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Research Article

The effect of recycled pervious concrete aggregate substitution on properties of pervious concrete

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ABSTRACT

Sustainability has gained significant importance in civil engineering and other areas in recent years. Numerous studies have been conducted on using recycled aggregates to demolish various structures in this context. However, almost all these studies have focused on recycled aggregates from traditional concrete. This study investigated the usability of recycled aggregates obtained from pervious concrete produced in a laboratory environment for use in pervious concrete production. Natural aggregate was substituted with recycled pervious concrete aggregate at weight ratios of 20%, 40%, 60%, 80%, and 100%. The concrete series' compressive, flexural, and splitting tensile strengths, water permeability coefficient, porosity values, and freeze-thaw resistance were examined. Additionally, the microstructure before and after the freeze-thaw effect was analyzed using scanning electron microscopy. The results showed that recycled aggregates increased the water permeability coefficient and porosity but negatively affected the mechanical properties.

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1. INTRODUCTION

Constructing pedestrian pathways, sidewalks, and roads with impermeable coverings like concrete and asphalt causes various adverse effects due to harsh climate transitions and climate change. As a habit or necessity inherited from past applications, impermeable coverings from impermeable materials occupy a significant area in cities. This leads to undesirable situations such as water accumulation on the surface, water pollution, interruption of the connection between air and soil, and delayed water transfer to the ground. These conditions increase the risk of flooding and disrupt traffic flow safety. Constructing pedestrian pathways, sidewalks, and highways from permeable materials like pervious concrete will facilitate rapid water transmission to the ground, preventing water accumulation on the surface. This will contribute to ensuring traffic safety, facilitating groundwater replenishment, and supporting the partial purification of water due to the retention of polluting particles by concrete [1–4].

Pervious concrete is a special type made from coarse aggregate and cement, without or with low amounts of fine aggregate. Although the porosity of pervious concrete varies in different ranges, it is generally reported to be 15–25% [5]. According to ACI 522-R [6], the porosity of pervious concrete is recommended to be between 15% and 35%. Due to the absence of fine aggregate or its use in only around 10%, the voids in pervious concrete are relatively large and interconnected. However, this structure has significantly lower strengths than previous concrete compared to traditional concrete, which limits its usage [6]. Although the strength ranges vary widely, the compressive strengths of

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pervious concrete are reported to be between 2.8–28 MPa, and flexural strengths range from 1.5–3.2 MPa. The mechanical properties of pervious concrete are influenced by various factors such as water-to-cement ratio, compaction degree, binder volume, and aggregate gradation [7].

One of the critical issues recently discussed in the construction sector is earthquakes and the existing building stock. As a result of the increasing need for shelter and recent natural disasters like the Kahramanmaraş earthquake, a significant amount of demolition waste is produced. The demolition caused by the Kahramanmaraş earthquake highlights the importance of the issue, with an estimated amount of waste ranging from 350 to 580 million tons [8]. Reusing these difficult-to-store wastes in new concrete production will add value to the economy and eliminate or reduce the need for landfilling. While countries like France and Japan have specific guidelines for the reuse of waste concrete, numerous researchers worldwide are conducting studies on recycling [9–13]. There are also environmental advantages to using RAs as aggregates in concrete mixtures. Normally, unused RAs are sent to landfills for storage. However, due to increasing urbanization and reconstruction, storage areas are insufficient, and new regions are needed. Therefore, the need for additional storage areas is reduced by re-evaluating RAs. In addition, RAs, which can be produced on-site, can be produced cheaper than virgin aggregates. Thus, it is possible to reduce the cost of aggregate production.

