ISSN: 1813-4890

CO_2 Research status and progress of carbonized solidified soil

Jiangshan Zhao, Qingjuan Meng

Engineering, North China University of Science and Technology, Tangshan 063210, Hebei, China

Abstract

Carbonation-curing soil technology, as a low-carbon and environmentally friendly method for soil reinforcement, has become a research hotspot in geotechnical and environmental engineering under the "dual carbon" context. This technique enhances soil mechanical properties and durability by utilizing carbon dioxide to react with alkaline cementitious materials (such as slag, MgO, CaO, etc.) through carbonation, forming carbonate crystals and gel substances. This paper systematically reviews the current research status and advancements of carbonation-curing soil technology, providing theoretical support for future applications. However, challenges remain in deep soil reinforcement, long-term performance prediction, and standardization. Future research should focus on regulating carbonation reaction mechanisms under multi-field coupling conditions, developing new low-carbon cementitious materials, and establishing engineering application technology systems to promote large-scale industrial implementation of carbonation-curing soil technology.

Keywords

Carbonization; curing; industrial waste residue; durability.

1. Introduction

In the context of global climate change, reducing carbon dioxide emissions has become a shared challenge for the international community. As one of the major sources of carbon emissions, the cement industry accounts for approximately 8% of global annual emissions. Meanwhile, weak soil structures prevalent in infrastructure construction require reinforcement treatment. Although traditional cement curing techniques are effective, they generate high carbon emissions. Therefore, developing low-carbon technologies that can both reinforce soil and sequester CO_2 holds significant strategic importance. Carbonation-curing soil technology emerged as a solution, utilizing industrial waste (such as slag, steel slag, red mud) or active oxides (MgO, CaO) as binding materials. These materials react with CO_2 through carbonization to form stable carbonates that cement soil particles. This technique not only utilizes industrial by-products but also sequesters substantial CO_2, achieving dual objectives of "waste-to-waste treatment" and carbon fixation. Studies indicate that treated soil exhibits 1.7-3 times greater strength than conventional cement-soil, with advantages like early high strength and low shrinkage. It demonstrates broad application prospects in roadbed reinforcement, contaminated soil remediation, and slope protection.

The core principle of carbonation-curing technology lies in the gas-solid-liquid multiphase reaction between alkaline binding materials and CO_2. Key processes include: CO_2 dissolving in pore water to form carbonic acid; release of Ca^{2+} and Mg^{2+} ions from binding materials; ion-binding with CO_3^{2-} to form carbonate precipitates; and growth of carbonate crystals that cement soil particles. These reactions are influenced by multiple factors including material composition, CO_2 partial pressure, environmental temperature/humidity, and soil characteristics. The technology originated from research on activated MgO-carbonated stabilized soil around 2010, later expanding to utilize industrial waste materials such as steel slag, mine slag, and red mud as cementitious materials. In recent years, researchers have further enhanced carbonization efficiency and application effectiveness by adding biochar and regulating the chemical properties of pore solutions.

