Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-2328

Hexavalent chromium suppression from wet carbonated recycled concrete aggregates using granulated blast furnace slag

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ABSTRACT: Carbon Capture and Utilization (CCU) in Recycled Concrete Aggregates (RCA) has gained significant attention as a promising sustainable solution to mitigate CO_2 emissions and depletion of natural granular resources. Carbonated RCA offers an alternative granular material for geotechnical engineering applications, contributing to carbon utilization and neutrality initiatives. However, a significant challenge arises due to the leaching of hexavalent chromium (Cr^{6+}) in this process, which poses severe environmental and human health risks. Therefore, suppressing Cr^{6+} in carbonated RCA is essential to ensure safe application in various fields. This study investigates the use of Granulated Blast Furnace Slag (GBFS) as a viable reducing agent for immobilizing Cr^{6+} in carbonated RCA. The effectiveness of GBFS was examined under two conditions: during-carbonation and post-carbonation treatment. The wet carbonation method was adopted as it generally facilitates uniform carbonation of RCA and enhances ion dissolution and mobility, thus accelerating and promoting the reactions between the dissolved ions from RCA and GBFS. RCA mixtures with varying GBFS content were tested to evaluate their CO_2 fixation ratios and Cr^{6+} concentrations. Overall, the results indicate that GBFS can effectively mitigate Cr^{6+} contamination and enhance the environmental safety of carbonated RCA. However, incorporating GBFS during the wet carbonation process was found to significantly reduce Cr^{6+} concentrations, with higher GBFS content resulting in greater suppression. The simultaneous carbonation of RCA and GBFS accelerates the reaction between Cr^{6+} and dissolved sulfide ions (S^{2-}) from GBFS, leading to more efficient Cr^{6+} reduction. In contrast, post-carbonation treatment showed limited Cr^{6+} reduction, indicating that the timing of GBFS incorporation plays a critical role in the reaction outcome. These findings provide new insights into Cr^{6+} mitigation strategies, which support environmentally safe and sustainable integration of carbonated RCA into geotechnical engineering applications, including ground improvement.

KEYWORDS: Granular material, carbon utilization, carbon neutrality.

1 INTRODUCTION

Global urbanization and economic development have rapidly increased the demand for concrete and granular materials. A rough estimate suggests that approximately 30 billion tons of concrete and 50 billion tons of sand and gravel are consumed globally each year, making them the second most used resource after water (UN Environment Programme, 2022; Council of Engineers for the Energy Transition (CEET), 2023). This surge in demand comes with environmental consequences, as the cement industry alone accounts for approximately 8% of global carbon dioxide (CO_2) emissions during cement production (Andrew, 2018). Concrete structures, which are widely reliant on cement, are eventually demolished, while the resulting concrete waste is crushed and processed into Recycled Concrete Aggregates (RCA) and fines (RCF). Reusing RCA has emerged across various fields, including geotechnical engineering, highlighting the urgent need for alternatives to natural granular materials.

In recent years, Carbon Capture and Utilization (CCU) in RCA has garnered significant attention as a promising sustainable solution to mitigate CO_2 emissions and depletion of natural granular resources. It involves fixing the industrial CO_2 in RCA by forming calcium carbonate ($CaCO_3$) at the aggregate surfaces (Hussary et al. 2024). Carbonated RCA substitutes granular material for ground reinforcement and reclamation while contributing to carbon utilization and neutrality initiatives. However, a significant challenge arises due to hexavalent chromium (Cr^{6+}) leaching from carbonated RCA (Mine et al. 2024), a toxic heavy metal that poses severe environmental and health risks to humans. Sakamoto et al. (2024) reported that Cr^{6+} eluted concentrations from carbonated RCA often exceed the environmental quality standard for soil contamination, set to 50 μg/L by Japan's Ministry of the Environment. Recent research has reported promising advances in suppressing Cr^{6+} leaching through the use of artificial reducing agents (Nishiie et al. 2025). Nonetheless, key issues concerning appropriate carbonation techniques, material sustainability, and fundamental mechanisms behind Cr^{6+} leaching have yet to be fully addressed. Therefore, further research into Cr^{6+} leaching and suppression in carbonated RCA is essential to ensure the safe application of this innovative material in geotechnical engineering.

