UDK 625.821.5:502.174.1
Original scientific article/Izvirni znanstveni članek

ISSN 1580-2949
Mater. Tehnol.

QUANTITATIVE CORRELATION BETWEEN AGGREGATE WATER ABSORPTION AND CONCRETE STRENGTH IN MULTI-CYCLE RECYCLING

KVANTITATIVNA KORELACIJA MED ABSORPCIJO VODE V AGREGATU IN TRDNOSTJO BETONA PRI VEČCIKLIČNEM RECIKLIRANJU

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Prejem rokopisa – received: 2026-01-29; sprejem za objavo – accepted for publication: 2026-04-03

doi:10.17222/mit.2026.1656

This study investigated the influence of quality enhancement of multi-recycled aggregates on the performance of concrete. First-generation (RA1) and second-generation (RA2) recycled aggregates were subjected to three conditions – untreated, mechanically treated, and chemically treated – and the corresponding concretes incorporating these aggregates as coarse aggregate were evaluated in terms of workability and compressive strength. For untreated RAs, water absorption sharply increased with increasing recycling cycles, accompanied by a marked decrease in density. These changes resulted in a slump loss of 47 % and a compressive strength reduction of up to 13 %. Mechanical treatment slightly reduced the water absorption, but the improvement was marginal for RA2. In contrast, chemical treatment improved the physical properties of both RA1 and RA2, bringing them close to those of natural aggregate, and the corresponding concretes achieved strengths equivalent to those of natural aggregate concrete. According to regression analysis, a strong negative linear correlation was observed, indicating that a 1 % reduction in water absorption of RAs leads to an approximate 1.9 % increase in compressive strength of concretes. The findings of this study indicate that improving the properties of RAs can effectively enhance the performance of concrete and demonstrate the feasibility of repeated recycling, regardless of the number of recycling cycles.

Keywords: concrete recycling, old mortar, aggregate treatment, repeated recycling

V študiji avtorji opisujejo raziskovanje vpliva izboljšanja kakovosti večkrat recikliranih agregatov (grobe frakcije kamenja) na lastnosti betona. Reciklirane agregate prve generacije (RA1) in druge generacije (RA2) so ocenili glede na njihovo stanje: neobdelano, mehansko obdelano in kemično obdelano. Ustrezne betone, ki so vsebovali te agregate v obliki grobega agregata, pa so ocenili glede na obdelovalnost in tlačno trdnost. Pri neobdelanih agregatih RA (angl.: recycled aggregate) se je absorpcija vode močno povečala z naraščajočim številom ciklov recikliranja, kar je spremljalo izrazito zmanjšanje gostote. Te spremembe so povzročile izgubo posedanja za 47 % in zmanjšanje tlačne trdnosti do 13 %. Mehanska obdelava je nekoliko zmanjšala absorpcijo vode, vendar je bilo izboljšanje pri RA2 zanemarljivo. Nasprotno pa je kemična obdelava izboljšala fizikalne lastnosti tako RA1 kot RA2, ki so po lastnostih blizu naravnim agregatom. Ustrezni betoni pa so imeli trdnosti, enakovredne trdnostim betona z naravnim agregatom. Regresijska analiza je pokazala močno negativno linearno korelacijo, kar kaže, da 1 %-no zmanjšanje absorpcije vode pri agregatih RA povzroči približno 1,9 %-no povečanje tlačne trdnosti betona. Avtorji ugotavljajo v članku, da lahko izboljšanje lastnosti RA učinkovito izboljša delovanje betona in dokaže izvedljivost ponovnega recikliranja, ne glede na število ciklov recikliranja.

Ključne besede: recikliranje betona, stara malta, obdelava agregata, ponovljeno recikliranje

1 INTRODUCTION

The construction industry is one of the major sectors that consumes substantial natural resources while simultaneously generating large amounts of waste. According to statistics from the Korean Ministry of Environment, construction waste accounts for more than 40 % of the total national waste generation, and the associated issues, including depletion of natural resources, shortage of landfill capacity, and environmental pollution, continue to intensify. Recycling of construction waste has therefore gained increasing attention as a potential solution, with the use of recycled aggregate (RA), produced by crushing waste concrete, emerging as an important research topic. RA is considered as an environmentally friendly alternative that can replace natural aggregate (NA), contributing to reduced consumption of natural resources and alleviation of landfill shortages. The most distinctive difference when compared to NA is that RA is a composite material consisting of the original aggregate (i.e., NA) and hydrated old mortar. Consequently, RA typically exhibits higher porosity, greater water absorption, and lower density. In other words, RA is considered to possess inferior quality compared to NA as a concrete

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material, and this quality inferiority is the main factor responsible for the lower strength and durability observed in recycled aggregate concrete (RAC) compared to natural aggregate concrete (NAC). Therefore, numerous studies have continuously attempted to use RA in structural concrete by improving its quality through diverse methods.

