Civil Engineering and Applied Solutions

Research Article

journal homepage: ceas.journals.umz.ac.ir

CEAS Civil Engineering and Applied Solutions

Improvement of Recycled Concrete Aggregate Properties by Polyvinyl Alcohol

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ARTICLE INFO

Keywords:
Recycled concrete aggregate (RCA)
Polyvinyl alcohol (PVA)
Natural aggregate (NA)
Concrete

Article history:
Received 29 September 2025
Accepted 23 November 2025
Available online 01 February 2026

ABSTRACT

This study examines liquid polyvinyl alcohol (PVA) impregnation of recycled concrete aggregate (RCA) to refine pore structure and evaluate its influence on the fresh and hardened properties of companion concretes, using natural aggregate concrete as the benchmark. Aggregates were pretreated at progressively higher PVA dosages and characterized for specific gravity, water absorption, and gradation, and concretes with untreated and PVA-treated RCA were assessed for slump, water absorption, compressive strength, and drying shrinkage. The investigation was intentionally designed for non-structural concrete applications such as paving blocks, curbs, and lightweight elements, where durability and sustainability are prioritized over high strength. Results indicated that increasing PVA dosage enhanced aggregate density and reduced water absorption at higher levels (10%), but also caused trade-offs in workability and mechanical strength. Workability improved at 6% PVA but declined at higher contents, while compressive strength decreased at 6–8% and partially recovered at 10%. Drying shrinkage increased slightly with PVA addition. Overall, PVA pretreatment improved aggregate densification and moisture resistance but required dosage optimization for practical use in durable, non-structural RCA concretes aimed at sustainable resource utilization.

1. Introduction

Construction and demolition activities generate vast amounts of waste from building, renovation, and demolition processes, which occupy valuable landfill space and negatively affect soil, water, and air quality [1]. In addition, the growing demand for construction materials has placed increasing pressure on natural resources, driving natural aggregate (NA) production from 21 billion tons in 2007 to 40 billion tons in 2014 [2]. The construction industry, being one of the largest globally, is also a significant contributor to carbon dioxide emissions. These combined challenges of waste management, resource depletion, and environmental impact highlight the need for more sustainable practices. One promising approach is the use of recycled concrete aggregate (RCA), which can reduce waste generation while conserving natural aggregates [3, 4].

However, despite its environmental benefits, RCA still faces significant technical challenges that limit its widespread application in structural concrete. Compared to natural aggregates, RCA exhibits higher porosity, greater water absorption, and higher bulk densities, largely due to the residual mortar adhered to its surface [5, 6]. As a result, recycled aggregate concrete (RAC) generally shows lower compressive and tensile strengths and weaker structural performance than conventional concrete [7-10]. Olorunsogo and Padayachee [11] investigated the durability of concrete with varying proportions of recycled aggregate (0, 50, and 100%) using indicators such as chloride conductivity, oxygen permeability, and water sorptivity. They reported that durability decreased as the RCA content increased, with mixes containing 100% RCA showing up to 86.5% higher chloride conductivity and 28.8% higher water sorptivity compared to natural aggregate concrete at 56 days.

A major factor behind such poor performance is the adhered mortar on RCA surfaces, which increases porosity, water absorption,

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https://doi.org/10.22080/ceas.2025.30167.1046
ISSN: 3092-7749/© 2026 The Author(s). Published by University of Mazandaran.

How to cite this article: Valizadeh Kiamahalleh, M., Khorshidi-Mianaei, A., Safari, A. Improvement of Recycled Concrete Aggregate Properties by Polyvinyl Alcohol. Civil Engineering and Applied Solutions. 2026; 2(2): 49–59. doi:10.22080/ceas.2025.30167.1046.

and reduces density, thereby weakening the aggregate's mechanical properties. While methods such as washing, chemical treatments, and the use of supplementary materials like fly ash or carbonation have been explored to improve RCA, their effectiveness remains limited and often inconsistent. As a result, researchers have sought alternative approaches that focus on strengthening the adhered mortar rather than removing it. One promising option is the use of polyvinyl alcohol (PVA), a water-soluble polymer known for its excellent bonding, film-forming, and durability-enhancing properties.

