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Sustainable stabilization of marginal silty sand through carbon mineralization using serpentinite rock powder

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ABSTRACT: The use of low-carbon materials in ground improvement is increasingly important for reducing the environmental impact of geotechnical construction. This study investigates the feasibility of serpentinite rock powder, an ultramafic quarry by-product, as a dual-function soil stabilizer and carbon sequestration agent through mineral carbonation. A locally sourced silty sand was treated with 1%, 3%, and 5% serpentinite (by dry weight of soil) in combination with a biodegradable chelating agent (GLDA). Specimens were evaluated under normal curing (7 and 28 days) and under accelerated carbonation curing using pressurized CO_2. Mechanical performance was assessed through unconfined compressive strength (UCS) testing, while carbonation behaviour was examined using pressure monitoring, X-ray diffraction (XRD), and total inorganic carbon (TIC) analysis. Under normal curing, strength enhancement was primarily attributed to physical filler effects and improved particle packing, with UCS increases of up to approximately 240% after 7 days. Carbonation curing significantly accelerated strength development, enabling specimens to reach peak strengths of approximately 215 kPa (5% serpentinite) within 24 hours. The rapid strength gain under carbonation curing is attributed to dissolution of magnesium-bearing phases from serpentinite and subsequent precipitation of hydrated magnesium carbonates within the soil matrix.Pressure reduction during curing indicated active CO_2 consumption. XRD patterns showed additional diffraction features consistent with hydrated magnesium carbonate formation, and TIC measurements indicated progressive inorganic carbon increase with serpentinite dosage, reaching nearly 10%. The results suggest that serpentinite-driven mineral carbonation can provide rapid strength enhancement while enabling CO_2 uptake. It is widely available as a quarry by-product in ultramafic rock regions, offering potential for valorization of low-value mineral residues.

1 INTRODUCTION

Anthropogenic CO_2 emissions from fossil fuel combustion and construction activities continue to drive global warming, with atmospheric CO_2 concentrations now exceeding 420 ppm and global temperatures rising by approximately 1.2 °C above pre-industrial levels (Metz *et al.*, 2007; Kelemen *et al.*, 2019). The construction sector, particularly soil stabilization works, contributes significantly to these emissions due to the extensive use of Portland cement (PC). Cement production is highly energy-intensive and releases nearly one ton of CO_2 per ton of cement produced, accounting for over 5% of global CO_2 emissions (Peng *et al.*, 2013; Yao *et al.*, 2021). In addition to its carbon footprint, PC-stabilized soils often exhibit durability limitations under adverse environmental conditions, highlighting the need for low-carbon and sustainable alternatives.

Mineral carbonation has emerged as a promising strategy for permanent CO_2 sequestration through the reaction of CO_2 with calcium and magnesium-rich silicate minerals to form stable carbonate phases (Oelkers, Gislason and Matter, 2008). Ultramafic rocks such as serpentinite are particularly attractive for this purpose due to their high magnesium content and widespread availability. Carbonation of serpentinite-derived minerals can produce hydrated magnesium carbonates, including nesquehonite and hydromagnesite, which possess cementitious characteristics capable of enhancing soil strength and particle bonding (Vandeperre and Al-Tabbaa, 2007; Cai, Liu and Cao, 2017).

In geotechnical systems, mineral carbonation offers a dual benefit of permanent CO_2 sequestration and enhancement of soil mechanical properties. Carbonate precipitation within soil pores can improve particle bonding, reduce porosity, and increase strength and stiffness, thereby contributing to ground improvement (DeJong *et al.*, 2010; Cheng, Shahin and Cord-Ruwisch, 2014). Compared to bio-mediated carbonation techniques, mineral-based approaches rely on inorganic reactions and are less sensitive to fluctuations in temperature, moisture conditions, and biological activity compared to bio-mediated carbonation systems, making them attractive for arid and semi-arid regions where environmental variability is high.

Soils themselves represent a substantial reservoir for carbon storage, capable of sequestering carbon in both organic and inorganic forms (Goh, 2004; Washbourne, Renforth and Manning, 2012). Among these mechanisms, mineral carbonation is particularly relevant for engineered applications due to its permanence and compatibility with construction processes. However, the efficiency of CO_2 mineralization in soils remains constrained by slow reaction kinetics and limited availability of reactive divalent cations (Pronost *et al.*, 2011). Experimental investigations have demonstrated that the use of finely ground natural minerals and appropriate chemical activators can significantly enhance dissolution rates and carbonation efficiency (Fagerlund and Zevenhoven, 2011; Swanson *et al.*, 2014).