Recycled aggregate (RA) is produced by crushing, sieving, and sorting old concrete into specific sizes. One of the significant challenges encountered when using RA in new concrete production is the presence of old cement paste and mortar adhering to the aggregate particles. This paste and mortar increase RA's water absorption capacity and porosity, decreasing strength properties [14–17]. There are numerous studies on using coarse, fine, or powdered recycled aggregate in different building materials. Hosseinnezhad et al. [18] examined the effect of recycled coarse aggregate substitution on the properties of roller-compacted concrete. Alghader et al. [19] investigated the usability of recycled aggregate in self-compacting concrete production. Kanagaraj et al. [20] studied the properties of geopolymers produced using recycled aggregate, while Tan et al. [21] examined the use of ground recycled aggregate powder as a binder in geopolymer production. Gültekin [22] explored the feasibility of using recycled aggregate in cement-based SIFCON composites, while Eryılmaz et al. [23] investigated using recycled geopolymer concrete aggregate in geopolymer production. Numerous studies have also been conducted on using RA in previous concrete outputs.

Zaetang et al. [10] examined the effect of RA usage on the properties of previous concrete. They reported that 60% RA instead of natural aggregate provided a reasonable compressive strength of 15 MPa. Sriravindrarajah et al. [24] stated that using RA to produce pervious concrete at constant porosity harms compressive strength. Nazari et al. [25] studied the use of recycled aggregates obtained from different types of bricks in pervious concrete. They noted that the increase in RA quantity led to a gradual increase in porosity and a gradual decrease in density, likely due to the porosity of RA. Similarly, Brasileiro et al. [26] reported a 10% increase in water permeability in pervious concrete with 50% RA usage but a 56% loss in compressive strength. Barnhouse et al. [27] examined the effects of RA usage on compressive strength and modulus of elasticity. There have been numerous studies on using recycled aggregate in various building materials, such as aggregate, filler, and even binder. However, most of these studies used recycled aggregate from traditional concrete. Therefore, there is a need for research on the use of recycled aggregate derived from pervious concrete in building material production.

In this study, the effect of recycled pervious concrete aggregate substitution on pervious concrete properties was investigated. In this context, 150x150x150 mm cube pervious concrete samples were produced in the laboratory using limestone aggregate. After determining the compressive strengths of these pervious concretes, they were crushed in a jaw crusher and sieved to obtain recycled pervious concrete aggregates in the range of 5–15 mm. The investigation of the effects of the thickness and properties of the mortar/paste layer adhering to the aggregate on the properties of pervious concrete, which may differ from those of recycled aggregates produced from traditional concrete, constitutes the original aspect of the study. Accordingly, six different series of pervious concrete were made, one containing only crushed limestone and the others containing 20%, 40%, 60%, 80%, and 100% recycled aggregates to replace limestone by weight. The compressive, splitting tensile, and flexural strengths, porosity values, water permeability coefficients, and freeze-thaw resistance of concretes were determined. Additionally, a scanning electron microscopy (SEM) examination was conducted to observe the changes in the internal structure caused by freeze-thaw cycles.

2. EXPERIMENTAL STUDY

2.1. Materials

The study used CEM I 42.5 R type Portland cement conforming to TS EN 197-1 [28] as the binder and crushed limestone in the 5–15 mm size fraction as the aggregate. Tap water was also utilized. The crushed limestone was obtained from a local ready-mix concrete plant. The recycled aggregate was produced under laboratory conditions using limestone and obtained from cement-based pervious concrete with compressive strength ranging from 10 to 15 MPa. After determining the compressive strength of the pervious concrete samples, they were crushed with a jaw crusher and sieved through sieves to obtain recycled aggregate in the 5–15 mm size fraction. Photographs and some physical properties of the aggregates are presented in Figure 1 and Table 1, respectively. The mortar/paste thickness around the recycled aggregate in pervious concrete differs from that in traditional concrete. This resulted in the specific gravity of the recycled aggregate being close to that of crushed limestone aggregate. However, it is observed that the water absorption capacity of the recycled aggregate is significantly higher than that of crushed limestone. To in-

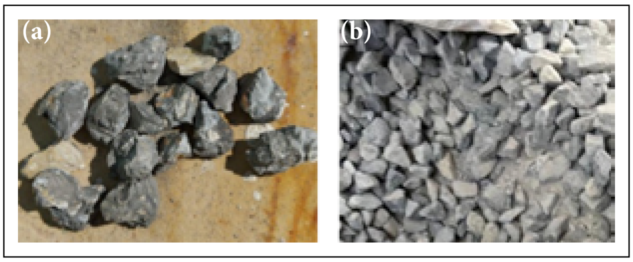

Figure 1. Aggregates **(a)** Recycled aggregate, **(b)** Limestone aggregate.

crease the fluidity of the paste phase, superplasticizer was used in varying proportions ranging from 0.1% to 0.8% of the cement weight, and silica fume was used at a rate of 5% of the total binder weight to increase both the paste volume and contribute to the mechanical properties.