Granulated Blast Furnace Slag (GBFS) has emerged as a promising material in geotechnical engineering due to its dual functionality as a sustainable resource and a chemical-reducing agent for environmental remediation. GBFS is a well-known by-product generated during the pig iron manufacturing process in a blast furnace. As an industrial by-product, GBFS contributes to the efficient use of resources, recycling, and waste reduction, aligning with global sustainability and responsible consumption goals. In geotechnical engineering, GBFS has been widely utilized as an additive for ground improvement and various soil stabilization applications (Wada et al. 2012; Ishikura et al. 2015; Sakata et al. 2018). Its hydraulic properties contribute to enhancing soil strength and long-term stability. It has been employed as a backfill material, offering desirable shear strength and drainage characteristics, particularly for lightweight embankments, landfills, and retaining structures. Moreover, it has been proposed as an additive material for Sand Compaction Piles (SCP), showing benefits for soil densification and liquefaction mitigation. In addition to its mechanical advantages, GBFS contains reactive components that have demonstrated the ability to immobilize Cr^{6+} during the curing of cementitious materials (Bae et al. 2018), highlighting its potential for mitigating heavy metal leaching in other applications.

Consequently, this study experimentally investigates the use of GBFS as a viable solution for immobilizing Cr^{6+} in carbonated RCA. The effectiveness of GBFS is evaluated under two distinct conditions: (i) direct incorporation into RCA during carbonation and (ii) application as a post-carbonation treatment. The experimental results in this study demonstrate the potential of GBFS to suppress Cr^{6+} leaching. Moreover, they highlight critical areas where further chemical and theoretical investigations are required to fully understand the leaching behavior under different treatment conditions and their impact on the overall suppression efficiency. By providing new insights into Cr^{6+} mitigation strategies, this study aims to support the safe and sustainable integration of carbonated RCA into various geotechnical engineering practices.

2 WET CARBONATION OF RECYCLED CONCRETE AGGREGATES: HEXAVALENT CHROMIUM LEACHING AND SUPPRESSION

Carbonation of RCA is commonly performed using either wet or dry carbonation. Wet carbonation involves immersing RCA in CO_2-enriched water, which accelerates the chemical reaction and promotes uniform carbonation of the aggregates. In contrast, dry carbonation occurs under lower humidity levels, where CO_2 reacts more slowly at the exposed surfaces of the aggregates. Since wet carbonation enhances ion dissolution, increasing their mobility and promoting faster reactions with added materials such as GBFS, this method is adopted in the present study to investigate Cr^{6+} leaching and suppression.

The overall wet carbonation of RCA is described in Equation (1). However, this reaction is believed to proceed through three primary steps. Initially, calcium ions (Ca^{2+}) are released from calcium hydroxide ($Ca(OH)_2$), which is naturally present in cement-based RCA, as shown in Equation (2). At this stage, hydroxide ions (OH^-) are released, causing an increase in the pH level. This alkaline environment is crucial for limiting the dissolution of chromium (Cr) ions from RCA (Bae et al. 2018) and promotes the dissolution of CO_2, as illustrated in Equation (3). However, as CO_2 continues to dissolve, the pH gradually decreases due to the release of hydrogen ions (H^+) and carbonate ions (CO_3^{2-}), thus increasing the solubility of Cr^{6+}. Ultimately, $CaCO_3$ forms and precipitates on the surfaces of the RCA, as represented in Equation (4).

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \qquad (1)$$

$$Ca(OH)_2 \rightarrow Ca^{2+} + 2OH^- \qquad (2)$$

$$CO_2 + H_2O \rightarrow 2H^+ + CO_3^{2-} \qquad (3)$$

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \qquad (4)$$

Numerous studies highlighted the challenges exposed by the high solubility, mobility, and toxicity of Cr^{6+} under aerobic conditions (Bae et al. 2018). In contrast, it was confirmed that its reduced form, trivalent chromium (Cr^{3+}), is known to be significantly less soluble and less toxic (Daiber, 2022). Consequently, investigating the reduction of Cr^{6+} to Cr^{3+} in carbonated RCA through the addition of reducing agents is of critical importance. GBFS has demonstrated the ability to immobilize Cr^{6+} through a reductive mechanism (Bae et al. 2018). Specifically, Macphee & Glasser (1993) reported that sulfide ions (S^{2-}) dissolved from GBFS facilitate the transformation of Cr^{6+} into Cr^{3+}. Building on this reaction mechanism, the present study examines the potential of GBFS in reducing Cr^{6+} leaching from carbonated RCA.

