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/ICSMGE2026-1353

Innovative Use of Baking Soda for Sustainable Cement Treatment in Soft Ground Improvement

Jiahui Ho, Ming Ze Chai
Engineering, Singapore Institute of Technology, Singapore, jiahui.ho@singaporetech.edu.sg

Rynus Ernald Lee
Infrastructure and Development, Land Transport Authority, Singapore

Yen Jee Moong
Civil and Structural, Woh Hup Engineering Pte Ltd, Singapore

ABSTRACT: The construction industry is under increasing pressure worldwide to reduce its carbon footprint, especially in light of international climate commitments targeting net zero emissions. Ground improvement works, which often require large volumes of cement exceeding 50 metric tonnes per application, contribute significantly to these emissions. Replacing Ordinary Portland Cement (OPC) with sustainable alternatives is critical for reducing emissions, as OPC production generates approximately 800 kg of CO_2 per ton. Although Portland Blast Furnace Cement (PBFC), which contains up to 80% Ground Granulated Blast-furnace Slag (GGBS), offers a lower-carbon option, its widespread use is constrained by limited GGBS availability due to the steel industry's transition toward lower-emission technologies. This study proposes the innovative use of baking soda as a supplementary cementitious material to address these challenges. Baking soda enables carbon sequestration during hydration, with up to 15% increased CO_2 uptake. Experimental results demonstrated that replacing 10% of OPC or PBFC with baking soda increased the Unconfined Compressive Strength (UCS) of treated soils by 7–26% and 50–63%, respectively, across binder dosages of 160–220 kg/m³, a range commonly employed in ground improvement. Notably, this strength enhancement enables a 20% reduction in binder content to achieve the same UCS target, translating to an estimated 18% reduction in material costs. Combined with carbon emission reductions from OPC substitution, carbon sequestration during curing, and reduced material usage, baking soda's cost-effectiveness, biodegradability, and wide availability from countries such as the United States, China, and Indonesia enhance its feasibility for large-scale applications. This pioneering approach represents a significant advancement in sustainable geotechnical engineering, offering a practical pathway to reduce emissions while maintaining technical performance in ground improvement projects.

KEYWORDS: Baking soda, sustainable cement treatment, CO_2 reduction, ground improvement, sustainable construction materials.

1 INTRODUCTION

The construction industry is a significant contributor to global carbon emissions, largely due to its heavy reliance on cement-based materials. Ordinary Portland Cement (OPC), the most widely used binder in soil stabilization, emits approximately 728–881 kg of carbon dioxide (CO_2) per ton (Prakasan et al., 2019). Recent estimates place global cement production at over 4.1 billion tonnes annually, with emissions from cement manufacturing accounting for more than 15% of global industrial CO_2 output (Cheng et al., 2023). These figures reflect the pressing need to reduce emissions from cement-intensive ground improvement methods such as deep soil mixing.

To support international climate goals under frameworks like the Paris Agreement, attention has shifted toward supplementary cementitious materials in geotechnical applications. Portland Blast Furnace Cement (PBFC), which includes up to 80% Ground Granulated Blast-furnace Slag (GGBS), can reduce carbon emissions by as much as 47.5% compared to OPC and is often more economical (Crossin, 2015). However, slag availability is declining as the steel industry transitions from traditional blast oxygen furnaces to lower-emission technologies, while global supply remains fully utilized due to growing demand (Arnold et al., 2023).

Sodium bicarbonate (baking soda) has emerged as a promising supplementary cementitious material. During early-stage carbonation, up to 15 weight percent of CO_2 can be sequestered into the cement matrix without compromising structural integrity (Stefaniuk et al., 2023). Low dosages up to 4 percent can also enhance compressive strength at early and 28-day ages (Nugroho et al., 2020; Wang et al., 2019).

