The oxide compositions of RHA and GGBS were determined by energy-dispersive X-ray fluorescence (EDXRF) at Spectrum Analytical Services, Kaduna, Nigeria. Granite and RCA were characterised by sieve analysis (ASTM C136/C136M), specific gravity (ASTM C127), bulk density (ASTM C29/C29M),

aggregate impact value (AIV, BS 812-112) and aggregate crushing value (ACV, BS 812-110). Water absorption of the aggregates was not determined and is therefore not reported.

2.3 Mixture proportions

The adopted mixture parameters were an assumed concrete density of 1,080 kg/m^3, an aggregate-to-binder ratio of 4:1, an alkaline activator-to-binder ratio of 0.4, a sodium silicate-to-sodium hydroxide solution ratio of 2:1 and a GGBS:RHA ratio of 60:40, all by mass. The binder content calculated from the assumed density was 200 kg/m^3, comprising 120 kg/m^3 of GGBS and 80 kg/m^3 of RHA. The coarse aggregate content was 800 kg/m^3 and the total activator content was 80 kg/m^3. RCA replaced granite by mass at 0, 25, 50 and 75%, and the mixtures are designated PG0, PG25, PG50 and PG75 (Table 1). The assumed density was a proportioning basis only and is not a measured hardened density.

Table 1. Mixture proportions of pervious geopolymer concrete (kg/m3).

Material	PG0	PG25	PG50	PG75
RCA replacement (%)	0	25	50	75
Granite	800	600	400	200
RCA	0	200	400	600
GGBS	120	120	120	120
RHA	80	80	80	80
Sodium silicate	53.3	53.3	53.3	53.3
NaOH solution (10 M)	26.7	26.7	26.7	26.7

2.4 Specimen production and curing

The NaOH solution was prepared by dissolving the pellets in distilled water and allowing it to cool, and was then combined with the sodium silicate solution. GGBS and RHA were blended manually, granite and the required RCA were added, and the combined activator was introduced gradually during manual mixing, which continued until a reasonably uniform mixture was obtained. The mixture was placed in moulds and compacted with a tamping rod in three layers of 25 blows each. Specimens were 150 mm cubes for the compressive strength, porosity, permeability and abrasion tests, 100 × 200 mm cylinders for splitting tensile strength and 100 × 100 × 400 mm beams for flexural strength. Three replicate specimens were cast for each mixture, test and age.

Specimens were oven-cured at 60 °C for 24 h to promote geopolymerisation, in line with the heat curing used in earlier studies of pervious geopolymer concrete [11, 12]. They were demoulded the following day and stored under laboratory conditions in a cool place until testing. Compressive strength was measured at 7, 14 and 28 days; splitting tensile strength, flexural strength, porosity and permeability at 28 days; and abrasion resistance at 56 days.

2.5 Test procedures

Compressive strength was determined on 150 mm cubes to BS EN 12390-3 using a 2,000 kN universal testing machine; strength is the maximum load divided by the loaded area. Splitting tensile strength was determined on 100 × 200 mm cylinders to BS EN 12390-6 using $f_{ct} = 2P/(\pi LD)$, where P

is the maximum load, L the cylinder length and D its diameter. Flexural strength was measured on 100 × 100 × 400 mm beams under centre-point (three-point) loading to BS EN 12390-5.

Porosity was determined by the water-displacement method with reference to ASTM C1754/C1754M. Permeability was measured with a manual constant-head arrangement at a hydraulic head of 100 mm on 150 mm cubes whose lateral faces were sealed with waterproofing resin. The coefficient is reported as a laboratory permeability coefficient (hydraulic conductivity) and not as an in-place infiltration rate. Abrasion resistance was assessed at 56 days on 150 mm cubes in a Los Angeles abrasion machine with five steel balls for 500 revolutions. The percentage of material passing the sieve after the test was taken as the abrasion loss and the remainder as the mass retained. Abrasion test procedures for pervious concrete differ between studies, so the results are used here to rank the mixtures and are not compared numerically with values from other studies.

2.6 Data treatment

Results are the means of three replicate specimens for each mixture and age. The analysis comprised descriptive comparison, percentage change relative to the control mixture (PG0), linear regression and correlation analysis, and ratios of splitting tensile and flexural strength to compressive strength. Regression and correlation used the four mixture-level means. They are therefore descriptive and exploratory, and they do not establish statistical significance or causal relationships.