Kim and Robertson [12] proposed the pre-wetting method to prepare polyvinyl alcohol-modified cement-based materials and found that the porosity of modified cement-based materials prepared by this method could be reduced to 6%. When a small amount of PVA is added (less than 2%), the air void content and apparent fluidity of fresh mortar and concrete increase, and the bleeding reduces. Due to the increase in fluidity, the slump of the modified concrete increases. Allahverdi et al. [13] studied the effects of different water–cement ratios and polymer–cement ratios on the workability of modified cement mortar. It was found that adding a small amount of polyvinyl alcohol can improve the fluidity of cement mortar. However, with the increase of PVA content, the fluidity of modified cement mortar will be adversely affected. Nguyen et al. studied the effects of molecular weight and dosage of PVA on rheological properties of cement-based materials and found that the yield stress and plastic viscosity of cement paste increased with the increasing content and molecular weight of PVA. Shear thinning occurs with the increase of shear rate. Zongcai et al. [14] showed that the load–deformation curve of PVA fibre-reinforced concrete indicates its ability to withstand load after cracking, with the failure mode shifting from brittle to ductile behavior. This demonstrates that PVA fibres can significantly enhance the ductility of concrete [15]. Compared with ordinary concrete and steel fibre-reinforced concrete, the PVA fibre-reinforced concrete enjoys a low self-weight and high toughness [16], durability, and fatigue resistance. Recent research by Xie et al. [17] demonstrated that the addition of PVA fibers in combination with limestone fines significantly influences the workability and mechanical properties of cementitious composites. An optimal dosage of 0.2% PVA fibers with 10% limestone fines was shown to enhance compressive and flexural strength, while excessive fiber content increased porosity and reduced performance. Wang and Zhu [18] studied the combined effect of nano-silica (NS) and PVA fibers on recycled aggregate concrete (RAC). Their results showed that PVA fibers enhanced the compressive strength and ductility of RAC by bridging microcracks and improving the interfacial bonding between aggregates and the matrix. The addition of nano-silica further improved compactness, leading to superior mechanical performance under uniaxial compression. The improvement was attributed to the better distribution of aggregates and the increased interlocking between fibres and aggregates. Yu et al. [19] showed that PVA fibers helped reduce crack width, delay fragmentation, and improve flexural behavior compared to RAC without fibers.

To address these limitations, this research investigates the use of liquid PVA to improve the properties of RCA, with the goal of producing durable, non-structural RCA concrete. The study focuses on determining the optimum PVA dosage that can enhance compressive strength and durability, while acknowledging its trade-off in reducing slump and workability. In this context, PVA is applied specifically to strengthen the adhered mortar and refine the micro-pores of RCA. The performance of PVA-treated RCA is evaluated through comparisons with control specimens in terms of compressive strength and water absorption.

2. Research significance

There has been an increasing number of research studies and findings focused on the modification of using fly ash for concrete pavement applications. RCA suffers from high porosity and weakly adherent mortar, which depresses strength and durability. There has been no study dedicated solely to recycled concrete aggregate using PVA treatment. This study investigates liquid PVA as a targeted pre-treatment for RCA applied to strengthen the adhered mortar and refine micro-pores before mixing. In this research, the optimum PVA dosage is identified to enhance compressive strength and reduce water absorption, while explicitly acknowledging the trade-off of reduced slump and workability. In this research, performance is benchmarked against untreated controls using standard compressive-strength and water-absorption tests. Because the treatment is a simple surface process that can be integrated into aggregate production, the approach is scalable for ready-mix and precast operations. The findings provide a practical pathway to durable, non-structural RCA concretes, enabling higher RCA replacement levels, conserving natural aggregates, and supporting decarbonization through higher-value recycling of demolition waste.

3. Experimentation

3.1. Materials and experiments

The materials used in this study comprised recycled concrete aggregate (RCA), natural aggregate, glass sand, glass powder (GP), ground granulated blast-furnace slag (GGBS), ordinary portland cement (OPC), and polyvinyl alcohol (PVA). These were selected to assess the effectiveness of PVA treatment on recycled aggregates and its influence on the performance of concrete mixes. To evaluate the properties of both the aggregates and the resulting concrete, a range of testing equipment was employed, including a concrete slump test set for workability, a water absorption test set for porosity, compression and flexural testing machines for mechanical performance, a shrinkage test set for dimensional stability, and desiccators for pre-treatment of aggregates. The picture of RCA, natural aggregate, and PVA, which was used in this study, is presented in Fig. 1.

(a) (b) (c)

Fig. 1. Materials used in the study: (a) RCA, (b) NA, and (c) PVA.

3.2. Experimental procedure

The methodology adopted in this research was based on and adapted from established procedures in previous studies [20]. The experimental procedure began with the pre-treatment of recycled concrete aggregates. Both 20 mm and 10 mm RCA were placed in desiccators connected to a vacuum pump operating at a pressure of 920 mbar for six hours.

In parallel, polymer solutions of different concentrations were prepared. Specifically, 120 g, 160 g, 200 g, and 240 g of PVA powder were separately dissolved in 2 L of boiled water to obtain 6%, 8%, and 10% PVA solutions, where the percentage represents the mass of PVA powder relative to the mass of water used in the solution. Once the powder was fully dissolved, the solutions were cooled to room temperature before use.

The polymer solutions were then introduced into the desiccators containing RCA through a funnel, and the aggregates were soaked under vacuum for 24 hours. After soaking, the treated aggregates were removed and tested to evaluate their physical properties. This process was repeated until sufficient quantities of PVA-impregnated RCA were obtained for concrete production.

Concrete mixtures were subsequently prepared using RCA treated with a 10% PVA solution, under two different moisture conditions: oven-dried and air-dried. For the oven-dried condition, PVA-impregnated RCA were dried at 60 °C for 24 hours, while for the air-dried condition, PVA-impregnated RCA were allowed to dry in a controlled laboratory environment (temperature = 23 ± 1 °C, relative humidity = 65 ± 2%) for two days before mixing. These procedures ensured consistency and allowed for comparison between the two moisture states.

3.3. Testing

A series of tests was carried out on the fresh and hardened concrete as per the international standard procedures. These tests were performed to characterize the physical properties of sand, natural aggregate, and recycled coarse aggregates based on the standards presented in Table 1.

Table 1. Standards of test and procedures.