Due to the old cement paste layer in RAs, their specific gravity is lower than natural aggregates (Table 1).

2.2. Concrete Production

The mixtures were prepared using a laboratory-type concrete mixer with a capacity of 40 dm^3. In all mixtures, the binder dosage was set as 400 kg/m^3, the water/binder ratio was fixed as 0.32, and concretes with a target porosity value of 15% were produced. First, cement, silica fume, and aggregates were dry-mixed for 2 minutes. Superplasticizer and water were mixed and added to the mixer in approximately 30 seconds, and the mixer was operated for 2 minutes. At the end of this period, the mixer was stopped, particles adhering to the bowl's walls were scraped off with a trowel, and the mixer was operated for another 2 minutes. At the end of the time, the consistency and homogeneity of the mixture were visually inspected, and the placement process was initiated.

The placement process was carried out in 3 layers, and each layer was compacted with 25 strokes with a tamping rod. The top surfaces of the samples were levelled with a trowel and left to cure under ambient conditions for 1 day. Afterward, specimens were de-molded and subjected to standard water curing for 27 days in lime-saturated water. Cubic specimens with dimensions of 150 mm for compressive strength, prism specimens of 100x100x400 mm for flexural strength, and cylindrical specimens with a diameter of 100 mm and a height of 200 mm for splitting tensile strength were prepared. Porosity and water permeability coefficient tests were also conducted using cylindrical specimens. Three specimens from each series were used for each test, and the average of the three was reported.

2.3. Mixtures

Within the scope of the study, six different concrete series were produced: one control mixture containing only limestone aggregate, one mixture containing entirely recycled aggregate, and four mixtures containing 20%, 40%, 60%, and 80% by weight of recycled aggregate substitution for limestone. Due to the loss of workability with recycled aggregate, superplasticizer was added in proportions ranging from 0.1% to 0.8% of the cement weight (Table 2).

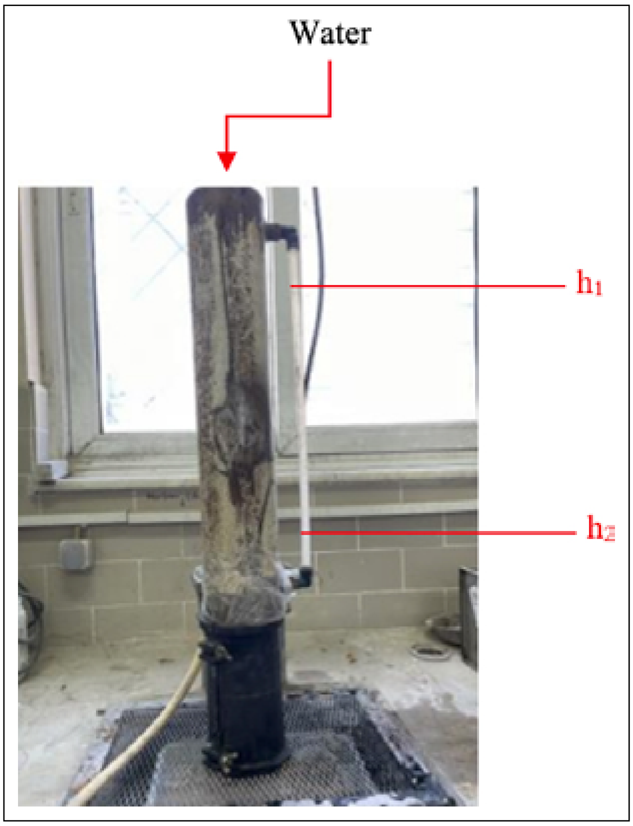

Figure 2. Water permeability coefficient test setup .

