

**MAGNESIA-BASED BINDERS FOR SOFT SOIL
STABILIZATION**

BY

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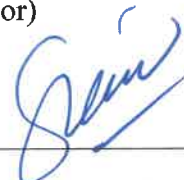


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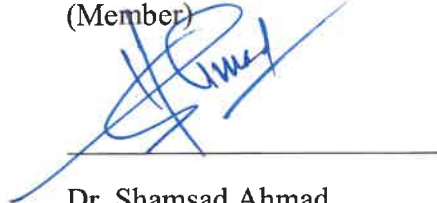
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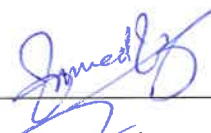
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Dedication

To my beloved family, whose unwavering support, endless encouragement, and boundless love have been my greatest source of strength, especially my parents, whose sacrifices and prayers carried me through every challenge. To all those who believed in me when the path seemed uncertain, this work is for you.

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ABSTRACT

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Conventionally, ordinary Portland cement has been employed to stabilize marl, which is known for its high compressibility, limited shear strength, and significant volumetric instability under moisture variation; however, its high carbon emissions and energy-intensive production process raise significant environmental concerns, especially in the context of sustainable construction practices. As environmentally responsible alternatives, this study explores the use of Reactive Magnesia Cement (RMC) and Magnesium Oxychloride Cement (MOC) for enhancing the engineering performance of marl soil. Marl is a calcareous, clay-rich sedimentary material characterized by high compressibility, low shear strength, and pronounced volume changes when exposed to moisture, which make it unsuitable for direct use in infrastructure projects without prior treatment. To address these challenges, marl specimens were treated with varying dosages of RMC and MOC, and the resulting improvements were evaluated through a series of mechanical and microstructural tests. The mechanical properties assessed included Unconfined Compressive Strength, Elastic Modulus, toughness, and failure strains, while the microstructural changes were investigated using X-ray Diffraction and Scanning Electron Microscopy. The results indicate that both RMC and MOC significantly enhanced the mechanical properties and microstructural integrity of the Soil, with MOC demonstrating particularly high early-age strength. These findings demonstrate the potential of magnesia-based binders as effective and environmentally conscious alternatives to OPC, offering promising solutions for stabilizing marl soil in geotechnical and infrastructure applications.

الملخص

الاسم الكامل: محمد مختار هارون

عنوان الرسالة: المواد الرابطة القائمة على الماغنسيوم لتحسين خصائص التربة الطرية

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يُستخدم الإسمنت البورتلاندي العادي تقليدياً في تحسين تربة المارل، والتي تُعرف بارتفاع قابليتها للانضغاط، وضعف إلا أن عملية إنتاجه تتسم بكثافة استهلاك الطاقة، مقاومتها للقص، وعدم استقرارها الحجمي الكبير عند تغير الرطوبة وانبعثات كربونية مرتفعة، مما يثير مخاوف بيئية كبيرة، خاصة في ظل التوجه نحو ممارسات إنشاء مستدامة. وفي هذا السياق، تهدف هذه الدراسة إلى استكشاف بدائل صديقة للبيئة، من خلال استخدام إسمنت الماغنسيوم التفاعلي وإسمنت أوكسي كلوريد الماغنسيوم. تُعد تربة المارل مادة رسوبية غنية بالطين وغنية بالكالسيوم، تتميز بقابليتها العالية للانضغاط، وانخفاض مقاومة القص، وتغيرات حجمية واضحة عند التعرض للرطوبة، مما يجعلها غير صالحة للاستخدام المباشر في RMC مشاريع البنية التحتية دون معالجة مسبقة. ولمعالجة هذه التحديات، تم معالجة عينات المارل بنسب مختلفة من ، وتم تقييم التحسينات الناتجة من خلال سلسلة من الاختبارات الميكانيكية والمجهريّة. شملت الخصائص MOC و الميكانيكية التي تم تقييمها كلاً من مقاومة الضغط غير المحصور، معامل المرونة، الصلابة، والانفعالات عند الفشل، في (SEM) والمجهر الإلكتروني الماسح (XRD) حين تم تحليل التغيرات المجهرية باستخدام حيود الأشعة السينية.

حسناً بشكل ملحوظ الخصائص الميكانيكية والسلامة المجهرية للتربة، حيث MOC و RMC أظهرت النتائج أن كلاً من قوة عالية في الأعمار المبكرة. وتدل هذه النتائج على أن المواد الرابطة القائمة على الماغنسيوم تُعد بدائل MOC أظهر فعالة وصديقة للبيئة للإسمنت البورتلاندي، مما يوفر حلاً واعداً لتنشيط تربة المارل في تطبيقات الهندسة الجيوتقنية ومشاريع البنية التحتية

CHAPTER 1: INTRODUCTION

Marl is a calcareous soil or rock-like material characterized by a calcareous content of 35–65% and varying percentages of clay, silt, sand, and organic matter [2]–[5]. Due to its heterogeneous composition, marl exhibits a wide range of engineering behaviors, often leading to problematic performance in geotechnical applications [4]. It is particularly sensitive to variations in water content, which can significantly degrade its strength and bearing capacity. Without proper stabilization, water infiltration can lead to swelling, strength loss, and structural instability in civil infrastructure [5], [4].

In eastern Saudi Arabia, marl soils are frequently used as fill material, despite their problematic nature [6]–[8]. The low bearing capacity and high expansion potential of marl can result in subgrade shrinkage and settlement, which adversely affect pavement and foundation performance [9], [10]. Consequently, pre-treatment or stabilization is commonly required before construction to ensure long-term durability and performance.

One widely used technique to improve soil properties is chemical stabilization, which involves mixing binders with the soil to enhance its mechanical and physical characteristics. Among these, lime and Ordinary Portland Cement (OPC) are the most commonly applied stabilizers [12]–[16], [21]. These binders improve soil strength, volume stability, and permeability through the formation of cementitious compounds such as calcium silicate hydrates (C-S-H), calcium aluminate hydrates (C-A-H), and calcium aluminum silicate hydrates (C-A-S-H) [23], [24]. The stabilization process includes cation exchange, flocculation, and pozzolanic reactions, particularly in clay-rich soils [23].

About 4 billion tonnes of Portland cement were produced in 2014, making it the most widely used type of cement globally. This cement, which was given its name in the 19th century due

to its apparent visual similarity to limestone quarried from the Isle of Portland in the United Kingdom, is made up mainly of hydraulic calcium silicate phases that are created in a kiln at high temperatures to create "clinker," which is subsequently cooled and mixed with gypsum [6]. When mixed with water, the resulting powder, which is hydraulic cement, will hydrate and form a cohesive, robust, and dimensionally stable monolith. However, due to its significant CO₂ emissions footprint [7], which currently accounts for about 8% of global anthropogenic greenhouse-gas emissions, there is a continuous search for alternatives [8]. The large class of MgO-based cements has been utilized in industrial practice for more than 150 years and has been recognized as a possible low-CO₂ substitute for PC.

The global cement and concrete association has set a goal to achieve net-zero CO₂ concrete by 2050, with substitution, carbon capture and utilization/storage (CCU/S) approaches and alternatives to Portland cement accounting for 45% of the reduction. Given their potential for low-to-negative CO₂ emissions (CCU/S) and their status as Portland cement substitutes, magnesium-based cements present a viable solution to this issue. Magnesia can originate from desalination brines or magnesium silicates, which are carbon-free for emissions related to raw materials [9]. This creates the potential for carbon emissions to be low or even negative.

Environmental concerns have been the primary driving force behind the development and adoption of MgO-based cements in recent decades. Many people see MgO-based cements as being essential to the production of environmentally friendly cements in the future because of the lower temperatures needed to produce MgO compared to the conversion of CaCO₃ to PC and the energy savings that come with this lower temperature. The discussion of "carbon-neutral" cements, which have the potential to absorb nearly as much CO₂ over the course of their service life as was released during their manufacture, is also made easier by MgO's capacity to absorb CO₂ from the atmosphere in order to form a variety of carbonates and

hydroxycarbonates. Due to these two interrelated factors, interest in MgO-based cements has recently skyrocketed on both a commercial and academic level [10].

1.1 Problem statement

The production and use of OPC represents the most significant environmental challenges of the construction sector, accounting for about 8% of the global CO₂ emissions. The manufacturing process is inherently carbon-intensive, requiring high-temperature kiln operations (1400-1500°C) that consume substantial energy while releasing nearly one ton of CO₂ for every ton of cement produced. The continued dominance of OPC in construction materials underscores the urgent need to develop and implement alternative binders with lower embodied energy and reduced carbon emissions.

Magnesia-based binders, such as Reactive Magnesia Cement (RMC) and Magnesium Oxychloride Cement (MOC), offer a sustainable solution due to their significantly lower production temperatures (700-1000°C) compared to OPC, resulting in reduced energy consumption and CO₂ emissions. These binders demonstrate unique environmental benefits through their ability to sequester CO₂ during their lifespan, contributing to a negative carbon footprint in some applications. Their rapid early strength development makes them particularly attractive for construction applications where fast setting is advantageous. The chemical composition of these binders, derived from magnesium oxide rather than calcium carbonate, presents fundamentally different hydration mechanisms that may prove more compatible with certain challenging materials. These materials offer a viable way to lessen the environmental impact of the construction sector.

RMC and MOC offer distinct advantages for soil stabilization, particularly for problematic soils like Marl, which often exhibit low bearing capacity, high compressibility, and swelling behavior. These binders demonstrate rapid strength development, making them suitable for

projects requiring quick turnaround times. Their lower carbon footprint compared to OPC aligns with growing demands for sustainable geotechnical solutions. However, despite their potential, the use of RMC and MOC in geotechnical applications remains largely unexplored, with limited research on their long-term performance, optimal dosages, and economic feasibility for soil stabilization. The purpose of this study is to fill in these gaps by rigorously evaluating the effectiveness of RMC and MOC as sustainable alternatives to traditional OPC-based stabilization methods, potentially paving the way for wider adoption in geotechnical engineering practice.