Test and procedures	Method
Sieve analysis	AS 1012.3.1:2014 (Standard 2014d)
Slump test	AS 1012.3.1:2014 (Standard 2014d)
Compressive strength	AS 1019.9:2014 (Standard 2014b)
Splitting tensile strength	AS 1012.10-2000 (Standard 2000)
Drying shrinkage	AS 1012.13:2015 (Standard 2015)
Curing	AS 102.8.1:2014 (Standard 2014a)
Mixing	AS 1012.2:2014 (Standard 2014a)

The aggregates sieve analysis test was performed in accordance with the specifications provided in AS 1012.3.1:2014 (Standard 2014d). The importance of this test was to know the particle size distribution of aggregates. For this research, the sizes of sieves used were 13.2 mm, 9 mm, 6.7 mm, 4.75 mm, 2.35 mm, 1.18 mm, 600 micron, 425 micron, 300 micron, 150 micron, 75 micron, and pan. The particle density and water absorption of fine aggregate were conducted in accordance with the specification provided in AS 1141.5-2000. The NA and RCA water absorption and specific gravity were performed with the requirements provided in AS1141.5-2000 (Standards 2000). The importance of the water absorption test was to determine the amount of water being absorbed by the aggregates. As reviewed from different literature, an aggregate that absorbs too much water has a bad mechanical property and is not fit for concrete production. This test helped in the differentiation of natural aggregates and RCAs based on the water absorption capacity.

3.3.1.Treatment of recycled concrete aggregate with polyvinyl alcohol

The treatment of recycled concrete aggregate with polyvinyl alcohol involves different stages.

a. Oven-dry process: In this phase, the RCA was placed in a thermostatic oven for up to 48 hours at a temperature of 107℃. This process was performed in order to dry up the aggregate particles, making it more possible to expose the pore spaces to be filled with PVA.

b. Mix design and concrete preparation: It is important to note that the water content was 1.3 kg and the cement value was 2 kg in every mix. For every 2 litres of water, there were 120 g of PVA.

GP and GGBS were the replacements for cement. In this project, five unique concrete mixes were prepared, including one control mix (0% PVA-treated RCA) and four mixes with 0, 6, 8, and 10% PVA-treated RCA. Fine and coarse aggregates were used in saturated-surface dry (SSD) conditions to prevent the water absorption of the aggregates. Mix designs of concrete specimens are presented in Table 2.

Table 2. Mix designs of concrete specimens.

	NA	RCA	PVA	GS	GP	Cement	GGBS
	kg/m^3						
Natural Aggregate	5.98	0.00	0.00	3.72	0.73	0.53	0.73
0% PVA	0	5.98	0.00	3.72	0.73	0.53	0.73
6% PVA	0	5.98	0.06	3.72	0.73	0.53	0.73
8% PVA	0	5.98	0.08	3.72	0.73	0.53	0.73
10% PVA	0	5.98	0.10	3.72	0.73	0.53	0.73

4. Experimental results

4.1. Water absorption

The water absorption test was conducted in two stages: (i) determination of the specific gravity and water absorption of loose aggregates, and (ii) measurement of water absorption for RCA specimens treated with different dosages of PVA.

The results of the first stage are presented in Table 3 and Fig. 2. Natural aggregate exhibited a specific gravity of 2.6 with a relatively low water absorption of 2.28%, indicating its dense and less porous structure. In comparison, untreated RCA (0% PVA) had a specific gravity of 2.4 and a much higher water absorption of 6.9%, reflecting the porous nature of adhered mortar. Upon PVA treatment, significant variations were observed. At 6 and 8% PVA dosages, specific gravity decreased to 2.06 and 2.02, respectively, with corresponding increases in water absorption (12.87 and 11.97%). Interestingly, the 10% PVA treatment increased the specific gravity to 3.00 and simultaneously reduced water absorption to 4.22%, suggesting improved densification of the aggregate.

Table 3. The water absorption for loose aggregate.

Aggregate type	Polyvinyl alcohol (%)	Specific gravity	Water absorption (%)
Recycled concrete aggregate	0	2.4	6.9
	6	2.06	12.87
	8	2.02	11.97
	10	3.00	4.22
Natural aggregate	-	2.6	2.28