Table 1. Physical properties of aggregates

Physical property	Limestone aggregate (LA)	Recycled aggregate (RA)
Specific gravity	2.67	2.63
Water absorption (%)	0.30	8.95

2.4. Tests

Compressive, flexural, and splitting tensile strength tests were conducted following TS EN 12390-3 [29], TS EN 12390-5 [30], and TS EN 12390-6 [31] Standards, respectively.

Porosity values were determined by measuring the weights of the samples after being kept in air and submerged in water for 24 hours. Subsequently, porosity values were calculated using Equation 1.

$$P = \left[1 - \frac{m_h - m_s}{\rho_s \, x \, V}\right] \tag{1}$$

Here, m_h represents the weight of the specimen in the air (g); m_s represents the weight of the specimen in water (g); or(g);ρ_s represents the density of water (g/cm^3); V represents the volume of the sample (cm^3); and P represents the porosity (%).

The water permeability coefficient test was conducted using a decreasing water level test setup, as shown in Figure 2. Firstly, the side surfaces of the sample were sealed with a waterproof insulation material, and the sample was placed in the test setup. Water was supplied from the top,

Table 2. Theoretical material quantities for 1 m^3 of pervious concrete

Code	Materials (kg)					
	Cement	Silica fume	Water	Aggregate		Plasticizer
				LA	RA	
Ref	380	20	128	1590	–	–
RA20	380	20	128	1272	318	0.04
RA40	380	20	128	954	636	0.06
RA60	380	20	128	636	954	0.08
RA80	380	20	128	318	1272	0.18
RA100	380	20	128	–	1590	0.32

LA: Limestone aggregate; RA: Recycled aggregate.

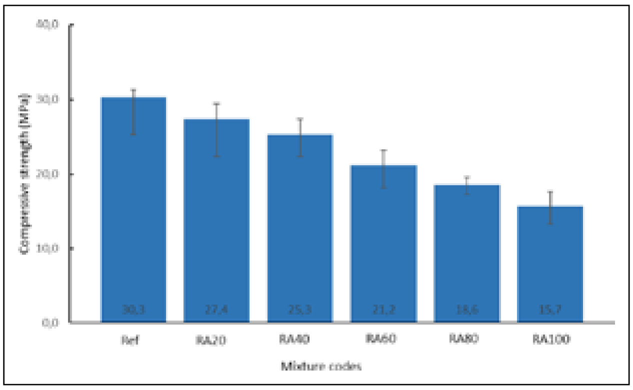

Figure 3. 28-day compressive strength test results.

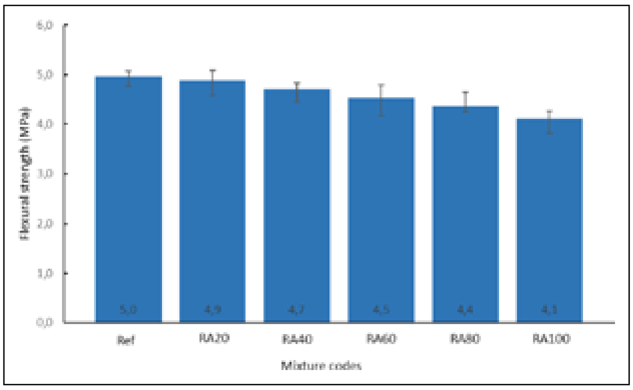

Figure 4. 28-day flexural strength test results.

and the total flow time was measured using a stopwatch. Based on the obtained data, the water permeability coefficient was determined using Equation 2. In the equation, k represents the water permeability coefficient in units of cm/s, a represents the cross-sectional area of the pipe in units of cm^2, l represents the length of the sample in units of mm, A represents the cross-sectional area of the sample in units of cm^2, and t represents the flow time of water in seconds. h_1 and h_2 values indicate the pipe's initial and final water heights in cm, respectively.

$$k = \frac{a\,x\,l}{A\,x\,t}\,In\frac{h_1}{h_2} \tag{2}$$

Freeze-thaw resistance tests were conducted following the GB/T 50082-2009 [32] Standard, with freezing at -18±2 °C for two hours followed by thawing at 5±2 °C for two hours. Weight losses were determined after 30, 60, 120, and 180 cycles.