Despite the recognized carbonation potential of ultramafic minerals, their application in improving marginal sandy soils remains insufficiently explored. Although clean sands are typically free-draining and stable, silty sands containing fines usually exhibit low apparent cohesion, limited bearing capacity, and susceptibility to deformation under loading, particularly in arid environments. In the present study, carbonation curing was performed under controlled laboratory conditions using compacted silty sand treated with varying proportions of serpentinite powder and a biodegradable chelating agent with sufficient interconnected porosity to allow CO_2 diffusion. The applicability of direct CO_2 injection to low-permeability soils may require alternative delivery strategies, such as staged injection, elevated pressures, or partial pre-treatment to enhance gas transport. The effects of this treatment were evaluated through unconfined compressive strength (UCS) testing, mineralogical and microstructural analyses, and total inorganic carbon measurements. The results provide insight into the feasibility of serpentinite-based carbonation as a low-carbon alternative to conventional cementitious stabilization for sustainable ground improvement.

2 MATERIALS AND METHODS

2.1 Material

The soil used in this study was a locally sourced silty sand representative of arid and marginal ground conditions. Based on particle size distribution (PSD) analysis (Figure 1a) and Atterberg limit tests, the soil was classified as silty sand (SM) according to the Unified Soil Classification System. The basic index properties of the untreated soil are summarised in Table 1, indicating moderate plasticity and a slightly alkaline pH. Microstructural observations of the untreated soil revealed irregular, loosely packed particles with relatively large intergranular voids, consistent with its low inherent strength. X-ray diffraction (XRD) analysis of the untreated soil (Figure 1b) confirmed the presence of carbonate-bearing phases, while X-ray fluorescence analysis indicated dominant SiO_2, CaO, and MgO contents, suggesting limited reactive aluminosilicate content.

Table 1. Basic index properties of the untreated silty sand.

Specific gravity	Liquid limit (%)	Plastic limit (%)	Plasticity index	pH	Linear Shrinkage
2.70	35	24	11	8.4	7.1

Serpentinite rock powder was used as the stabilizing and carbon-reactive material due to its high magnesium content and suitability for mineral carbonation. XRD analysis of the serpentinite (Figure 2) showed that the material was primarily composed of lizardite-1T as the dominant phase, with minor amounts of olivine and forsterite. These Mg-rich phases, including lizardite ($Mg_3Si_2O_5(OH)_4$), forsterite (Mg_2SiO_4), and antigorite ($Mg_3Si_2(OH)_4$), provide a reactive source of divalent cations capable of participating in carbonation reactions. Under CO_2 exposure and in the presence of the chelating agent, partial surface dissolution of these magnesium-bearing phases such as lizardite and periclase can release Mg^{2+} ions into the pore solution. These dissolved ions subsequently participate in carbonate precipitation reactions during carbonation curing. To enhance mineral dissolution during carbonation, a biodegradable chelating agent, L-glutamic acid N, N-diacetic acid (GLDA), was incorporated at a constant dosage of 0.5% by dry weight of soil using a 40% aqueous solution. The role of GLDA was to promote chelation-assisted dissolution of calcium and magnesium-bearing phases, thereby increasing the availability of Ca^{2+} and Mg^{2+} ions for carbonation

during CO_2 curing without increasing system alkalinity.