3 MATERIALS

Uncarbonated RCA (No.3T40) was used for CO_2 fixation. Its commercial name refers to its raw material, Ordinary Portland cement (No.3), and its processing conditions (T40). GBFS, provided by Nippon Steel Trading Corporation, Ltd., was adopted as a reducing agent (Sakata et al. 2018). The particle size distribution curves and the physical properties of the used materials are delineated in Figure 1. It must be noted that while RCA and GBFS have similar particle densities, RCA is typically finer in texture. The effect of GBFS on Cr^{6+} suppression in carbonated RCA was evaluated by comparing one control RCA-only sample containing 0% GBFS with three other mixtures incorporating GBFS at added amounts of 3%, 5%, and 10% by weight.

4 METHODOLOGY

4.1 *Wet carbonation*

For CO_2 fixation in RCA, the wet carbonation method was employed. The carbonation process was conducted using the apparatus shown in Figure 2. The water-to-RCA ratio was maintained at 2:1 across all the tested samples, with 1.5 Kg of RCA submerged in 3 L of distilled water within the column. The sample was allowed to stand for 20 minutes before CO_2 inflow was introduced from the bottom of the column at a rate of 5 L/min for 30 minutes, controlled by the regulator attached to the top of the CO_2 gas cylinder. After carbonation, the sample was left to settle for 30 minutes in the water before being vacuumed out and filtered from the bottom of the column. During carbonation, pH and CO_2 outflow were recorded every 30 seconds, using the pH meter inserted from the column's top and a CO_2 meter attached to the outlet, respectively.

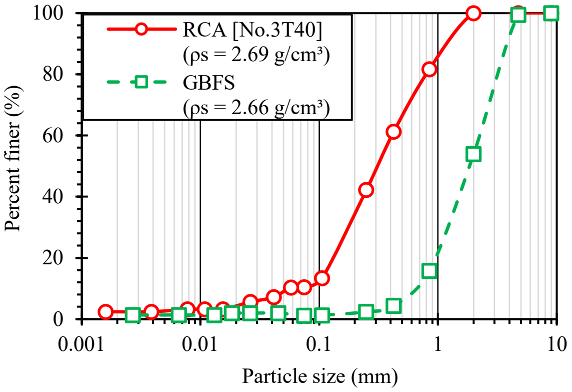

Figure 1. Physical properties of the tested materials.

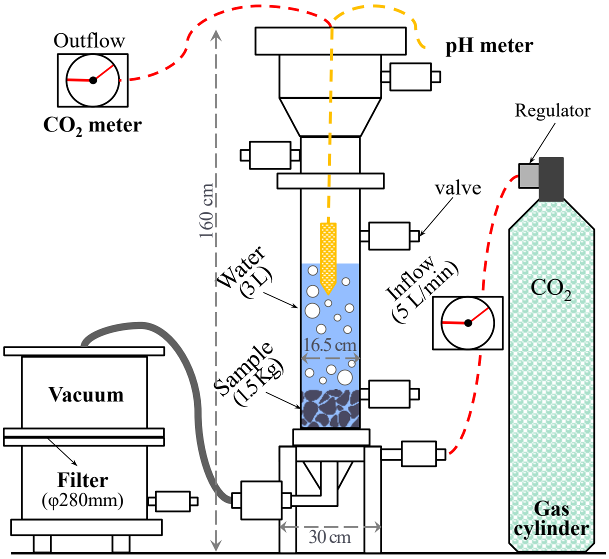

Figure 2. Wet carbonation testing apparatus.

4.2 *Cr^{6+} treatment patterns*

The effectiveness of GBFS in reducing Cr^{6+} was examined under two distinct conditions: (i) direct incorporation into RCA during carbonation, referred to as “during-carbonation treatment,” and (ii) addition after RCA carbonation, referred to as “post-carbonation treatment.” In the during-carbonation treatment, GBFS was added to 1.5 Kg of RCA at addition levels of 3%, 5%, and 10% by weight, and then the mixture was subjected to wet carbonation. For the post-carbonation treatment, RCA was first carbonated independently, after which the pre-carbonated RCA was mixed with uncarbonated GBFS at the same weight ratios (3%, 5%, and 10%). This approach enabled a direct comparison of the Cr^{6+} suppression performance between the addition of GBFS during wet carbonation and its application as a post-treatment.