3. RESULTS AND DISCUSSION

3.1. Compressive Strength

The compressive strengths of the series produced within the scope of the study are presented in Figure 3. The negative effect of using RA on the compressive strength of pervious concrete is evident in Figure 3. While the compressive strength of the concrete containing only limestone aggregate is 30.3 MPa, the strengths gradually decrease with the substitution of RA, reaching 15.7 MPa in the series produced entirely with RA, representing a 48% decrease. The highest compressive strength is obtained from the control sample without RA, and as the RA content increases gradually, the compressive strength decreases. Since the water absorption value of RA is higher than that of limestone aggregate, these aggregates absorb some of the mixing water, reducing the water-to-cement ratio in mixtures where RA is used. Additionally, due to the lower compressive strengths of RA compared to limestone aggregates, the fact also negatively affects the compressive strength of pervious concrete.

In a similar study, Yang et al. [33] reported that pervious concrete produced with 60% RA compressive strength was 31% to 32.5% lower than the control mixture. Nazeer et al. [34] investigated the effect of RA usage on the mechanical properties of pervious concrete. They noted that substituting natural aggregate with 50% and 100% RA reduced compressive strengths by 21% and 32%, respectively. Li et al. [35] also determined sharp decreases in the compressive strength of pervious concrete when RA substitution exceeded 40%.

3.2. Flexural and Splitting Tensile Strength

The flexural and split tensile strengths of concrete series produced with different proportions of RA substitution are presented in Figure 4 and Figure 5, respectively. Like compressive strength, the flexural and split tensile strengths decreased with RA substitution, and the reductions continued as the substitution ratio increased. The flexural and splitting tensile strengths of the control sample without RA, which

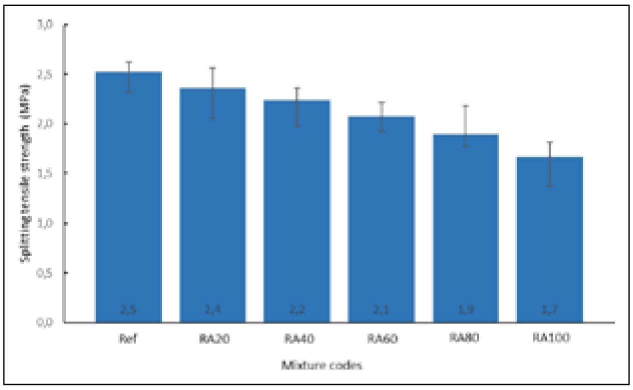

Figure 5. 28-day splitting tensile strength test results.

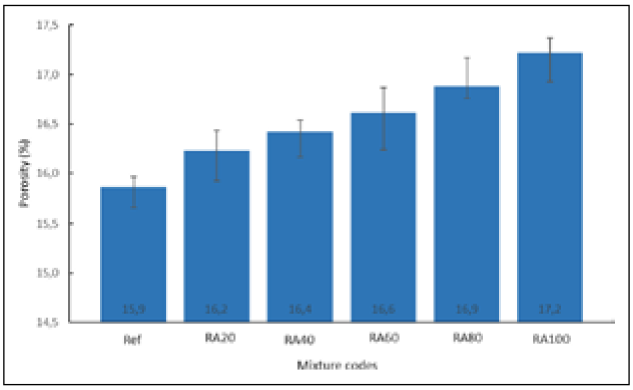

Figure 6. 28-day porosity test results.