More recently, research has expanded toward secondary or multi-cycle recycling of concrete, often designated as repeated, multiple, or multi-generation recycling. Most studies commonly report a decline in concrete performance with an increase in the number of recycling cycles. According to a comprehensive review on the properties of multi-recycled aggregate concrete (MRAC),[1] the compressive strength of MRAC decreases to 82.1–96.4 % of NAC in the first recycling cycle, 83.4–93.8 % in the second cycle, and 57.6–90.1 % in the third recycling cycle. Similar results were reported in another study,[2] where RAC incorporating 100 % RCA exhibited 90-day strength losses of (12, 25 and 34) % for the first to third cycles, along with corresponding reductions in elastic modulus of 25, 31, and 52 %. The performance degradation is not limited to mechanical properties but also severely affects the durability of the concrete. Across three recycling cycles, the capillary absorption of MRAC increased by (119, 168 and 212) % compared to NAC, and chloride penetration increased by (26, 40 and 47) %.[3] MRAC also develops structural defects more readily, leading to earlier damage initiation under lower stress levels.[4–6]

To mitigate the aforementioned performance degradation, approaches have also been discussed in some studies. For example, adjusting the water-to-cement ratio was shown to maintain compressive strength after multiple recycling cycles.[7] The use of magnesium phosphate cement (MPC), which exhibits lower porosity and higher density than ordinary Portland cement, has also been reported to offset the strength loss in MRAC.[8] The authors of that study explained that the proportion of MPC mortar attached to the RA increased with each recycling cycle, leading to a denser microstructure and superior mechanical properties. Another study applied vibration-assisted mixing, reporting that the 28-day compressive strengths of RAC and MRAC were 11.5 % and 8.7 % higher, respectively, than those made with non-vibratory mixing. According to the authors, the vibration during the mixing stage effectively breaks down the agglomeration of cement particles, increases the amount of cement participating in the hydration reaction, and consequently lowers the effective w/c ratio.[9]

Considering the positive correlation between aggregate quality and concrete performance,[10] the observed degradation in MRAC is closely associated with progressive deterioration of aggregate quality during repeated recycling. As previously described, RA consists of original aggregate combined with old mortar. Therefore, RAC, containing both new and old mortar, possesses a higher mortar fraction than NAC, which contains only new mortar. Hence, RA obtained from RAC consequently contains original aggregate, first-generation old mortar, and second-generation old mortar. Concrete produced with the second-cycle RA subsequently includes a larger mortar volume than the first-cycle RAC. That is, during the process of concrete production and crushing for repeated recycling, layers of old mortar progressively accumulate on the aggregate surface, increasing porosity and water absorption while reducing strength and durability.[1,11] Conversely, this implies that the improvement of aggregate quality would lead to the enhancement of concrete performance. However, there has been a notable lack of research investigating the influence of quality improvement on the performance of concrete incorporating multi-recycled aggregates. Most existing studies have focused on reporting performance degradation with increasing recycling cycles and have rarely addressed the potential for quality recovery in multi-recycled aggregates or the contribution of this recovery to concrete properties. Therefore, the objective of this study is to clarify the relationship between the quality of multi-recycled aggregates and the mechanical behavior of concretes incorporating them. Specifically, this study aims to: (i) investigate the effects of recycling cycles (first and second) and pre-treatment methods on the physical properties of aggregates; (ii) evaluate the performance of concretes incorporating these treated aggregates; and (iii) establish quantitative correlations between aggregate characteristics and concrete strength.

The outcomes contribute to assessing the feasibility of multi-cycle recycling of concrete and highlight the significance of RA quality improvement for sustainable construction.

2 RESEARCH METHODOLOGY

To investigate the influence of quality enhancement of multi-recycled aggregates on the properties of corresponding concretes, a sequential process of concrete manufacturing, crushing, and aggregate pretreatment was carried out. The overall experimental workflow is illustrated in **Figure 1**.