3 Results and discussion

3.1 Chemical composition of the precursors

XRF analysis (Table 2) showed that the RHA was almost pure silica, containing 90.97% SiO_2, 0.38% Al_2O_3 and 0.71% CaO, with a loss on ignition (LOI) of 2.14%. The GGBS contained 32.26% SiO_2, 8.64% Al_2O_3 and 7.54% CaO, together with 16.70% Fe_2O_3, 13.27% TiO_2 and 7.44% MnO, and its LOI was 12.60%. The calculated 60:40 binder contained 55.74% SiO_2, 5.34% Al_2O_3 and 4.81% CaO, so the RHA acted mainly as a silica-rich component of the blend.

Table 2. Oxide composition of the precursors and calculated binder (%).

Oxide	GGBS	RHA	60:40 binder
SiO_2	32.26	90.97	55.74
Al_2O_3	8.64	0.38	5.34
Fe_2O_3	16.70	1.75	10.72
CaO	7.54	0.71	4.81
MgO	0.67	ND	0.40
TiO_2	13.27	0.05	7.98
MnO	7.44	0.13	4.52
LOI	12.60	2.14	8.42

Note: ND = not detected. Binder values are calculated from the precursor compositions and the 60:40 mass blend.

The GGBS was low in calcium: its (CaO + MgO)/(SiO_2 + Al_2O_3) ratio was 0.20, so less calcium was available for C–A–S–H gel formation than in the calcium-rich slags used in other studies [9]. XRF gives

elemental oxide composition only. It does not show whether the silica of the RHA is amorphous and reactive, or whether the iron-, titanium- and manganese-bearing constituents of the GGBS take part in reaction, and mineralogy was not determined.

3.2 Aggregate characteristics and grading

The RCA had lower specific gravity and bulk density than granite (Table 3): 2.47 and 1,264.72 kg/m^3 against 2.67 and 1,478.64 kg/m^3, which is 7.5% and 14.5% lower. Its AIV (22.38%) and ACV (25.67%) were higher than those of granite (15.18 and 21.35%), indicating lower resistance to impact and crushing. Water absorption was not measured, which limits comparison with studies that report it.

Table 3. Physical and mechanical properties of granite and RCA.

Property	Granite	RCA
Specific gravity	2.67	2.47
AIV (%)	15.18	22.38
ACV (%)	21.35	25.67
Bulk density (kg/m^3)	1,478.64	1,264.72

Sieve analysis (Figure 1) showed that 84.6% of the granite lay between 13.2 and 25 mm, whereas 58.75% of the RCA lay between 19 and 25 mm. The cumulative percentage retained on the 19 mm sieve was 43.80% for granite and 76.61% for RCA, so the RCA was coarser and more broadly graded. Aggregate type and grading therefore changed together as RCA replacement increased, and the effect of RCA content cannot be separated completely from the effect of grading. Both aggregates contained almost no material finer than 4.75 mm (0.12% for granite and 0.30% for RCA), as is appropriate for pervious concrete.