1.2 Objectives of the study

1.2.1 Improve the Mechanical Properties of Marls using RMC and MOC

Improving the effect of RMC and MOC on the mechanical parameters, including shear strength (via direct shear or triaxial tests), stiffness (E50), toughness (energy absorption capacity), and failure strain (deformation at peak stress) of Marl soil.

1.2.2 Evaluate the Performance of RMC, MOC and OPC Stabilized Marl Soil

Compare the stabilization efficiency and material costs of RMC and MOC with Conventional OPC. The results will guide future applications of eco-friendly binders in geotechnical engineering by providing data-driven insights into both technical and economic feasibility.

1.3 Significance of the study

The use of RMC and MOC for soil stabilization has been explored in various contexts, but this study represents the first known application of these binders to stabilize marl soil. Marl soil, characterized by its high calcium carbonate content and variable plasticity, poses unique challenges in achieving durable stabilization due to its susceptibility to shrinkage and swelling under moisture changes. Whereas conventional binders like OPC have been widely used for soil stabilization, their environmental impact and limited efficacy in certain soil

types necessitate alternative solutions. RMC, with its capacity for carbon sequestration and self-healing properties, and MOC, known for its superior strength and fast-setting characteristics, offer innovative approaches to address these challenges. This novel application of RMC and MOC to marl soil aims to enhance the mechanical properties of Marl while contributing to sustainable construction practices.

1.4 Scope of the study

This study is confined to a laboratory-based investigation of the mechanical behavior and microstructural characteristics of Marl soil stabilized with RMC and MOC, with comparisons made to OPC stabilization. The research focuses on assessing key engineering properties, including shear strength, stiffness, and deformation characteristics, alongside microstructural evolution through advanced analytical techniques. While the findings aim to provide insights into the performance of alternative binders, the scope is limited to controlled laboratory conditions, excluding field-scale validation and long-term durability assessments. The comparative analysis emphasizes the potential of RMC and MOC as sustainable substitutes for OPC in soil stabilization applications.

CHAPTER 2: LITERATURE REVIEW

2.1 Soil Stabilization

The challenge of constructing roads, dams, foundations, and other engineering projects in places with inadequate or substandard soils is a significant issue for engineers. In some cases, subgrade soils that are deemed inadequate in their inherent condition might be enhanced using certain geotechnical techniques [11]. The process of altering the properties of soil using chemical or physical means in order to enhance the soil's engineering qualities is known as soil stabilization [12],[13],[14]. Finding the best soil stabilizers to solve the problems with soft soils continues to be the key priority. This entails addressing cost-effectiveness and environmental impact in addition to achieving the intended soil engineering qualities [15],[16].

Combining several soil types to improve the original soil's properties is known as mechanical stabilization. Other methods, however, entail altering the original soil and improving its engineering qualities by adding particular additives, including cement, lime, grouts, chemicals, etc. Through this procedure, the soil will be made acceptable for a wide range of engineering uses, such as a subgrade for highways and many other engineering settings. The various methods for stabilizing soil have unique advantages and disadvantages, making them suitable for some technological uses but unfitting for others. The main factor influencing the use of soil stabilization technology is the mineral makeup of the host soil. Other factors that influence this utilization include the kind of engineering structure and the local environmental conditions, among others [11].

There are many soil stabilization methods, including Polymer stabilization, as discussed by

[77]. This process entails the utilization of a diverse range of polymers, including geopolymers, biopolymers, and synthetic organic polymers, with the aim of augmenting the characteristics of soil. These polymers engage in interactions with soil particles via processes such as electrostatic forces, resulting in enhanced soil strength and stability. The efficacy of these polymers is contingent upon their physicochemical characteristics, including factors such as molecular weight, particle dimensions, and pH levels. Naimoon et. al.[17] The approach emphasizes the use of economically viable resources such as Portland cement, lime, fly ash, and scrap tire for the purpose of soil stabilization. These materials not only provide a cost-effective option but also contribute to waste management and environmental preservation. This study investigates specific techniques for soil stabilization, such as the use of sodium hydroxide additive, fly ash geo-polymeric binder, and other cementation binders, in order to address the issue of stabilizing soft soil [15].

The use of lime treatment has been shown to be efficacious in enhancing the performance of soils with high activity levels, leading to notable improvements in key attributes such as bearing capacity and resistance to weathering [12]. Helwig et. al. [18] examines contemporary methodologies, such as the use of bituminous stabilizing agents and cementation materials, emphasizing the significance of selecting an appropriate stabilizing agent based on the Plasticity Index (PI) of the soil. Jawad et. al. [19] presents a comprehensive examination of lime treatment, including an analysis of its advantages and problems. Additionally, other treatments such as magnesium oxide/hydroxide are proposed as potential substitutes. While lime treatment has several benefits, it is not without its limitations, notably carbonation and sulphate attack.

Furthermore, the addition of leftover marble powder to MPC has demonstrated notable improvements in the soils' shear strength and load-bearing ability. By employing waste

products and stabilizing the soil at the same time, this method offers two benefits [20]. Moreover, using binders based on magnesia provides an environmentally friendly choice, lowering energy use and carbon dioxide emissions throughout the production process [21]. According to research, binders based on magnesia can improve soft soils' compressive strength, which is essential for a structure's ability to support loads. Precise chemical balancing is necessary because the $\text{H}_2\text{O}/\text{MgCl}_2$ molar ratio and curing time affect the UCS of such soils [22]. Using techniques like the response surface approach, the optimal binder compositions for maximal UCS have been determined. [21]. Fast early strength improvements have been associated with optimal MgO , MgCl_2 , and H_2O levels, which is advantageous for building schedules [23].

Soil toughness has increased when MPC is combined with organic elements like jute fibers [24]. In sulfate-rich soils, MgO -based binders with GGBS have exceeded the strength provided by lime [25]. Additionally, MgO has successfully stabilized peat soils, especially when the OPC to MgO ratio is at its ideal after adequate curing [26]. The diverse prospectives of MgO -based binders for soil Treatment is highlighted by these findings, which call for tailored strategies for various soil types. Researchers saw significant improvements in soil stabilization indicators when they combined MPC with MP. After a 28-day curing period, soils treated with 7.5% MPC and 15% MP had enhanced CBR value, higher MDD, and a UCS of 1953.65 kPa. A denser soil structure and increased load-bearing capacity are correlated with these improvements.

Furthermore, a decrease in OMC and Atterberg limits was noted, indicating a more stable soil that is less sensitive to moisture and suitable for strong engineering applications. [20]. Several Studies [23], [27], and [28] accentuate the fact that binders based on magnesia increase the solidified soils' resilience. With the exception of nickel, these binders not only provide more durability than traditional cement in MOC-solidified soil, as demonstrated by

improved mechanical property maintenance following cycles of capillary soaking and drying, but they also have a smaller environmental impact, with heavy metal leaching over a three-year period staying below drinking water standards.

2.1.1 Effect of Cement Treatment on UCS

Figure 2.1 illustrates how cement treatment affects the unconfined stress-strain behavior of Aberdeen soil. Although the corresponding strain to peak axial stress dropped from about 4% to just over 1%, it is noted that cement treatment causes a significant increase in peak axial stress. Therefore, compared to untreated soils, cement-treated soils behave much more brittle. Figure 2.2 illustrates the impact of cement addition on Aberdeen soil's unconfined compressive strength. Unconfined compressive strength has been shown to significantly increase with cement treatment, particularly for cement contents higher than 5% [29].

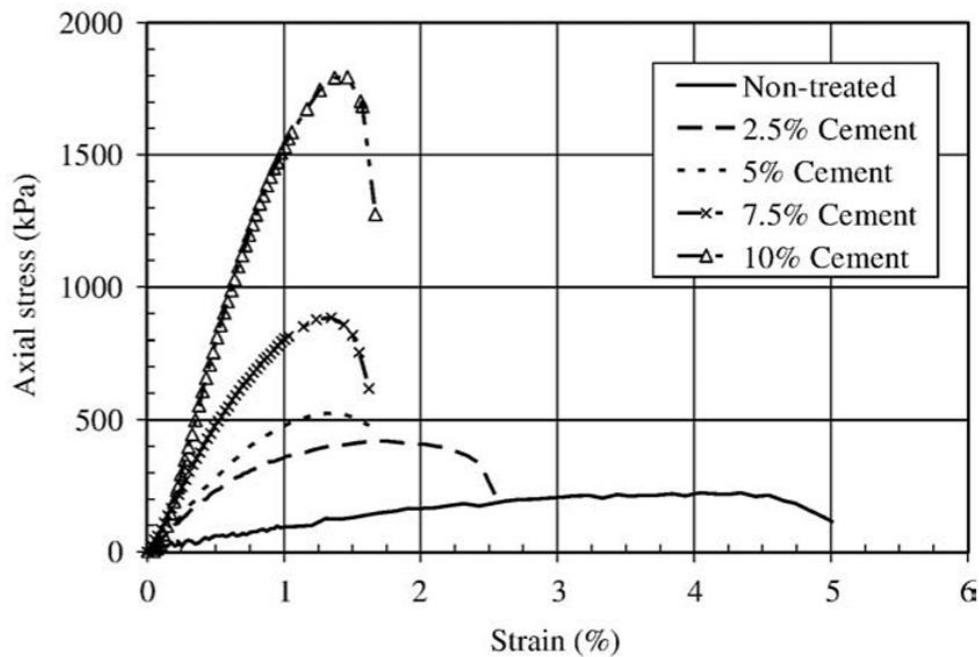


Figure 2.1 Effect of cement treatment on unconfined stress-strain behavior of Aberdeen soil [29].