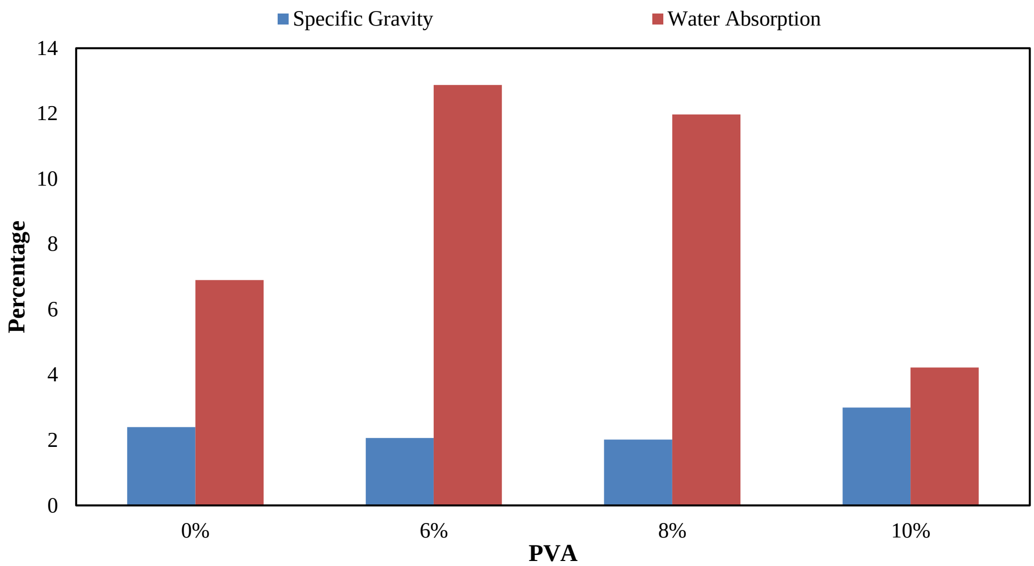

Fig. 2. Specific gravity and water absorption for loose aggregate.

The second stage involved detailed water absorption testing of both natural aggregates and RCA with varying PVA contents.

The average results are summarized in Table 4 and illustrated in Fig. 3. Natural aggregate specimens recorded an average absorption of 6.76%, while untreated RCA (0% PVA) showed a much higher value of 11.37%. With PVA treatment, the absorption initially increased, reaching 12.17% at 6% dosage, before gradually declining to 11.27 and 10.84% at 8 and 10% PVA, respectively.

Table 4. The average water absorption of manufactured concrete specimens.

Spcimen	Water absorption (%)
Natural aggregate	6.76
0% PVA	11.37
6% PVA	12.17
8% PVA	11.27
10% PVA	10.84

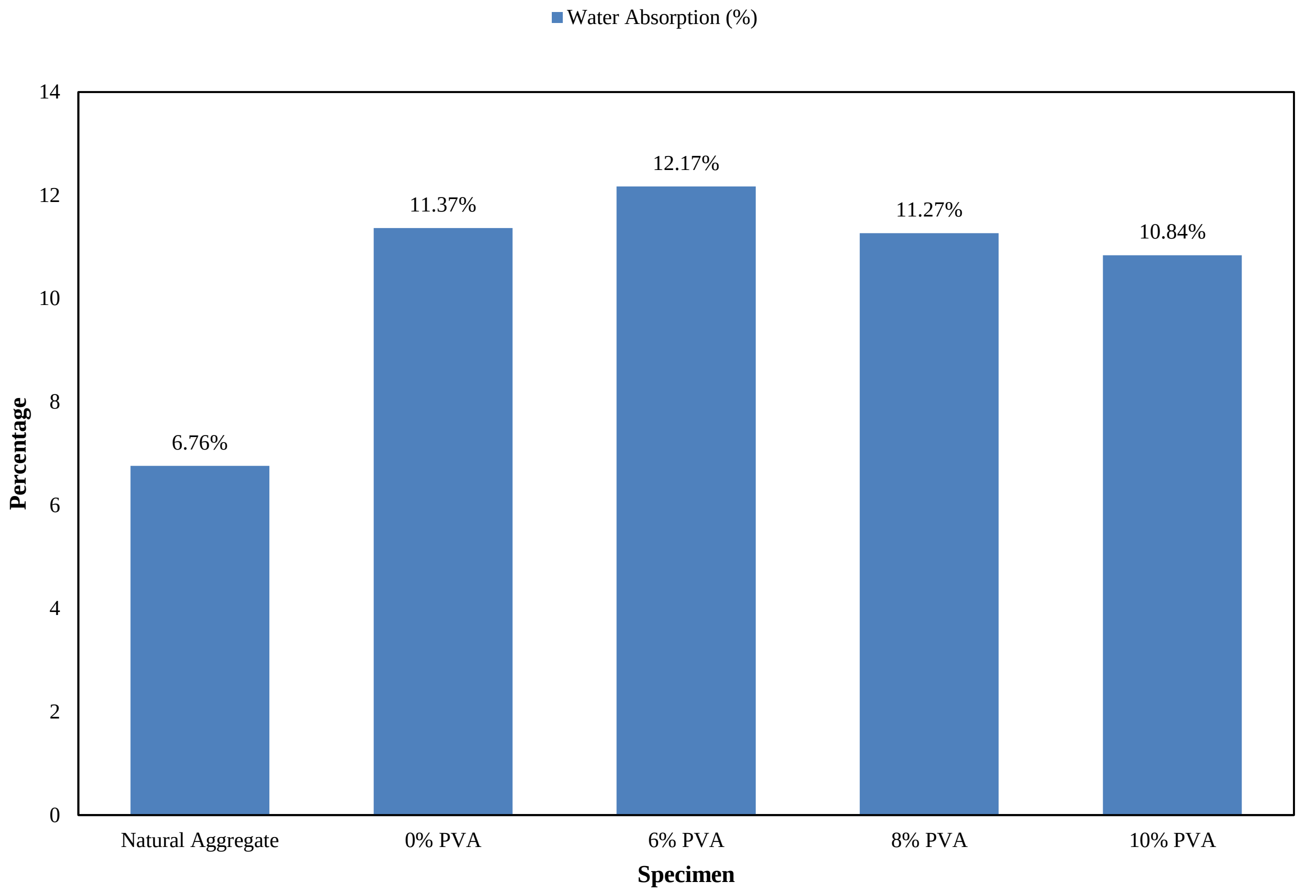

Fig. 3. Water absorption graph.