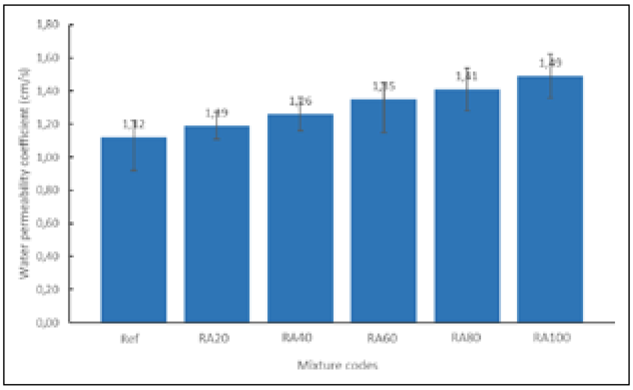

Figure 7. 28-day water permeability test results.

were 5.0 MPa and 2.5 MPa, decreased to 4.1 MPa and 1.7 MPa, respectively, with 100% RA substitution, representing reductions of 18% and 32%, respectively. The cutbacks in splitting tensile strength were higher than those of the losses in flexural strength at all substitution ratios. Yang et al. [33] reported losses in flexural strength ranged from 18% to 26% as RA usage increased from 0% to 60% in pervious concrete. In a similar study, Nazeer et al. [34] noted a 13% loss in flexural strength with 50% RA usage, which increased to 41% when RA was used entirely.

3.3. Porosity

The porosity values of the pervious concrete produced in the study are presented in Figure 6. The mixture with the lowest porosity value, at 15.9%, is the reference mixture,

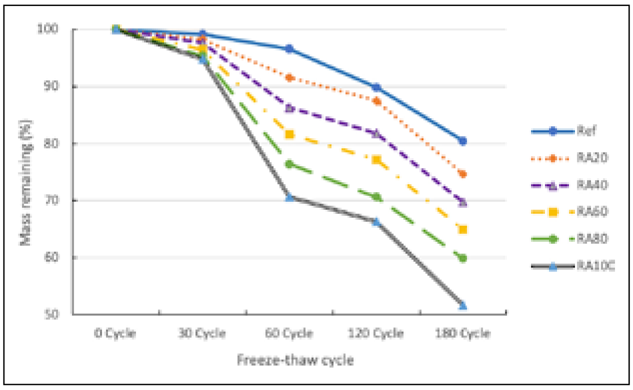

Figure 8. Mass remaining after 0, 30, 60, 120 and 180 freeze-thaw cycles.

while, as expected, porosity values increased gradually with RA usage, reaching 17.2% with an 8% increase at a 100% substitution ratio. Consistent with previous studies on RA usage, contrary to the results in mechanical properties, an increase in porosity values is observed with RA usage. This is primarily attributed to a more significant number of relatively larger voids in coarse aggregates due to the effect of the previous mortar layer adhering to the aggregates [15, 36, 37]. Similar results to those obtained with RA produced from traditional concrete were also obtained in this study. Nazeer et al. [34] reported increased porosity from 19.4% in pervious concrete without RA to 19.8% with 50% RA substitution. Similar studies by El-Hassan et al. [38], Tuan et al. [39], and Malayali et al. [36] have reported increases in porosity values with RA usage.

3.4. Water Permeability Coefficient

The water permeability coefficients of the concrete produced in the study are presented in Figure 7. Similar to the trends in porosity values, it is observed that the permeability coefficient increases with RA usage. The coefficient, which was 1.12 cm/s in the reference series, increased by 33% to 1.49 cm/s with 100% RA substitution. The voids in the aggregate are believed to contribute to this increase and enhance permeability. In previous studies on this matter, Nazeer et al. [34] and Lyu et al. [40] reached similar conclusions to this study, while Yang et al. [33] reported opposite findings, suggesting that although RA usage may increase the permeability of pervious concrete, the decrease in connected voids and practical porosity values might be the cause.