2. Research status and progress

Scholars have achieved numerous innovative research outcomes in carbonization-curing soil technology. Regarding excipient selection, MgO has been predominantly chosen. In terms of research subjects, most studies focused on weak soils or coastal river silt. Wang Zhengqing selected engineering waste materials from Zijingang Campus of Zhejiang University as treatment subjects, using three industrial residues—steel slag, fly ash, and calcium carbide slag—as curing raw materials. Through a combination of laboratory unit tests, model experiments, microscopic examinations (SEM, EDS, XRD, XRF, TGA), and theoretical analysis, he investigated the curing effectiveness, micro-mechanism, and practical applications of CO2-industrial residue synergistic curing. The study confirmed that CO2 carbonization synergistically improved the bearing performance of engineering waste materials. Shi Fangzhen explored the mechanical deformation characteristics and sealing capacity of MgO-calcium carbide slag-cured soil during carbonization, as well as its performance under freeze-thaw cycles and wet-dry cycles. Results showed that under curing conditions, MgO-calcium carbide slag-cured soil exhibited enhanced strength while achieving effective sealing. When the MgO-calcium carbide slag ratio reached 4:6, the cured soil achieved maximum strength. Zheng Chenhui et al. conducted carbonization curing of silty clay soil using calcium carbide slag-active MgO composite curing agent and CO2 gas, setting two variables: curing agent dosage (single addition of calcium carbide slag) and mixing ratio (calcium carbide slag: MgO). They analyzed the engineering properties of carbonized cured soil from physical-mechanical and chemical perspectives. Results showed that when calcium carbide slag was added at 20%, the carbonized soil exhibited the highest strength. Hong Guoqian applied carbonized active magnesium oxide technology to solidify soft clay in Wuxi. The study investigated the effects of initial moisture content and active magnesium oxide dosage on direct carbonization of active Mg O-cured soil, measuring the strength of carbonized samples. Results indicated that the carbonization process caused volume expansion in cured soil. When active MgO or initial moisture content was below 25%, the expansion disrupted particle bonding, leading to cracking and loosening with significant strength reduction. Conversely, when both active MgO and initial moisture content exceeded 25%, crystalline products from the carbonization process filled soil pores and rapidly formed cementation, significantly enhancing cured soil strength. Wang Dongxing et al. used slag as primary material with active MgO and CaO as curing agents, mixing them with soft soil for CO2 carbonization tests. Through unconfined compressive strength testing, they found that 24-hour carbonized samples achieved a maximum compressive strength improvement of 25.77 times. Some scholars have also conducted research on the micro-mechanisms, durability, and model experiments of carbonized cured soil. Yuan proposed analyzing the mechanism of enhancing strength efficiency in active MgO-cement curing soft soil from a micro perspective. X-ray diffraction and scanning electron microscopy experiments revealed the formation of magnesium carbonate and hydrotalcite as products. After curing, flake-like crystalline structures in the original soil transformed into larger skeletal block-shaped grains. Wang Dongxing et al. conducted durability tests on carbonized cured materials using active MgO-fly ash to treat Wuhan East Lake silt, demonstrating improved water stability post-treatment. Qin Chuan et al. performed indoor model tests on silty clay using carbonization technology, evaluating bearing capacity and compressive properties through micro-penetration and compression tests. The allowable bearing capacity calculated from micro-penetration tests exceeded 300 kPa. Xiao Jie introduced active MgO-cement mixed with industrial by-products fly ash/ slag, combined with CO2 carbonization technology to achieve dredged silt reinforcement and CO_2 permanent storage. Through compressive strength tests, scanning electron microscopy, and mercury compression tests, the study investigated how carbonization time and curing agent ratios affect mechanical properties and microstructure. Results showed enhanced compressive strength after carbonization for active MgO-cement-cured silt, with different curing agent ratios yielding optimal compression modes that influence strength. The expansion and cementing effects of magnesium carbonates (such as hydrotalcite, ball carbonite, and magnesium carbonate) were identified as primary contributors to the enhanced strength of silt through the carbonization-curing integrated technique. Liu Songyu and colleagues developed five activated MgO-cemented soil samples with initial compaction degrees of 86%,87%,89%,91%, and 92% using the static pressure method, followed by laboratory carbonation tests. Measurements of moisture content, dry density, and unconfined compressive strength before and after carbonation revealed that the process consumed substantial amounts of CO_2 and water, producing rod-shaped trisodium magnesium sulfate and flake-like hydrated magnesium carbonate/carbonated magnesium carbonate as primary carbonized products. These materials demonstrated significant cementing and filling effects, resulting in marked increases in dry density and strength of the magnesium oxide-cemented soil samples. Cai Guanghua conducted systematic studies on how MgO content, initial moisture content (equivalent water-cement ratio), carbonation duration, MgO activity index, natural soil properties, and CO_2 permeability pressure influence physical characteristics of MgO-carbonated cemented soils, elucidating their physical mechanisms. The findings indicated that MgO-cemented soil undergoes intense exothermic carbonation with temperature increases exceeding 25℃. When MgO content is low, MgO activity index is insufficient, fine-grained soil content is high, or permeation time is prolonged, transverse cracks predominantly form along sample surfaces. Cui Shuai conducted unconfined compressive strength tests on carbonized and solidified dredged sediments, evaluating the effects of active MgO dosage, moisture content, compaction degree, and carbonation time to determine optimal curing conditions. X-ray diffraction and scanning electron microscopy analyses revealed mineral composition, particle distribution, pore structure, and product morphology during carbonization, elucidating its mechanism. Road dynamic performance was assessed using rebound modulus and split strength tests. Comprehensive long-term evaluations included water immersion, dry-wet cycle/coupled salt solution erosion, and freeze-thaw cycles, providing theoretical support for practical applications. This study investigates the application of sodium bicarbonate ($NaHCO_3$) as a CO_2 carrier for treating MgO-cured clay through indirect carbonation. Experimental methods including unconfined compressive strength (UCS), moisture content, and X-ray diffraction (XRD) were employed to evaluate the effects of MgO:$NaHCO_3$ ratio, curing duration, temperature, and acidity on the mechanical properties and swelling characteristics of reinforced clay. Results indicate that unconfined compressive strength initially increases with $NaHCO_3$ addition but then decreases, peaking at MgO:$NaHCO_3$=2:1. Strength generally increases with prolonged curing duration and elevated temperatures. In terms of strength and swelling resistance, the MgO:$NaHCO_3$=2:1 ratio outperforms direct carbonation curing. XRD analysis reveals that the unconfined compressive strength originates from crystalline structures of dolomite or tridolomite, with water-carbonated dolomite crystals being predominant.

While existing research focuses on immediate strength and stability, future studies should prioritize long-term stability and practical applicability in foundation engineering.