4.3 *CO_2 fixation ratio measurement*

The loss on ignition (LOI) test was conducted to estimate the CO_2 content in RCA-GBFS mixtures before and after carbonation. According to Kanda et al. (2011), $CaCO_3$, the primary carbonation product, dehydrates and thermally decomposes within the temperature range between 500 and 900°C. However, Sano et al. (2015) further reported that the $CaCO_3$ contained in slag completely decomposes when the sample is ignited for more than 3 hours at 700°C. In the present study, considering the presence of GBFS in the RCA mixture, the LOI test was performed at 500 and 750°C. The change in weight between the two ignition stages reflects the amount of CO_2 released, as governed by the decomposition reaction presented in Equation (5). Approximately 20 g of each sample was placed in pre-weighed crucibles and heated in a high-temperature furnace at 500°C. Once the mass stabilized, it was recorded with a precision of 0.0001 g. The same procedure was repeated after the ignition at 750°C.

$$CaCO_3 \rightarrow CaO + CO_2 \qquad (5)$$

Consequently, the CO_2 content ratio, (m_{CO_2}) was calculated as the ratio of the mass loss observed between 500 and 750°C ($m_{500°C}$ - $m_{750°C}$) to the initial mass of the sample before ignition (m_i), as shown in Equation (6). Furthermore, the CO_2 fixation ratio was determined by the difference in CO_2 content ratios after ($m_{CO_2\,after}$) and before ($m_{CO_2\,before}$) carbonation, as described in Equation (7).

$$m_{CO_2}\ (\%) = \frac{(m_{500°C} - m_{750°C})}{m_i} \times 100\% \qquad (6)$$

$$Fixed_{CO_2}\ (\%) = m_{CO_2\,after} - m_{CO_2\,before} \qquad (7)$$

4.4 *Cr^{6+} concentration measurements*

The concentration of Cr^{6+} in the tested mixtures was determined in accordance with the Japanese Leaching Test No. 46 (JLT 46), commonly referred to as the batch test. Oven-dried samples were first sieved through a 2 mm sieve, and the fraction passing the sieve was used for batch testing. A 50 g portion of the sieved sample was mixed with 500 mL of distilled water, corresponding to a solid-to-liquid ratio of 10% (w/v). The suspension was then subjected to horizontal shaking for 6 hours at room temperature (approximately 20°C) using a mechanical shaker operating at 200 oscillations per minute with a shaking amplitude of 4-5 cm. After shaking, the mixture was allowed to stand undisturbed for 10 to 30 minutes, after which it was filtered using a 0.45 μm membrane filter with a diameter of 90 mm. The resulting leachate was collected for Cr^{6+} analysis.

Cr^{6+} concentrations were measured using a high-range photometer (HI97723, Hanna Instruments, Inc.). For each measurement, 10 mL of the leachate was transferred into a compatible glass cuvette using a pipette. A Cr^{6+} specific high-concentration reagent, suitable for use with a photometer, was added to the cuvette. The solution was then vigorously mixed, and the Cr^{6+} concentration was quantified by the photometer, which measures the absorbance corresponding to the intensity of the resulting color change.

5 RESULTS AND DISCUSSION

5.1 *During-carbonation Cr^{6+} treatment*

Figure 3 illustrates the changes in pH levels during the carbonation of RCA and RCA-GBFS mixtures, highlighting GBFS’s influence on the wet carbonation process. It can be observed that the pH behavior of all samples followed similar patterns under identical carbonation conditions. Initially, the pH was high, ranging from 12 to 13, attributed to the release of Ca^{2+} (Equation (2)). Upon the introduction of CO_2 at 20 minutes, a sharp drop in pH occurred, stabilizing at a near pH 6 within minutes. The rapid transition reflects the release of CO_3^{2-} (Equation (3)). The comparable pH trajectories observed for RCA and all RCA-GBFS mixtures (3%, 5%, and 10%) indicate that the incorporation of GBFS at these low addition levels does not remarkably alter the acidity of the system during carbonation under similar experimental conditions. Given the critical role of pH in governing carbonation kinetics, this finding suggests that GBFS, at such levels, is unlikely to hinder CO_2 diffusion or its reaction with Ca^{2+}. These results preliminarily support the potential of incorporating GBFS into RCA without significantly compromising carbonation. However, further investigation into the underlying chemical and predominant mechanisms is essential to elucidate the role of GBFS and to confirm these observations.