3.5. Freeze-Thaw Resistance

The changes in the weights of the concrete series after 30, 60, 90, 120, and 180 cycles of freeze-thaw are in Figure 8. It is observed that as the RA usage rate increases, the remaining weight after freeze-thaw cycles decreases. It was previously mentioned that, compared to limestone aggregates, RAs have higher water absorption values and thus absorb some mixing water. Therefore, the water present in their structure freezes as the temperature drops and melts as it rises. With repeated occurrences of this process, the cement paste structure is estimated to deteriorate more

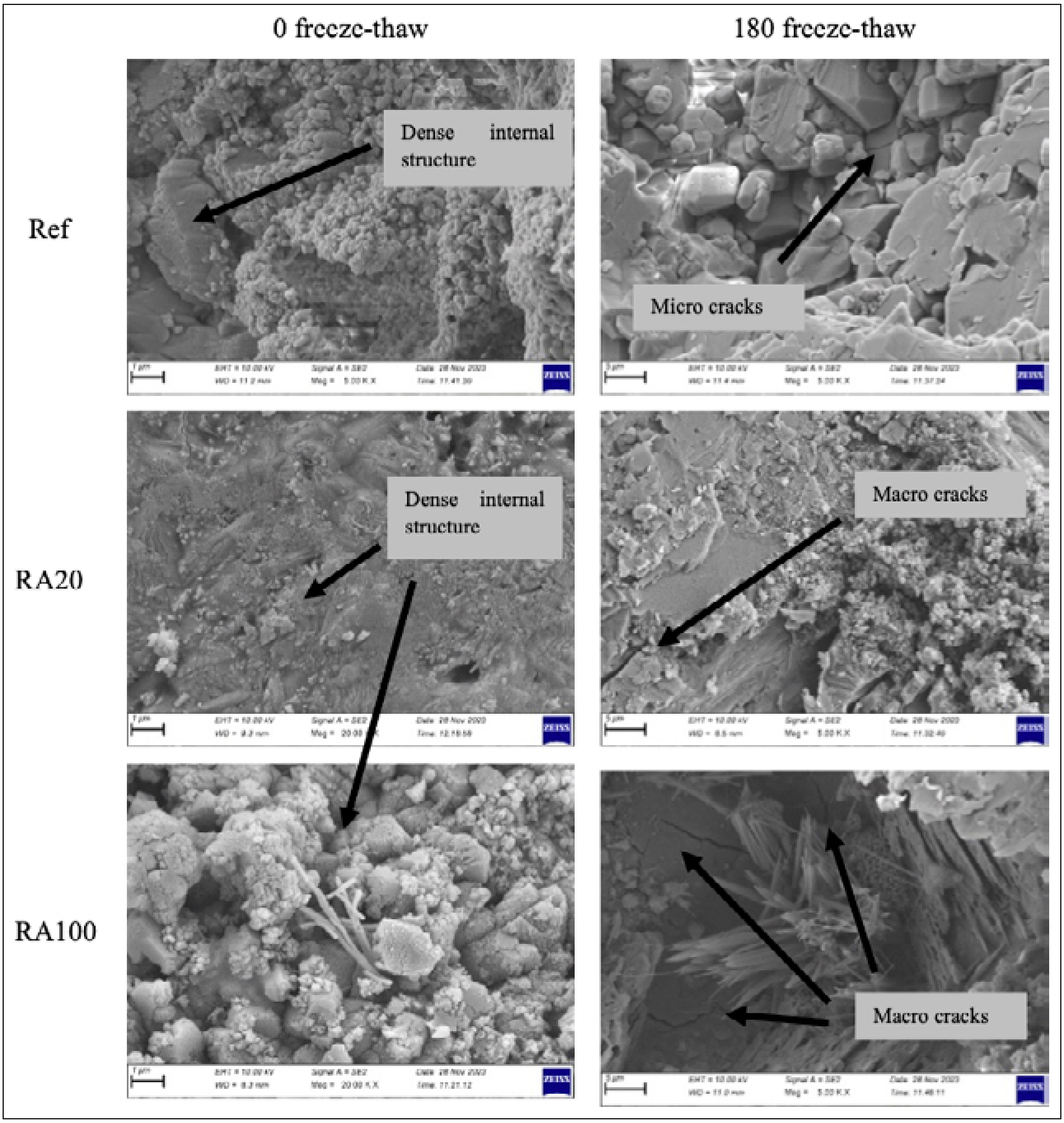

Figure 9. Internal structures of selected samples after 0 and 180 freeze-thaw cycles.

rapidly than the concrete produced with limestone, leading to lower freeze-thaw performance. The weaker interfacial transition zone in concrete produced with RAs has also contributed to this behavior.