The mechanism involves multiple synergistic reactions. First, sodium bicarbonate reacts with calcium hydroxide from cement hydration to form calcium carbonate and sodium carbonate (Equation (1)), accelerating carbon immobilization. Second, carbonate ions undergo hydrolysis, raising alkalinity (Equation (2)). This promotes pozzolanic reactions involving silica and alumina from clay or supplementary binders, forming strength-enhancing calcium silicate hydrate and calcium aluminate hydrate (Equation (3) and Equation (4)). Lastly, residual sodium carbonate can react with atmospheric carbon dioxide and water to regenerate sodium bicarbonate (Equation (5)), enabling continued carbon uptake during curing.

$$\mathrm{2NaHCO_3 + Ca(OH)_2 \rightarrow CaCO_3 + Na_2CO_3 + 2H_2O} \quad (1)$$

$$\mathrm{CO_3^{2-} + H_2O \leftrightharpoons HCO_3^- + OH^-} \quad (2)$$

$$\mathrm{SiO_2 + Ca(OH)_2 \rightarrow C\text{-}S\text{-}H} \quad (3)$$

$$\mathrm{Al_2O_3 + Ca(OH)_2 \rightarrow C\text{-}A\text{-}H} \quad (4)$$

$$\mathrm{Na_2CO_3 + CO_2 + H_2O \rightarrow 2NaHCO_3} \quad (5)$$

Although most existing studies have examined baking soda as a concrete admixture or accelerator in cement pastes (Nugroho et al., 2020; Wang et al., 2019), its role as a cement replacement in ground improvement is still underexplored. This study addresses this gap by investigating the use of baking soda as a partial substitute for cement in soft clay stabilization, using both OPC and PBFC as base binders. Unconfined compressive strength tests were conducted across different replacement levels and curing periods, and scanning electron microscopy was performed on selected OPC-treated specimens to examine the underlying mechanisms of strength development.

2 MATERIALS

This study uses Singapore Marine Clay, classified as very soft to soft Upper Marine Clay, with key index properties shown in Table 1. To replicate conditions typical of deep soil mixing, the clay was reconstituted to a water content of 100% (Xiao, 2009). Mixing was conducted using a Hobart HL 200 electric mixer at 125 rpm for 10 minutes to ensure uniform homogenization (JGS, 2000), and the slurry was sieved through a 2 mm mesh to remove oversized particles. Cementitious binders were prepared by combining predefined ratios of OPC or PBFC with baking soda. Table 2 presents the chemical compositions of these materials.

Table 1. Index properties of clay used in this study.

Property	Range
Liquid Limit (%)	80 to 88
Plastic Limit (%)	26 to 34
Plasticity Index (%)	46 to 62
In-Situ Water content (%)	75 to 87
Bulk Density (kg/m^3)	1395 to 1454

Table 2. Chemical composition of OPC, PBFC and baking soda.

Component	Chemical Compound	% Composition
OPC	Calcium Oxide (CaO)	63 to 67
	Silicon Dioxide (SiO_2)	20 to 24
	Iron III Oxide (Fe_2O_3)	2.1 to 4.1
	Aluminum Oxide (Al_2O_3)	3 to 7
	Magnesium Oxide (MgO)	1 to 4
	Sulphur Trioxide (SO_3)	1 to 3
PBFC	OPC	40 to 45
	GGBS	60 to 65
Baking Soda	Sodium Bicarbonate ($NaHCO_3$)	100

3 UNCONFINED COMPRESSIVE STRENGTH TEST

3.1 *Sample preparation and test setup*

A total of 84 unconfined compressive strength (UCS) tests were conducted to evaluate the optimal Replacement Ratio (RR) of baking soda substituting cementitious binders (OPC or PBFC). RR is defined as the percentage of cementitious binder replaced by baking soda on a dry mass basis. Consistent with deep soil mixing practices, the water-to-cement ratio was maintained at 1.1:1, and the binder content (OPC or PBFC with baking soda blend) ranged from 160 to 220 kg/m^3 of reconstituted clay. RR values were 0% (control), 10%, and 15%.

Binder and reconstituted Singapore Marine Clay were mixed following JGS 0821 (2000) standards using a Hobart N50 mixer at 125 rpm for 10 minutes. The mixture was placed into cylindrical molds (50 mm diameter, 100 mm height), providing a 1:2 aspect ratio in compliance with BS EN ISO 17892-7 and ASTM D2166-06. To minimize air voids, specimens were tapped 20 times in three stages at 40%, 80%, and 100% filling. Ends were sealed with thick plastic to prevent moisture loss, following Xiao (2009) and Gullu et al. (2017).