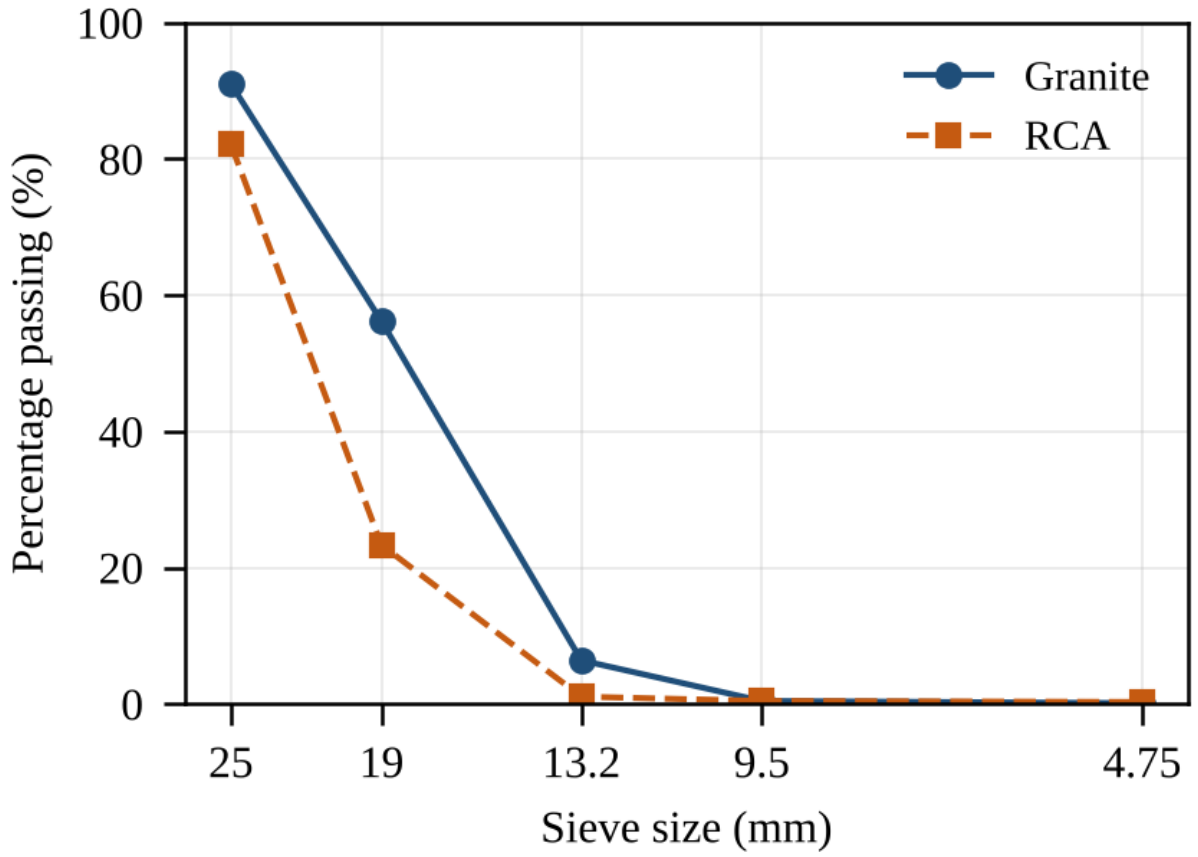


Figure 1. Particle-size distribution of granite and recycled concrete aggregate.

3.3 Compressive strength

Compressive strength increased with age in all mixtures but decreased progressively as RCA replacement increased (Table 4, Figure 2). At 28 days the control PG0 achieved 22.8 MPa, compared with 20.5, 18.7 and 16.5 MPa for PG25, PG50 and PG75, which are reductions of 10.1, 18.0 and 27.6% relative to PG0. The same ranking was observed at 7 and 14 days. The lower strength of the RCA mixtures is consistent with the lower specific gravity and higher AIV and ACV of the RCA. The adhered old mortar may also form a weak zone within the aggregate particle and at the new paste–aggregate interface. These mechanisms are plausible, but their individual contributions were not measured.

Table 4. Mechanical properties of the mixtures (mean of three specimens).

Mix	RCA (%)	$f_{c,7}$	$f_{c,14}$	$f_{c,28}$	f_{ct}	f_r
PG0	0	16.2	19.4	22.8	2.35	3.85
PG25	25	14.4	17.2	20.5	2.27	3.72
PG50	50	12.8	15.9	18.7	2.08	3.48
PG75	75	10.8	13.8	16.5	1.91	3.19

Note: $f_{c,7}$, $f_{c,14}$, $f_{c,28}$: compressive strength at 7, 14 and 28 days; f_{ct}: splitting tensile strength at 28 days; f_r: flexural strength at 28 days. All values in MPa.

