Optimizing Chemical Pretreatment of Recycled Concrete Aggregate: Microscopic Insights into Acetic Acid Effects

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Abstract

As efforts towards sustainable construction intensify, recycled concrete aggregate (RCA) offers a viable and sustainable alternative to natural aggregates in construction. However, its mechanical properties, primarily high-water absorption and low specific gravity, impede widespread adoption. Scholars attribute these property deficiencies to the presence of adherent mortar and multiple interfacial transition zones (ITZ) within RCA particles. Chemical treatments, especially strong acids like HCl and H_2SO_4, remove mortar effectively but harm concrete durability by introducing chloride and sulfate ions. Weak acids, such as acetic acid, have been proposed as safer alternatives but lack detailed microstructural analysis regarding their selectivity and impact on the natural aggregate beneath. This study used scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDAX) to examine RCA samples treated with 0.2 mol acetic acid for 24 hours. Two RCA sources were analyzed at magnifications from 50x to 1300x, focusing on mortar, old aggregate (OA), and ITZ areas. Elemental mapping measured changes in Ca/Si and (Al+Fe)/Ca ratios to assess phase changes and damage. The findings challenge assumptions about the selectivity of acetic acid treatment. Although acetic acid effectively degraded the adhering mortar, depleting Ca/Si ratios to below 2.5 and (Al+Fe)/Ca ratios above 0.4, extensive deterioration occurred in the old aggregate zones. SEM images revealed widespread cracking in both mortar and aggregate, varying with mineral composition. The ITZ consistently suffered extensive damage. The study concludes that acetic acid treatment is less selective than believed, with treatment effects depending strongly on the original aggregate mineralogy. These insights aid in refining chemical pretreatments and suggest mechanical methods may offer more reliable RCA improvement.

Keywords: Recycled concrete aggregate, acetic acid treatment, scanning electron microscopy, interfacial transition zone, microstructure

1.0 Introduction

Globally, concrete ranks as the second most consumed material on Earth due to its wide range of applications [1,2]. However, its 32 billion tonne annual production is responsible for a substantial portion of the human-made carbon dioxide emissions at 7-8% [3,4]. Additionally, concrete production depends heavily on the extensive extraction of natural aggregates (NA), which significantly contributes to resource depletion and waste generation [5,6]. As efforts to find sustainable alternatives intensify, recycled concrete aggregate (RCA) offers a promising pathway by reducing landfill use and consumption of virgin NA. Sourced from demolition waste, its widespread adoption in structural applications remains limited due to its inherently inferior properties compared to NA [7,8]. Unlike NA, RCA is a heterogeneous material comprising old aggregates and adherent mortar (M). This mortar, which sticks to the original natural aggregates, is highly porous and brittle, compromising the performance of RCA. Its high porosity and brittleness lead to multiple weak interfacial transition zones (ITZs) forming between the aggregate and the new concrete matrix [9,10,11]. As a result, RCA mixes are characterized by higher water absorption, lower specific gravity, and reduced mechanical strength, properties that NA typically does not exhibit [11].

To mitigate these drawbacks, various pre-treatment methods aimed at removing or strengthening the adhered mortar have been explored, including mechanical abrasion, thermal heating, and chemical immersion. However, each method has its limitation. Thermal treatment raises questions about its sustainability when the source of thermal energy is not directly linked to the chosen process [12,13,14,15]. The use of strong acids such as hydrochloric acid (HCl), sulfuric acid (H_2SO_4), or phosphoric acid (H_3PO_4), while effective, raises serious concerns regarding worker safety, environmental impact from waste disposal, and

potential damage to the natural aggregates in RCA [16,17]. Mechanical treatment can be effective but typically generates low-quality fines [18]. Given these challenges, untreated RCA is typically limited to around 25% replacement in good mixtures, highlighting the need for more effective solutions [19]. Recent research has investigated milder alternatives, such as acetic acid (CH_3COOH), a weak acid. Preliminary studies suggest acetic acid can help dissolve mortar components and improve RCA properties, but a comprehensive understanding of its microstructural and chemical effects is still lacking. Crucially, it remains unclear whether the acid selectively attacks the mortar or also degrades the valuable original natural aggregates [16,17]. The uncertainty about acetic acid's effect on NA vs mortar makes it hard to develop effective, efficient treatment methods. This is because if the acid harms the NA, then it undermines the treatment's goal of improving RCA quality.

1.1 Study Objectives

This gap in knowledge shows the need for detailed microstructural and compositional analysis. Therefore, this study focuses on characterizing the microstructure of RCA before and after acetic acid treatment. The study specifically aims to investigate: *(i) the morphological changes to the adhered mortar and the OA surface, (ii) the integrity of the ITZ post-treatment, and (iii) the* chemical changes through elemental ratios*, particularly Calcium to Silicon (Ca/Si).* By studying how RCA interacts with acetic acid at the microscopic level, this work aims to help advance the pursuit of environmentally friendly chemical treatments and support the reliable use of high-quality RCA in sustainable concrete construction.

2.0 Methodology

2.1 Sample Preparation

Two RCA samples from different sources were selected for this study to account for variability in original aggregate mineralogy, as is often necessary in research of this kind[20,21]. The first RCA sample was from a single source (SRC) and made almost entirely of recycled concrete. The aggregates showed no signs of soil or other waste, making it easy to separate fine particles from coarse ones. This sample helped the study focus on the acid's effect on mortar (M) and old aggregate (OA) in a typical concrete mix. The second RCA sample came from general recycled concrete (GRC). It included not only concrete but also brick, bituminous materials, and some stones. This sample represents a real-world, "contaminated" mix. Adopting this sample enables the understanding of how acetic acid reacts with a mixed, often contaminated, material typical of recycling centres. The aggregates were carefully prepared for microscopic examination by selecting particles approximately 10 mm in size. To ensure accurate before-and-after comparison, specific regions on each aggregate surface were marked, allowing the same regions to be re-identified following treatment. This marking targeted three distinct zones within each RCA particle:

- the adherent mortar (M)
- the old aggregate (OA), and
- the interfacial transition zone (ITZ) between them.

Thus, these three zones enabled data collection solely from uniform regions, avoiding mixing results that could obscure treatment effects. For mounting, each aggregate was placed with a flat surface aligned perpendicular to the electron beam path to improve image quality and ensure consistent analytical conditions. General-purpose virgin NA samples were also prepared as reference materials to establish baseline surface characteristics and elemental compositions.

2.2 Acetic Acid Treatment Protocol

This study used a 0.2 mol acetic acid (CH_3COOH) solution for the chemical treatment. This concentration has been shown as optimal for mortar removal [22,23]. Following initial SEM imaging, the marked aggregates were immersed in the acetic acid solution for 24 hours at room temperature. This duration allowed sufficient reaction time while avoiding excessive deterioration observed in preliminary trials. After soaking, the aggregates were removed and thoroughly rinsed with tap water to stop the acid reaction and remove dissolved residues, as recommended by [24,25]. All samples were oven-dried at 110 ± 5°C for 24 hours before the initial SEM examination to eliminate moisture that could interfere with imaging and vacuum conditions. The relatively dilute acid concentration and moderate exposure time were carefully chosen to balance treatment effectiveness with potential aggregate damage, allowing investigation of the selectivity across all two RCA source types, which is central to this study.

2.3 Microstructural Analysis

To be able to characterize the RCA's microstructure before and after the acetic acid treatment, the Scanning Electron Microscopy - Energy Dispersive X-ray Spectroscopy (SEM-EDAX) was employed. Studies have shown it is a powerful, combined analytical technique to visualize surface morphology and identify the elemental composition of materials simultaneously [26-27]. In this study, the characterization was conducted using an FEI Quanta 200 FEG Environmental Scanning Electron Microscope equipped with an EDS Dispersive X-ray Analyzer EDAX Octane Plus SDD detector. All imaging and analysis were done at 15 kV operating voltage in low vacuum mode to accommodate the non-conductive nature of concrete, without requiring conductive coatings that could mask surface features. Magnifications ranged from 50x to 1300x to capture both broad and detailed microstructural features. Lower magnifications (50x) provided comprehensive overviews of each aggregate surface, enabling identification of the targeted three distinct and marked zones. These overview images are important for finding and recording the marked areas for before-and-after comparison. Intermediate magnifications (250x to 500x) examined crack patterns and surface damage, while the highest magnification (1300x) revealed fine microstructural details, including individual pore structures, microcrack morphology, and phase boundaries. Working distances were adjusted for each magnification to achieve maximum resolution and depth of field. This imaging approach allowed clear documentation and comparison of both large-scale damage and small-scale changes across all two RCA source types.