Curing was carried out at approximately 20°C under controlled laboratory conditions per JGS 0821 (2000). Three specimens per mix were tested for UCS to ensure repeatability, with standard deviations ranging from 0.7% to 5.0%.

3.2 *Effects of RR on UCS*

To quantify the effect of replacement ratio (RR) on unconfined compressive strength (UCS), the UCS values of all specimens were normalized against the average UCS of the control specimens without baking soda. Figure 1 presents the normalized UCS of specimens cured for 28 days plotted against binder content. Grey markers indicate individual specimen results, while black markers represent the average UCS of the three specimens per mix.

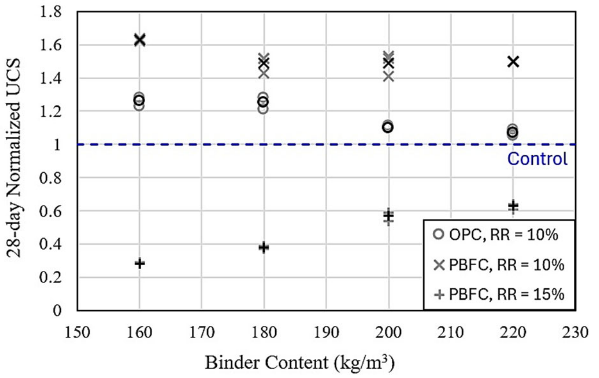

Figure 1. Normalized UCS at 28 days versus binder content for specimens treated with RR = 10% and RR = 15%.

For RR = 10%, the addition of baking soda to OPC- and PBFC-treated specimens led to UCS increases of 7–26% and 50–63%, respectively, corresponding to normalized UCS values of 1.07–1.26 for OPC and 1.50–1.63 for PBFC. In both cases, a decreasing trend in normalized UCS is observed as the binder content increases. This decline is attributed to the decreasing proportion of clay in the mix, which reduces the available reactive silica and alumina needed to form the strength-contributing compounds C–S–H and C–A–H (Equation (3) and Equation (4)). The decline is less pronounced in PBFC-treated specimens due to the presence of 60–65% GGBS, which provides an additional source of reactive silica and alumina to sustain pozzolanic reactions.

When RR increases to 15%, the normalized UCS of PBFC-treated specimens drops significantly to values between 0.28 and 0.63, indicating a strength reduction of 37–72% compared to the control. For OPC-treated specimens at RR = 15%, UCS testing could not be performed as the samples were too soft to handle. At this high replacement level, the absolute amount of cement becomes too low to generate sufficient Ca(OH)$_2$ through hydration, limiting the initial carbonation reaction (Equation (1)). As a result, much of the added baking soda remains unreacted, potentially leading to salt precipitation and pore blockage, which reduce strength. However, as binder content increases, the total amount of Ca(OH)$_2$ also increases, allowing more baking soda to react. This raises system alkalinity (Equation (2)), promoting pozzolanic reactions and the gradual formation of C–S–H and C–A–H. Consequently, while UCS remains lower than the control, a gradual strength recovery is observed with higher binder content.

Figure 2 presents a conceptual schematic illustrating the chemical interactions among cement, baking soda, and clay (or clay and GGBS in the case of PBFC). Central to this mechanism is the role of Ca(OH)$_2$, which feeds three concurrent reactions: carbonation with baking soda (Equation (1)), and pozzolanic reactions with silica and alumina (Equation (3) and Equation (4)). These reactions compete for the same source of Ca(OH)$_2$, and the strength development of the treated soil depends on how this resource is distributed.

If the baking soda-to-(clay and GGBS) ratio becomes too high, a disproportionate share of Ca(OH)$_2$ is diverted toward carbonation, reducing its availability for pozzolanic reactions. This imbalance suppresses the formation of C–S–H and C–A–H, leading to lower strength, as reflected in the declining normalized UCS at high replacement ratios. In contrast, a well-calibrated ratio ensures that $Ca(OH)_2$ is adequately available for both carbonation and pozzolanic reactions, achieving synergy between carbon sequestration and mechanical performance.