NAC was prepared using crushed rock, sand, and cement, and its properties were evaluated. The NAC was then crushed to obtain first-generation RA (RA1). RA1 was subsequently categorized into three distinct conditions based on the pretreatment types: non-treated, mechanically treated, and chemically treated. Each type of RA1 was then used as coarse aggregate in concrete mixtures, and the resulting concrete properties were tested. The concrete prepared with the non-treated RA1 was crushed again to produce second-generation RA (RA2). To isolate the effect of recycling cycles, concretes containing pre-treated aggregates were deliberately excluded from the RA2 production process. Following the same classification used for RA1, RA2 was also classified into non-treated, mechanically treated, and chemically treated groups based on the applied treatment. Through this procedure, the study aimed to clarify the combined effects of recycling cycles and pre-treatment methods on the quality of RA and on the mechanical performance of the concretes incorporating them. Ultimately, the study sought to experimentally verify the feasibility of multi-cycle recycling of concrete.

3 MATERIALS AND METHODS

3.1 Materials

The concrete mixtures in this study utilized a total of seven types of coarse aggregates, one type of fine aggregate, Type I Portland cement, water, and a plasticizer.

The coarse aggregates consisted of NA, two untreated RAs, and four pre-treated RAs. The NA was a crushed stone aggregate with a 25 mm maximum nominal size, satisfying the requirements of KS F 2527, and was used for NAC. RAs were obtained by sequential crushing of concrete. RA1 was produced by crushing NAC, and RA2 was obtained by crushing concrete that incorporated RA1. RA1 and RA2 used in this study were sieved to match the maximum size of 25 mm.

Natural sand conforming to KS F 2527 requirements was employed as the fine aggregate. The density and water absorption of the sand were 2.63 g/cm^3 and 1.01 %, respectively.

Ordinary Portland cement (Type I), conforming to KS L 5201, was used as the binder.

A plasticizer was used in all mixtures at a dosage of 1 % by mass of cement to ensure adequate workability. Following the usage instructions, the plasticizer was dissolved in the mixing water and homogeneously dispersed.

3.2 Aggregate treatment

To examine the influence of RA quality on the corresponding concrete properties, three treatment conditions were applied: untreated (as-is), mechanical treatment, and chemical treatment.

The untreated condition refers to RA (RA1-N and RA2-N) obtained directly from the crushing process without undergoing any separate physical or chemical quality enhancement procedures.

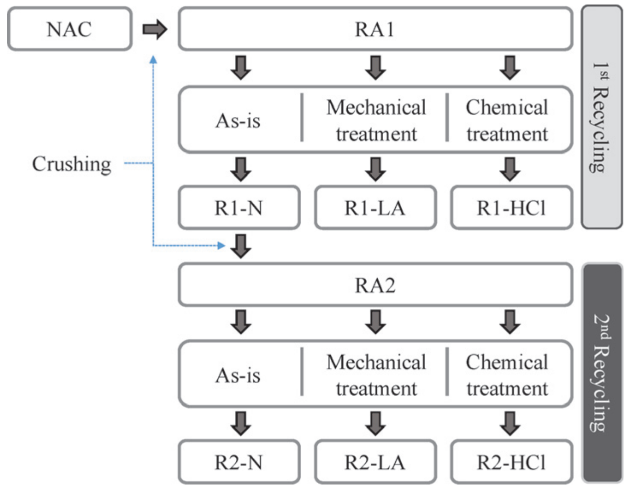


Figure 1: Flow of experimental work

The mechanical treatment was performed according to the procedure specified in KS F 2508 (Standard test method for resistance to abrasion of coarse aggregate by use of the Los Angeles machine). 5 kg of RA and the specified number of steel balls were placed in the abrasion drum, which was then rotated for 250 cycles. The friction and impact generated inside the drum removed the weak old mortar adhered to the aggregate surface.[12,13] RAs processed through this method are hereafter denoted as RA-LA.

The chemical treatment involved immersing RAs in a 4 M hydrochloric acid (HCl) solution for 24 h. Following the treatment, the solution was carefully removed, and the aggregates were washed several times with clean water to neutralize and remove any remaining acid. Although acid treatment has been widely reported as an effective method for improving RA quality,[14–16] immersing large volumes of RA in acidic solutions poses environmental and economic challenges for industrial-scale application. However, it should be noted that the application of HCl treatment in this study was not to propose it as a primary method for field recycling, but rather to simulate the high-quality recycled aggregates produced in industrial facilities. In addition, the objective of this study is not to compare the efficiency of the treatment methods, but rather to evaluate the influence of quality-enhanced RA on concrete properties. Therefore, the

Table 1: Mix proportions of concrete (kg/m^3)