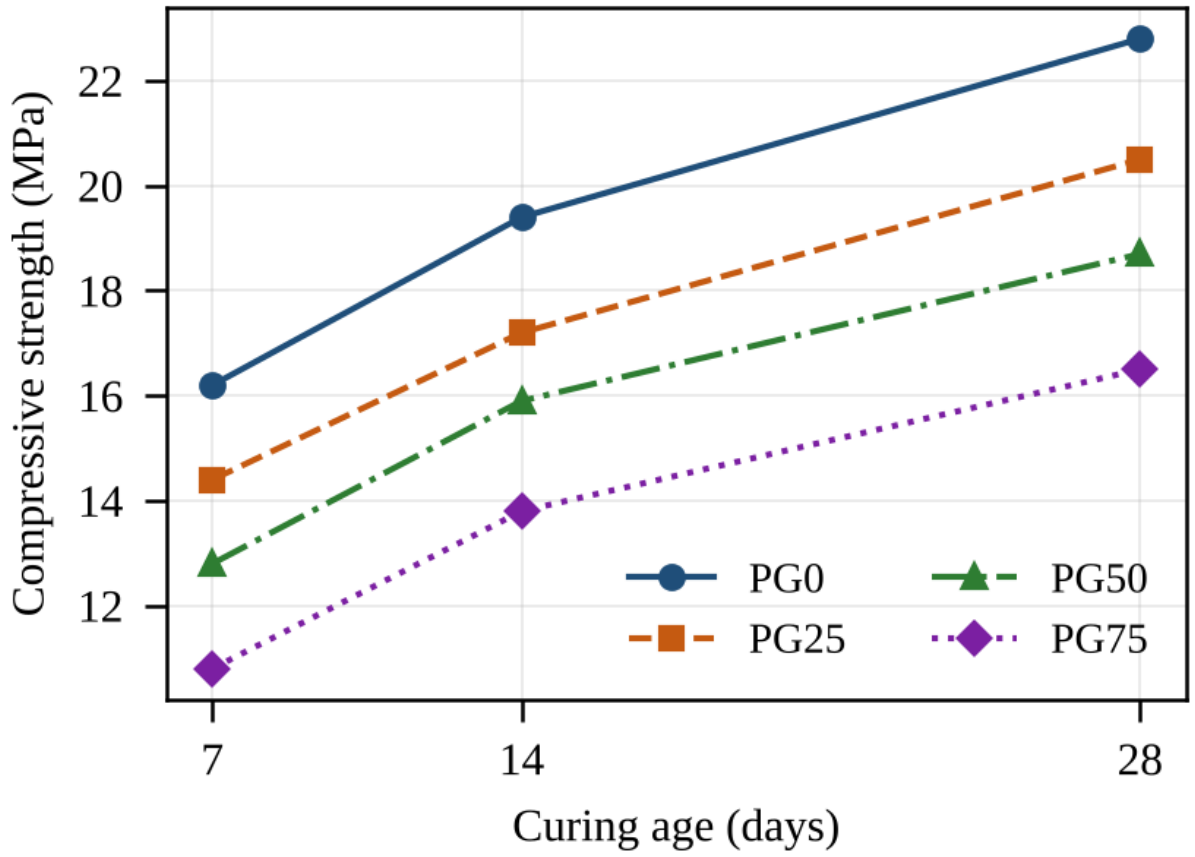


Figure 2. Compressive strength development of the mixtures at 7, 14 and 28 days.

The 18.0% reduction at 50% RCA is close to the 18.6% reduction reported for a slag–bagasse ash pervious concrete with 50% RCA [13]. This comparison is indicative because the precursor blend, aggregate characteristics and test conditions differ. Anwar et al. [9] reported a larger reduction at full RCA replacement in a GGBS-based pervious geopolymer concrete, but their cylinder results cannot be compared numerically without accounting for specimen geometry and mixture design. Other studies have reported different trends, which shows that RCA quality, grading, porosity and binder chemistry jointly influence strength [14].

3.4 Splitting tensile and flexural strength

At 28 days, splitting tensile strength decreased from 2.35 MPa for PG0 to 2.27, 2.08 and 1.91 MPa for PG25, PG50 and PG75, and flexural strength decreased from 3.85 to 3.72, 3.48 and 3.19 MPa (Table 4, Figure 3). At 75% RCA the reductions relative to the control were 18.7% for splitting tensile strength and 17.1% for flexural strength, smaller than the 27.6% reduction in compressive strength. The splitting tensile-to-compressive strength ratio therefore rose from 10.31 to 11.58%, and the flexural-to-compressive ratio from 16.89 to 19.33%. These ratios show that tensile and flexural strength declined less rapidly than compressive strength across the four mixtures; they are not evidence that tensile or flexural capacity improved.