The CO_2 content before and after carbonation, as well as the fixation ratio, was determined by averaging three LOI tests. Figure 4 shows the results of the during-carbonation treatment. The bars indicate a significant increase in CO_2 content following carbonation across all samples, with higher CO_2 content observed in RCA-GBFS mixtures. The fixation ratio, indicated by the red-circled scatter, was 0.2% for the RCA-only sample containing 0% GBFS content. In contrast, RCA-GBFS mixtures exhibited a higher average fixation ratio of 0.9 ± 0.1%. It must be noted that the peak in the CO_2 fixation ratio observed at 3% GBFS content may be associated with its comparatively lower initial pH of 12 (Figure 3). This observation highlights the need for further investigation into the impact of the initial pH on the carbonation behavior of RCA-GBFS mixtures, thereby enhancing the understanding of its relationship with carbonation patterns. Nevertheless, an average increase of 0.7% in the fixation ratio was confirmed with the incorporation of GBFS, suggesting that GBFS may either enhance CO_2 fixation in RCA by improving its reactivity or by directly fixing CO_2

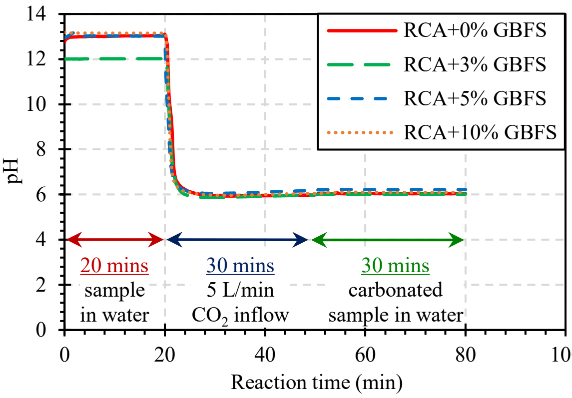

Figure 3. pH changes during the wet carbonation process.

within its structure. However, further analysis of the material's microstructural and chemical changes is required to clarify the underlying mechanism.

Batch tests were conducted on RCA-GBFS mixtures to determine Cr^{6+} concentrations based on the average of three leachate samples. Figure 5 illustrates the results of the during-carbonation treatment mixtures. For the RCA sample with 0% GBFS content, the carbonated RCA exhibited a Cr^{6+} concentration that exceeded the environmental quality standard for soil contamination. However, with the addition of GBFS, a notable reduction in Cr^{6+} concentration was observed. At 3% GBFS content, Cr^{6+} concentration levels dropped below the environmental quality threshold, with further decreases recorded at 5% and 10% GBFS content, indicating enhanced environmental compatibility of the RCA as a granular material. This result suggests that Cr^{6+} reduction to Cr^{3+} is facilitated during the wet carbonation of RCA-GBFS mixtures, where Cr^{6+} reacts with S^{2-} ions that are released from GBFS. Thus, under wet carbonation, GBFS appears to be an effective additive for mitigating the leaching of toxic heavy metals associated with RCA's carbonation while not compromising the amount of CO_2 fixed. This supports the material's potential for environmentally safe and carbon-efficient utilization.

5.2 *Post-carbonation Cr^{6+} treatment*

Pre-carbonated RCA was mixed with the designated uncarbonated GBFS percentages for the post-carbonation treated mixtures. The CO_2 content before and after carbonation, as well as the fixation ratio, was determined by averaging three LOI tests. Figure 6 shows the results of the post-carbonation treatment. The bars show a noticeable increase in CO_2 content following carbonation across all samples. Notably, the CO_2 content values remained relatively close, even with the addition of GBFS. The fixation ratio, indicated by the navy-triangle scatter, was 0.2% for the RCA-only sample containing 0% GBFS content. The RCA-GBFS mixtures exhibited a slightly higher average fixation ratio of 0.4 ± 0.1% representing a 0.2% increase compared to the RCA-only sample, potentially due to sample variation or the effect of GBFS incorporation. These results suggest that the addition of GBFS has a limited influence on the overall amount of CO_2 fixed in pre-carbonated RCA.