ID	Water	Cement	Coarse aggregate							Sand	Plasticizer
			NA	RA1-N	RA1-LA	RA1-HCl	RA2-N	RA2-LA	RA2-HCl		
NAC	172	399	1005	0	0	0	0	0	0	863	3.99
R1-N	166	387	0	976	0	0	0	0	0	838	3.87
R1-LA	168	391	0	0	985	0	0	0	0	846	3.91
R1-HCl	172	399	0	0	0	1005	0	0	0	863	3.99
R2-N	160	371	0	0	0	0	936	0	0	804	3.71
R2-LA	162	377	0	0	0	0	0	950	0	815	3.77
R2-HCl	171	398	0	0	0	0	0	0	1004	862	3.98

acid treatment was applied. RAs processed through this method are denoted as RA-HCl.

3.3 Mix proportions

The concrete mixtures in this study were prepared using a laboratory mechanical mixer with a capacity of 60 L. To ensure adequate mixing homogeneity and operational safety, the volume of each batch was limited to approximately 45 L. All constituent materials for the concrete mixtures were weighed according to the same mass ratio. The detailed mix proportions, converted to a 1 m^3 basis, are presented in **Table 1**. The control mix (NAC) proportion per 1 m^3 consisted of 172 kg of water, 399 kg of cement, 863 kg of sand, 1005 kg of coarse aggregate, and 3.99 kg of plasticizer. This mix was designed targeting normal strength concrete with a water-to-cement ratio of 0.43.

3.4 Testing

The water absorption and oven-dry density were used as the primary quality indicators for the aggregates. These properties were measured for both NA and RA in accordance with KS F 2503.

For concrete properties, the slump in the fresh state was measured immediately after discharge from the mixer following KS F 2402. In the hardened state, the compressive strength was determined in accordance with KS F 2405 at the age of 28 days, using a minimum of three cylindrical specimens with a diameter of 100 mm and a height of 200 mm.