In PBFC-treated specimens, the GGBS provides additional reactive silica and alumina that help sustain pozzolanic activity even as baking soda levels increase. However, this buffering capacity is not unlimited. Excess baking soda can still overwhelm the system, leading to incomplete reactions and strength loss.

This interplay highlights the necessity of tailoring the baking soda content not just as a percentage of the binder, but in relation to the reactive components present in the entire mix, including the available $Ca(OH)_2$ and pozzolanic materials. In the present study, 10% replacement appears to achieve this balance, enabling strength enhancement alongside carbon reduction in cement-treated soils.

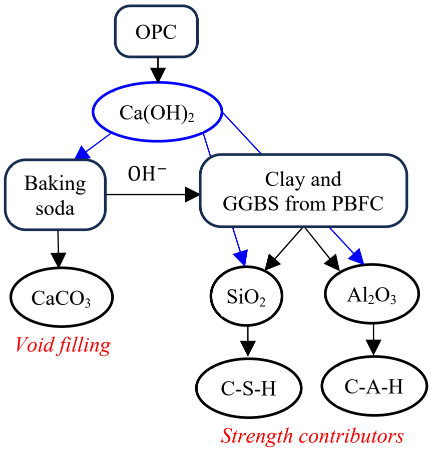

Figure 2. Schematic of the five-step chemical mechanism showing interactions between baking soda, cement, and clay in treated soils.

To further investigate strength development over time, Figure 3 presents the normalized UCS of PBFC-treated specimens with 10% RR at 28, 42, and 56 days of curing. The UCS values were normalized against the averaged 28-day UCS of the control specimens without baking soda. The results show a consistent increase in strength with curing duration across all binder contents, with 56-day normalized UCS values reaching up to twice the control strength. This highlights the sustained contribution of pozzolanic reactions over time, particularly in systems containing GGBS and maintaining a chemically balanced baking soda-to-reactive-material ratio.

While the 28-day normalized UCS follows a decreasing trend with increasing binder content, the 42-day and 56-day results reveal a reversal in trend, where strength improves as binder content increases. This delayed gain is attributed to the progressive activation of GGBS, which provides additional sources of reactive silica and alumina beyond what the clay can offer. Furthermore, the increased binder content ensures a higher supply of $Ca(OH)_2$ from cement hydration, sustaining the alkaline conditions needed to drive both clay-based and GGBS-based pozzolanic reactions.

Together, these findings reinforce that a 10% replacement ratio achieves a stable balance between carbonation (Equation (1)) and pozzolanic activation (Equation (3) and Equation (4)). It leverages early-stage void filling from $CaCO_3$ precipitation while still enabling long-term strength gain from GGBS- and clay-derived pozzolanic reactions.

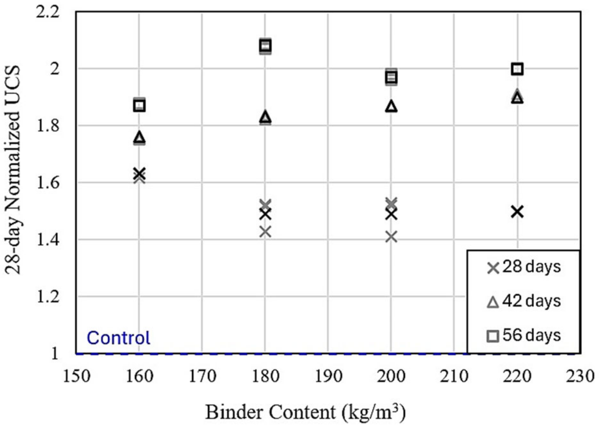

Figure 3. Normalized UCS of PBFC-treated specimens with RR = 10% after 28, 42, and 56 days of curing. Grey markers represent individual specimen results, while black markers show the average UCS of three specimens per mix.

4 SCANNING ELECTRON MICROSCOPE

4.1 *Sample preparation and test setup*

After UCS testing, selected sheared specimens were oven dried at 105°C for 24 hours to remove all moisture, as Scanning Electron Microscope (SEM) imaging requires a vacuum environment. A small fragment of the dried specimen was mounted on a metal stub using conductive carbon tape. To improve imaging quality and minimize charging, the specimen was sputter-coated with a 2 nm platinum layer at 30 mA for 30 seconds, following the procedure recommended by Xiao (2009).