Batch tests were conducted on mixtures of pre-carbonated RCA and uncarbonated GBFS to determine Cr^{6+} concentrations based on the average of three leachate samples. Figure 7 illustrates the results of the post-carbonation treatment mixtures. The RCA-only sample containing 0% GBFS content exhibited a Cr^{6+} concentration that exceeded the environmental quality standard for soil contamination. Upon the addition of GBFS, a reduction in Cr^{6+} concentration was observed, reaching concentration levels slightly below the environmental quality threshold. However, the extent of reduction did not follow a consistent trend with increasing GBFS content, suggesting a limited release of sulfide ions from GBFS under these conditions and at such low addition levels.

5.3 *Effectiveness of Cr^{6+} treatment methods utilizing GBFS*

The findings suggest that incorporating GBFS generally reduces Cr^{6+} leaching associated with the carbonation of RCA, thereby enhancing the material's environmental compatibility. However, to confirm the effectiveness of this approach, a comparative evaluation of the two treatment methods is presented in the following section, focusing on their impacts on heavy metal immobilization and overall performance.

Figure 8 illustrates the effect of the treatment method on the CO_2 fixation ratio as a function of GBFS content. It can be observed that the CO_2 fixation ratio for the during-carbonation treatment mixtures was nearly twice as high as that in the post-

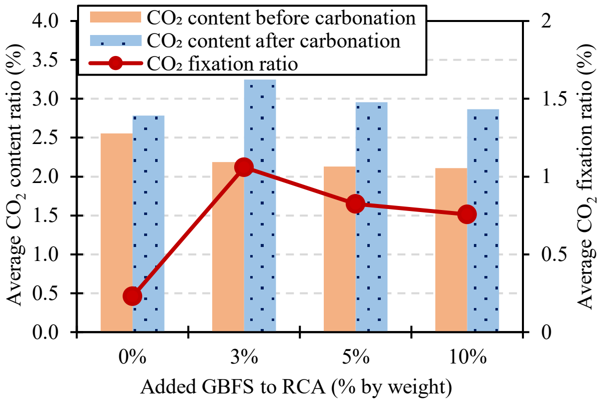

Figure 4. CO_2 fixation ratio of "during-carbonation" treated mixtures.

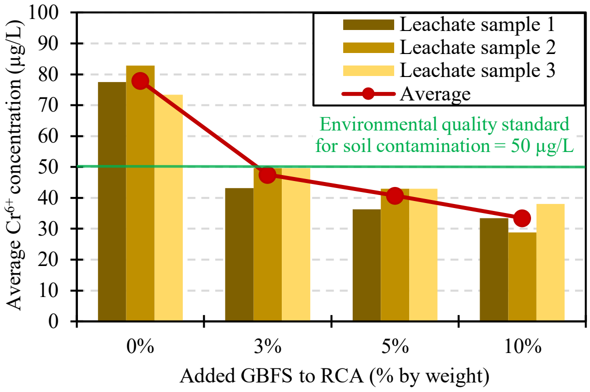

Figure 5. Cr^{6+} concentration "during-carbonation" treated mixtures.

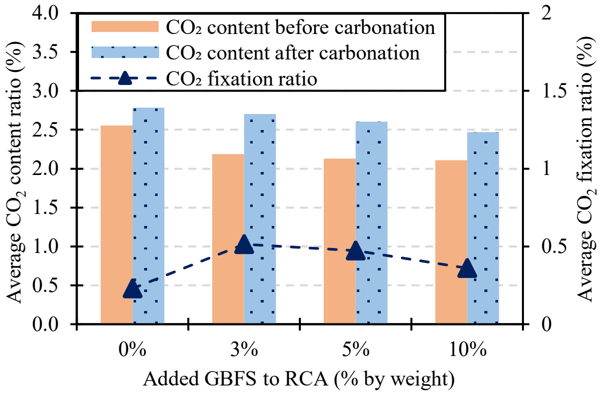

Figure 6. CO_2 fixation ratio of "post-carbonation" treated mixtures.