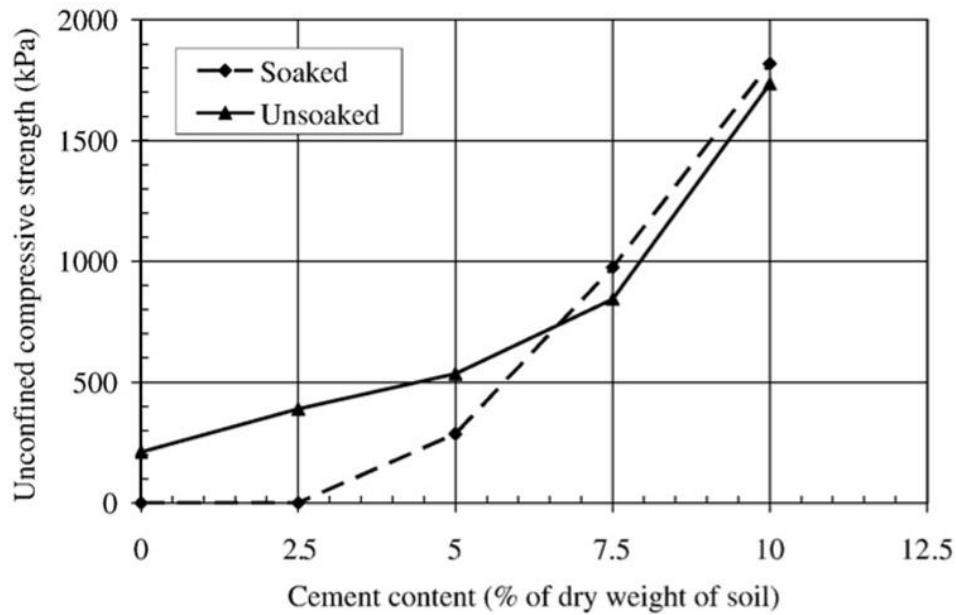


Figure 2.2 Effect of cement stabilization on UCS of Aberdeen soil [29].

Figure 2.3 shows the stress-strain relationships between clays that have been treated with cement and those that have not. The samples with 10% cement and 40% water content had the highest UCS value after 28 days. Nevertheless, the untreated samples with 60% water content had the lowest UCS value.

Because of the hydration processes and ongoing pozzolanic reactions between cement, soil, and water mixtures, the UCS of cement-treated clay generally rises as the curing time increases. The strength increase for cement-soil-water mixtures is significant in the first 28 days and becomes gradual after that. **Error! Reference source not found.** displays the average UCS increasing ratio in order to clearly examine the UCS increasing over time. The average UCS increasing ratio is the amount of UCS that increases daily. According to the findings, strength increases quickly during the first two weeks of treatment and gradually over the next four weeks. The pattern is consistent with cement hydration processes, which stabilize clay soils by reacting cement with water to produce stable calcium silicate and calcium aluminate hydrates. It should be mentioned that the cement content has a direct

correlation with the UCS increasing ratio. The UCS increasing ratio increases with cement content. With 20% cement content, the UCS increasing ratio is two to three times higher than it is with 15% cement content. This further supports the previously stated finding that soils with higher cement content are more resilient to the negative effects of salts than soils with a lower cement content [30].

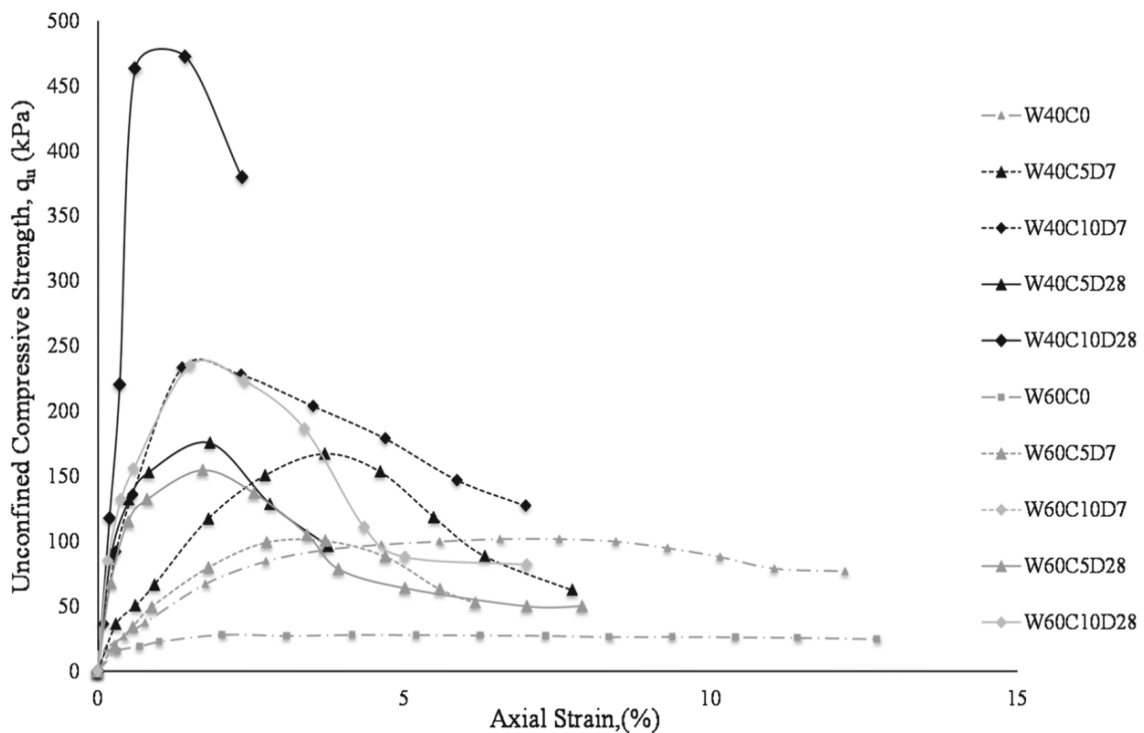


Figure 2.3 stress-strain behavior of Clay and cement-treated clay specimens with varying water and cement contents and curing period [30].

For cement-improved and cement-fiber-improved specimens without curing stress, the correlations between peak strength and curing time are shown in Figure 2.4 even after 90 days for specimens improved with cement and 120 days for specimens enhanced with cement fiber, UCS seems to continue to increase, even though the existing design requirement only requires UCS at a 28-day curing interval. Although there is presently no data for lengthy

curing times, such 180 days or 1 year, it is reasonable to state that the ultimate UCS for cement-treated soils can grow by more than 30% when compared to the UCS at 28 days. The present design criterion for employing 28-day UCS should therefore be cautious with regard to unconfined compressive strength. However, the cement-soil mixture does get more rigid with time [31].

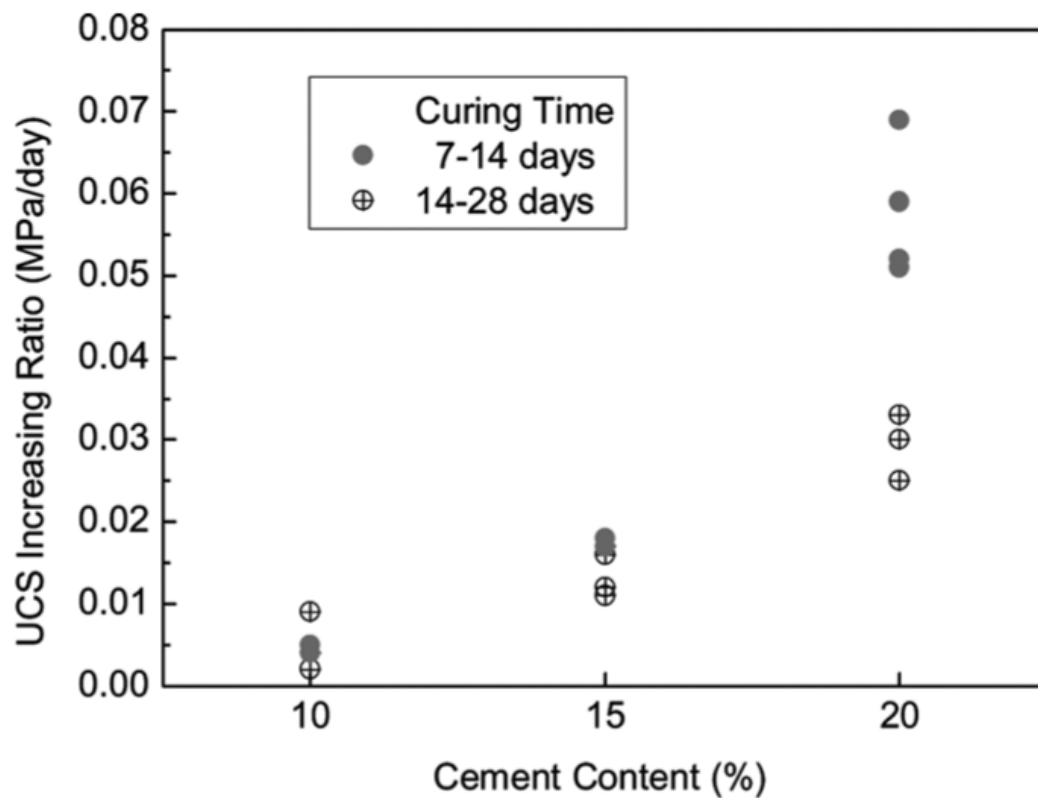


Figure 2.4 UCS increasing ratio versus cement content [30].