These results demonstrate that RCA generally exhibits higher water absorption than natural aggregate, due to the porous adhered mortar. Although moderate PVA dosages (6–8%) did not improve absorption, higher treatment levels (10%) reduced water absorption significantly, indicating that polymer impregnation at sufficient dosage can enhance aggregate quality by sealing micro-pores and reducing permeability

4.2. Sieve analysis

Sieve analysis was carried out to determine the particle size distribution of the recycled aggregate, natural aggregate, and glass sand used in this study. The results are presented in Fig. 4. As shown in Fig. 4, the recycled aggregate exhibited a wider gradation curve with a relatively higher proportion of fine particles compared to the natural aggregate. This behavior can be attributed to the adhered mortar and micro-cracks formed during the crushing process of recycled concrete. The natural aggregate displayed a steeper gradation curve, indicating a more uniform particle size distribution and a lower percentage of fines. In contrast, the glass sand showed a much finer gradation profile, with a significant proportion of particles passing through the smaller sieve sizes. This makes glass sand comparable to natural sand in terms of fineness, though it differs in angularity and surface texture due to its origin. Overall, the comparison of these gradation curves indicates that recycled aggregates tend to contain more fines and exhibit different packing characteristics than natural aggregates, which may affect the workability and mechanical properties of concrete mixes. The inclusion of glass sand, with its fine particle size distribution, can enhance particle packing and reduce void content within the mix.

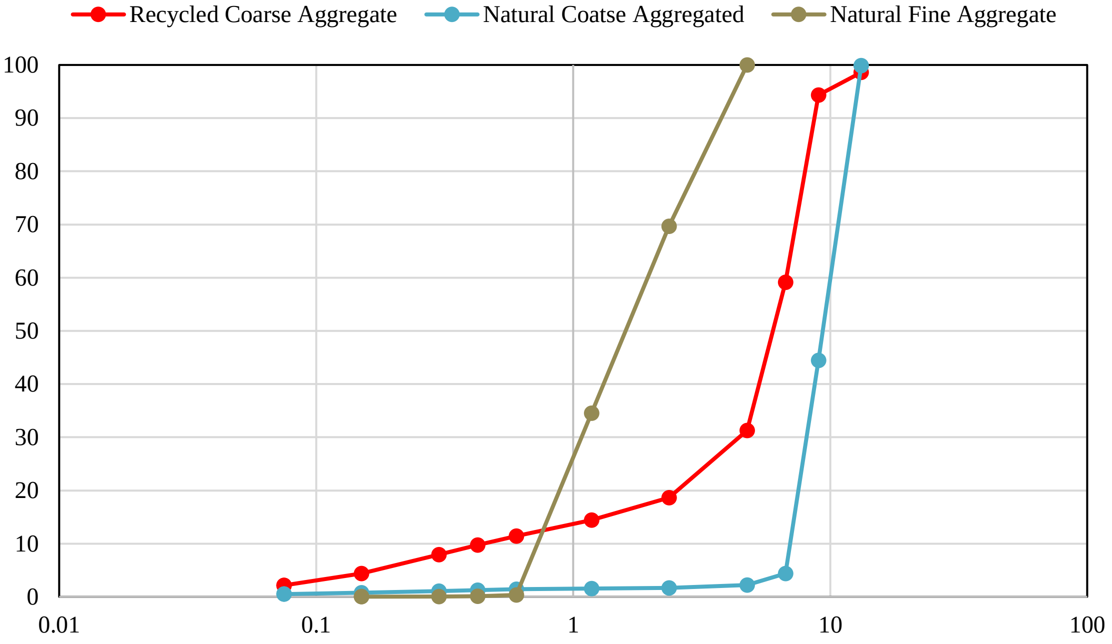

Fig. 4. Sieve analysis curve of aggregates.

4.3. Slump test

The workability of fresh concrete mixtures was assessed using the slump test in accordance with AS 1012.3.1:2014. The results are summarized in Table 5 and illustrated in Fig. 5.

Table 5. Slump test results.

Specimen	Natural aggregate (Control)	PVA 0%	PVA 6%	PVA 8%	PVA 10%
Slump	15 mm	15 mm	20 mm	15 mm	10 mm

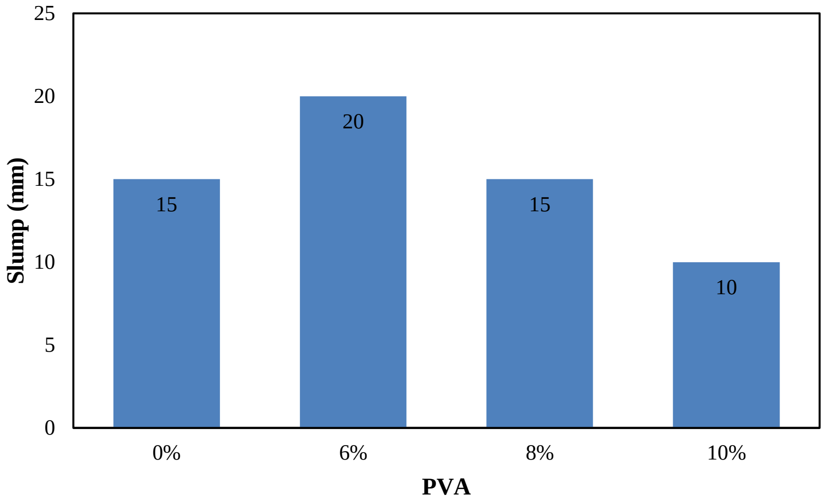

Fig. 5. Bar graph of the slump test.