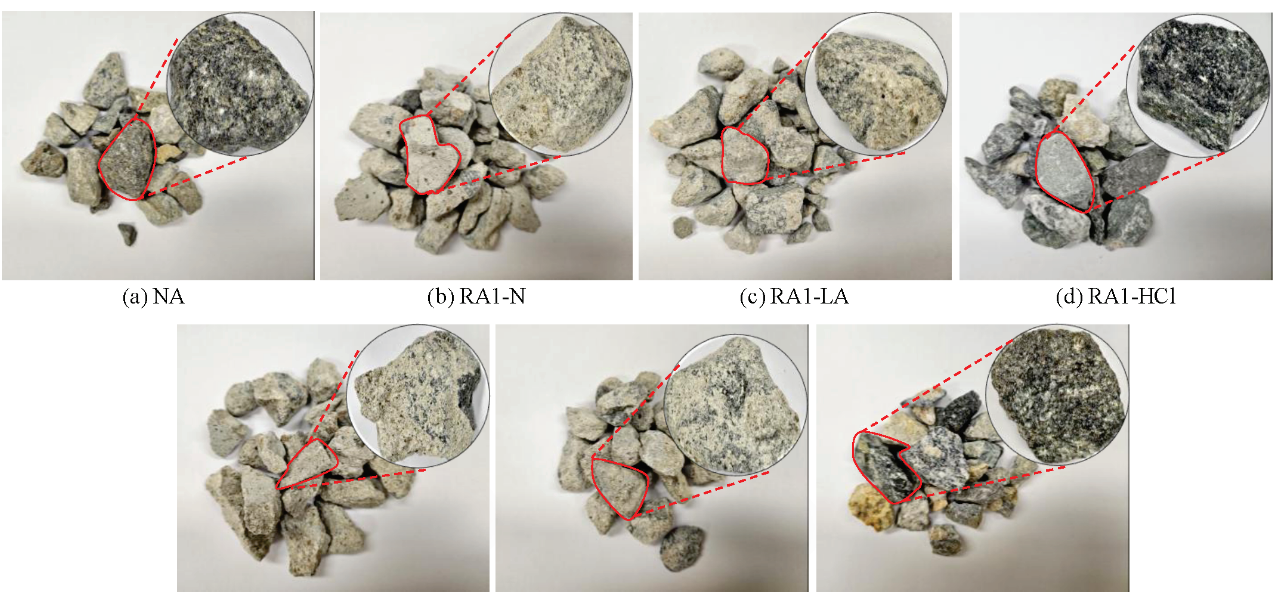
4 RESULTS AND DISCUSSION

4.1 Properties of aggregates

The appearance of NA and both untreated and treated RAs is presented in **Figure 2**. The untreated aggregates (i.e., RA1-N and RA2-N) exhibited a grayish color, with their surfaces heavily coated with old mortar. The mechanically treated RAs (RA1-LA and RA2-LA) showed partially removed mortar due to abrasion and impact during the milling process, resulting in more clearly exposed original aggregate surfaces compared to the untreated RAs. The HCl-treated RAs (RA1-HCl and RA2-HCl) retained some old mortar on certain particles; however, the original aggregate color was more pronounced, giving an appearance closer to that of NA. It should be noted that RA1 and RA2 were virtually not possible to distinguish visually, regardless of treatment condition. Consequently, visual inspection alone is insufficient for evaluating RA quality, thus highlighting the necessity of quantitative physical characterization.

The differences observed in the appearance of RAs due to different treatments are not merely visual distinctions but are directly associated with variations in key physical properties. **Figure 3** presents the measured water absorption and oven-dry density of the aggregates. Overall, the aggregates exhibited a clear inverse relationship between water absorption and density.

The RA-Ns failed to satisfy the quality requirements specified in KS F 2573 for recycled aggregates used in concrete (water absorption ≤3 %, oven-dry density ≥2.5 g/cm³). This is attributed to the porous old mortar layer on the original aggregate, which readily absorbs moisture and reduces the particle density. The water absorption and density of RA1-N were 4.8 % and 2.35 g/cm^3, respectively, which are significantly lower



(a) NA (b) RA1-N (c) RA1-LA (d) RA1-HCl

(e) RA2-N (f) RA2-LA (g) RA2-HCl

Figure 2: Appearance of recycled aggregates subjected to different treatment methods: untreated, mechanically treated, and chemically treated

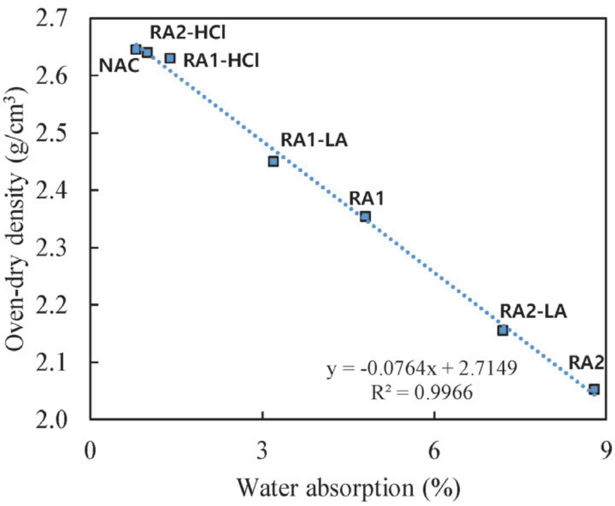


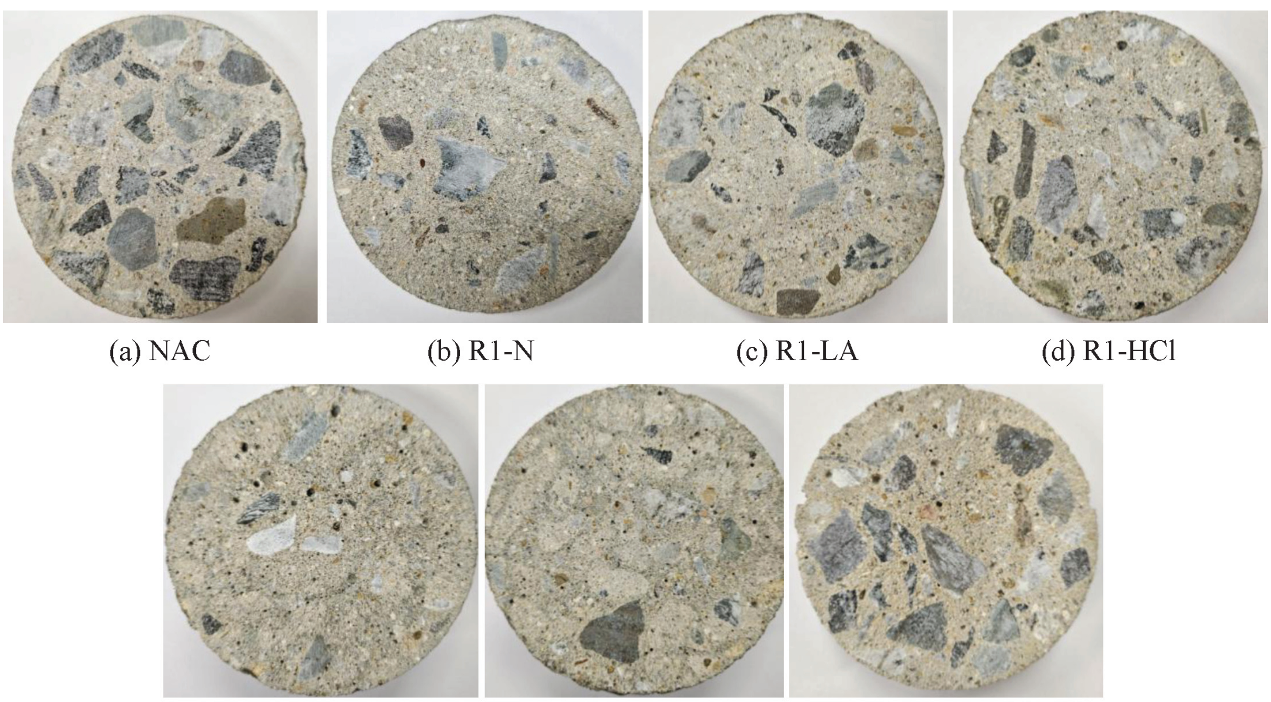
Figure 3: Physical properties of treated and untreated aggregates