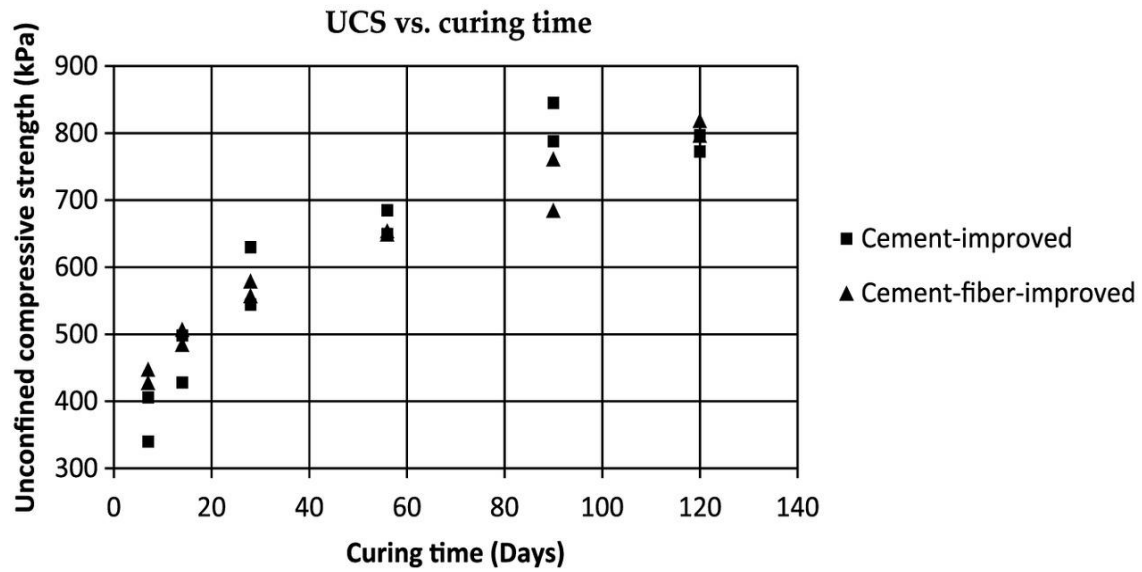


Figure 2.5 UCS versus curing time for soil specimens enhanced with cement and cement-fiber [31].

For deep soil mixing construction, a novel approach to choosing the water-to-cement ratio was studied. Unconfined compressive tests were conducted and the results showed that as the cement content increases, q_u rises for each type of soil as shown in the Figure 2.6 [32]. UCS tests were conducted in order to examine the impact of cement stabilization on the geotechnical characteristics of sandy soils. The fitted lines for the stabilized specimens' maximum UCS as a function of cement percentage (C), taking curing time into account, are shown in Figure 2.7. It is evident that the peak strength of stabilized soil is significantly influenced by the cement content. Small additions of cement, up to 2%, alter the soil's characteristics, whereas large additions drastically alter these characteristics. It is evident that when the cement content rises, UCS rises roughly linearly [33].

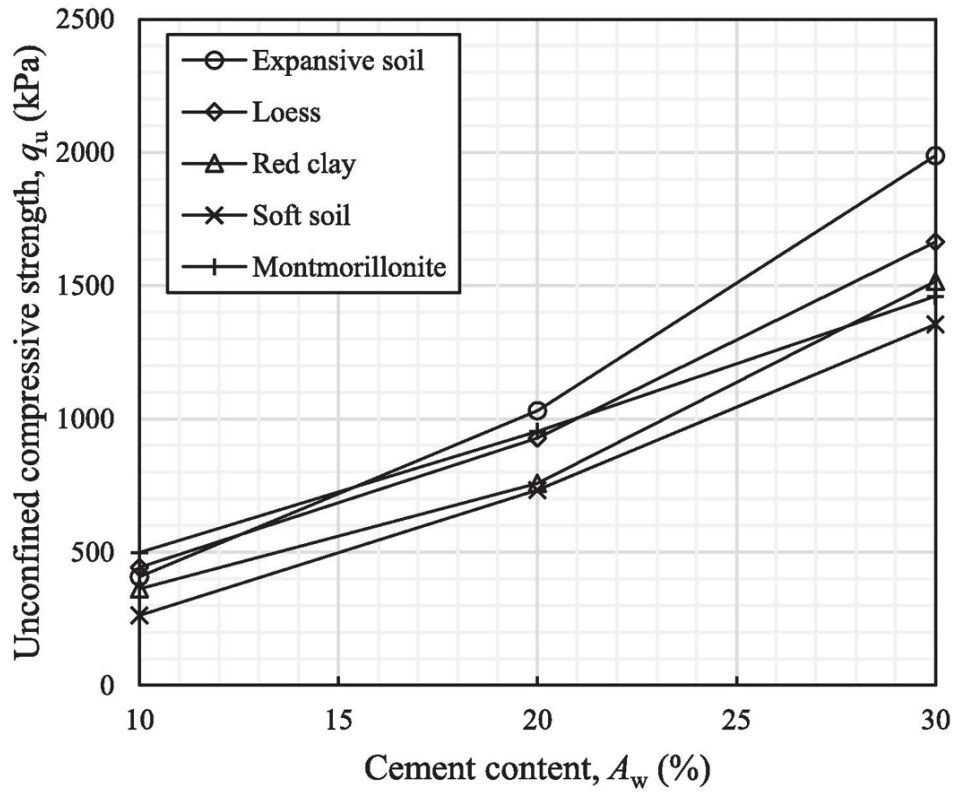


Figure 2.6 variation of q_u with cement content [32].

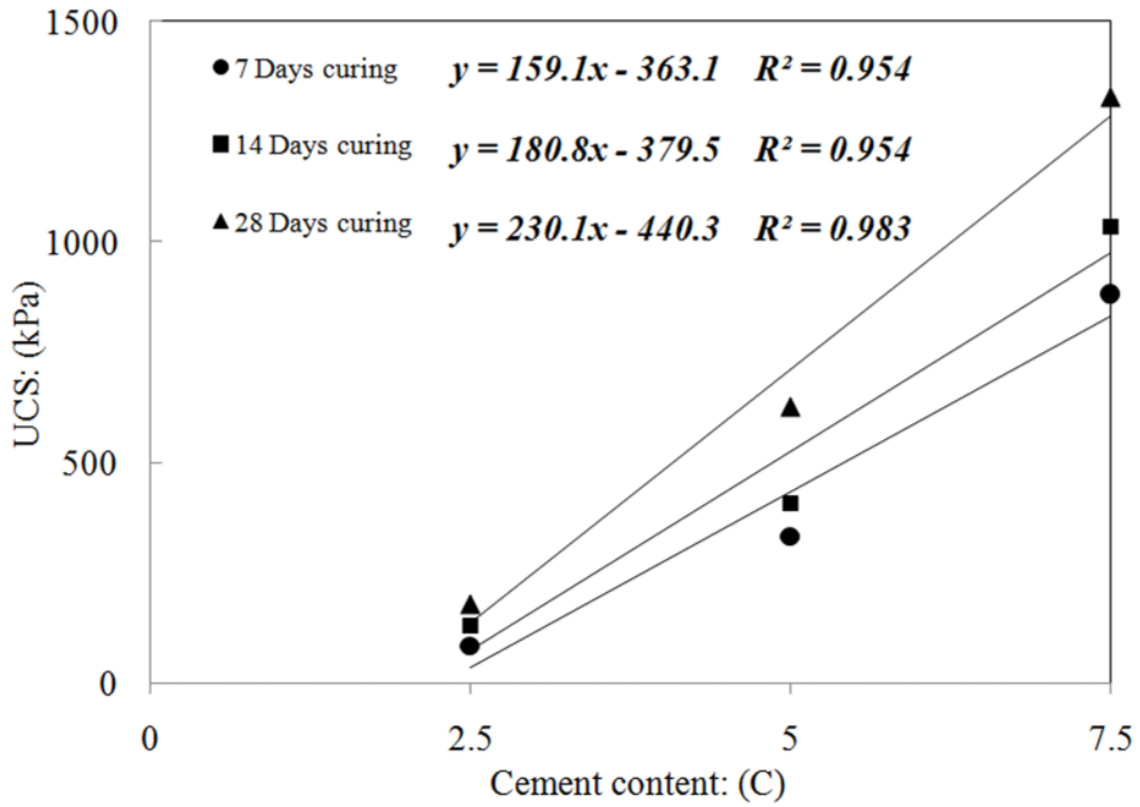


Figure 2.7 Effect of cement contents on UCS [33].

2.1.2 Effect of Cement Treatment on the Modulus of Elasticity

Figure 2.8 illustrates how cement treatment affects the modulus of elasticity for both soaked and unsoaked samples at 30% of the peak axial stress. It is evident that the cement content considerably raised the modulus of elasticity. Fills compacted with cemented soils will therefore experience significantly less deformation [29].