The coated sample was then placed in the SEM chamber and imaged under high vacuum mode to eliminate air molecules, thereby reducing electrical discharge risk and allowing free travel of electrons. SEM imaging was used to examine microstructural features of cement-treated soil. In the grayscale SEM images, white regions typically correspond to conductive phases such as C–S–H and $Ca(OH)_2$, while darker regions represent non-conductive voids or less dense phases. The brightness intensity correlates with the atomic weight of the imaged compounds.

4.2 *Microstructure analysis*

Figure 4 presents SEM images of cement-treated Singapore Marine Clay after unconfined compression testing, comparing a previously published reference (Figure 4a) with specimens from the current study at different RRs. Images were taken at comparable magnifications to allow direct microstructural comparison.

Figure 4(a), from Chin (2006), shows a dense OPC-treated matrix with abundant hydration products. A similar microstructure is observed in Figure 4(b), which represents the 0% RR specimen from the current study. In both images, the gel-like and irregularly shaped formations represent C–S–H, appearing as bright, cloud-like structures interwoven with the clay particles. These features are indicative of effective cement hydration. Scattered throughout the matrix are flatter and more angular crystals, appearing even brighter than the surrounding gel. These are $Ca(OH)_2$, distinguishable by their plate-like geometry and higher backscatter contrast due to their relatively greater atomic weight.

In Figure 4(c), the 10% RR specimen maintains a similarly compact structure. The presence of C–S–H remains evident, although the gel texture appears slightly more disordered. The matrix shows moderate porosity, with dark regions indicating small voids. This suggests that at 10% replacement, the system retains adequate $Ca(OH)_2$ to drive pozzolanic reactions involving both clay and any supplementary binder components. The continued formation of C–S–H and C–A–H contributes to densification and mechanical strength.

By contrast, Figure 4(d), corresponding to the 15% RR specimen, shows a much looser and more porous microstructure. Larger black voids are visible, and the presence of hydration products is visibly reduced. Fewer C–S–H gels and $Ca(OH)_2$ crystals can be seen. The weaker connectivity between particles suggests that excess baking soda may have consumed a significant portion of the available $Ca(OH)_2$, limiting pozzolanic activity and weakening the cementitious network.

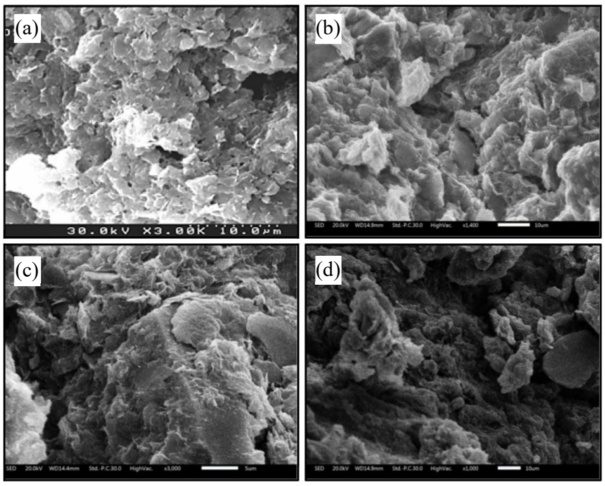

Figure 4. SEM images of cement-treated Singapore Marine Clay after unconfined compression testing: (a) OPC-treated specimen from Chin (2006); (b) OPC-treated specimen from current study with 0% RR; (c) OPC-treated specimen with 10% RR; and (d) OPC-treated specimen with 15% RR.

Overall, the SEM observations corroborate earlier UCS findings. At 10% RR, the microstructure remains chemically active and mechanically cohesive. At 15% RR, however, the lack of available $Ca(OH)_2$ compromises both reaction pathways and leads to microstructural degradation.