For elemental analysis, energy-dispersive X-ray spectroscopy (EDAX) was performed on homogeneous areas within the mortar, old aggregate, and ITZ regions separately. Elemental mapping visualized the distribution of key elements, particularly calcium and silicon, while quantitative point analysis measured atomic percentages to calculate Ca/Si and (Al+Fe)/Ca ratios critical for phase identification and damage assessment. In RCA, these ratios function as diagnostic tools for the ITZ, the weakest link in recycled concrete. The Ca/Si ratio is primarily used to identify the presence and purity of Calcium-Silicate-Hydrate (C-S-H), the main glue of the concrete [28]. A lower ratio typically indicates a more stable, dense C-S-H, while higher ratios point toward the presence of Calcium Hydroxide (CH) [29,30,31]. On the other hand, the (Al+Fe)/Ca ratio helps detect sulfate-based phases, monosulfate (AFm) that may indicate past chemical attacks or late-stage hydration changes [29]. From current cement chemistry literature, the following criteria was used for determining these intermix hydrate phases [32,33,34]Calcium-Silicate-Hydrate $(CSH)\ phase$: $0.8 \leq Ca/Si \leq 2.5$, $(Al + Fe)/Ca \leq 0.2$

Calcium Hydroxide $(CH)\ phase$: $Ca/Si \geq 10$, $(Al + Fe)/Ca \leq 0.4$

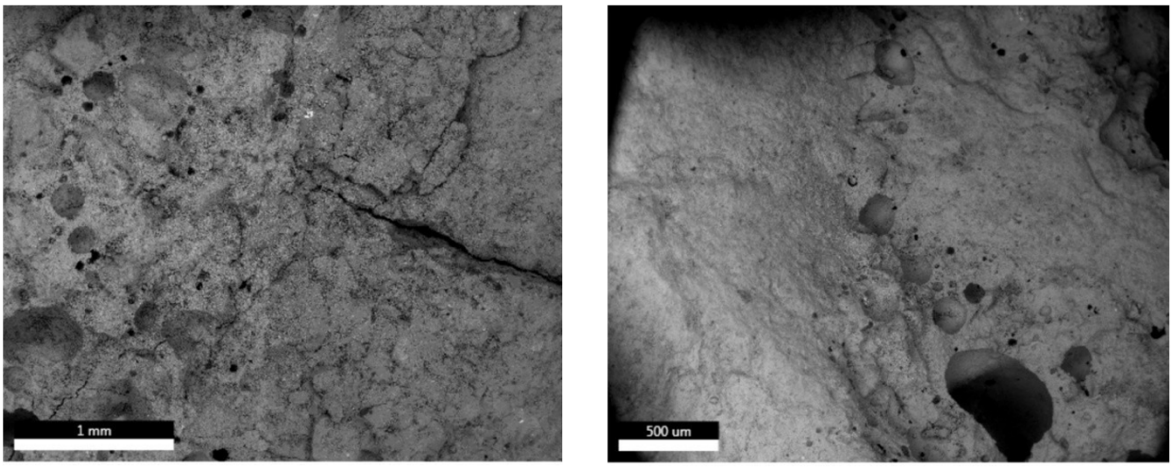
Monosulfate $(AFm)\ phase$: $Ca/Si \geq 4$, $(Al + Fe)/Ca > 0.4$

3.0 Result and Discussion

3.1 Microstructural Characteristics of Untreated RCA

The SEM analysis of the untreated RCA showed microstructural features different from NA. At low magnification (50x), the heterogeneous nature of RCA becomes immediately apparent, with clear visual differentiation between the OA and the M regions, as shown in Figure 1.

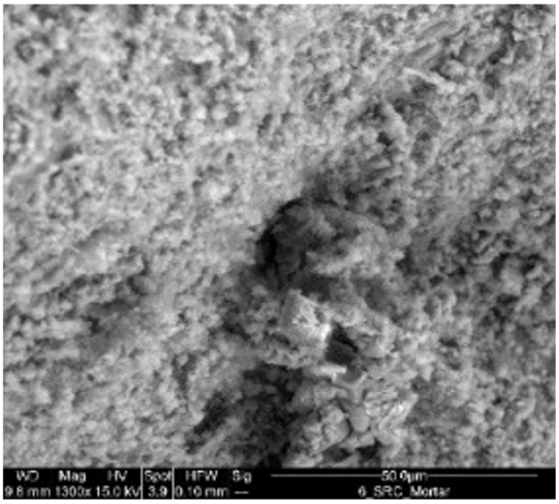
Figure 1. Magnified 50x SEM image



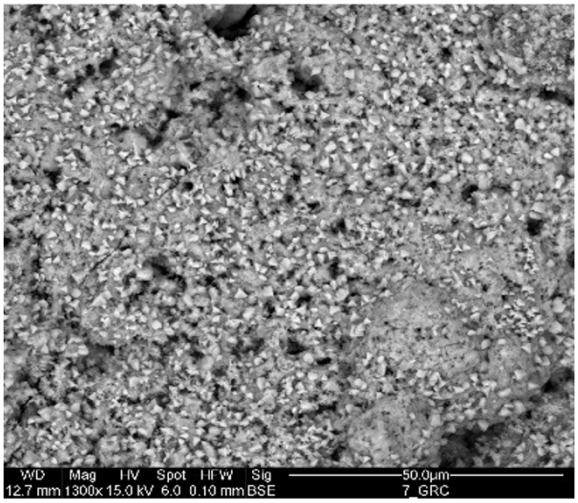
Sample A (SRC) *Sample B (GRC)*

The mortar phase consistently showed a more granular and porous texture compared to the denser OA with visible microcracks traversing the surface. This difference in porosity is especially clear at the ITZ, which is the 10-50µm region between the mortar and aggregate. The ITZ showed signs of higher void content and microcracking. This observation is consistent with the wall effect mechanism. In this mechanism, fine particles arrange themselves in lines around larger aggregates. This arrangement encourages water to gather in specific areas, leading to increased porosity [33,35,34]. From Figure 1, the RCA sources show clear differences in microstructural quality. Sample A showed better ITZ integrity than Sample B. Sample A had no visible interfacial splitting, even though there were clear porosity differences between the M and OA regions. This suggests that the original aggregate source and processing history have a strong effect on the RCA's microstructure before any treatment. At a higher magnification (1300x), the surface morphology of mortar appears rough and irregular across both RCA types, as shown in Figure 2. The OA surfaces show varied textures, as seen in Figure 3. In contrast, NA displays a consistent, uniform surface throughout, as shown in Figure 4. This highlights the inherent microstructural complexity of RCA. NA samples, which inherently lack any adherent mortar, were examined as controls to establish baseline surface morphology and elemental composition. Their uniform, non-porous surfaces (Figure 4) contrast sharply with the heterogeneous and porous surfaces observed in RCA.

Figure 2. Magnified 1300x SEM image of the Mortar Surface

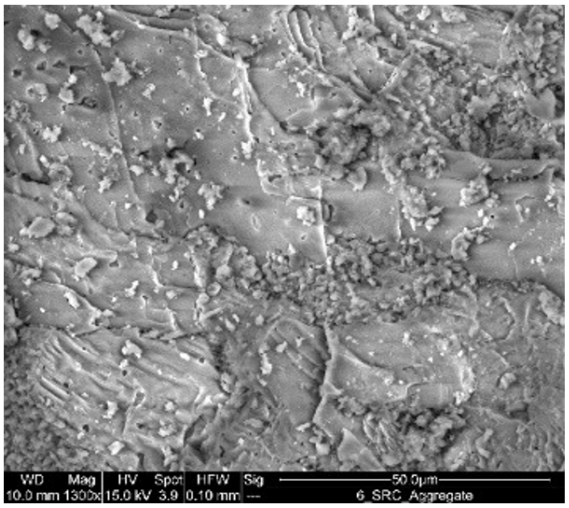


Sample A (SRC)

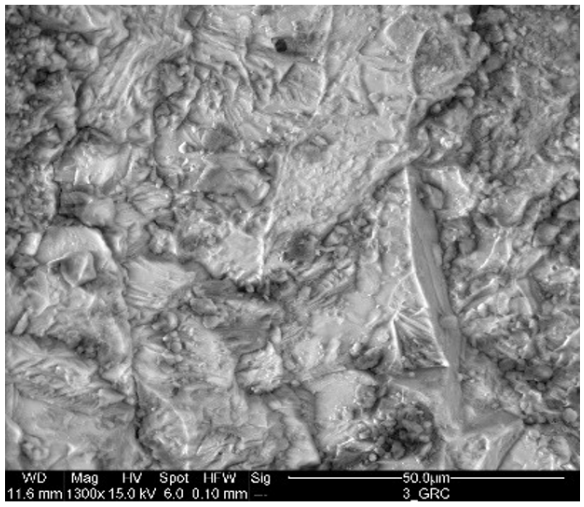


Sample B (GRC)

Figure 3. Magnified 1300x SEM image of the Surface of Old Aggregate

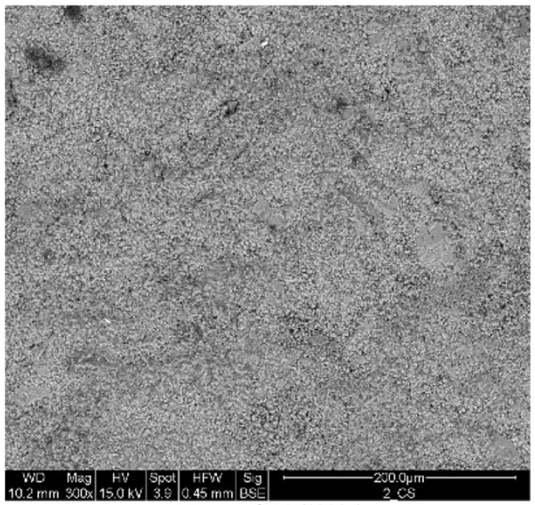


Sample A (SRC)

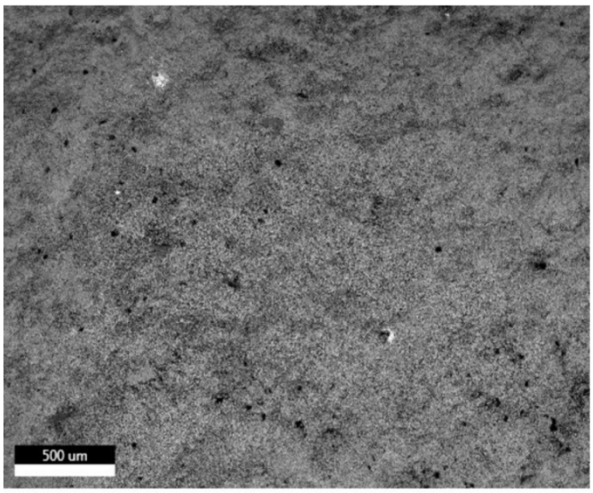


Sample B (GRC)