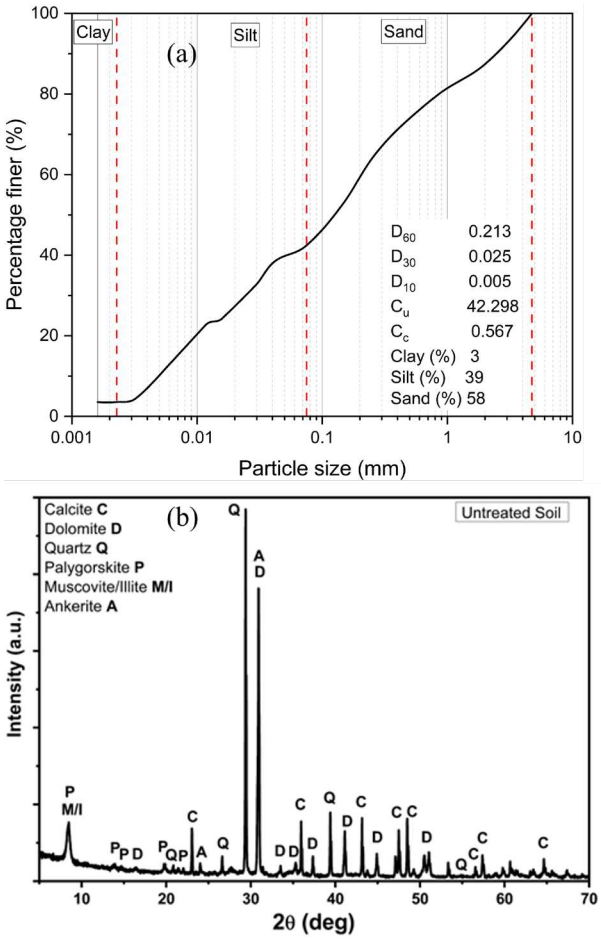

Figure 1. (a) Particle size distribution curve and (b XRD of the untreated silty sand

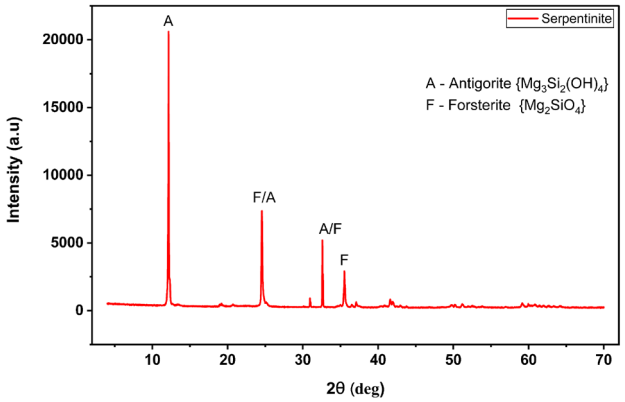

Figure 2. X-ray diffraction pattern of serpentinite rock powder showing dominant magnesium-rich mineral phases

2.2 Specimen preparation and testing program

Silty sand specimens were prepared by air-drying the soil and sieving it through a 4.75 mm sieve in accordance with (ASTM D6913, 2009). Serpentinite rock powder was incorporated at dosages of 1%, 3%, and 5% by dry weight of soil and dry-mixed to ensure uniform distribution. A 40% aqueous GLDA solution was added at a constant dosage of 0.5% by dry weight of soil, along with the required amount of water to achieve the target moisture content. The mixtures were thoroughly homogenized prior to compaction. Standard Proctor compaction testing of the untreated silty sand yielded a maximum dry density (MDD) of 18.2 kN/m^3 at an optimum moisture content (OMC) of 15.6%. The inclusion of serpentinite slightly influenced the compaction characteristics. For mixtures containing 1%, 3%, and 5% serpentinite, the OMC values were 15.41%, 15.27%, and 15.09%, respectively, while the corresponding MDD values were 18.31 kN/m^3, 18.19 kN/m^3, and 18.05 kN/m^3. All specimens were compacted to approximately 95% of their respective maximum dry densities to ensure consistent relative compaction across all mixtures (ASTM D698, 2021).

Following compaction, the specimens were divided into two curing regimes. One set of specimens was cured under ambient laboratory conditions for periods of 7 and 28 days to serve as the normally cured reference. The second set was subjected to carbonation curing in a sealed ageing cell under pure CO_2 immediately after compaction to minimize moisture redistribution and allow early-stage gas-liquid interaction. A constant initial CO_2 pressure of 95 psi was applied, and the internal pressure was continuously monitored with time (Figure 3). Carbonation was allowed to proceed until pressure stabilization was observed and no further measurable reduction occurred. This stabilization was interpreted as cessation of significant CO_2 consumption under the applied curing conditions, indicating that the system had reached a near-equilibrium state for the given pressure and temperature.