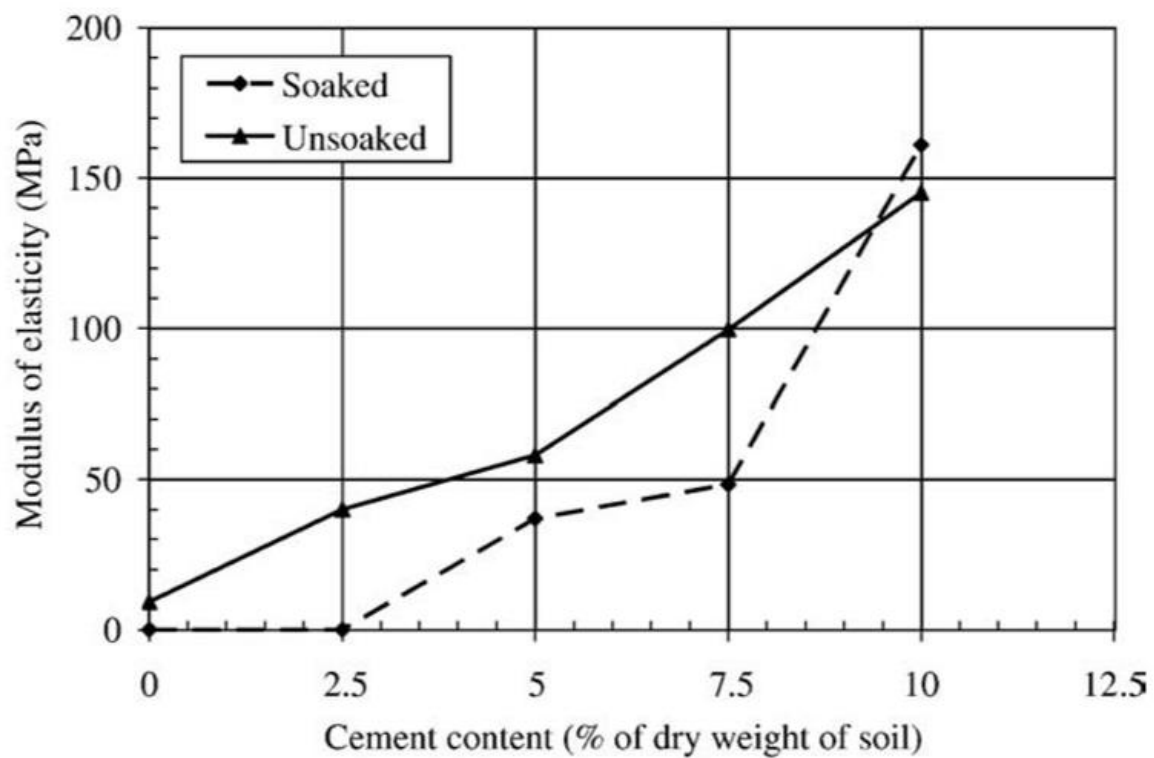


Figure 2.8 Effect of cement treatment on the stiffness of Aberdeen soil [29].

For deep soil mixing construction, a novel approach to choosing the water-to-cement ratio was studied. Secant modulus E_{50} were determined and the results showed that as the cement content increases, E_{50} rises for each type of soil as shown in the Figure 2.9.

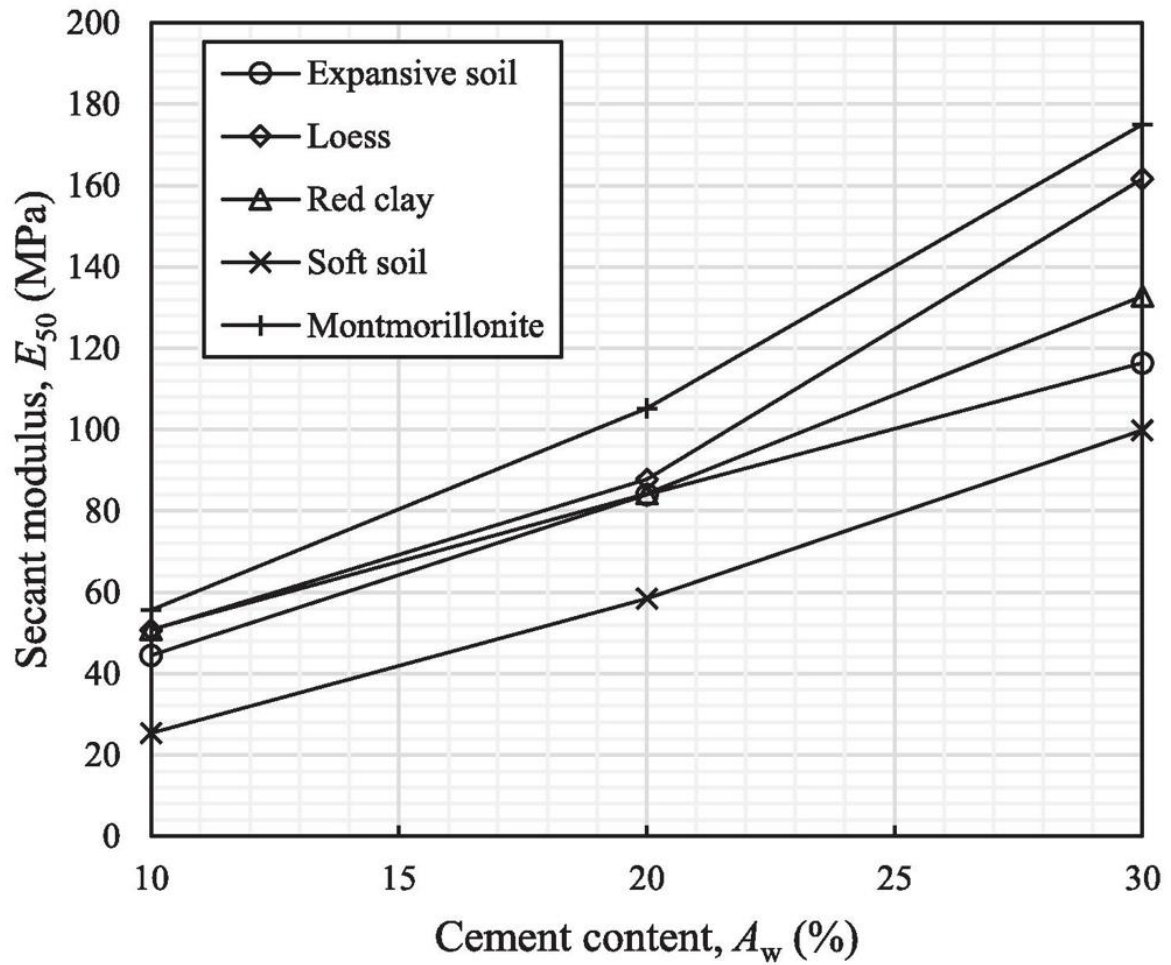


Figure 2.9 variation of E_{50} with cement content [32].

Cement stabilization impact on the modulus of elasticity at 50% of the maximum axial stress (E_{50}) is depicted in Figure 2.10. Cement stabilization and curing time result in a significant improvement in modulus of elasticity, particularly for cement contents higher than 5%. In summary, cement-stabilized soils will withstand significantly less deformation. [33].

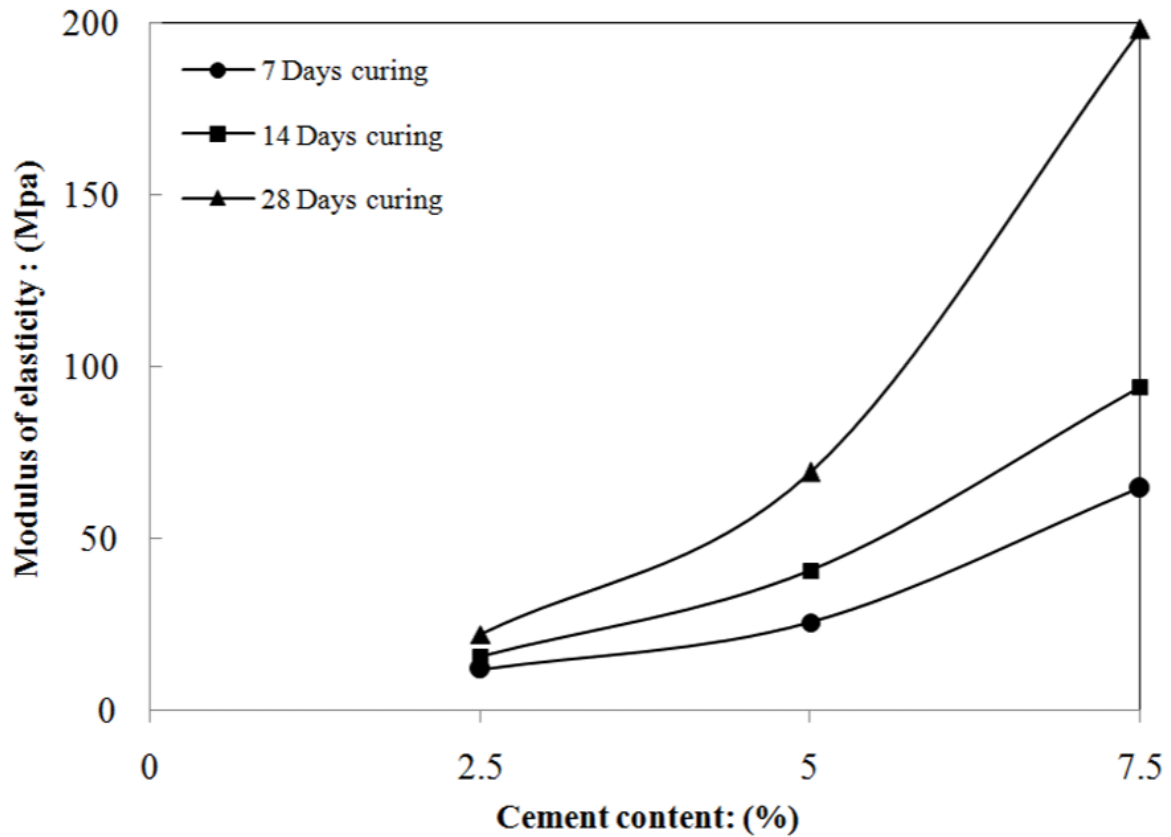


Figure 2.10 Impact of curing time and cement dosage on the modulus elasticity of the soil [33].

2.1.3 Effect of Cement Treatment on the Microstructure Characteristics

The mechanical qualities of soil can be successfully enhanced by the hydration and pozzolanic reactions. The soil particles can be cemented by the hydration products, which include calcium silicate hydrate (C-S-H), ettringite (AFt), and calcium sulfoaluminate hydrates (AFm). Figure 2.11 illustrates the microstructures of cement-stabilized soil and natural soil. The fibrous, acicular, and irregularly petaloid structures of the hydration products give the soil more strength and stiffness [32].