Figure 4. Magnified SEM image of the Surface on the mortar of NA



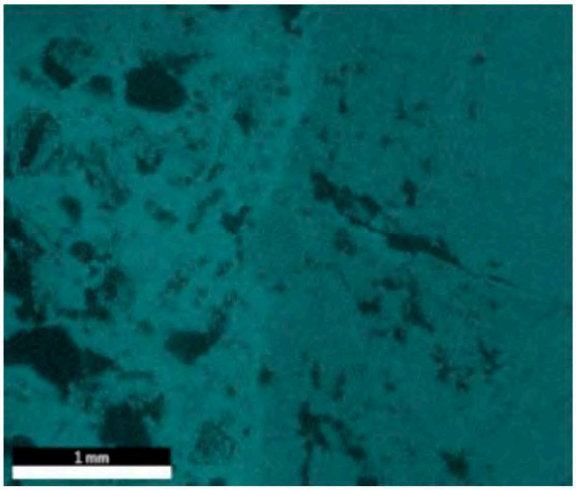
Mortar of NA (1300x)



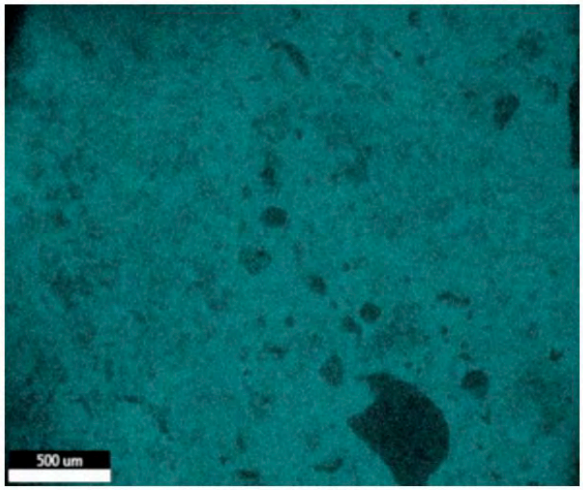
Mortar of NA (50x)

The EDAX mapping provided quantitative data to differentiate RCA constituents. In general, both calcium and silicon are found on the surfaces of the mortar (M) and old aggregate (OA). At 50x magnification, the calcium distribution exhibited concentrated enrichment in the mortar regions, as shown in Figure 5. Meanwhile, the silicon distribution appears more uniformly dispersed, as displayed in Figure 6. By evaluating whether the silicon-to-calcium ratio changes in both the mortar and aggregate regions, this analysis helps determine if acid treatments are effective, not only in removing the M but also in assessing whether they might damage the OA.

Figure 5. Magnified 50x EDAX image showing the distribution of Calcium

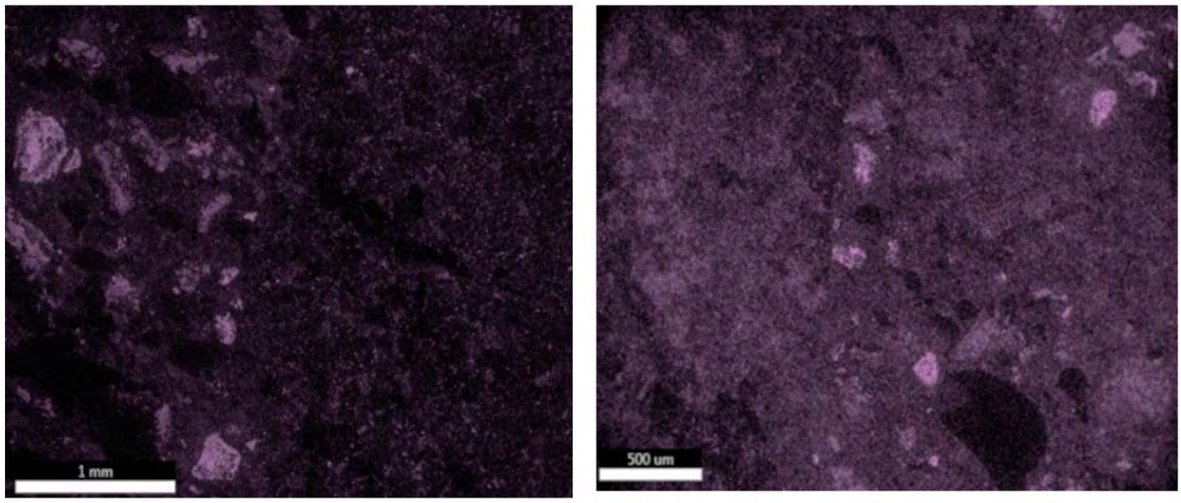


Sample A (SRC)



Sample B (GRC)

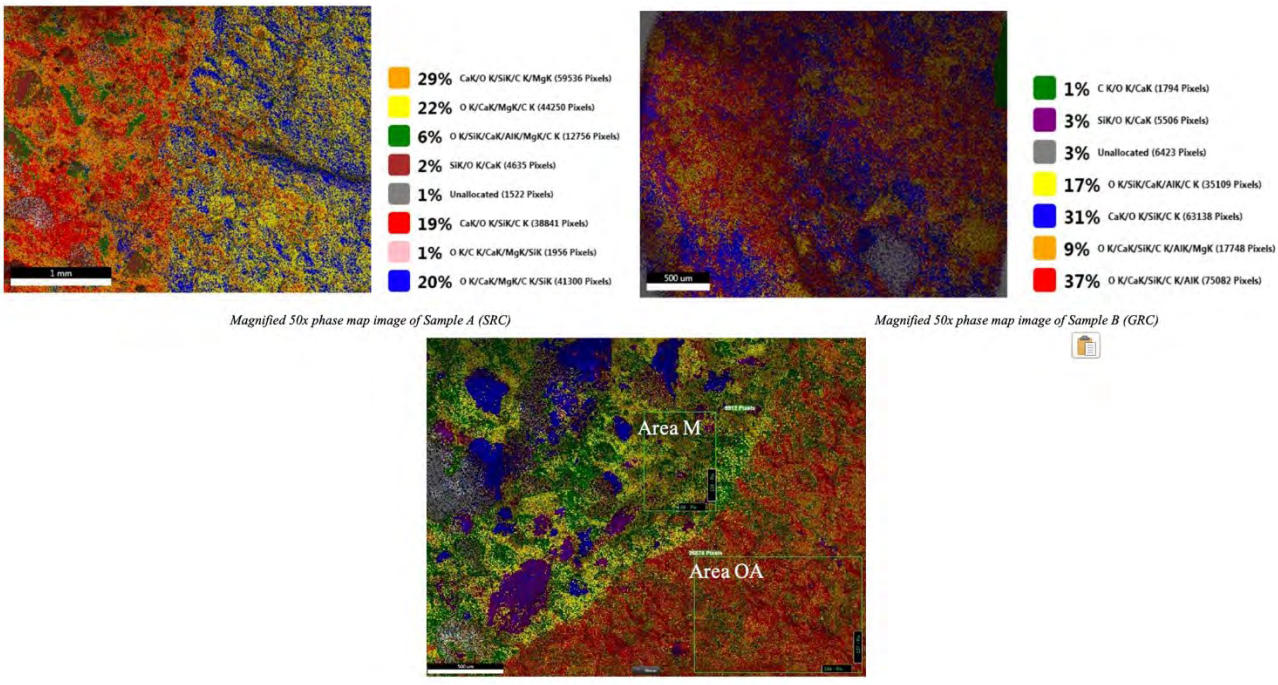
Figure 6. Magnified 50x EDAX image showing the distribution of Silicon



Sample A (SRC) *Sample B (GRC)*

The study further subjects the samples to phase mapping to differentiate between M and OA zones, as shown in Figure 7. Accordingly, Figures 8 and 9 establish baseline elemental ratios for the mortar and OA.

Figure 7. Phase Mapping



Magnified 50x phase map image of Sample A (SRC)

Magnified 50x phase map image of Sample B (GRC)

Phase map of a portion of surface of a RCA aggregate

Figure 8. Spectrum of the portion of surface in the old aggregates (Area OA).

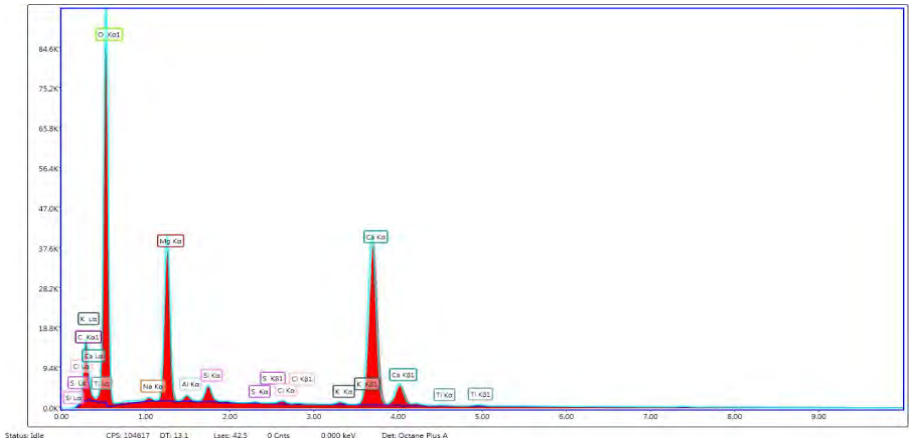


Figure 9. Spectrum of the portion of surface in the Mortar (Area M).