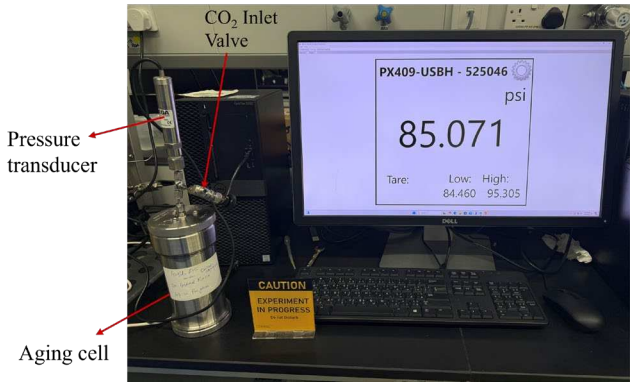

Figure 3. Carbonation test setup with real time pressure monitoring

After curing, UCS tests were performed in accordance with (ASTM D2166, 2021) to evaluate the mechanical performance of the treated soils under

both curing regimes. Mineralogical changes induced by carbonation were analysed using XRD. The extent of CO_2 uptake and carbonate formation was quantified using total inorganic carbon (TIC) analysis. This experimental framework enabled a systematic comparison of conventional curing and carbonation-assisted stabilization across varying serpentinite contents and curing durations.

3 RESULTS AND DISCUSSION

3.1 Unconfined compressive strength behaviour under normal curing

Figure 4 illustrates the axial stress-strain response of untreated silty sand (SM) and specimens treated with 1%, 3%, and 5% serpentinite (SM-S1, SM-S3, and SM-S5) under normal curing conditions at 1 and 7 days. The untreated soil exhibited low peak axial stress and strain-softening behaviour, reflecting its weak particle bonding and loose fabric. In contrast, serpentinite-treated specimens showed a clear increase in peak stress and improved strain capacity, with strength enhancement becoming more pronounced as serpentinite content increased.

After 1 day of curing, the untreated soil exhibited peak axial stress of approximately 50 kPa. The inclusion of serpentinite resulted in substantial early-age strength gains, with peak stresses of about 105 kPa, 130 kPa, and 155 kPa for 1%, 3%, and 5% serpentinite contents, respectively. These values correspond to approximate UCS improvements of 110%, 160%, and 210% relative to the untreated soil. The enhanced response at higher serpentinite contents can be attributed primarily to the physical filler effect and improved particle packing, which increase interparticle contact and load transfer even at early stages of curing.

At 7 days of normal curing, further strength development was observed for all treated specimens. The untreated soil reached a peak axial stress of approximately 60 kPa, while specimens treated with 1%, 3%, and 5% serpentinite achieved peak stresses of about 140 kPa, 185 kPa, and 205 kPa, respectively. These correspond to UCS increases of approximately 133%, 208%, and 242% compared to the untreated soil. The continued strength gain with curing time suggests progressive densification and fabric stabilization within the soil matrix, although the absence of CO_2 curing limits the extent of chemical bonding and cementation. Overall, the normal curing results demonstrate that serpentinite contributes to significant mechanical improvement even without carbonation, with strength increasing systematically with dosage and curing time. However, stress-strain responses indicate that strength enhancement under normal curing is governed primarily by physical mechanisms rather than chemical cementation, highlighting the importance of carbonation-assisted curing for achieving higher strength levels, as discussed in the subsequent sections.