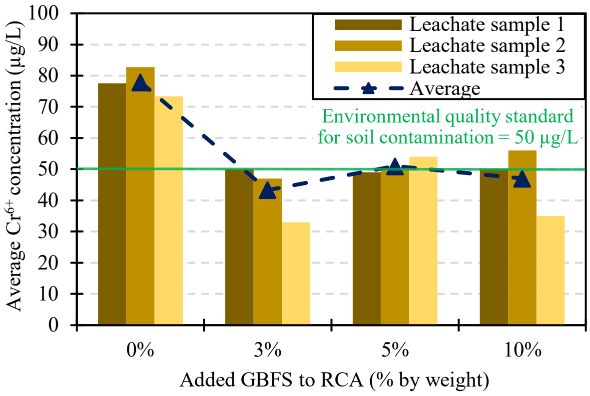

Figure 7. Cr^{6+} concentration of "post-carbonation" treated mixtures.

carbonation ones. This result indicates that the during-carbonation treatment method is more effective in fixing CO_2 within the RCA. This enhanced effectiveness might be related to the simultaneous carbonation of RCA and GBFS in CO_2-enriched water, which likely enhances ion dissolution, mobility, and reactivity, potentially enabling GBFS to contribute to CO_2 fixation within its structure. However, further analysis is needed to understand the underlying mechanisms, determine the key reaction parameters, and confirm the role of GBFS in CO_2 fixation.

Figure 9 illustrates the effect of the treatment method on the Cr^{6+} concentration as a function of GBFS content. The during-carbonation treatment proved more effective in reducing Cr^{6+} levels, achieving concentration consistently falling below the environmental quality standard of 50 µg/L when the GBFS content was 3% or higher. In contrast, the post-carbonation treatment resulted in relatively constant Cr^{6+} concentrations, showing minimal reduction as GBFS content increased. The values remained close to the environmental threshold, indicating limited treatment effectiveness.

This disparity in the suppression potential between the two applied treatment methods can be explained by the role of GBFS activation under different chemical conditions. GBFS is known to become active in highly alkaline environments (Bae et al. 2018). In the during-carbonation process, the RCA-GBFS mixture was under strongly alkaline conditions (pH around 12-13) before carbonation. Under these conditions, GBFS was activated, releasing S^{2-} ions. The high ion mobility of the wet environment further facilitated the interaction between Cr^{6+} and S^{2-} ions once the CO_2 was introduced to the system, promoting the reduction reaction of Cr^{6+} to Cr^{3+} and thus enhancing its suppression potential. On the contrary, in the post-carbonation treatment, GBFS was added to pre-carbonated RCA when conditions were no longer strongly alkaline. Although the exact chemical environment was not verified in this study, the delayed addition of GBFS may have limited its reactivity and the availability of reducing agents. As a result, the capacity of GBFS to contribute to Cr^{6+} reduction in the post-carbonation process was substantially diminished.

The suppressed Cr^{6+} concentration for each mixture under the respective treatment method was determined by subtracting the Cr^{6+} concentration of the control RCA-only sample with 0% GBFS content from that of the corresponding RCA-GBFS mixture. This calculation enabled the quantification of the Cr^{6+} immobilization effect attributable to the addition of GBFS. Figure 10 illustrates the relationship between GBFS content and the corresponding suppressed Cr^{6+} concentration.

For the during-carbonation treatment, a strong positive correlation was observed between GBFS content and suppressed Cr^{6+} concentration, as indicated in the red-circled scatter. Under the tested addition levels, the suppressed Cr^{6+} concentration increased linearly with increasing GBFS content, surpassing 40 µg/L at a 10% GBFS addition. This trend indicates that increasing the amount of GBFS during the wet carbonation process significantly enhances Cr^{6+} immobilization. In contrast, the post-carbonation treatment exhibited only a weak correlation between the GBFS content and Cr^{6+} suppression, as indicated in the navy-triangle scatter. Even with increased GBFS addition to the pre-carbonated RCA, the reduction in Cr^{6+} concentration remained limited, with values stabilizing around 30 µg/L.

These findings underscore the importance of incorporating GBFS during the wet carbonation process of RCA, where the prevailing alkaline conditions favor GBFS's activation and enhance Cr^{6+} immobilization. This approach not only improves the environmental performance of RCA but also supports its safe and sustainable application in geotechnical engineering practices, such as ground reinforcement and land reclamation.