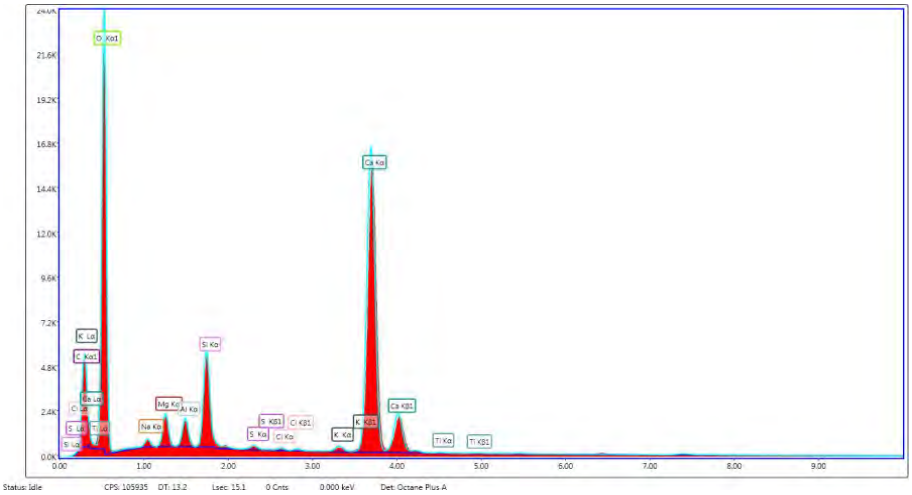
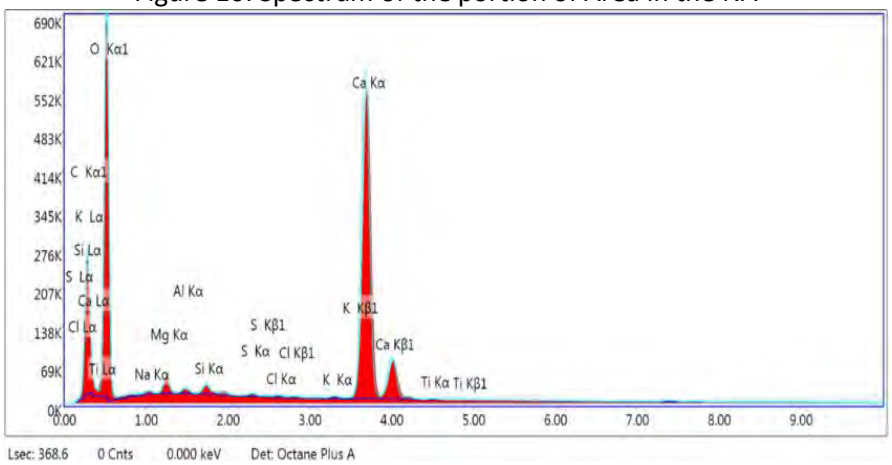


Figure 10. Spectrum of the portion of Area in the NA



In Figure 8, the ratio is about 6, while in Figure 9 it reaches as high as 22. It is worth noting that, besides these elements, it is common to find elements such as carbon, magnesium, sodium, and small amounts

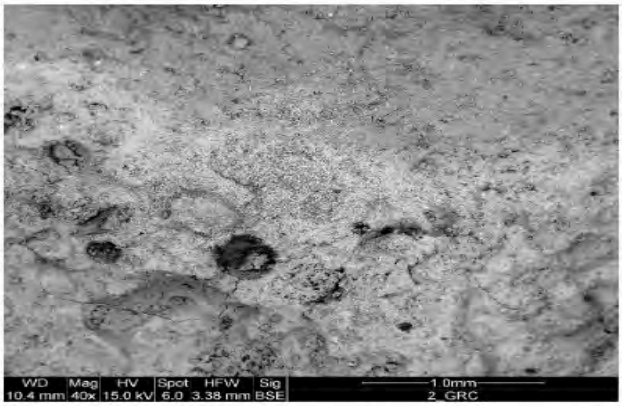
of aluminum and iron in RCA. The atomic ratio of (Al+Fe)/Ca was evaluated, yielding 0.05 for the mortar and 0.02 for the old aggregate. In the natural aggregates in Figure 10, the Ca/Si ratio is even higher at 66, while the atomic ratio of (Al + Fe)/Ca is lower, around 0.01. The NA demonstrates the highest Ca/Si (66) with minimal (Al+Fe)/Ca (0.01), confirming its compositional purity relative to RCA constituents.

3.2 Morphological and Chemical Changes After Acetic Acid Treatment

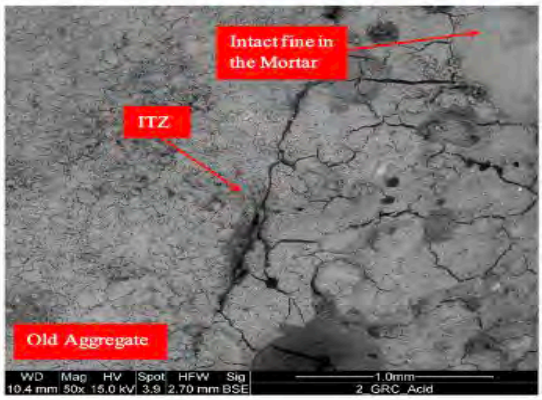
Immersing RCA in 0.2 mol acetic acid for 24 hours caused pronounced morphological changes across all phases. A direct before-and-after comparison of identical surface regions, as shown in Figure 11, visualizes these acid-induced modifications. The most noticeable changes occur within the adherent mortar phase. In Sample B, before treatment, mortar surfaces showed a granular texture with moderate porosity but limited cracking. After acid exposure, these areas became extensively fractured, displaying dense networks of interconnected microcracks. The interfacial transition zone (ITZ) was particularly vulnerable, often showing complete separation between the mortar and old aggregate in many specimens. This preferential attack aligns with the ITZ's naturally higher porosity caused by the wall effect [36,37], which allows acid to penetrate and dissolve calcium.

Importantly, the old aggregate is not immune to acid attack. The response of OA populations was notably variable and appears primarily governed by mineralogical composition. Some OA zones remained structurally intact (Ca/Si > 6.44) despite nearby mortar deterioration, while others underwent near-complete phase transformation (Ca/Si = 0.04). This differential susceptibility aligns with the inherent acid resistance of siliceous aggregates compared to the vulnerability of carbonate-based aggregates. Crack morphology further distinguishes these responses: resistant aggregates exhibit only superficial etching, while susceptible aggregates develop deep, penetrating fissures that compromise structural integrity. In Sample A, specimens with pre-existing microcracks or weaker ITZ integrity before treatment developed more extensive damage networks after acid exposure, indicating that treatment outcomes are partly predetermined by RCA source characteristics.

Figure 11. Surface of Samples before and after treatment



Surface of Sample B (GRC) before treatment



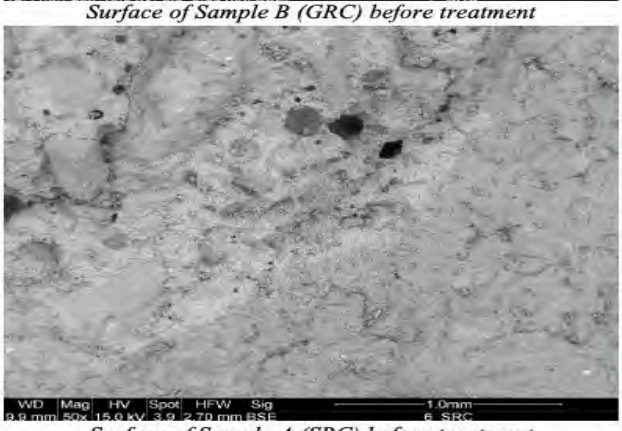
Surface of the Sample B (GRC) after acetic acid treatment



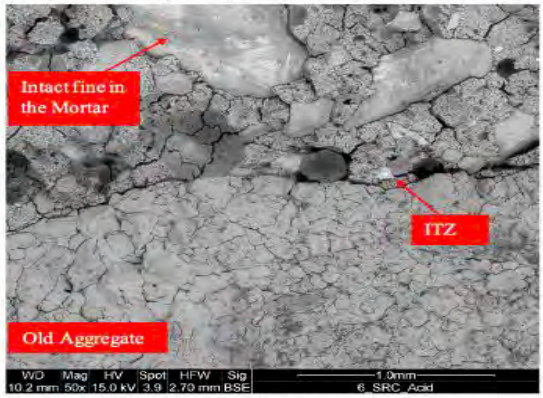
Surface of Sample B (GRC) before treatment



Surface of the Sample B (GRC) after acetic acid treatment



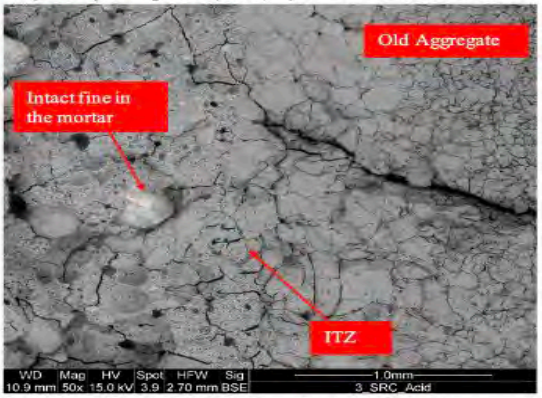
Surface of Sample A (SRC) before treatment