5 CONCLUSIONS

This study investigated the use of baking soda as a partial cement replacement for stabilizing soft clay using OPC and PBFC binders. Through UCS testing and SEM imaging, the findings demonstrate that a 10% RR effectively enhances both strength and carbon sequestration. At this dosage, the system maintains a favorable balance between carbonation and pozzolanic reactions, leveraging the available $Ca(OH)_2$ to form C–S–H and C–A–H while promoting early-stage densification through $CaCO_3$ precipitation. OPC-treated specimens showed strength increases of up to 26% at 28 days, while PBFC-treated specimens, benefiting from additional reactive components in GGBS, achieved up to 63% improvement at 28 days and further gains with extended curing. SEM imaging confirmed a compact microstructure at 10% RR, while excessive replacement at 15% led to weakened connectivity and porosity.

Beyond technical performance, the results also indicate meaningful cost efficiencies. Although baking soda is approximately 20% more expensive than OPC and around 33% costlier than PBFC on a per gram basis, the strength enhancement at 10% RR allows for a lower overall binder content to meet project specifications. For example, an OPC-treated specimen with 10% baking soda at 160 kg/m³ achieved a 28-day UCS comparable to a control mix with 200 kg/m³ of pure OPC. This 20% reduction in binder usage results in an overall material cost saving of approximately 18% per m³, even after accounting for the higher cost of baking soda. These findings emphasize the practical feasibility of baking soda as a cost-conscious and environmentally beneficial additive for soil stabilization.

6 ACKNOWLEDGEMENTS

This research was conducted at and funded by the Singapore Institute of Technology. The authors would like to express their sincere appreciation to Zhao Yang Geotechnic Pte Ltd for their support in providing the soil specimens and for sponsoring the cementitious materials used in this study.

7 REFERENCES

Arnold, W., Astel, P., Forman, T., and Drewniok, M. 2023. The efficient use of GGBS in reducing global emissions. *Institution of Structural Engineers: London*, UK.

ASTM International. 2024. *ASTM D2166 Standard Test Method for Unconfined Compressive Strength of Cohesive Soil*. West Conshohocken, PA: ASTM International.

British Standards Institution. 2015. *BS EN ISO 17892-7:2015 Geotechnical Investigation and Testing – Laboratory Testing of Soil – Part 7: Unconfined Compression Test*. London: BSI Standards Publication.

Cheng, D., Reiner, D. M., Yang, F., Cui, C., Meng, J., Shan, Y., Liu, Y, Tao, S and Guan, D. 2023. Projecting future carbon emissions from cement production in developing countries. *Nature Communications* 14(1), 8213.

Chin, K. G. 2006. Constitutive behavior of cement treated marine clay. PhD thesis, National University of Singapore, Singapore.

Crossin, E. 2015. The greenhouse gas implications of using ground granulated blast furnace slag as a cement substitute. *Journal of Cleaner Production* 95, 101–108.

Gullu, H., Canakci, H., and Al Zangana, I.F. 2017. Use of cement-based grout with glass powder for deep mixing. *Construction and Building Materials* 137, 12-20.

Japanese Geotechnical Society. 2000. *JGS 0821-2000 Method for Preparing and Testing of Cement-Stabilized Soil*. Tokyo: Japanese Geotechnical Society.

Nugroho, F.B., Sumarni, S., Thamrin, A.G., Roemintoyo, N., and Isnantyo, F. 2020. Using baking powder as additional concrete material. *IOP Conference Series: Materials Science and Engineering* 858(1), 012005.

Prakasan, S., Palaniappan, S. and Gettu, R., 2020. Study of energy use and CO_2 emissions in the manufacturing of clinker and cement. *Journal of The Institution of Engineers (India): Series A* 101(1), pp.221-232.

Stefaniuk, D., Hajduczek, M., Weaver, J. C., Ulm, F. J., and Masic, A. 2023. Cementing CO_2 into C-S-H: A step toward concrete carbon neutrality. *PNAS Nexus* 2(3), pgad052.

Wang, Y., He, F., Wang, J., and Hu, Q. 2019. Comparison of effects of sodium bicarbonate and sodium carbonate on the hydration and properties of Portland cement paste. *Materials* 12(7), 1033.

Xiao, H.W. 2009. Yielding and failure of cement treated soil. PhD thesis, National University of Singapore, Singapore.