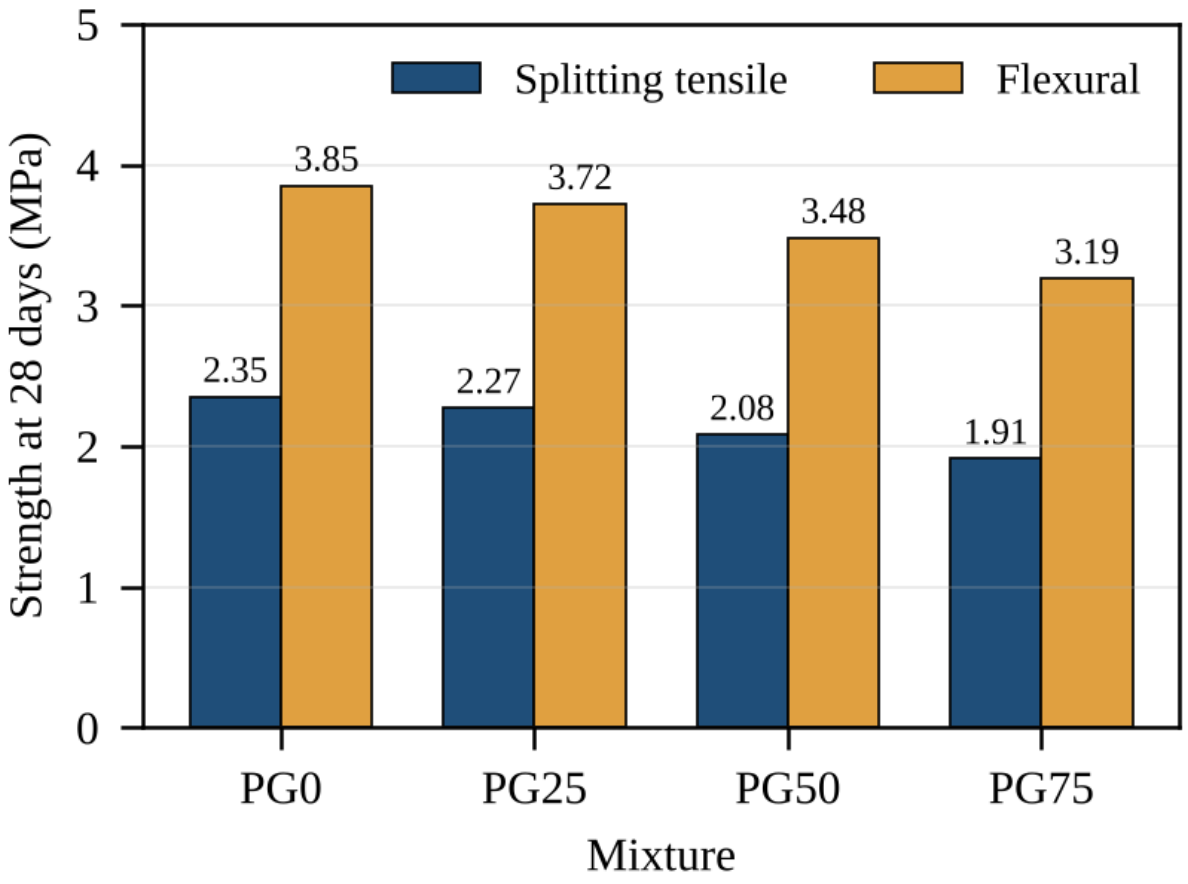


Figure 3. Splitting tensile and flexural strengths of the mixtures at 28 days.

3.5 Porosity and permeability

Measured porosity increased from 10.5% in PG0 to 11.7, 12.5 and 14.0% in PG25, PG50 and PG75 (Table 5, Figure 4). The permeability coefficient increased from 1.2 mm/s in PG0 to 1.4 mm/s in PG25 and 1.6 mm/s in PG50, before decreasing to 1.3 mm/s in PG75. PG75 therefore had the highest total porosity but not the highest permeability, which confirms that void content alone does not determine water flow: the continuity, size and constriction of connected pore channels are also important [2].

Table 5. Porosity, permeability and abrasion loss of the mixtures.

Mix	RCA (%)	Porosity (%)	k (mm/s)	Abrasion loss (%)
PG0	0	10.5	1.2	12
PG25	25	11.7	1.4	14
PG50	50	12.5	1.6	16
PG75	75	14.0	1.3	19

Note: Porosity and *k* (laboratory permeability coefficient) at 28 days; abrasion loss after 500 revolutions at 56 days.