Surface of Sample A (SRC) after acetic acid treatment



Surface of Sample A (SRC) before treatment



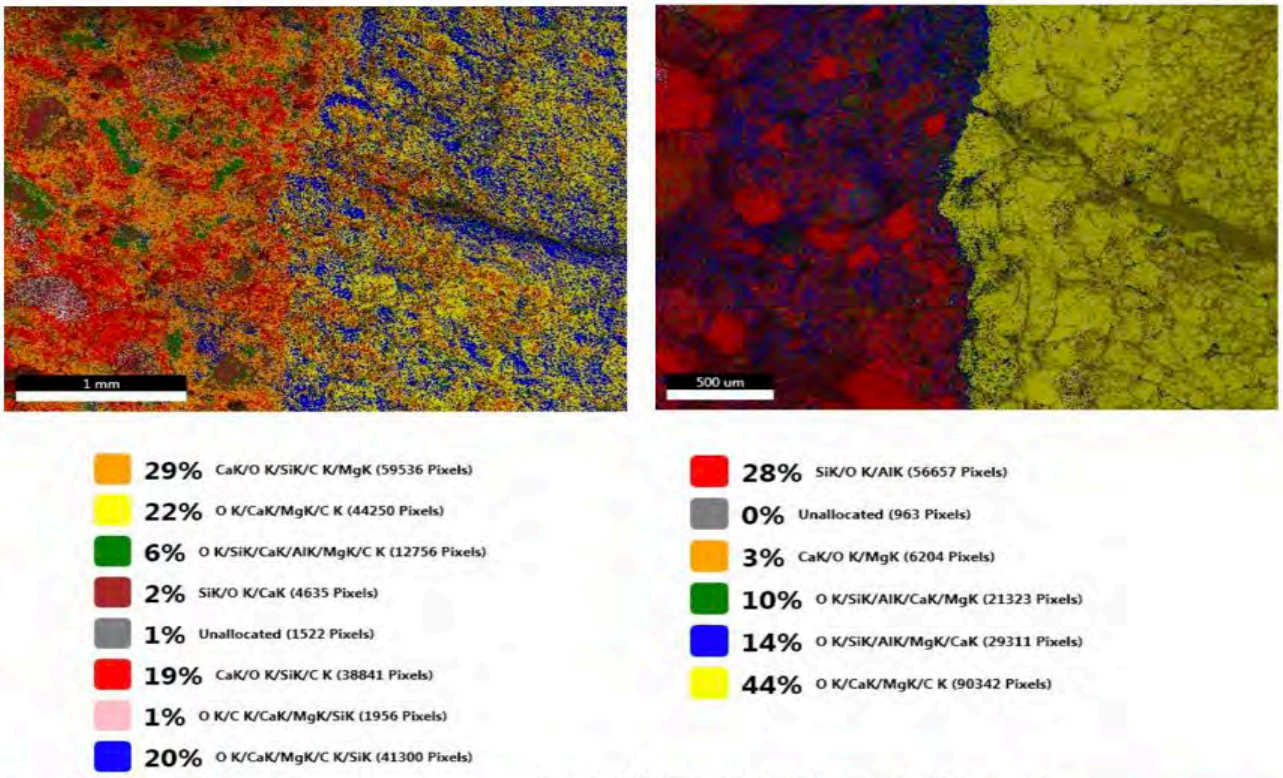
Surface of Sample A (SRC) after acetic acid treatment

Figures 12-15 show the most significant elemental maps from a portion of the aggregate. Spectra were collected exclusively from homogeneous areas of the aggregate, and thus data from the M and OA regions were acquired separately. This approach was taken to investigate differences in the spectrum between OA and M after treatment. The EDAX analysis confirms substantial chemical modifications concurrent with morphological changes. Mortar regions underwent pronounced calcium depletion, with Ca/Si ratios decreasing from approximately 4.38–5.62 before treatment to values below 0.62 after treatment. This reduction is accompanied by a marked increase in (Al+Fe)/Ca ratios from 0.06–0.10 to values exceeding 0.70. These compositional shifts indicate extensive dissolution of calcium-rich phases, particularly portlandite (CH), and significant decalcification of C–S–H gel. The resulting post-treatment ratios fall outside conventional hydrate phase classification ranges, suggesting the formation of silica-rich amorphous residues.

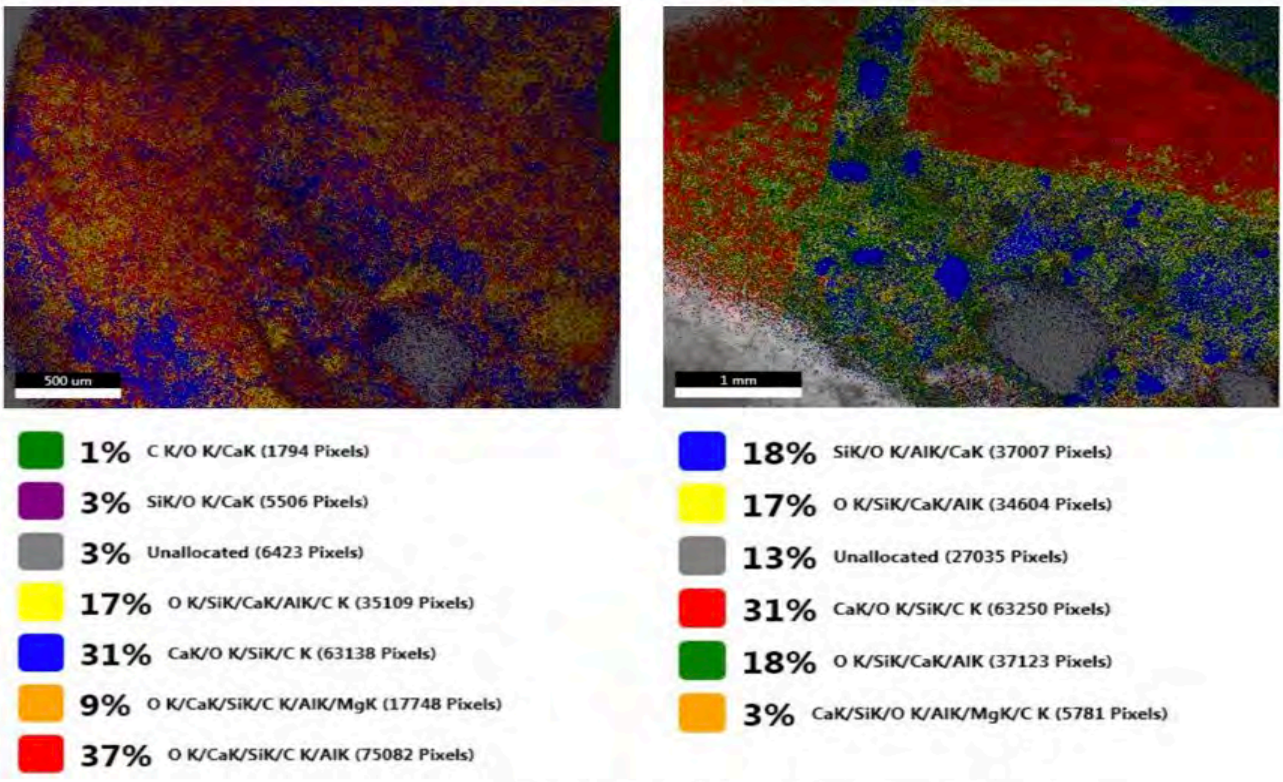
In contrast, the response of OA regions is more variable and appears to depend strongly on aggregate composition. Prior to treatment, OA exhibits higher Ca/Si ratios (8.61–13.09) and lower (Al+Fe)/Ca ratios (0.04–0.05), confirming its distinct chemical signature relative to the mortar phase. After acetic acid exposure, some aggregates maintain relatively high Ca/Si ratios (6.44–8.74) and low (Al+Fe)/Ca values (0.06–0.08), indicating limited chemical attack. Other aggregates, however, display significant calcium depletion approaching mortar-like levels (Ca/Si=0.04) with substantial increases in (Al+Fe)/Ca (up to 4.86), demonstrating that certain aggregate types undergo near-complete phase transformation.

These chemical alterations correspond closely with the cracking patterns observed in the microstructural analysis, confirming that acid exposure alters both the morphology and chemical composition of RCA constituents. Notably, when mortar and OA spectra are analyzed collectively, intermediate values are obtained as shown in Table 1 (Ca/Si=3.36 and (Al+Fe)/Ca=0.16), which obscure the extreme transformations occurring within individual phases. This highlights the importance of phase-specific analysis when evaluating the chemical effects of acid treatment on recycled concrete aggregates. In the overview, the EDAX results show that weak organic acid exposure transforms both the morphology and composition of RCA constituents, challenging assumptions about weak acid selectivity.