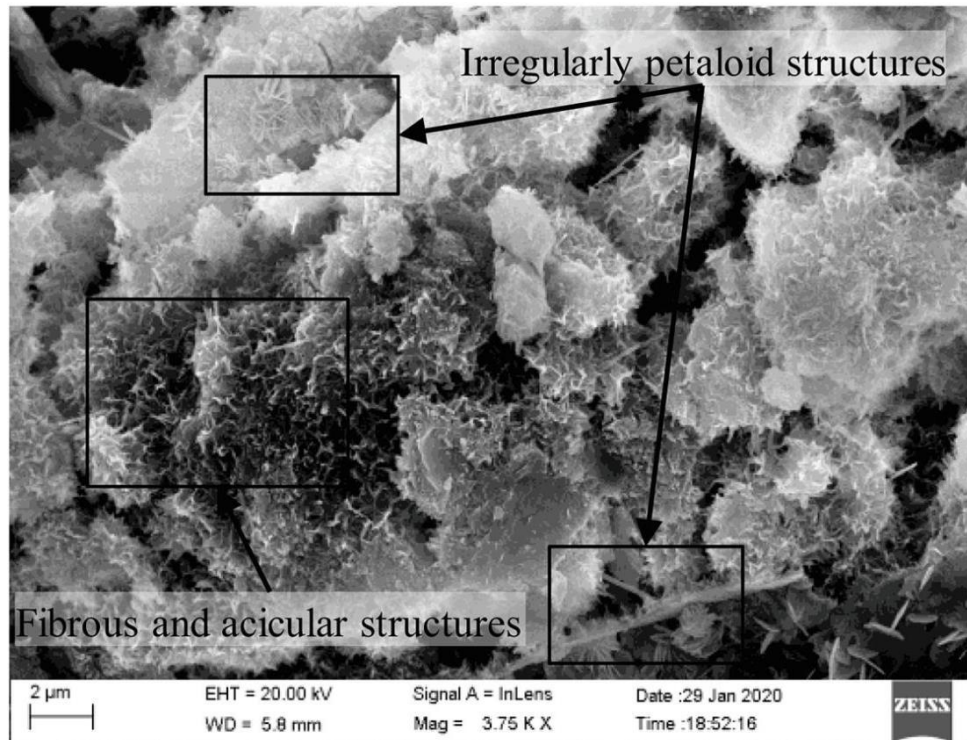


Figure 2.11 SEM image of cement treated soil [32].

The strength development in cement-stabilized salty clay was investigated based on microstructural factors. The microstructure is investigated both qualitatively and quantitatively using a scanning electron microscope, thermal gravity analysis, and studies of the size distribution of mercury intrusion pores. The three primary factors in this study are cement content, curing time, and water content. Soil structure is improved by cement stabilization, which reduces pore space and improves inter-cluster cementation bonding.

Figure 2.12 shows SEM images of the 10% cement samples that were compacted using the modified Proctor energy at different water concentrations and left to cure for seven days. The hydration products (well-knitted framework) are clearly packed in the pores, especially for the samples with $w = 17\%$ (OWC) and 20% (1.2OWC). $w = 14\%$ (0.8OWC) and 24% (1.4OWC) samples have fewer hydration products. The pore volume and the hydration products are both impacted by the water content, especially for the biggest $1.0\text{--}0.1\text{ }\mu\text{m}$ pores [32].

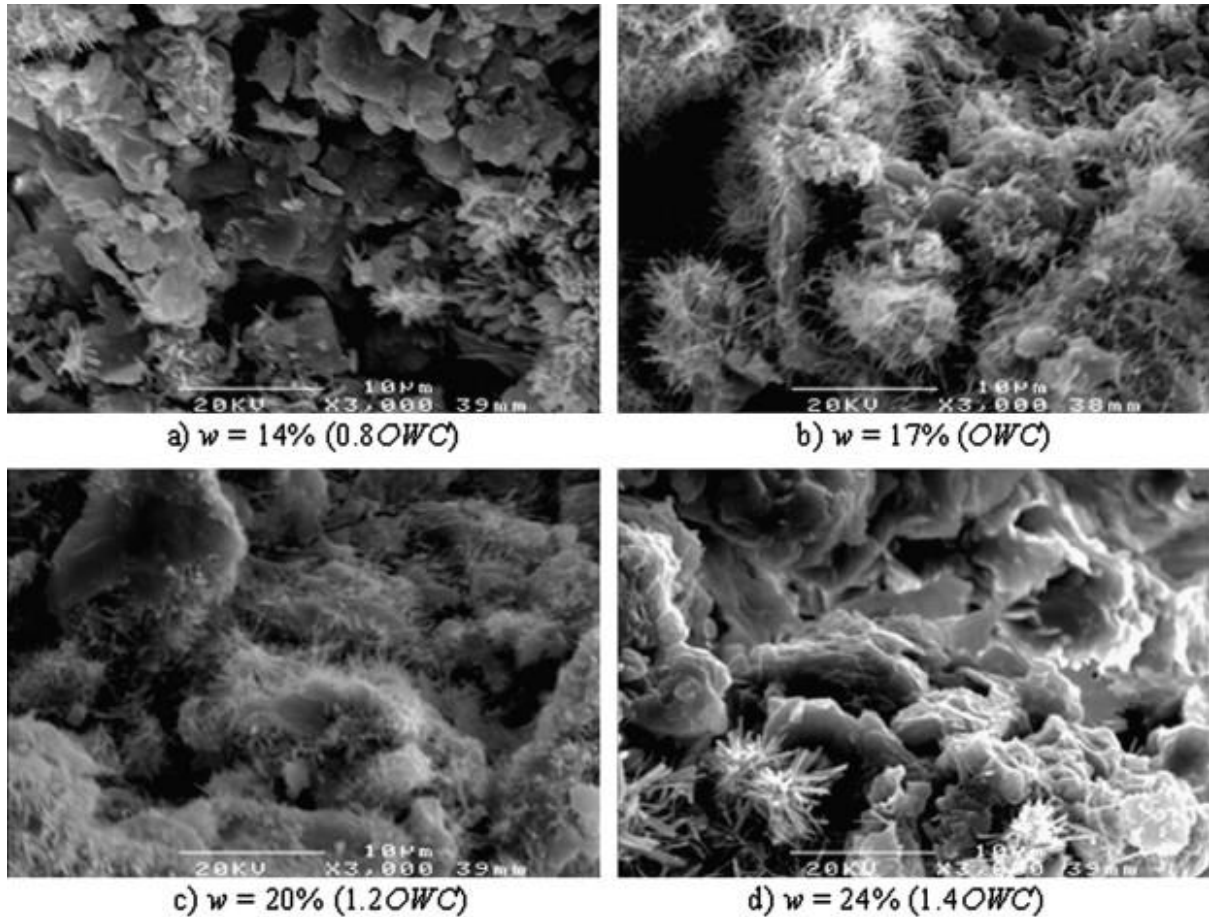


Figure 2.12 SEM Images of the 10% cement samples compacted [32].

2.2 Magnesia Based Binders

2.2.1 Reactive Magnesia Cement

The research community has been aggressively looking for new ecologically friendly building materials to suit the expanding demand and ensure the construction industry's long-term viability. One of the many promising cement alternatives is reactive magnesium oxide (MgO) cement (RMC). In order to create light-burned magnesium oxide (MgO) that is more porous, less crystalline, has a greater surface area, and is more reactive than other grades of MgO, magnesite ($MgCO_3$) is calcined at a relatively low temperature (700–1000 °C) [34],[35]. Recent years have seen the rise of RMC as a practical and sustainable building material due to its unique ability to gain strength by permanently sequestering environmental

CO₂ [10]. Since the strength of the many RMC-based mixes that have been documented so far is on par with OPC, there is a greater need to learn more about the commercial application of RMC [36].

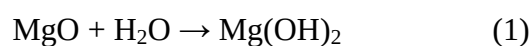
Magnesium oxide is an inorganic substance that occurs naturally as the mineral periclase. Another way to make it is to heat various forms of magnesium carbonate. The degree of reactivity of magnesium oxide depends on the temperature and duration of heating of the magnesium compounds during manufacture. The reactivity of a magnesium oxide sample determines how quickly and how much it rehydrates when exposed to water.

a) Hydration of magnesium oxide

MgO, which is typically made industrially by calcining the mineral magnesite (primarily MgCO₃), can be hydrated to form Mg(OH)₂. The reactivity of the MgO formed, which is defined as the degree and rate of hydration of MgO to Mg(OH)₂ upon exposure to water and moisture, is significantly impacted by the temperature and duration of the calcination process [37]. Magnesium hydroxide is typically made by hydrating magnesium oxide in water, and Feitknecht and Braun [38] have suggested the following reaction mechanism:

- ¶ Adsorbed water vapor causes a liquid layer to form on the solid's surface.
- ¶ After that, water and magnesia combine to form magnesium hydroxide on the surface.
- ¶ As a result, the water layer dissolves magnesium hydroxide.
- ¶ Precipitation happens when the water solution is saturated with magnesium hydroxide particles.

The reaction in the equation describes how magnesium oxide reacts with water.



Because the density of the formed brucite $\text{Mg}(\text{OH})_2$ is 33% lower than the density of periclase MgO , time and high humidity greatly accelerate the MgO hydration reaction, resulting in a large volumetric expansion. As volume increases, tensile and compressive stresses are Developed, which cause cracks and further material damage. Consequently, it is worthwhile to highlight the issue of MgO hydration since it could have an impact on the quality of the finished product that contains MgO [39].