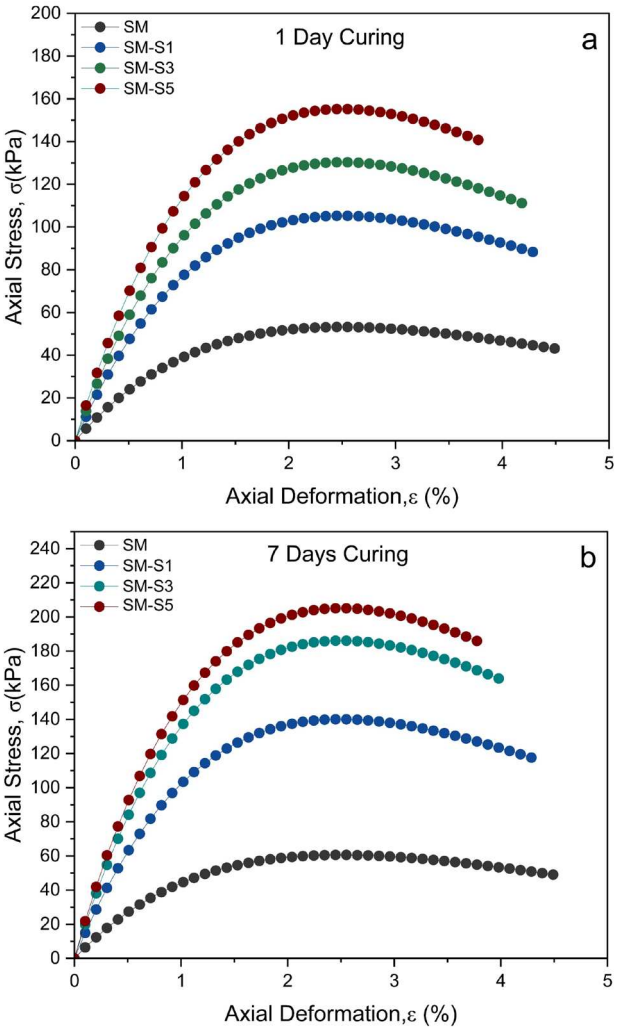

Figure 4. Axial stress-strain response of untreated and serpentinite-treated silty sand under normal curing of (a) 1 day and (b) 7 days

3.2 Unconfined compressive strength behaviour after carbonation

Figure 5 presents the axial stress-strain response of silty sand specimens treated with 1%, 3%, and 5% serpentinite after carbonation curing for only 24 hours under pressurised CO_2 conditions designated as SM-C-S1, SM-C-S3, and SM-C-S5 respectively. Compared to normally cured specimens, carbonation resulted in a marked enhancement in both peak axial stress and stiffness, despite the significantly shorter curing duration. This demonstrates the effectiveness

of carbonation-assisted stabilization in accelerating strength development in serpentinite-treated soils.

After 24 hours of carbonation, peak axial stresses of approximately 90 kPa, 160 kPa, and 215 kPa were achieved for specimens containing 1%, 3%, and 5% serpentinite, respectively. When compared with the 7-day normally cured results, these values represent substantial strength gains. For instance, specimens treated with 5% serpentinite reached a UCS of approximately 215 kPa after just 24 hours of carbonation, exceeding the 7-day normally cured strength of about 205 kPa. Similarly, the 3% serpentinite specimen exhibited a peak strength of approximately 160 kPa under carbonation, compared to about 185 kPa after 7 days of normal curing, while achieving this strength in a fraction of the curing time. Even at the lowest dosage, the carbonated 1% serpentinite specimen displayed a UCS approximately 50% higher than its 7-day normally cured counterpart.

These comparisons clearly indicate that carbonation curing is significantly more effective than conventional curing in promoting early strength development. While normal curing relies primarily on gradual densification and physical rearrangement of particles, carbonation curing induces rapid chemical bonding through mineral carbonation reactions. The dissolution of magnesium-bearing phases from serpentinite, enhanced by the presence of the chelating agent, leads to the precipitation of hydrated magnesium carbonates within the soil matrix. These reaction products act as cementitious bridges between soil particles, resulting in enhanced load transfer, reduced pore connectivity, and increased resistance to deformation.

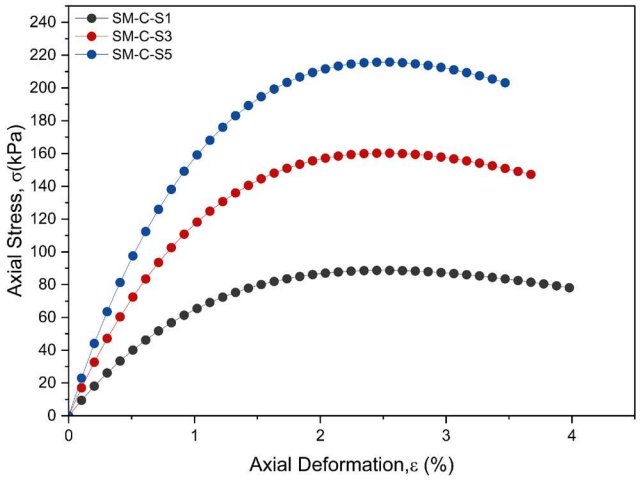

Figure 5. Axial stress-strain response of serpentinite-treated silty sand after 24 hours of carbonation curing under pressurized CO_2

The stress-strain curves further reveal that carbonated specimens exhibit higher initial stiffness and delayed post-peak softening compared to normally cured samples. This behaviour reflects the formation of a more cohesive and interlocked soil fabric due to carbonate precipitation. The ability to achieve strengths comparable to, or exceeding, 7-day normal curing within only 24 hours of carbonation highlights the potential of serpentinite-based carbonation as a rapid and efficient stabilization technique. Overall, the results demonstrate that carbonation curing not only enhances the magnitude of strength gain but also significantly accelerates the stabilization process. This rapid strength development is particularly advantageous for time-sensitive construction applications, where early load-bearing capacity is required. The findings confirm that serpentinite-driven carbonation provides a superior alternative to conventional curing, offering both mechanical improvement and permanent CO_2 sequestration within a substantially reduced curing period.