3. Conclusion and Prospect

Carbonization and solidification technology represents a promising low-carbon reinforcement method in geotechnical engineering. Its core mechanism involves utilizing calcium and magnesium ions from industrial byproducts (e.g., slag, steel slag) or active oxides (e.g., MgO, CaO) to react with CO_2, forming cementitious carbonate compounds that both reinforce soil and permanently sequester CO_2, achieving the dual objectives of "waste-to-waste" treatment and "turning waste into treasure". Compared to traditional cement-based methods, carbonized solidified soil demonstrates superior advantages including high early strength development (achieving significant strength within hours), final strength reaching 1.5-3 times that of conventional techniques, minimal dry shrinkage, excellent impermeability, and high corrosion resistance. These characteristics make it particularly suitable for high-performance and time-sensitive projects such as roadbed construction, slope stabilization, and foundation pit backfilling. This technology not only effectively utilizes industrial solid waste and reduces carbon emissions from cement production but also directly immobilizes industrial CO_2, with a lifecycle carbon footprint significantly lower than traditional reinforcement methods – actively supporting China's "dual-carbon" strategy.

Although this technology shows great potential, challenges remain in transitioning from laboratory research to large-scale engineering applications. Future studies should focus on deepening mechanistic understanding and quantitative analysis, particularly investigating how altered carbonation pathways in complex soil environments (e.g., high-organic soils, heavy metal-contaminated soils) affect the long-term stability of solidified materials. Secondly, the breakthrough and standardization of process technology, to overcome the technical bottleneck of deep and in-situ soil carbonation reinforcement, and to develop efficient CO_2 transportation, diffusion and recovery processes and supporting equipment. Innovative technologies such as electrochemical-carbonization joint reinforcement are worth further exploration.With long-term performance and systems engineering research as breakthrough directions, we conduct studies on the long-term durability of carbonized stabilized soil under harsh environments including dry-wet cycles, freeze-thaw cycles, and acid rain erosion to obtain predictive data for service life. A comprehensive Life Cycle Assessment (LCA) integrating technical, economic, and environmental (TEA) aspects is performed to scientifically evaluate its economic viability and carbon reduction benefits across different application scenarios, providing support for policy-making and engineering decisions. In summary, carbonized stabilized soil technology integrates economic, environmental, and social benefits, representing a crucial direction for low-carbon development in civil engineering materials. By deeply integrating industry, academia, and research to address these key scientific and technological challenges, this technology will accelerate large-scale engineering applications and provide core technological support for green and sustainable infrastructure developmen.

References

[1] Wang Zhengqing. CO2-Study on the Control of In-Situ Solidification Performance of Industrial Waste Residues [D]. Zhejiang University of Science and Technology, 2024.

[2] Shi Fangzhen. Study on mechanical and deformation characteristics of carbonized MgO-carbide slag stabilized soil [D]. Anhui University of Science and Technology, 2024.

[3] Zheng Chenhui, Cai Guanghua, Zhong Yuqing, et al. Experimental study on the curing of silty soil with calcium carbide slag-magnesium oxide under carbonization conditions [J]. Science and Technology Industry, 2023,23(09):233-238.

[4] Hong Guoqian. Experimental study on carbonization activity MgO curing of silty clay [D]. Jiangnan University, 2023.

[5] Wang Dongxing, He Fujin, Zhu Jiaye.CO_2 Carbonized slag-CaO-MgO Mechanism and effectiveness of reinforced soil [J]. Journal of Geotechnical Engineering, 2019,41(12):2197-2206.

[6] Yuan Jian, Yuan Jianhua, Wu Chenghao et al. Microscopic mechanism analysis of activated magnesium oxide curing soft soil [J]. Journal of Hubei University of Technology, 2020,36(05):28-32+39.

[7] Wang Dongxing, Xiao Jie, Li Lihua, et al. Microscopic Mechanism of Durability Evolution of Wuhan East Lake Silt Based on Carbonization-Curing Technology [J]. Geotechnical Mechanics, 2019,40(08):3045-3053.

[8] Qin Chuan, Liu Songyu, Du Guangyin, et al. Experimental study on the overall carbonization and solidification model of silty soil [J]. Journal of Engineering Geology, 2019,27(06):1302-1310.

[9] Xiao Jie.CO2 Carbonization combined with MgO-fly ash/mineral slag synergistic curing of sludge mechanical properties and micro-mechanism [D]. Wuhan University, 2019.

[10] Liu Songyu, Cao Jingjing, Cai Guanghua, et al. Effect and mechanism of compactness on the reinforcement effect of MgO carburized soil [J]. Journal of Highway Research in China, 2018,31(08):30-38.

[11] Cai Guanghua. Experimental and applied research on carbonization of activated magnesium oxide to reinforce weak soil [D]. Southeast University, 2017.

[12] Cui Shuai. Experimental study on activated MgO-carbonation and solidification for dredged sediment removal [D]. Shandong Jianzhu University, 2023.