than those of NA (0.8 % and 2.65 g/cm^3). RA2-N showed further degraded characteristics, with a water absorption of 8.8 % and a density of 2.05 g/cm^3. This deterioration can be explained by the decrease in the proportion of original aggregate relative to the old mortar as the number of recycling cycles increases. This trend is also evident in the cross-sections of the concrete specimens (**Figure 4**). These findings are consistent with previous studies,[17–19] confirming that RA2 contains a greater amount of old mortar than RA1. The application of mechanical pretreatment to RA1-LA and RA2-LA resulted in a moderate reduction in water absorption to 3.2 % and 7.2 %, respectively, and a corresponding increase in density to 2.45 g/cm^3 and 2.16 g/cm^3. This partial quality improvement is a result of the abrasion and impact selectively removing some of the weaker bonded mortar. The most significant enhancement was observed in the chemically treated RAs. For RA1-HCl and RA2-HCl, water absorption decreased to 1.4 % and 1.0 %, while density recovered to 2.63 g/cm^3 and 2.64 g/cm^3, approaching the values of NA. These values meet the quality requirements for RAs used in concrete as specified in KS F 2573, indicating that the chemical treatment effectively restores the essential physical properties. The minimal difference in properties between RA1-HCl and RA2-HCl is noteworthy, as it strongly suggests that stable quality can be achieved irrespective of the number of recycling cycles with appropriate treatment.

4.2 Properties of concretes

4.2.1 Slump

The results for slump test for all concrete mixtures are presented in **Figure 5**. As expected, the NAC exhibited the highest workability with a slump of 150 mm. The slump of R1-N decreased to 120 mm due to the presence of old mortar and the high water absorption of the RA1-N, which reduced the amount of effective mixing water. The mechanical treatment resulted in R1-LA showing a slight recovery in workability to 130 mm. This is interpreted as a result of the partial removal of old mortar through abrasion, leading to reduced water absorption. The R1-HCl achieved a highest slump of 150



(a) NAC (b) R1-N (c) R1-LA (d) R1-HCl

(e) R2-N (f) R2-LA (g) R2-HCl

Figure 4: Section of concrete specimens with recycled aggregates subjected to different pretreatment methods: untreated, mechanically treated, and chemically treated