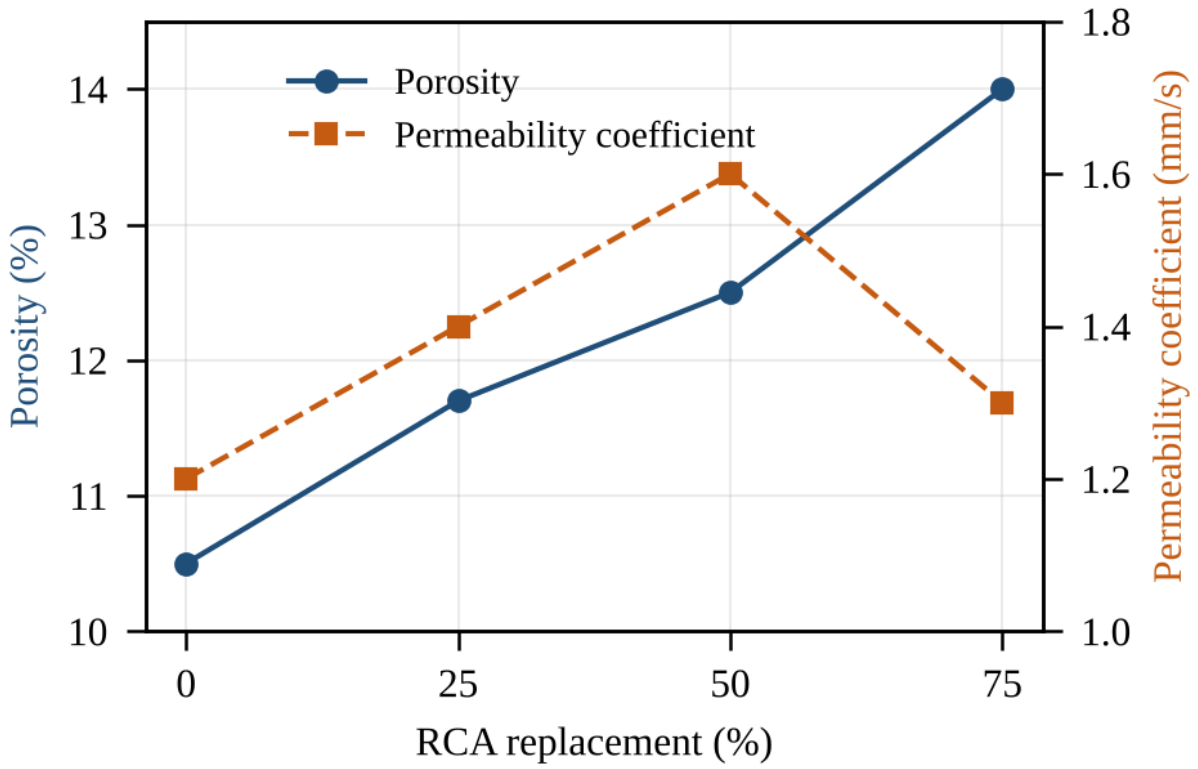


Figure 4. Porosity and permeability coefficient versus RCA replacement level at 28 days.

The reduction in permeability at 75% RCA, despite the higher porosity, may be associated with less well-connected pore channels, the coarser and wider RCA grading, or fines generated from the weaker adhered mortar during mixing and compaction. These explanations are hypotheses, because pore connectivity and fines generation were not measured by microscopy, tomography or particle-size analysis. The permeability values of 1.2–1.6 mm/s lie near the lower end of the range commonly reported for pervious concrete, and the control value is slightly below the commonly cited lower benchmark of 1.3 mm/s [9]. Because test methods and specimen sizes differ between studies, such comparisons are indicative. The measured coefficient is not an in-place infiltration rate, and the results do not establish field drainage performance or resistance to clogging.

The permeability trend also differs from the monotonic trends in strength and porosity. Linear regression on the four mixture means gave a weak relationship between RCA content and permeability (R^2 = 0.143), and the correlation with porosity was also weak (r = 0.29). Permeability should therefore not be estimated from porosity or strength using these four points.

3.6 Abrasion resistance

Abrasion loss after 500 revolutions increased from 12% for PG0 to 14, 16 and 19% for PG25, PG50 and PG75 (Table 5, Figure 5); the loss of PG75 was 58.3% higher than that of the control. The trend is consistent with the lower impact and crushing resistance of the RCA and the progressive fall in compressive strength. A plausible explanation is that weaker RCA particles and their adhered mortar detach more easily under repeated impact.