The results indicate that the slump value for natural aggregate concrete (control) was 15 mm. For RCA mixes without PVA treatment (0%), the slump remained the same (15 mm), suggesting comparable workability at this stage. At 6% PVA treatment, the slump increased to 20 mm, indicating a temporary improvement in workability. However, as the PVA concentration increased further, the slump decreased; at 8% PVA, it returned to 15 mm, and at 10% PVA, it reduced to 10 mm. This trend demonstrates that while a moderate dosage of PVA (6%) can enhance workability due to improved surface lubrication of aggregates, higher concentrations tend to reduce slump. This reduction may be attributed to the thickening effect of the polymer solution and its tendency to coat aggregate surfaces, thereby restricting free water movement within the mix. Overall, the results highlight the balance required in selecting the optimum PVA dosage to improve durability while maintaining adequate workability.

4.4. Drying shrinkage

The drying shrinkage test was performed on concrete specimens made with natural aggregate (NA), untreated RCA (0% PVA), and PVA-treated RCA (6%, 8%, and 10%). The readings obtained during the test represent the total comparator readings of specimen length (in micrometres), not the actual shrinkage deformation. These readings are summarized in Table 6 and Fig. 6, while the calculated shrinkage strain values (difference in length divided by gauge length, expressed in µm/m) are provided in Table 7.

Table 6. Average drying shrinkage of concrete specimens.

Specimen	1 day (micrometres)	4 days (micrometres)	21 days (micrometres)	28 days (micrometres)
NA	163090	163050	162920	162920
0% PVA	163170	163150	163100	163050
6% PVA	163140	163050	163050	162950
8% PVA	163200	163160	163130	163080
10% PVA	163200	163150	163110	163040

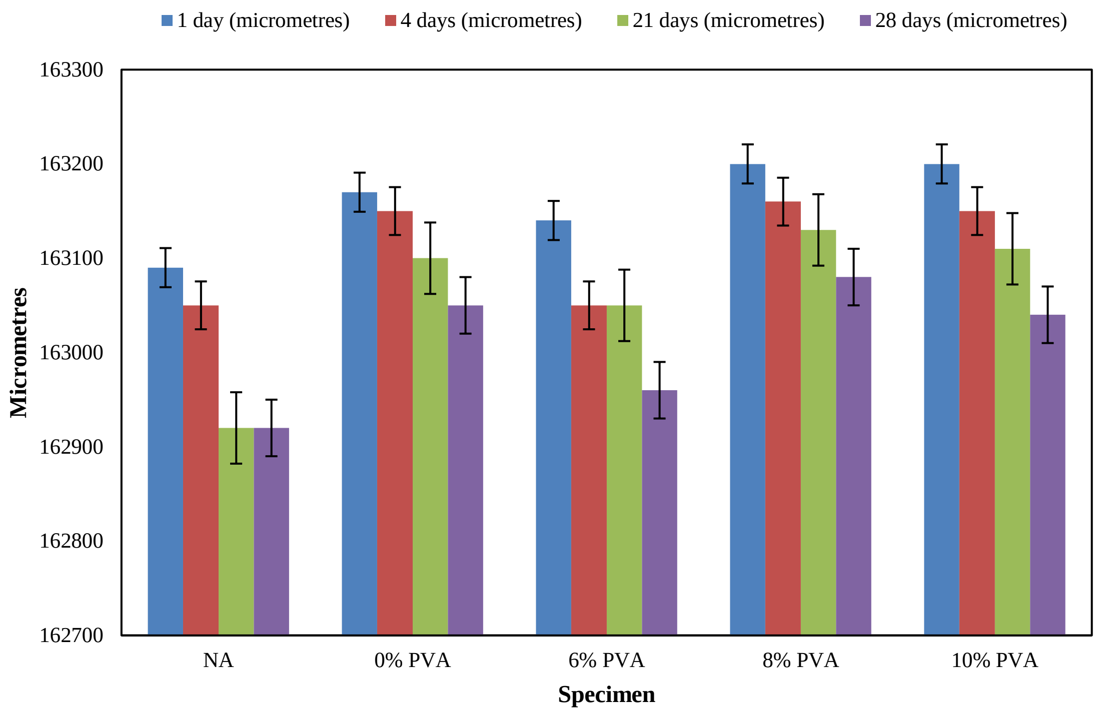

Fig. 6. Drying shrinkage strains of concretes with different PVA dosages.

Table 7. Calculated drying shrinkage strain of concrete specimens (µm/m)

Specimen	Shrinkage strain (µm/m)
NA	≈ 170
0% PVA	≈ 120
6% PVA	≈ 190
8% PVA	≈ 120
10% PVA	≈ 160

Table 6 readings represent the total specimen length measured by the comparator, while Table 7 shows the corresponding calculated shrinkage strains, which fall within the typical range for concrete (50–200 µm/m). Natural aggregate concrete exhibited the lowest shrinkage, confirming its superior dimensional stability. In contrast, RCA concretes displayed slightly higher shrinkage, and the PVA-treated mixes (particularly at 8–10%) showed marginally increased values. This increase is attributed to the polymer coating reducing internal moisture exchange, thereby producing small but measurable differences in shrinkage strain.