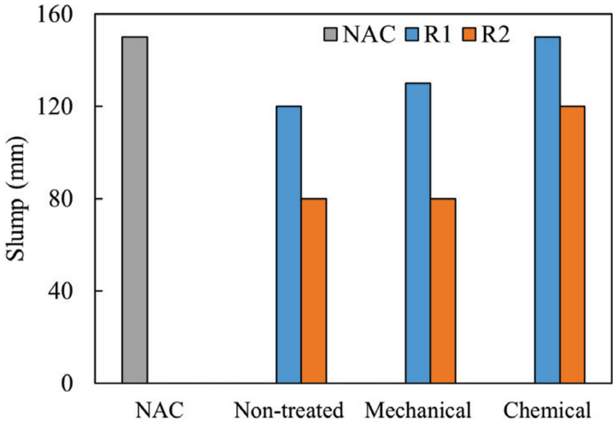


Figure 5: Slump of concretes

mm, identical to that of NAC, demonstrating the superior effectiveness of chemical treatment in removing old mortar. The R2 concretes showed lower slump compared with the R1 concrete counterparts. R2-N recorded the lowest slump at 80 mm, which is explained by the increased porosity and water absorption arising from additional recycling cycles, leading to a greater loss of mixing water. R2-LA also exhibited 80 mm, indicating that mechanical treatment is insufficient to remove the accumulated mortar layer. Conversely, R2-HCl reached 120 mm, showing a substantial recovery in workability; this improvement is attributed to the significant removal of old mortar, which mitigated water loss during mixing. In summary, the concrete slump showed a tendency to decrease as the number of recycling cycles increased. However, it was confirmed that appropriate treatment can restore the workability to a practical level, even in cases of severe degradation like R2.

4.2.2 Properties of the hardened concrete

The properties of the hardened concrete mixtures, including density and 28-day compressive strength, are presented in **Figure 6**. NAC, the reference mixture, exhibited a density of 2379 kg/m³ and a compressive strength of 32.8 MPa. R1-N recorded a density of 2245 kg/m³ and a compressive strength of 29.9 MPa, showing a degradation of approximately 6 % in density and 9 % in strength, compared with NAC. These reductions are reportedly attributed to the old mortar in RAs, which lowers the specific gravity and weakens the interfacial transition zone. This result is consistent with general findings from previous studies.[20,21] R1-LA exhibited improvements to 2344 kg/m³ in density and 31.1 MPa in strength, representing increases of about 4 % relative to R1-N. Meanwhile, R1-HCl achieved a density of 2365 kg/m³ and a strength of 32.8 MPa, recovering the performance to a level nearly identical to that of NAC.

The R2 concretes generally exhibited lower performance than the R1 concrete counterparts. The density and strength of R2-N were 2187 kg/m³ and 28.6 MPa, respectively, representing decreases of 8 % and 13 % relative to NAC and reductions of approximately 3 % and 4 % compared with R1-N. These trends are stemmed from the progressive degradation of physical properties of RA2 over RA1 due to the increased old mortar content and reduced original aggregate content during multiple

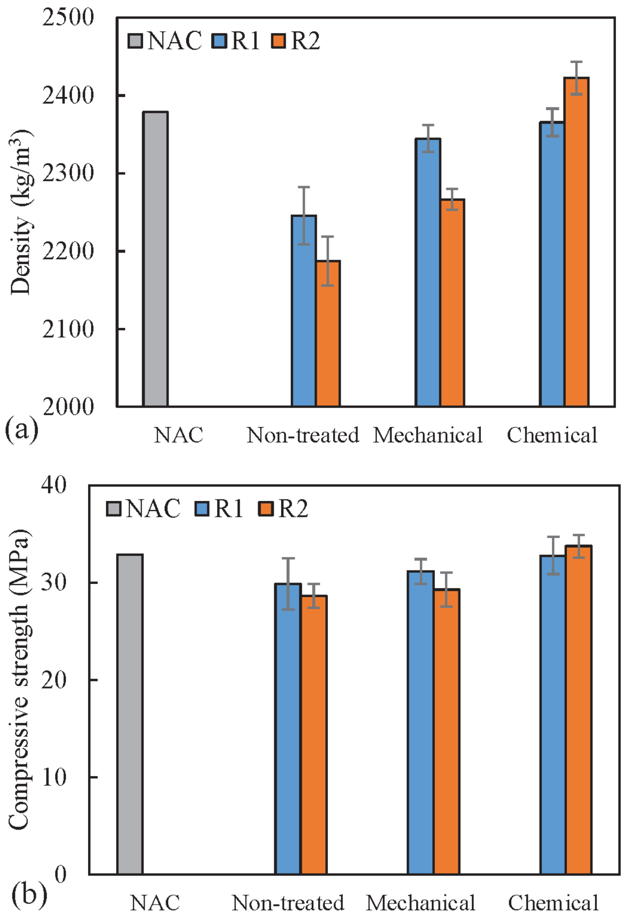


Figure 6: Properties of hardened concretes: (a) density; (b) compressive strength