The magnesia hydration reaction is influenced by a few factors. These include the size and crystallographic orientation of MgO crystals, the temperature of the surrounding environment, relative humidity, time, and the chemical and phase composition of magnesia raw materials. The rate of hydration increases with temperature, and time. Furthermore, the hydration reaction is facilitated and accelerated by the oxide particles' smaller crystal sizes, higher specific surface area, and larger pore volume [40].

b) Effect of temperature

One of the primary variables influencing the hydration of MgO is temperature, which also influences the amount of magnesium hydroxide formed and the degree of magnesia hydration, both of which impact the suspension's homogeneity. [41] Talked about how the product weight is impacted by temperature. As illustrated in Figure 2.13, the author compared samples of calcined and un-calcined magnesia at three different temperatures (40, 60, and 80 °C) and discovered that the calcined sample's higher weight amply demonstrated the significance of the calcination step prior to the hydration process.

Kurama et al. [41] demonstrated that TG curves can be used to discuss the mass loss percentage difference between calcined and uncalcined magnesia samples as a result of temperature changes. Both samples have a significant mass loss percentage, but the calcined

sample's mass loss percentage decreased to 78% when the temperature was raised to 600 °C, which was lower than the uncalcined sample's mass loss percentage of 83%.

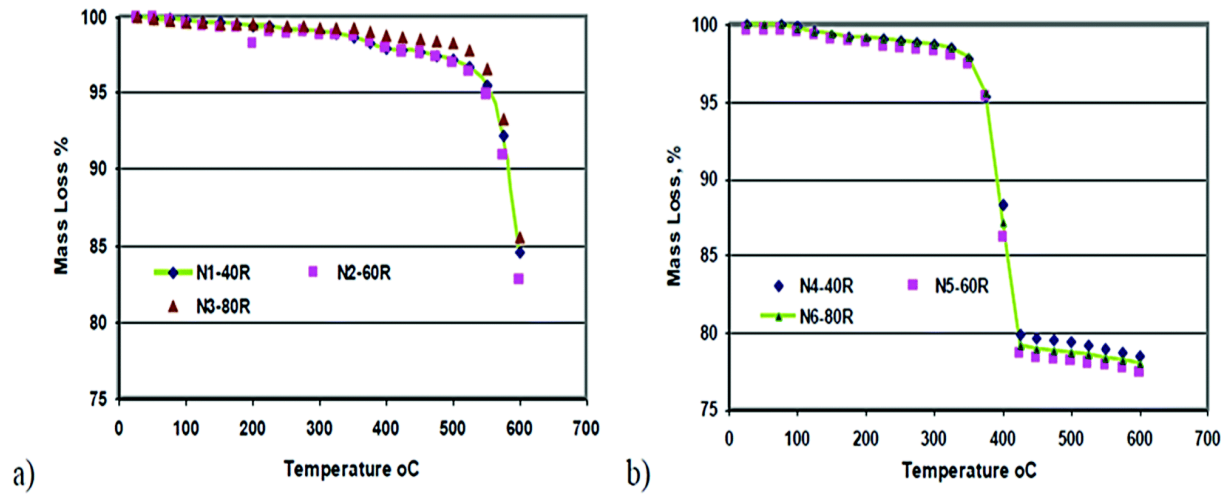


Figure 2.13 TG results of samples: (a) uncalcined and (b) calcined magnesia [41].

c) Effect of particle size

The rate of hydration is influenced by the size of the magnesia powder particles. As the mean particle size decreases, the hydration rate rises [42]. Smaller particles of magnesium have a larger specific surface area, which increases the area in contact with water and, consequently, the rate of hydration. Magnesia powder dissolves during the hydration process, forming magnesium hydroxide on the parent particles surface. As a result, the larger magnesia particles dissolve during the reaction, causing the particle size to gradually decrease until the steam stripping ability is no longer sufficient to reduce the particle diameter. The magnesia hydration rates for the two types of magnesia powder with varying initial particle sizes agree with Ohira et al.[43] findings.

In addition to its catalytic qualities, synthetic magnesium oxide exhibits superior adsorption capabilities due to its large surface areas and small particle sizes. The number of defect sites per unit area, which facilitates the adsorption process, determines MgO's reactivity more so

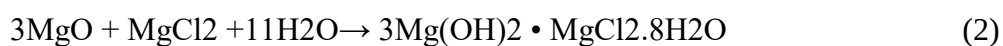
than its comparatively large surface area. The process used to obtain magnesium oxide has a fundamental impact on its catalytic and adsorptive qualities [44].

d) Effect of hydrating agent

The use of various hydrating agents determines the level of hydration, according to the literature. The impact of each hydrating agent on the hydration of magnesium oxide was examined by Kgabo et al., who came to the conclusion that there were no appreciable differences in the hydrating agents' hydration behaviors. Aqueous solutions of ammonium chloride, magnesium acetate, magnesium nitrate, nitric acid, acetic acid, magnesium chloride, sodium acetate, and hydrochloric acid were employed as hydrating agents. Distilled water served as the control [45].

2.2.2 Magnesium Oxychloride Cement (MOC)

The development of Portland cement coincided with the discovery of MOC. MgO powder or calcined magnesite powder, of which MgO is the main ingredient, and MgCl₂ solutions at particular quantities within the MgO-MgCl₂-H₂O system make up MOC pastes. The presence of two hydrate phases, namely 5Mg(OH)₂ · MgCl₂ · 8H₂O (referred to as the 5 phase) and 3Mg(OH)₂ · MgCl₂ · 8H₂O (referred to as the 3 phase), has been established as the primary factors contributing to the solidification and enhanced mechanical properties of MOC [46]. Compared to OPC, MOC provides a number of advantages. The material has remarkable compressive and flexural strengths, a high degree of resistance to abrasion, a low degree of thermal conductivity, and a considerable level of fire resistance. Together with oxychloride cement, a range of organic and inorganic aggregates that might not have the required qualities for usage in Portland cement concrete can be utilized successfully.[46]. MOC has the following chemical equations [47]:





a) Hydration of MOC

The hydration process of MOC is multifaceted, involving the formation of critical phases like Phase 5 and Phase 3, which significantly influence its mechanical properties.[48] has demonstrated that adding synthesized 5-phase seed crystals notably accelerates the formation of Phase 5, enhancing early-stage compressive strength and water resistance, particularly in MOC systems with added phosphoric acid. Complementary study done by Zhang et. al. [49] further reveal that additives like nano-silica synergistically enhance these properties. The importance of curing conditions, highlighted by Sglavo et. al. [50] shows that specific temperatures are crucial for forming these noble phases, impacting strength and solubility. Additionally, Singh et. al. [51] underscores the role of variables like MgO calcination temperature and MgCl₂ solution concentration in strength development, along with the flexibility of using various inert fillers, pointing to the nuanced interplay of factors in optimizing MOC's properties for diverse applications.

b) Factors Influencing MOC Properties

¶ Constituents

The properties of MOC are deeply influenced by its primary constituents, magnesium oxide (MgO) and magnesium chloride (MgCl₂), each playing a distinct role in its hydration process and final characteristics. MgO, usually derived from magnesite, requires careful consideration of its purity, particle size, and calcination temperature during production, as these factors critically affect MOC's hydration process and ultimate strength. As Dehua and Chuanmei [51] discussed, higher calcination temperatures result in less reactive MgO, leading to weaker MOC, while lower temperatures produce more reactive MgO, enhancing

its strength. Conversely, MgCl_2 , acting as a soluble binder, has its concentration and purity crucially impacting MOC formation, with higher concentrations leading to more stable hydration phases and greater strength, as indicated by Zhang et. al. [49]. However, impurities in MgCl_2 can adversely affect MOC's properties. The hydration process, primarily the reaction between MgO and MgCl_2 , forms various phases like Phase 5 and Phase 3, with curing conditions, especially temperature, playing a significant role in their formation, as shown by Sglavo et. al. [50]. Moreover, the addition of 5-phase seed crystals, as explored by Wang et. al. [48] can further enhance Phase 5 formation, improving early-stage compressive strength and water resistance, thereby offering a potential strategy to mitigate MOC limitations such as water sensitivity.

¶ **Molar and water to binder ratios**

The properties of MOC are significantly influenced by the molar ratios of MgO to MgCl_2 and H_2O to MgCl_2 , as well as the incorporation of certain additives, as demonstrated in several key studies. Sglavo et. al. [52] provides a comprehensive analysis of how these ratios affect MOC's strength and setting characteristics, revealing that optimal molar ranges, specifically a MgO/MgCl_2 ratio of 11–17 and a $\text{H}_2\text{O}/\text{MgCl}_2$ ratio of 12–18, are critical for the development of the desired 5-phase ($5\text{MgO}\cdot\text{MgCl}_2\cdot 8\text{H}_2\text{O}$) and thus enhance material properties. This research also points out the importance of MgO reactivity in influencing the hydration reaction and resultant phase assemblages. Complementing this,[53] highlights the interplay between molar ratios and curing temperature, noting that lower temperatures during curing favor the stability of certain hydrated phases, which is vital for the final properties of MOC. Additionally, Zhang et. al. [49] explores how additives like nano-silica, when combined with these specific molar ratios, can significantly enhance the mechanical strength and water resistance of MOC, indicating the effectiveness of using additives to manipulate the hydration process and improve MOC's overall performance.

¶ Other factors

[48]reveals that incorporating synthesized 5-phase seed crystals into MOC significantly boosts the formation rate of the 5-phase, leading to enhanced compressive strength, particularly in the early stages, and improved water resistance, especially in formulations with added phosphoric acid. Complementing these findings, Zhang et. al. [49] delves into the effects of additives like fly ash, phosphoric acid, and nano-silica on MOC. It discovers that these additives, notably nano-silica, not only decrease the initial and final setting times but also substantially improve the compressive strength and water resistance of MOC. Together, these studies underscore the effectiveness of specific additives and seed crystals in optimizing the mechanical properties and durability of MOC, highlighting their potential to significantly advance the material's performance in various applications.