4.5. Compressive strength

The compressive strength test was conducted on concrete specimens made with natural aggregate, untreated RCA (0% PVA), and PVA-treated RCA at different dosages (6, 8, and 10%). The compressive strength test setup and failure mode of a concrete specimen are shown in Fig. 7. The average load and stress values are summarized in Table 8, while the stress distribution is illustrated in Fig. 8.

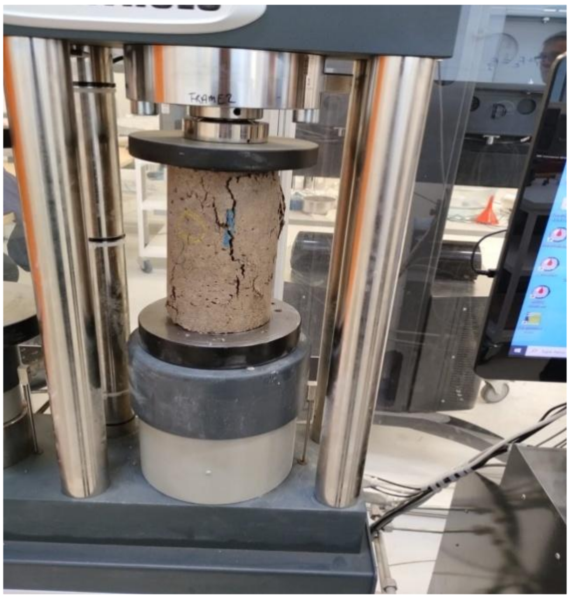

Fig. 7. A view of the compressive strength instrumentation and test.

Table 8. Average compressive strength of concrete specimens.

Specimen	Load (kN)	Stress (MPa)
Natural aggregate	129.19	16.46
0% PVA	180.0	11.47
6% PVA	61.20	7.80
8% PVA	64.04	8.16
10% PVA	84.88	10.81

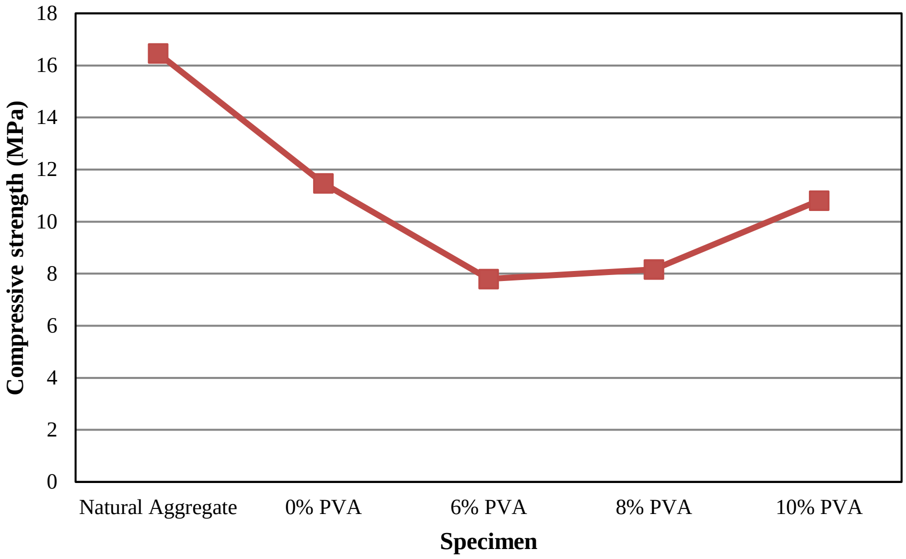

Fig. 8. Compressive strength of concrete specimens.

The results indicate that the natural aggregate concrete exhibited the highest compressive strength (16.46 MPa), reflecting the superior quality and density of natural aggregates. In contrast, all RCA-based concretes showed lower compressive strengths, which can be attributed to the presence of adhered mortar and higher porosity of recycled aggregates. Among the RCA mixes, the untreated specimen (0% PVA) achieved 11.47 MPa, which was higher than the strengths of the PVA-treated specimens at 6% (7.80 MPa) and 8% (8.16 MPa). Interestingly, the 10% PVA treatment showed partial recovery in strength, reaching 10.81 MPa, although it remained below that of the untreated RCA. This trend suggests that moderate polymer impregnation did not significantly enhance compressive strength and, in some cases, may have reduced it due to restricted bonding and microstructural changes. The results highlight the need for dosage optimization, as excessive polymer content may compromise mechanical performance even if it improves durability-related properties.

5. Discussion

The incorporation of polyvinyl alcohol (PVA) into recycled concrete aggregate (RCA) produced mixed effects on the physical and mechanical performance of the resulting concretes. The observed trends were highly dependent on the PVA dosage, and they did not follow a linear pattern. This highlights the complex interaction between polymer coating, pore refinement, and aggregate–paste bonding. The following discussion clarifies these relationships in line with the experimental results.