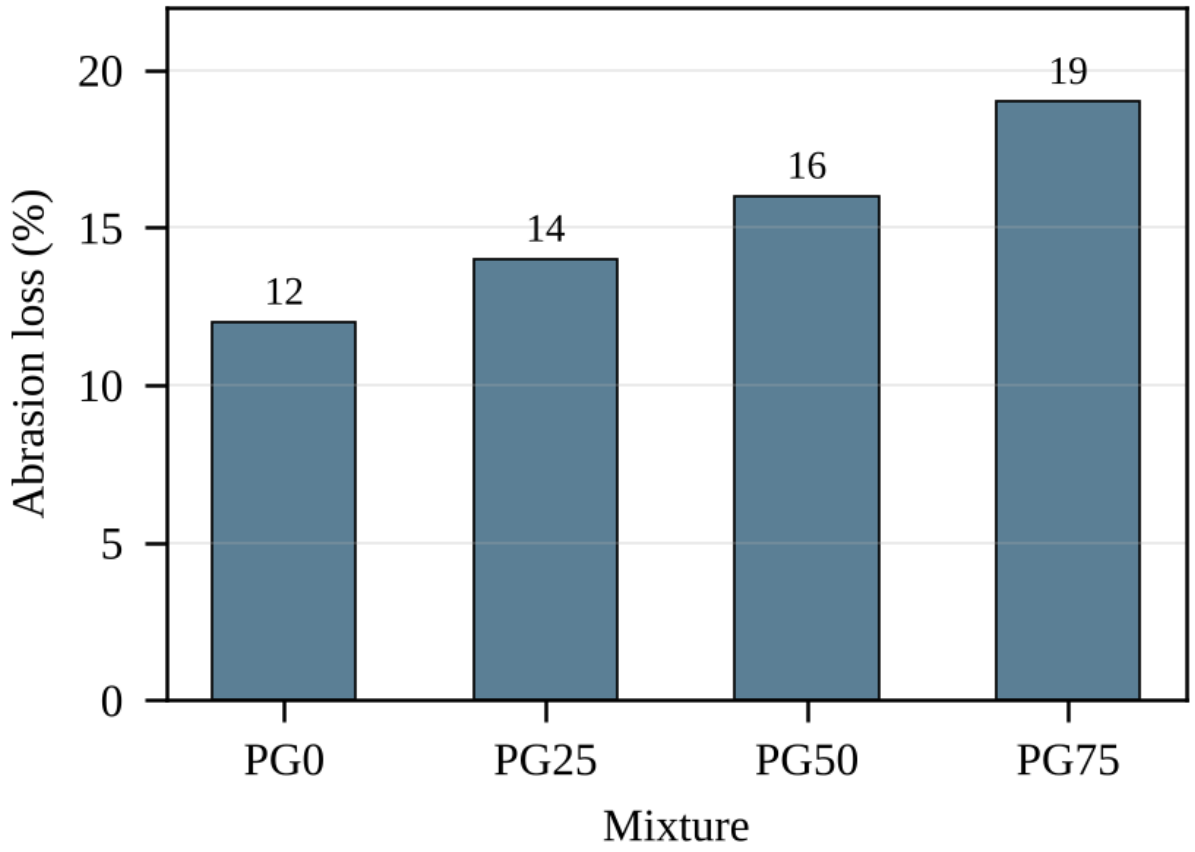


Figure 5. Abrasion loss of the mixtures after 500 revolutions.

3.7 Relationships among properties and overall performance

Regression analysis showed strong linear trends between RCA content and compressive strength, splitting tensile strength, flexural strength, porosity and abrasion loss (R^2 = 0.974–0.998). Compressive strength decreased by about 1.8 MPa for each 1% increase in porosity (R^2 = 0.992), and splitting tensile and flexural strengths were strongly associated with compressive strength. These high values reflect consistent monotonic changes across only four mixture-level means and should not be read as validated predictive models. Because all these properties changed systematically with RCA content, their correlations may partly reflect a common dependence on the replacement level rather than direct causal relationships.

The permeability response was different: it peaked at PG50 and declined at PG75, so no single RCA level maximised every indicator. PG25 retained compressive, tensile and flexural strengths relatively close to the control, whereas PG50 gave the highest permeability coefficient (1.6 mm/s) while retaining 18.7 MPa compressive strength at 28 days. PG75 had the lowest strengths and the highest abrasion loss without a corresponding permeability advantage. An RCA content of 25–50% is therefore the most promising range among the mixtures tested, but this is a performance compromise and not a validated optimum for pavement design.

3.8 Implications and limitations

The use of RHA, GGBS and RCA offers a potential route to valorise agricultural, industrial and construction wastes and to reduce demand for virgin coarse aggregate. This study did not, however, quantify embodied carbon, energy demand, transport impacts, leaching or life-cycle performance, so

the environmental benefits remain potential rather than measured. Published life-cycle assessments of alkali-activated pervious concrete report reductions in global warming potential, but the outcome depends strongly on system boundaries, functional units, activator production and transport [13, 15]. Sodium silicate production and heat curing can materially affect the environmental profile, and a comparative life-cycle assessment is required before environmental superiority is claimed.

The findings are subject to several limitations. Only four RCA replacement levels, one binder composition, one activator, one curing regime and one RCA source were examined. The RCA and granite had different gradings, so aggregate type and grading effects are confounded. Aggregate water absorption and precursor mineralogy were not measured. Only mean values of three specimens are reported, without dispersion statistics. Permeability was a laboratory constant-head test that does not evaluate in-place infiltration or clogging, and abrasion was the only durability test; chemical attack, freeze–thaw exposure and long-term field performance were not investigated.

4 Conclusion

This study examined the effect of replacing granite with RCA at 0, 25, 50 and 75% by mass in pervious geopolymer concrete made with a 60:40 GGBS–RHA binder. Within the materials, mixture proportions, curing regime and test methods used, the following conclusions are drawn.