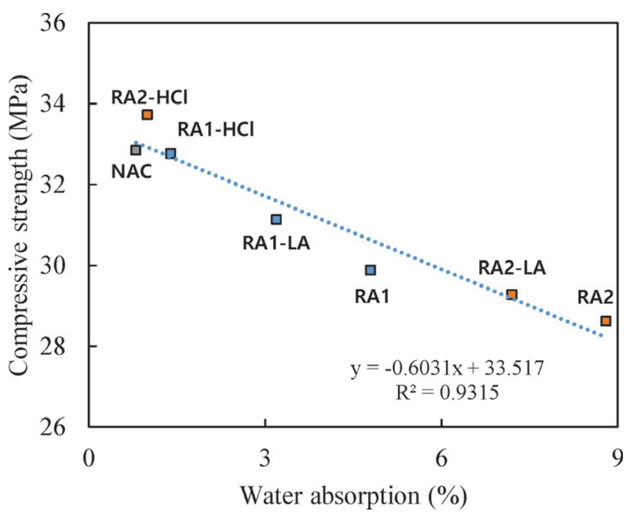


Figure 7: Correlation between aggregate water absorption and concrete compressive strength

recycling cycles. R2-LA subjected to mechanical treatment showed a marginal increase over R2-N, with a 2.4 % increase in strength. R2-HCl exhibited the highest density (2422 kg/m³) and compressive strength (33.7 MPa) among all mixtures. This exceptional result stems from the extensive removal of accumulated old mortar from RA2-N.

The experimental results indicate that while the repeated recycling of recycled aggregate (RA) causes a degradation of fundamental physical properties, the extent of this influence varies depending on the treatment method applied. While mechanical treatment offered a certain level of improvement, chemical treatment proved to be the most effective in enhancing the concrete strength. Specifically, the R2-HCl results provide compelling evidence supporting the feasibility of multi-cycle concrete recycling when aggregate quality is improved.

To quantitatively assess the relationship between water absorption of aggregate and compressive strength of concrete, a scatter plot of the two variables for all seven mixtures is presented in **Figure 7**. A clear negative linear correlation was observed, indicating that lower water absorption is associated with higher concrete strength. This confirms that the quality improvement of RA through treatment can quantitatively contribute to the enhancement of concrete strength.

The results of the linear regression analysis for the two properties yielded a high coefficient of determination (R^2) of 0.93, and the regression equation is given as Equation (1):

$$f_c(\mathrm{MPa}) = -0.6031\ WA(\%) + 33.517 \tag{1}$$

where f_c is the 28-day compressive strength (MPa), and WA is the aggregate water absorption (%).

The equation shows that a 1 % increase in water absorption results in a strength reduction of approximately 0.6 MPa, corresponding to about a 1.9 % relative loss. These results are consistent with previous findings, which reported strength reductions of approximately 3 % and 1.3 %, respectively.[22,11] This indicates that variations in aggregate water absorption can exert a dominant influence on the compressive strength of concrete. In particular, unlike NA whose properties show minimal property variations, RA exhibits much greater fluctuations in its characteristics.[23,10] Therefore, when applying RA in concrete, the investigation of fundamental properties such as water absorption is required, and for RA with high water absorption, quality improvement through appropriate pretreatment is necessary.

5 CONCLUSIONS

In this study, the influence of quality enhancement through a pretreatment of multi-RAs on the properties of concrete was investigated. The main conclusions are as follows:

- Untreated RAs exhibited an increase in water absorption, rising from 4.8 % to 8.8 %, and a decrease in density with repeated recycling. The progressive deterioration in aggregate quality led to decreases in slump and compressive strength by up to 47 % and 13 %.
- Compared to mechanical treatment, chemical treatment was markedly more effective in improving aggregate quality, enabling both RA1 and RA2 to achieve water absorption and density values comparable to NA. Notably, the R2-HCl concrete exhibited the highest density and compressive strength among all mixtures, experimentally demonstrating that appropriate pretreatment can enable multiple recycling of concrete without compromising performance.
- Between aggregate water absorption and concrete compressive strength, a strong negative linear correlation (R^2 = 0.93) was observed. Regression analysis showed that a 1 % increase in water absorption results in an approximately 1.9 % reduction in 28-day strength.

The multi-cycle recycling of concrete may hold significant implications for the sustainability of the concrete industry, and the findings of this study demonstrate that overcoming the performance degradation through aggregate quality enhancement is feasible. Given that this study was conducted at a laboratory scale focusing on strength characteristics, future research should address practical techniques suitable for industrial-scale applications, improve the recovery efficiency of high-quality recycled aggregates, and evaluate the overall economic and environmental impacts.

Acknowledgment

This research was funded in part by the National Science Centre, Poland (Grant number 2023/51/B/ST8/00621). This paper was supported by the Education and Research Promotion Program of KOREATECH in 2026.

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