3.3 Mineralogical and microstructural evidence of carbonation

Figure 6 presents the XRD patterns of untreated silty sand and serpentinite-treated specimens after carbonation curing. The untreated soil exhibits diffraction peaks associated with its native mineral assemblage, with no evidence of newly formed carbonate phases beyond naturally occurring constituents. In contrast, the carbonated specimens display clear mineralogical changes, with the emergence and progressive intensification of carbonate-related peaks as serpentinite content increases.

For carbonated specimens containing serpentinite, additional diffraction features appear in the 2θ range typically associated with hydrated magnesium carbonate phases. The intensity of these peaks increases systematically from SM-C-S1 to SM-C-S5, indicating a higher extent of carbonation with increasing serpentinite dosage. This trend confirms that serpentinite provides a reactive source of magnesium-bearing minerals that actively participate in CO_2 mineralization under pressurised carbonation conditions. The absence of comparable peak development in the untreated soil further demonstrates that carbonation is driven primarily by the introduced serpentinite rather than by native soil minerals.

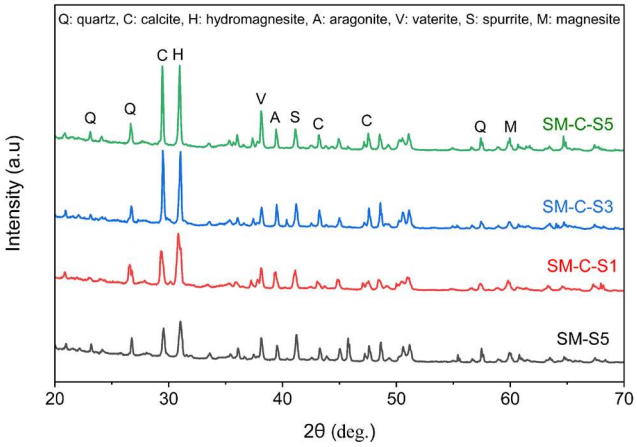

Figure 6. XRD patterns of untreated and serpentinite-treated silty sand before and after carbonation curing

The mineralogical observations are strongly supported by total inorganic carbon (TIC) measurements. TIC was determined using acid digestion followed by CO_2 quantification using a carbon analyzer. In this method, carbonate-bound carbon reacts with acid to release CO_2 gas, which is measured and converted to inorganic carbon content. The analysis isolates carbonate-derived carbon and excludes organic carbon fractions. As shown in Figure 7, the untreated soil exhibits a baseline TIC of approximately 3.05%, attributable to naturally occurring carbonates. Following carbonation curing, TIC increased progressively to 4.16%, 6.35%, and 9.68% for 1% (SM-C-S1), 3% (SM-C-S3), and 5% (SM-C-S5), serpentinite-treated specimens, respectively. The observed increase suggests enhanced CO_2 uptake with increasing serpentinite dosage. Although the relationship was non-linear, likely due to kinetic and diffusion constraints, the trend is consistent with mineralogical changes observed in XRD patterns. These results indicate precipitation of hydrated magnesium carbonates under the applied curing conditions.

The combined XRD and TIC results provide compelling evidence that carbonation curing induces the formation of thermodynamically favorable hydrated magnesium carbonate phases under ambient conditions. The higher TIC values associated with increased serpentinite content indicate more extensive precipitation of magnesium carbonates, which act as cementitious products bridging soil particles. This mineral carbonation mechanism directly explains the substantial strength gains observed in carbonated specimens, particularly the ability to achieve UCS values exceeding those of 7-day normally cured samples within only 24 hours of carbonation.