1. The RHA was almost pure silica (90.97% SiO_2), whereas the GGBS was low in calcium (7.54% CaO) and rich in Fe_2O_3 (16.70%). The RCA was lighter, weaker and coarser than the granite.
2. Increasing RCA content reduced compressive, splitting tensile and flexural strengths. At 75% RCA the 28-day compressive strength fell by 27.6% (from 22.8 to 16.5 MPa), while splitting tensile and flexural strengths fell by 18.7 and 17.1%.
3. Porosity rose from 10.5 to 14.0% and abrasion loss from 12 to 19% with RCA content, whereas permeability peaked at 1.6 mm/s at 50% RCA and fell to 1.3 mm/s at 75%, so total porosity alone did not control water flow.
4. An RCA content of 25–50% gave the most favourable balance of strength, drainage and abrasion resistance: PG25 stayed closest to the control and PG50 gave the highest permeability, subject to the low permeability values and the laboratory limitations noted above.
5. The results support the technical potential of combining RHA, GGBS and RCA in pervious geopolymer concrete but do not establish field suitability or quantified environmental benefit. Further work should control aggregate grading, measure RCA absorption and pore connectivity, include clogging and long-term durability tests, and undertake a life-cycle assessment.

References

[1] Zhong R, Leng Z, Poon CS. Research and application of pervious concrete as a sustainable pavement material: A state-of-the-art and state-of-the-practice review. *Constr. Build. Mater*. 2018;183:544–553. https://doi.org/10.1016/j.conbuildmat.2018.06.131

[2] Chandrappa AK, Biligiri KP. Pore structure characterization of pervious concrete using X-ray microcomputed tomography. *J. Mater. Civ. Eng*. 2018;30(6):04018108. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002285

[3] Davidovits J. Geopolymers: Inorganic polymeric new materials. *J. Therm. Anal*. 1991;37:1633–1656. https://doi.org/10.1007/BF01912193

[4] Duxson P, Provis JL, Lukey GC, van Deventer JSJ. The role of inorganic polymer technology in the development of 'green concrete'. *Cem. Concr. Res*. 2007;37(12):1590–1597. https://doi.org/10.1016/j.cemconres.2007.08.018

[5] Ramani PV, Chinnaraj PK. Geopolymer concrete with ground granulated blast furnace slag and black rice husk ash. *Građevinar*. 2015;67(8):741–748. https://doi.org/10.14256/JCE.1208.2015

[6] Rizvi R, Tighe S, Henderson V, Norris J. *Evaluating the use of recycled concrete aggregate in pervious concrete pavement*. Transp. Res. Rec. 2010;2164(1):Res. https://doi.org/10.3141/2164-17

[7] Sriravindrarajah R, Wang NDH, Ervin LJW. Mix design for pervious recycled aggregate concrete. *Int. J. Concr. Struct. Mater*. 2012;6(4):239–246. https://doi.org/10.1007/s40069-012-0024-x

[8] Yap SP, Chen PZC, Goh Y, Ibrahim HA, Mo KH, Yuen CW. Characterization of pervious concrete with blended natural aggregate and recycled concrete aggregates. *J. Clean. Prod*. 2018;181:155–165. https://doi.org/10.1016/j.jclepro.2018.01.205

[9] Anwar FH, El-Hassan H, Hamouda M, El-Mir A, Mo KH. Performance evaluation of pervious geopolymer concrete incorporating recycled concrete aggregate. *Int. J. Sustain. Eng*. 2024;17(1):149–166. https://doi.org/10.1080/19397038.2024.2417003

[10] Coffetti D, Rapelli S, Coppola L. Alkali-activated slag as sustainable binder for pervious concrete and structural plaster: A feasibility study. *Materials*. 2024;17(16):4084. https://doi.org/10.3390/ma17164084

[11] Tho-in T, Sata V, Chindaprasirt P, Jaturapitakkul C. Pervious high-calcium fly ash geopolymer concrete. *Constr. Build. Mater*. 2012;30:366–371. https://doi.org/10.1016/j.conbuildmat.2011.12.028

[12] Ma Q, Yang W, Duan Z, Liu H, Hua M, Deng Q. Influence of alkali-activators on acid rain resistance of geopolymer-recycled pervious concrete with optimal pore size. *Materials*. 2022;15(23):8368. https://doi.org/10.3390/ma15238368

[13] Marathe S, Sheshadri A, Nikolaiev V. Life cycle assessment of sustainable air-cured alkali-activated concrete for permeable pavements using agro-industrial wastes. *Sci. Rep*. 2025;15:22012. https://doi.org/10.1038/s41598-025-04783-x

[14] Nazeer M, Kapoor K, Singh SP. Strength, durability and microstructural properties of geopolymer pervious concrete containing recycled concrete aggregates. *Mag. Concr. Res*. 2025;77(7–8):371–383. https://doi.org/10.1680/jmacr.24.00160

[15] Merino-Lechuga AM, et al. Technical and environmental assessment of CO_2-cured alkali-activated pervious paving blocks incorporating recycled aggregates. *Constr. Build. Mater*. 2025;489:142286. https://doi.org/10.1016/j.conbuildmat.2025.142286