Results show that mass losses increase in all samples with successive freeze-thaw cycles. As freeze-thaw continues, the water in the large and wide pores of PCs freezes and then melts. When water changes from liquid to solid, it expands and stresses the pore boundaries. The cement paste structure deteriorates with each cycle, losing its adhesive properties between aggregates. In this study, it is noted that initially, mass losses in the samples during the first freeze-thaw cycles were relatively low. Still, as freeze-thaw continued, mass loss increased cumulatively. The increased ratio of RA usage adversely affected the freeze-thaw behavior of PCs. It is known that concretes with lower mechanical behavior also exhibit relatively lower freeze-thaw performance. Therefore, mixtures containing RAs are expected to show lower freeze-thaw resistance. After 180 cycles, the mass loss in the control sample was 80.46%, while for RA20, RA40, RA60, RA80, and RA100 samples, these values were 74.65%, 69.74%, 64.88%, 59.87%, and 51.68%, respectively. Considering that the samples lost approximately half of their mass after 180 cycles, the effect of freeze-thaw damage becomes evident.

Liu et al. [41] produced pervious concretes by substituting RA for natural aggregates at ratios of 0%, 25%, 50%, 75%, and 100%, and reported that as the RA usage ratio increased, the freeze-thaw resistance of these concretes decreased significantly. Wu et al. [42] stated that among the RA-containing pervious concretes they produced at ratios of 0%, 30%, 50%, 70%, and 100%, the mixture with RA% had the worst freeze-thaw resistance. They mentioned that this mixture lost its strength before reaching 100 cycles. Still, by adding sufficient amounts of fly ash and air-entraining admixture to the same mix, the freeze-thaw performance could be extended up to 150 cycles. Yan et al. [43] replaced natural aggregates with RA at 0%, 30%, 70%, and 100% ratios and examined their effects on pervious concrete. It was noted that the compressive strength after freeze-thaw cycles decreased gradually with increasing RA ratio and cycle duration.

Figure 9 presents SEM images of the control, RA20, and RA100 specimens after 0 and 180 freeze-thaw cycles. Upon examining the SEM images, it can be observed that the internal structures of the specimens not subjected to freeze-thaw cycles are denser and undamaged. At the same time, deep cracks are formed in the internal structures of the pervious concretes after 180 cycles.

4. CONCLUSIONS AND RECOMMENDATIONS

In this study, recycled aggregates obtained from pervious concrete were used by replacing specific proportions of limestone, and the compressive, flexural, and splitting tensile strengths, porosity, and water permeability coefficient, as well as freeze-thaw performance of the produced pervious concretes, were investigated. Considering the materials used and the experimental methods applied, it is possible to state the following results:

- Substituting recycled aggregate resulted in decreases in compressive, flexural, and splitting tensile strengths, with reductions intensifying as the substitution rate increased. Specifically, at a 100% substitution rate, the decrease in compressive strength was 48%, while the losses in flexural and splitting tensile strengths were 17% and 34%, respectively.
- Both porosity and permeability coefficients increased gradually with recycled aggregate and an increase in substitution rate. The lowest water permeability value was obtained in the reference mixture at 1.12 cm/s, while the highest value of 1.49 cm/s was observed at 100% recycled aggregate substitution.
- As the freeze-thaw cycles increased, the mass loss observed in pervious concrete also increased. Additionally, the usage rate of recycled aggregate negatively impacted the freeze-thaw performance. The control mixture, produced solely with limestone aggregate without recycled aggregate, exhibited the best freeze-thaw performance, while the mixture with 100% recycled aggregate showed the lowest performance.
- When SEM images taken before and after freeze-thaw cycles were examined, it was observed that there were no micro or macro cracks in the internal structure of the cement paste before the cycles. With an increase in the number of cycles, it was determined that microcracks appeared partially at low replacement rates, while at high replacement rates, larger cracks accompanied the microcracks.

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ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

The author confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declares that she has no conflict of interest.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

PEER-REVIEW

Externally peer-reviewed.

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