Figure 12. Elemental Mapping before and after treatment

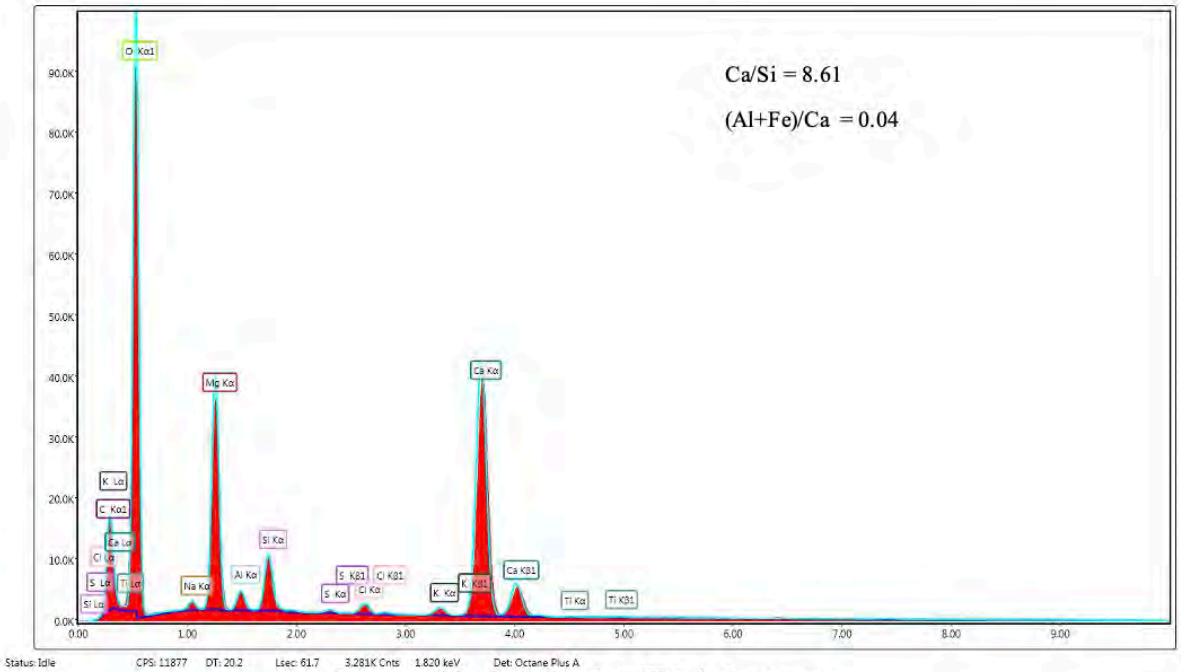


Sample A (SRC) Before and After acetic acid Treatment

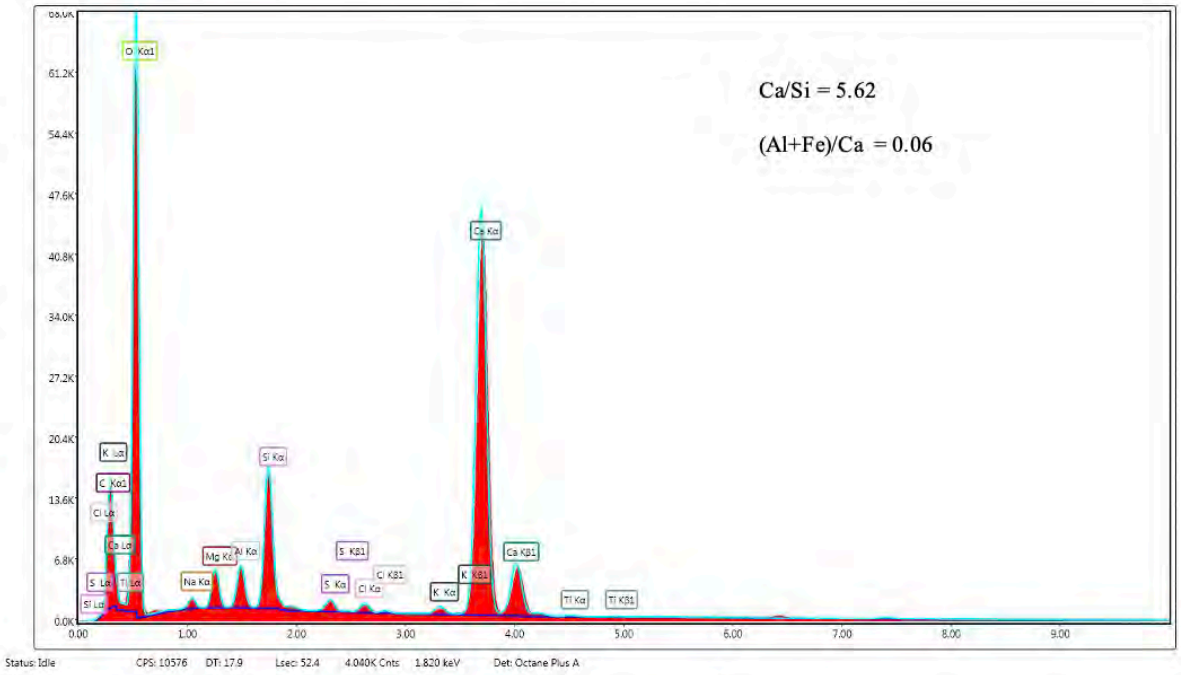


Sample B (GRC) Before and After acetic acid Treatment

Figure 13. Sample A (SRC) Spectrum Analysis-Part I

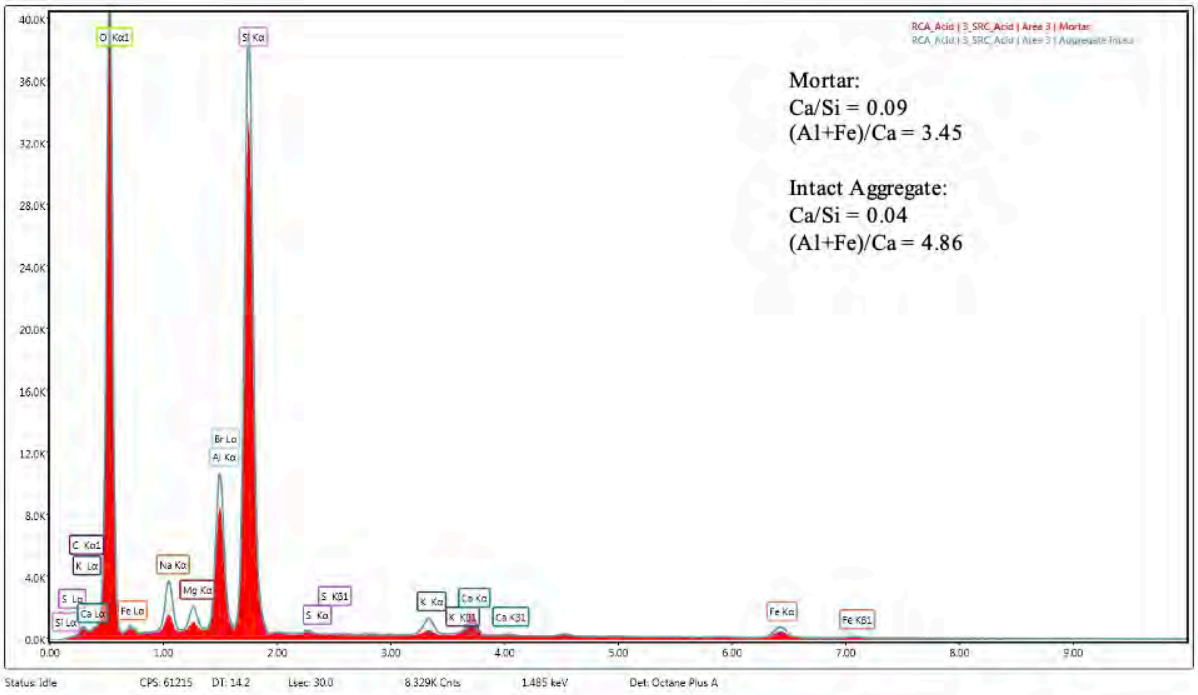


Spectrum of the OA in Sample A (SRC) before treatment.

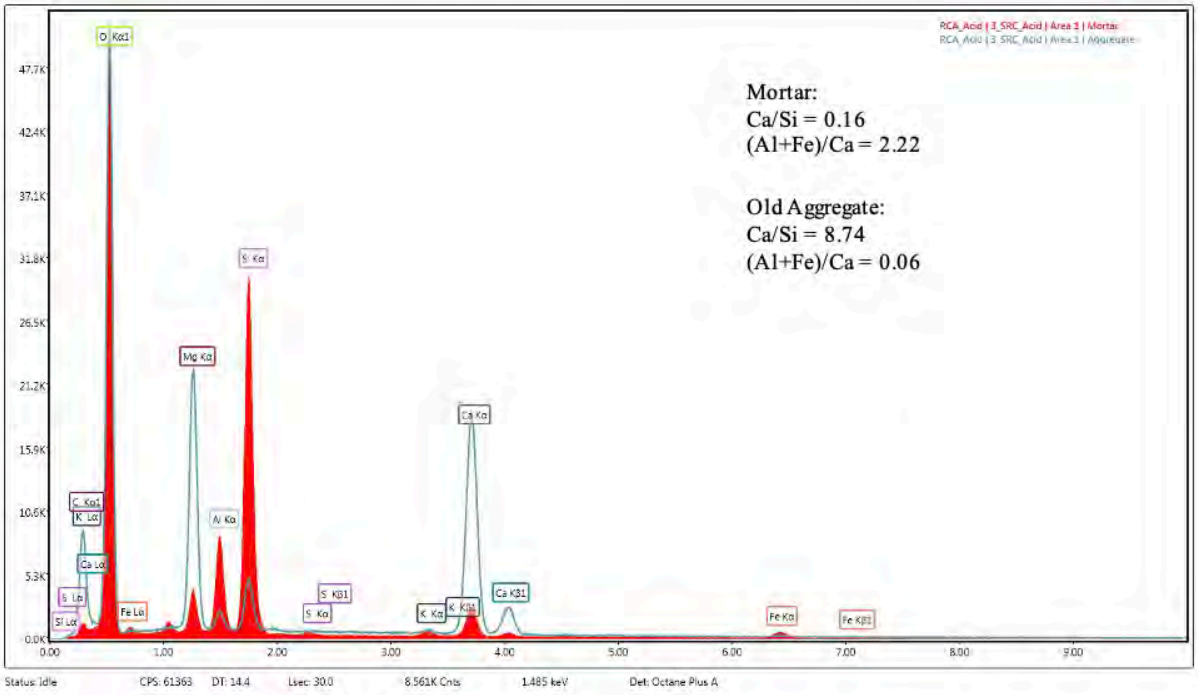


Spectrum of the M in Sample A (SRC) before treatment.

Figure 14. Sample A (SRC) Spectrum Analysis-Part II

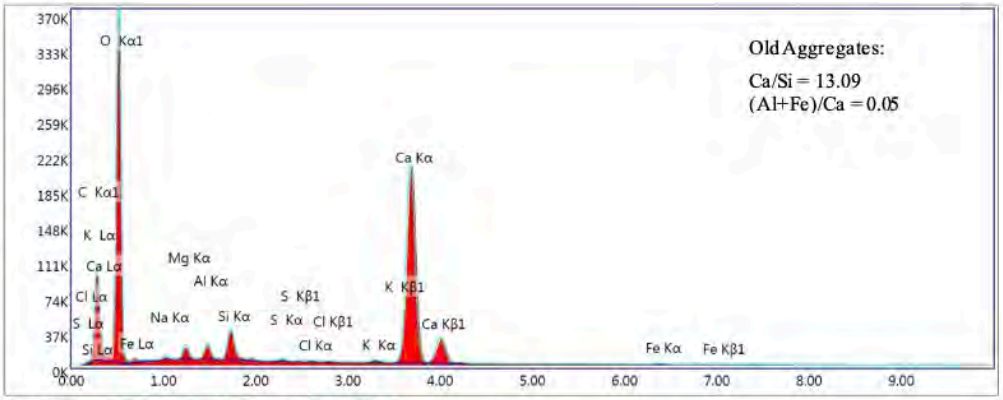


Spectra comparison between the intact aggregate (blue) and M (red) in Sample A (SRC) after treatment.