5.1. Specific gravity and water absorption of treated RCA

The results demonstrated that at low and intermediate PVA dosages (6–8%), both specific gravity and water absorption of RCA were adversely affected; specific gravity decreased, and water absorption increased relative to untreated RCA. This can be attributed to incomplete or uneven polymer coating, which may have introduced additional voids or prevented full penetration of PVA into the micro-pores.

At 10% dosage, however, the PVA layer effectively sealed the surface pores, resulting in a significant increase in specific gravity (to 3.00) and a reduction in water absorption (to 4.22%). This non-linear behavior indicates that adequate polymer concentration and impregnation time are necessary for meaningful pore sealing and densification. Hence, PVA treatment improves RCA properties only at higher dosages, while moderate levels may worsen absorption due to partial coating effects

5.2. Slump of concrete

The workability of RCA concretes exhibited a distinct peak at 6% PVA dosage (20 mm slump), followed by a steady decline at higher levels (10 mm at 10% PVA). This trend suggests that a small amount of PVA solution initially improves surface lubrication and particle dispersion, leading to better flowability. However, as polymer concentration increases, viscosity and surface tension effects dominate, restricting free water movement and reducing slump. Therefore, the influence of PVA on workability is dosage-dependent, improving it slightly at low levels but reducing it at higher concentrations.

5.3. Compressive strength

All RCA concretes recorded lower compressive strength than natural aggregate concrete (16.46 MPa), consistent with the porous and weaker nature of recycled aggregates. Within the RCA series, the 6% and 8% PVA-treated mixes exhibited reduced strength (7.80 and 8.16 MPa), while the 10% PVA mix partially recovered to 10.81 MPa. These results indicate that low-to-medium PVA concentrations may form a weak polymer film at the interface, hindering effective bond formation between aggregate and cement paste. In contrast, higher polymer content can densify the aggregate surface and partially improve bonding. Overall, PVA treatment does not uniformly increase strength, but a 10% dosage showed limited recovery compared to untreated RCA.

5.4. Drying shrinkage

Drying shrinkage increased with PVA treatment, particularly at 8% and 10% dosages. While PVA was expected to enhance microstructural integrity, the polymer coating may have restricted internal moisture exchange, leading to higher residual stresses during drying. The untreated RCA mix showed slightly lower shrinkage, while natural aggregate concrete remained the most dimensionally stable. These results indicate that although PVA may improve aggregate densification, it can exacerbate shrinkage in concrete due to altered moisture diffusion pathways. Therefore, any mechanical benefits from PVA must be balanced against potential shrinkage drawbacks.

5.5. Overall Interpretation

The combined findings suggest that PVA treatment of RCA produces both beneficial and adverse effects, depending on dosage. Higher PVA content (10%) effectively reduces water absorption and increases aggregate density, but compromises workability and dimensional stability. Moderate dosages (6–8%) may lead to inconsistent coating and reduced strength. Thus, optimizing PVA dosage is essential to achieve the desired balance between durability improvement and mechanical performance.

6. Conclusion

In this research, the effects of polyvinyl alcohol (PVA) treatment on recycled concrete aggregate (RCA) and companion concretes were evaluated against natural aggregate benchmarks. PVA impregnation altered pore structure and fresh properties in a nonmonotonic manner. At higher treatment levels, the aggregates became denser and less absorptive, while concrete workability and mechanical performance exhibited trade-offs that depended on dosage.

A 10% PVA treatment increased the specific gravity of loose RCA to 3.00 and reduced its water absorption to 4.22%, indicating effective pore sealing and densification. In concrete specimens, the same dosage lowered water absorption to 10.84% compared with untreated RCA at 11.37%, although absorption remained higher than that of natural aggregate concrete (6.76%). Workability peaked at the 6% PVA dosage (20 mm slump) and declined at higher concentrations.

Compressive strength values remained modest, with the natural aggregate control achieving 16.46 MPa and PVA-treated RCA concretes ranging from 7.8–10.8 MPa. These values confirm that the mixtures were designed for non-structural applications, such as paving, curbing, and partition elements, where durability and sustainability are more critical than structural load-bearing capacity.

Drying shrinkage increased slightly with higher PVA levels, reflecting reduced internal moisture exchange due to polymer coating.

Overall, PVA treatment offers a viable approach to improving the quality of recycled aggregates for non-structural, durable concrete production. However, dosage optimization is essential to balance reduced water absorption with acceptable workability and dimensional stability. This work contributes to the development of sustainable RCA utilization strategies that support environmental conservation and resource efficiency in the construction industry.

Statements & declarations

Author Contributions

Mohammad Valizadeh Kiamahalleh: Investigation, Formal Analysis, Resources, Writing – Review & Editing.

Aref Khorshidi-Mianaei: Conceptualization, Investigation, Formal analysis, Resources, Writing - Original Draft.

Amin Safari: Conceptualization, Methodology, Project administration.

Acknowledgments

The authors gratefully acknowledge the support provided by the College of Science and Engineering at Flinders University. Special thanks are also extended to Ahmad Muhammad Ali for his valuable contributions as part of his Master's thesis project at Flinders University.

Funding

Funding information is not available.

Declarations

The authors declare no conflict of interest.

Data availability

Data available on request due to restrictions, e.g., privacy or ethics: The data presented in this study are available on request from the corresponding author.

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