6 CONCLUSIONS

This study investigates the potential of the Granulated Blast Furnace Slag (GBFS) for suppressing hexavalent chromium (Cr^{6+}) leaching induced by the carbonation of Portland cement-based Recycled Concrete Aggregates (RCA). The effectiveness of GBFS was evaluated under two conditions: (i) direct incorporation into RCA during carbonation (during-carbonation treatment) and (ii) application as a post-carbonation treatment (post-carbonation treatment). The wet carbonation method was employed, as it promotes uniform carbonation of RCA and enhances ion dissolution and mobility, thereby facilitating more effective interactions between the

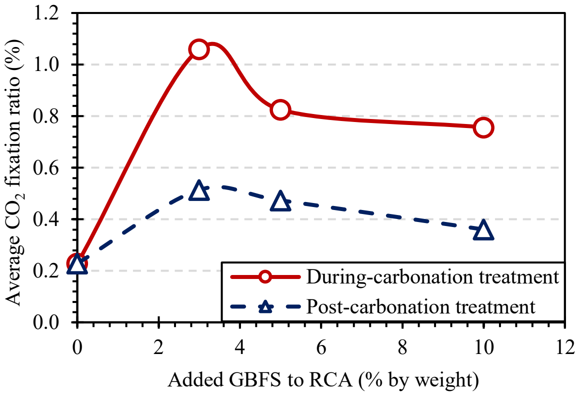

Figure 8. Effect of treatment methods on the CO_2 fixation ratio.

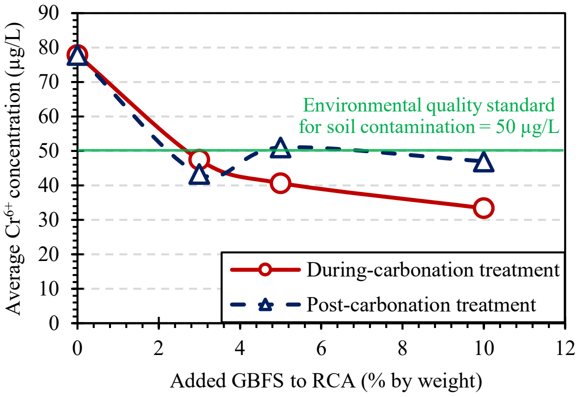

Figure 9. Effect of treatment methods on the Cr^{6+} concentration.

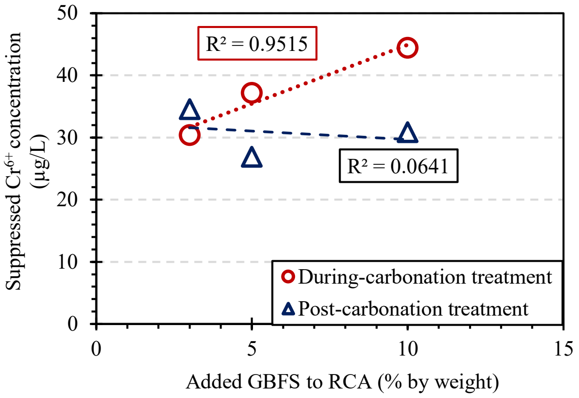

Figure 10. Relationship between the suppressed Cr^{6+} concentration and the amount of GBFS added.

dissolved ions from RCA and GBFS. RCA-GBFS mixtures with varying GBFS contents were tested to assess both CO_2 fixation ratios and Cr^{6+} concentrations in leachate.

The results demonstrated that GBFS can effectively reduce Cr^{6+} leaching below the environmental quality standard for soil contamination (50 µg/L) and improve the environmental safety of carbonated RCA. In practice, incorporating GBFS during the wet carbonation process significantly enhanced Cr^{6+} suppression, with greater reductions observed at higher GBFS content. This improved performance is attributed to the accelerated reaction between Cr^{6+} and the dissolved sulfide ions (S^{2-}) released from the GBFS under alkaline conditions, facilitating the reduction of Cr^{6+} to its less toxic form, trivalent chromium (Cr^{3+}). In contrast, post-carbonation treatment showed limited Cr^{6+} reduction, indicating that the timing of GBFS incorporation plays a critical role in the reaction outcome and emphasizes the importance of the treatment during carbonation, which maximizes Cr^{6+} immobilization efficiency. These findings highlight the promising potential of GBFS to improve the environmental sustainability of RCA, supporting its safe and practical application in various geotechnical projects.

7 ACKNOWLEDGMENT

This research was supported by the Green Innovation Fund Project (JPNP21023), initiated by the New Energy and Industrial Technology Development Organization (NEDO). The authors would like to express their sincere gratitude to Assistant Professor Adel Alowaisy from Kyushu University for his valuable contributions to this research, Dr. Eng. Takao Kono and Mr. Sho Nishiie from Takenaka Corporation for their insightful discussions, and Mr. Kouki Hiramatsu, a graduate student at Kyushu University, for his assistance in conducting some of the experiments.

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