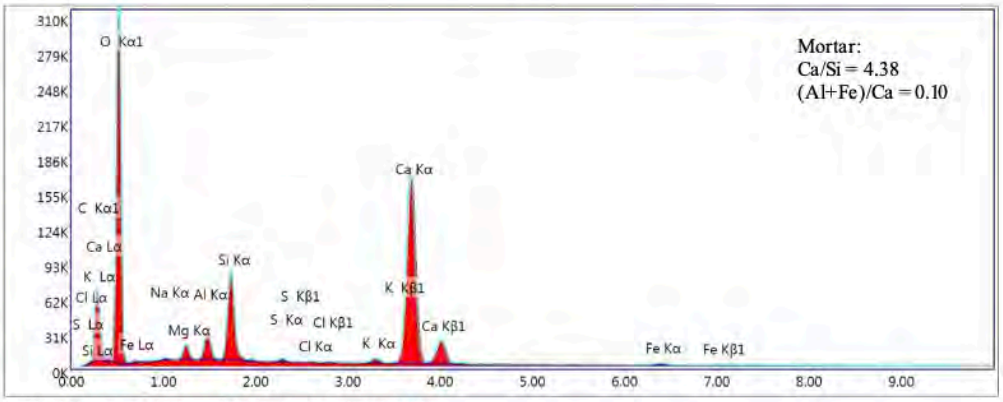


Spectra comparison between the OA (blue) and M (red) in Sample A (SRC) after treatment.

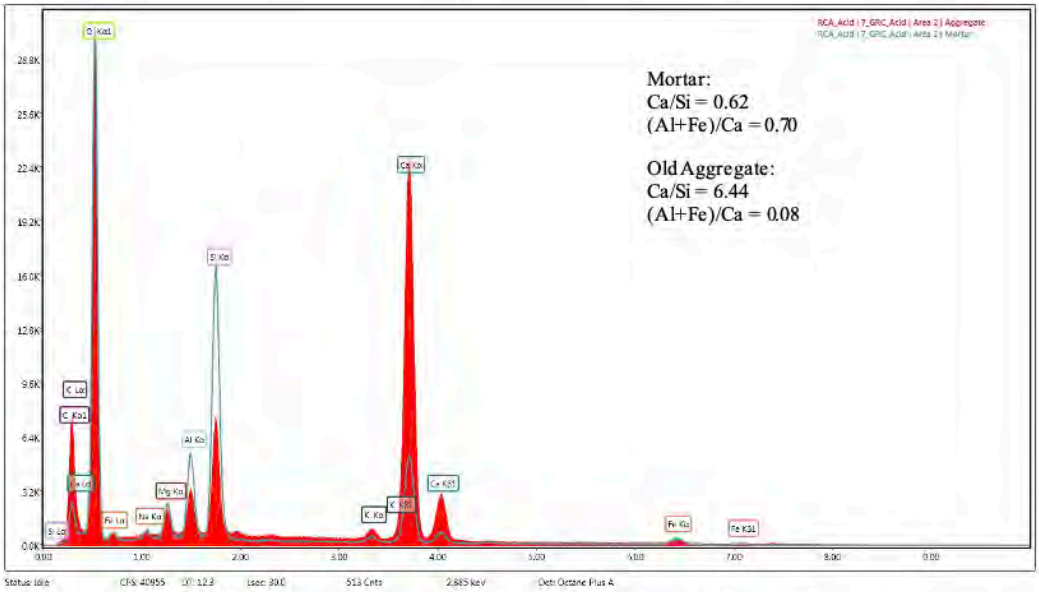
Figure 15. Sample B (GRC) Spectrum Analysis



Spectrum of the OA in Sample B (GRC) before treatment.



Spectrum of the M in Sample B (GRC) before treatment.



Spectra comparison between the OA (blue) and M (red) in Sample B (GRC) after treatment.

4.0 Implication of Acetic Acid Treatment on RCA

4.1 Weak Acid Selectivity

The study's findings challenge assumptions about the selectivity of weak acid treatment for RCA. An acetic acid concentration of 0.2 mol remains optimal for removing adherent mortar [22,23]. This is shown by the Ca/Si ratio dropping from 4.38–5.62 to below 0.62 and the (Al+Fe)/Ca ratio exceeding 0.70, indicating degradation of OA zones. However, the study's microstructural evidence contradicts the presumption of aggregate immunity after weak acid exposure. The extensive crack networks observed in OA regions post-treatment show that acetic acid penetrates beyond the intended mortar phase. The chemical process involves protons attacking calcium-bearing phases, whether in C-S-H gel, portlandite crystals in mortar, or calcite and dolomite in carbonate aggregates. Similar Ca/Si depletion patterns in both mortar and susceptible aggregates (from 8.61–13.09 to as low as 0.04) suggest that dissolution occurs similarly across these phase boundaries. The lack of uniform selectivity indicates that the current understanding of the mechanism of acetic acid treatment must be reconsidered. This finding aligns with Thaue et al.'s (2024) observations regarding ITZ vulnerability but extends their conclusions by documenting that aggregate damage is not merely superficial but chemically substantive.

4.2 Mineralogical Control of Aggregate Susceptibility

One noteworthy finding is the striking variability in OA response to the acid's exposure. This ranges from intact surfaces (Ca/Si >6.44) to completely transformed zones (Ca/Si = 0.04). This differential susceptibility appears governed by OA mineral composition. The acid resistance of siliceous aggregates, which consist of quartz and feldspar-based materials, results from the ability of their silicon-oxygen tetrahedra to maintain stability in acidic conditions. On the other hand, carbonate-based aggregates (limestone, dolomite) undergo rapid dissolution via the following reaction:

- $CaCO_3 + 2CH_3COOH \rightarrow Ca(CH_3COO)_2 + H_2O + CO_2$
- Calcium Carbonate + Acetic Acid → Calcium Acetate + Water + Carbon Dioxide

The calcium acetate formed in the process is water-soluble, thus leading to the significant calcium loss that occurs in OA-prone populations. The mineralogical control explains why Sample B (GRC) with its mixed aggregate sources, showed more post-treatment condition changes than Sample A (SRC). This means that RCA sourced from concrete originally containing limestone aggregates may suffer more severe acid-induced damage than RCA from siliceous aggregate concrete.

4.3 Interfacial Transition Zone Vulnerability

Consistent ITZ deterioration in all samples deserves careful attention. The ITZ's naturally higher porosity [35]allows acids to penetrate through its structure, causing both calcium dissolution and phase transformation. In multiple specimens, complete separation between mortar and aggregate shows that acetic acid treatment can increase weak particles by creating new fracture planes along ITZ boundaries. This challenges the effectiveness of weak acid treatments because, while the acid removes some mortar, it also creates defects that may propagate under mechanical stress. These newly introduced effects should be considered when revising treatment methods.

5.0 Conclusion

Given the absence of a comprehensive understanding of the microstructural and chemical effects on RCA after acetic acid treatment, this study sought to investigate these changes in detail. The scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy was employed to examine these microstructural alterations in recycled concrete aggregate following immersion in 0.2 mol acetic acid for 24 hours. The findings provide conclusive microscopic evidence that challenges conventional assumptions regarding the selectivity of weak acid treatment. Three principal conclusions emerge from this investigation. First, acetic acid treatment is non-selective. While the adherent mortar phase degrades substantially, old aggregate zones also suffer significant deterioration. Second, the severity of aggregate damage depends critically on mineralogical composition. Carbonate-based aggregates show extensive calcium depletion and crack formation, whereas siliceous aggregates remain relatively intact. This mineralogical control explains the variable treatment outcomes observed among different RCA sources. Third, the interfacial transition zone consistently experiences complete separation between mortar and aggregate after acid exposure, indicating that chemical treatment may introduce new defects rather than merely removing existing ones. These findings have direct implications for RCA treatment protocols. The assumption that acetic acid concentration can be universally optimized is untenable given the documented variability in aggregate response. Instead, treatment protocols should be tailored to the specific characteristics of the RCA source. For RCA containing predominantly siliceous aggregates, acetic acid treatment may offer net benefits by removing mortar with minimal aggregate damage. However, for RCA with carbonate aggregates or heterogeneous sources, mechanical treatment methods may provide more predictable outcomes. The phase-specific analytical approach used in this study (separating mortar, old aggregate, and ITZ contributions rather than relying on bulk analysis) was essential for detecting these differential responses. Future research should focus on developing rapid mineralogical screening methods to predict RCA acid susceptibility prior to treatment, enabling optimized protocols that balance mortar removal and aggregate preservation.