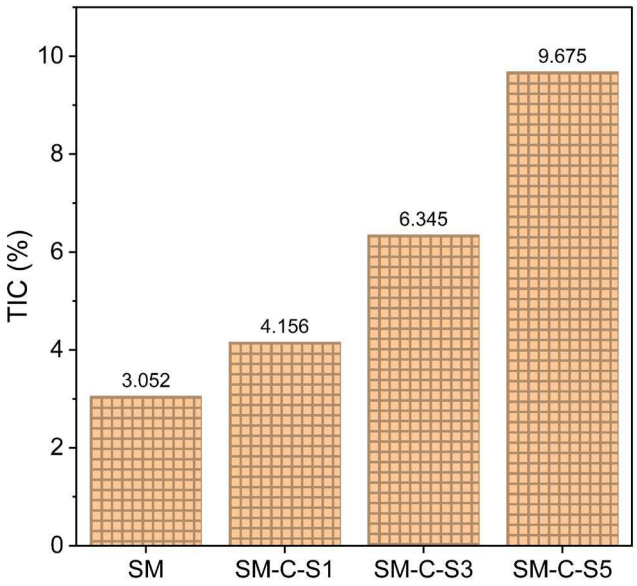

Figure 7. TIC content of untreated and carbonated silty sand specimens at different serpentinite dosages

4 FIELD APPLICABILITY AND PRACTICAL IMPLICATIONS

The results of this study demonstrate that serpentinite-based carbonation stabilization has strong potential for practical ground improvement applications, particularly where rapid strength development and reduced carbon footprint are required. The ability to achieve strength levels comparable to, or exceeding, 7-day normally cured specimens within only 24 hours of carbonation highlights the suitability of this approach for time-sensitive construction scenarios such as temporary working platforms, pavement subgrades, and foundation preparation in marginal soils.

From a field implementation perspective, serpentinite rock powder is a viable stabilizing material due to its wide availability as a quarry by-product and its high content of reactive magnesium-bearing minerals. The dosages investigated in this study are within practical ranges for large-scale soil treatment and do not require excessive material handling or specialized mixing equipment. The carbonation process relies on controlled CO_2 exposure rather than high-temperature processing, making it compatible with modular or mobile curing systems that could be deployed on-site or at centralized treatment facilities.

The carbonation curing approach is particularly well suited for applications where controlled environments can be established, such as prefabricated soil blocks, mechanically stabilized layers, or confined ground improvement zones. Pressure monitoring, as demonstrated in this study,

provides a simple and effective means of tracking carbonation progress and ensuring reaction completion. Moreover, the conversion of injected CO_2 into stable carbonate minerals ensures permanent sequestration, reducing concerns related to long-term CO_2 leakage or durability.

Despite these advantages, field-scale application will require further consideration of factors such as moisture control, gas distribution efficiency, and curing uniformity in heterogeneous soil masses. Long-term durability under cyclic loading, wetting-drying, and freeze-thaw conditions should also be evaluated. Nevertheless, the present findings establish a strong experimental foundation for scaling serpentinite-driven carbonation stabilization as a low-carbon alternative to conventional cement-based ground improvement methods.

5 CONCLUSIONS

This study investigated the potential of serpentinite rock powder as a dual-function material for sustainable ground improvement and carbon sequestration through mineral carbonation. Based on the experimental results, the following conclusions can be drawn:

1. Serpentinite significantly improved soil strength under normal curing, with UCS increasing systematically with dosage and curing time. At 7 days of normal curing, UCS improvements of up to approximately 240% were achieved for specimens treated with 5% serpentinite compared to untreated silty sand.
2. Carbonation curing resulted in rapid and substantial strength enhancement, enabling specimens to achieve UCS values comparable to or exceeding 7-day normally cured samples within only 24 hours of CO_2 exposure. This demonstrates the effectiveness of carbonation-assisted stabilization in accelerating strength development.
3. Pressure reduction during carbonation indicated active CO_2 consumption. Subsequent pressure stabilization suggests that measurable gas-solid reactions diminished under the applied curing conditions.
4. XRD patterns and TIC measurements provided evidence consistent with precipitation of hydrated magnesium carbonate phases and increased inorganic carbon content with increasing serpentinite dosage.
5. The findings demonstrate that serpentinite-assisted carbonation under controlled laboratory conditions has potential as a low-carbon alternative to conventional stabilization methods. Further investigation is required to evaluate long-term durability, field implementation, and the specific contribution of GLDA to reaction enhancement.

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