References

[1] H.; Afsoosbiria, H. (2024). *Mechanical properties and durability assessment of sustainable green concrete incorporated with rice husk ash as partial replacement of cement. Trans. VSB Tech. Univ. Ostrav. Civil Eng. Ser, 24, 7-12*

[2]Adesina, A., & Zhang, J. (2024). *Impact of concrete structures durability on its sustainability and climate resiliency. Next Sustainability, 3, 100025. https://doi.org/10.1016/j.nxsust.2024.100025*

[3]Zunino, F. (2023). *A two-fold strategy towards low-carbon concrete. RILEM Technical Letters, 8, 45-58. https://doi.org/10.21809/rilemtechlett.2023.179*

[4]Barbhuiya, S., Das, B. B., Adak, D., Kapoor, K., & Tabish, M. (2025). *Low carbon concrete: advancements, challenges and future directions in sustainable construction. Discover Concrete and Cement, 1(1). https://doi.org/10.1007/s44416-025-00002-y*

[5]Olsson, J. A., Miller, S. A., & Alexander, M. G. (2023). *Near-term pathways for decarbonizing global concrete production. Nature Communications, 14(1), 4574. https://doi.org/10.1038/s41467-023-40302-0*

[6]Ariana, M. R., & Kuchta, K. (2025). *Recycled concrete aggregate in self-consolidating concrete: a systematic review and meta-analysis of mechanical properties, RCA pre-treatment and durability behaviour. TUHH Open Research. https://doi.org/10.15480/882.16271*

[7]Marinković, S., Radonjanin, V., Malešev, M., & Ignjatović, I. (2010). *Comparative environmental assessment of natural and recycled aggregate concrete. Waste Management, 30(11), 2255-2264. https://doi.org/10.1016/j.wasman.2010.04.012*

[8]Danish, A., & Mosaberpanah, M. A. (2021). *A review on recycled concrete aggregates (RCA) characteristics to promote RCA utilization in developing sustainable recycled aggregate concrete (RAC). European Journal of Environmental and Civil Engineering, 26(13), 6505-6539. https://doi.org/10.1080/19648189.2021.1946721*

[9]Li, W., Xiao, J., Sun, Z., Kawashima, S., & Shah, S. P. (2012). *Interfacial transition zones in recycled aggregate concrete with different mixing approaches. Construction and Building Materials, 35, 1045-1055. https://doi.org/10.1016/j.conbuildmat.2012.06.022*

[10]Lu, C., Yu, Q., Wei, J., Niu, Y., Zhang, Y., Lin, C., Chen, P., Shi, C., & Yang, P. (2024). *Influence of interface transition zones (ITZ) and pore structure on the compressive strength of recycled aggregate concrete. Construction and Building Materials, 456, 139299. https://doi.org/10.1016/j.conbuildmat.2024.139299*

[11]Monaco, P., Richardson, A., Ishaq, L., Habtamu, N., Baldo, N., & Oyeyi, A. G. (2025). *Study of the circularity of recycled concrete aggregates subjected to different mechanical and chemical treatments. Transportation Research Record Journal of the Transportation Research Board, 2679(7), 732-745. https://doi.org/10.1177/03611981251328988*

[12]Katz, A. (2004). *Treatments for the improvement of recycled aggregate. Journal of Materials in Civil Engineering, 16(6), 597-603. https://doi.org/10.1061/(asce)0899-1561(2004)16:6(597*

[13]Akbarnezhad, A., Ong, K., Zhang, M., Tam, C., & Foo, T. (2011). *Microwave-assisted beneficiation of recycled concrete aggregates. Construction and Building Materials, 25(8), 3469-3479. https://doi.org/10.1016/j.conbuildmat.2011.03.038*

[14]Pandurangan, K., Dayanithy, A., & Prakash, S. O. (2016). *Influence of treatment methods on the bond strength of recycled aggregate concrete. Construction and Building Materials, 120, 212-221. https://doi.org/10.1016/j.conbuildmat.2016.05.093*

[15]Kapoor, K., & Bohroo, A. U. R. (2019). *Study on the influence of attached mortar content on the properties of recycled concrete aggregate. In Lecture notes in civil engineering (pp. 337-347). https://doi.org/10.1007/978-981-13-6717-5_33*

[16]Wang, L., Wang, J., Qian, X., Chen, P., Xu, Y., & Guo, J. (2017). *An environmentally friendly method to improve the quality of recycled concrete aggregates. Construction and Building Materials, 144, 432-441. https://doi.org/10.1016/j.conbuildmat.2017.03.191*

[17]Al-Bayati, H. K. A. (2019). *Evaluation of various treatment methods for enhancing the properties of recycled concrete aggregate for hot mix asphalt. In UWSpace (University of Waterloo). http://hdl.handle.net/10012/14579*

[18]Nedeljković, M., Visser, J., Šavija, B., Valcke, S., & Schlangen, E. (2021). *Use of fine recycled concrete aggregates in concrete: A critical review. Journal of Building Engineering, 38, 102196. https://doi.org/10.1016/j.jobe.2021.102196*

[19]Hawileh, R. A., Mhanna, H. H., Abdalla, J. A., AlMomani, D., Esrep, D., Obeidat, O., & Ozturk, M. (2023). *Properties of concrete replaced with different percentages of recycled aggregates. Materials Today Proceedings. https://doi.org/10.1016/j.matpr.2023.03.336*

[20]Limbachiya, M., Marrocchino, E., & Koulouris, A. (2006). *Chemical-mineralogical characterisation of coarse recycled concrete aggregate. Waste Management, 27(2), 201-208. https://doi.org/10.1016/j.wasman.2006.01.005*

[21]Sanchez-Cotte, E. H., Fuentes, L., Martinez-Arguelles, G., Quintana, H. a. R., Walubita, L. F., & Cantero-Durango, J. M. (2020). *Influence of recycled concrete aggregates from different sources in hot mix asphalt design. Construction and Building Materials, 259, 120427. https://doi.org/10.1016/j.conbuildmat.2020.120427*

[22]Pan, Z., Wang, S., Liu, Y., Li, B., Jia, Z., Zhang, Y., & Wang, J. (2019). *The hydration, pore structure and strength of cement-based material prepared with waste soaking solution from acetic acid treatment of regenerated aggregates. Journal of Cleaner Production, 235, 866-874. https://doi.org/10.1016/j.jclepro.2019.06.335*

[23]Zhang, S., & Zhang, Y. (2025). *Green Mild Acid Treatment of Recycled Concrete Aggregates: Concentration Thresholds for Mortar Removal While Avoiding Degradation of Original Limestone Aggregate and Concrete. Materials (Basel, Switzerland), 18(15), 3673. https://doi.org/10.3390/ma18153673*

[24]Poon, C., Shui, Z., & Lam, L. (2004). *Effect of microstructure of ITZ on compressive strength of concrete prepared with recycled aggregates. Construction and Building Materials, 18(6), 461-468. https://doi.org/10.1016/j.conbuildmat.2004.03.005*

[25]Tam, V. W., Tam, C., & Le, K. (2006). *Removal of cement mortar remains from recycled aggregate using pre-soaking approaches. Resources Conservation and Recycling, 50(1), 82-101. https://doi.org/10.1016/j.resconrec.2006.05.012*

[26]Castorena, C., Pape, S., & Mooney, C. (2016). *Blending Measurements in Mixtures with Reclaimed Asphalt: Use of Scanning Electron Microscopy with X-Ray Analysis. Transportation Research Record Journal of the Transportation Research Board, 2574(1), 57-63. https://doi.org/10.3141/2574-06*

[27]Panghal, H., & Kumar, A. (2023). *Enhancing concrete performance: Surface modification of recycled coarse aggregates for sustainable construction. Construction and Building Materials, 411, 134432. https://doi.org/10.1016/j.conbuildmat.2023.134432*

[28]Richardson, I. (1999). *The nature of C-S-H in hardened cements. Cement and Concrete Research, 29(8), 1131-1147. https://doi.org/10.1016/s0008-8846(99)00168-4*

[29]Kunther, W., Ferreiro, S., & Skibsted, J. (2017). *Influence of the Ca/Si ratio on the compressive strength of cementitious calcium-silicate-hydrate binders. Journal of Materials Chemistry A, 5(33), 17401-17412. https://doi.org/10.1039/c7ta06104h*

[30]Cuesta, A., Santacruz, I., De La Torre, A. G., Dapiaggi, M., Zea-Garcia, J. D., & Aranda, M. A. (2021). *Local structure and Ca/Si ratio in C-S-H gels from hydration of blends of tricalcium silicate and silica fume. Cement and Concrete Research, 143, 106405. https://doi.org/10.1016/j.cemconres.2021.106405*

[31]Thaue, W., Iwanami, M., Nakayama, K., & Yodsudjai, W. (2024). Influence of acetic acid treatment on microstructure of interfacial transition zone and performance of recycled aggregate

[32]Kurdowski, W. (2014). *Cement and concrete chemistry*. https://doi.org/10.1007/978-94-007-7945-7

[33]Erdem, S., Dawson, A. R., & Thom, N. H. (2011). *Influence of the micro- and nanoscale local mechanical properties of the interfacial transition zone on impact behavior of concrete made with different*

aggregates. Cement and Concrete Research, 42(2), 447-458. https://doi.org/10.1016/j.cemconres.2011.11.015

[34]Al-Bayati, H. K. A., Das, P. K., Tighe, S. L., & Baaj, H. (2016). *Evaluation of various treatment methods for enhancing the physical and morphological properties of coarse recycled concrete aggregate. Construction and Building Materials, 112, 284-298. https://doi.org/10.1016/j.conbuildmat.2016.02.176*

[35]Jawahar, J. G., Sashidhar, C., Reddy, I. R., & Peter, J. A. (2012). *Micro and macrolevel properties of fly ash blended self compacting concrete. Materials & Design (1980-2015), 46, 696-705. https://doi.org/10.1016/j.matdes.2012.11.027*

[36]Scrivener, K. L., Crumbie, A. K., & Laugesen, P. (2004). *The interfacial Transition Zone (ITZ) between cement paste and aggregate in concrete. Interface Science, 12(4), 411–421. https://doi.org/10.1023/b:ints.0000042339.92990.4c*

[37]Kanagaraj, B., Lubloy, E., Anand, N., Hlavicka, V., & Kiran, T. (2022). *Investigation of physical, chemical, mechanical, and microstructural properties of cement-less concrete – state-of-the-art review. Construction and Building Materials, 365, 130020. https://doi.org/10.1016/j.conbuildmat.2022.130020*