Current literature on marl soil stabilization has predominantly focused on conventional binders like lime and ordinary Portland cement (OPC), with limited exploration of alternative sustainable binders. While lime and cement have been widely studied, their application follows traditional approaches without sufficient critical evaluation of their limitations or potential environmental impacts. Notably, the use of Reactive Magnesia Cement (RMC) and Magnesium Oxychloride Cement (MOC) for marl soil stabilization remains largely unexplored, despite their promising attributes such as lower carbon footprint and potential for carbon sequestration. Previous studies have not systematically assessed how these magnesium-based binders interact with marl's unique mineralogical composition, nor have they compared their mechanical and microstructural performance against conventional methods. This research gap highlights the need for a comprehensive study to evaluate RMC and MOC as viable alternatives, providing new insights into sustainable soil stabilization techniques for problematic marl formations.

CHAPTER 3: METHODOLOGY

This study employs a comprehensive experimental methodology to systematically investigate the viability of RMC and MOC as sustainable substitutes for OPC in stabilizing problematic Marl soils. The research methodology has been carefully structured to evaluate multiple aspects of soil-binder interaction, including geotechnical performance enhancement and microstructural Analysis. All experimental procedures strictly adhere to relevant ASTM standards to guarantee methodological rigor and result reliability. The standardized approach encompasses soil characterization tests, stabilized specimen preparation, mechanical property evaluation, and microstructural analysis, ensuring consistent and reproducible experimental outcomes. By maintaining strict compliance with established testing protocols while investigating innovative binder applications, this study aims to generate scientifically valid data that can contribute meaningfully to advancing sustainable soil stabilization technologies in geotechnical engineering practice.

3.1 Raw Materials

The Marl soil utilized in this study (Figure 3.2) was collected from (26°18'44.2"N 50°10'10.3"E) Dhahran, Saudi Arabia. This soil type was specifically chosen due to its widespread occurrence in the study region and its relevance to local construction challenges. Ordinary Portland Cement (OPC) was procured from the local market and used as the sole binder in the soil stabilization process. Its proven ability to enhance soil strength and durability makes it a conventional choice for this application. Lightly burnt magnesium oxide (MgO) Figure 3.3a was sourced from Sigma-Aldrich, Germany, and employed as the primary binder in the preparation of Reactive Magnesia Cement (RMC). Its high reactivity and fine particle size contribute to the improvement of soil stabilization outcomes. $MgCl_2$ Figure 3.3b, also obtained from Sigma-Aldrich, Germany, was combined with MgO to synthesize MOC.

This binder was utilized for its superior chemical and mechanical properties, which are advantageous for soil stabilization.

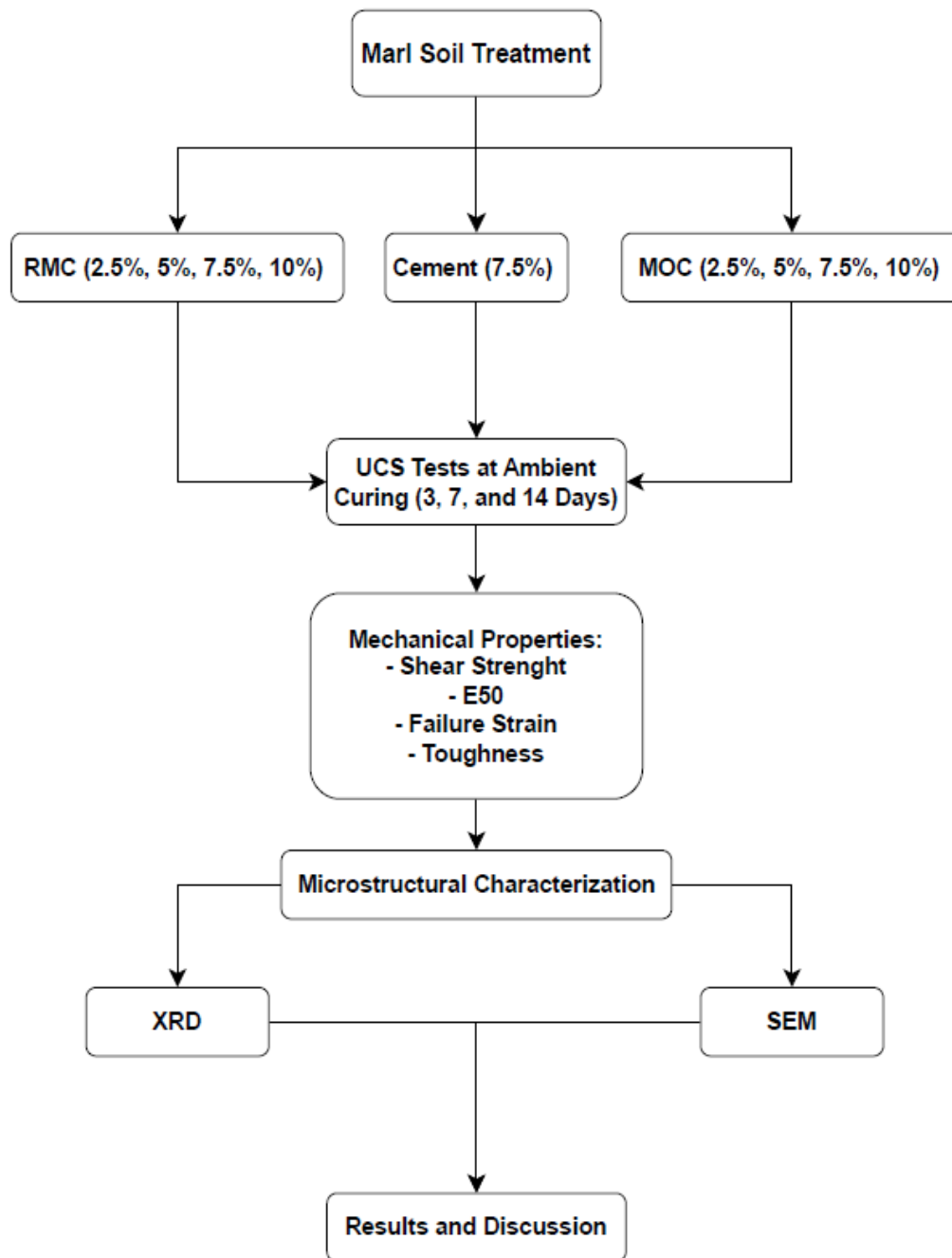


Figure 3.1 Flowchart of the experiment

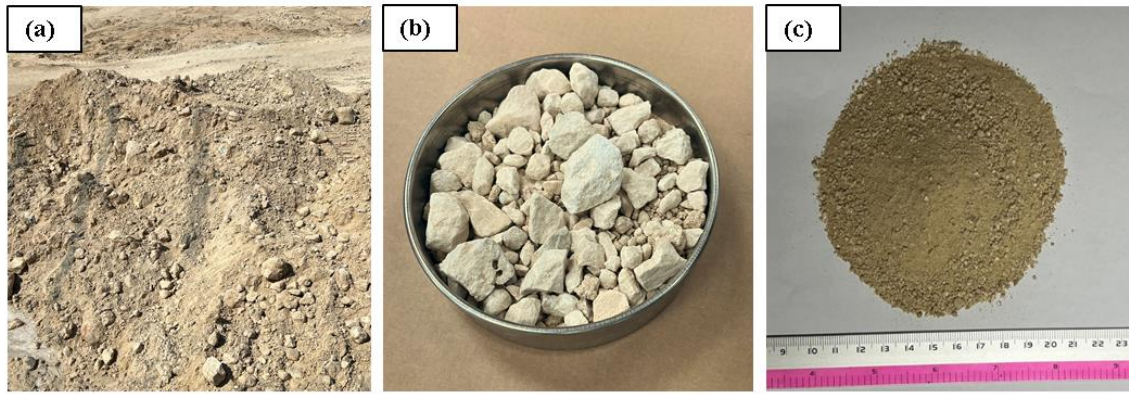


Figure 3.2 Marl Soil Samples: (a) In-situ, (b) Lumped form, (c) Crushed form.

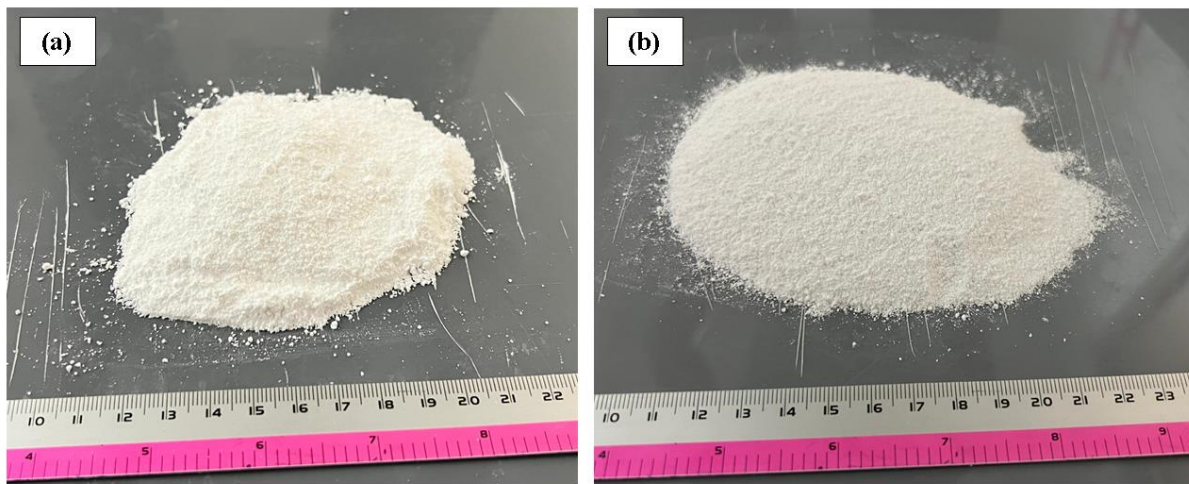


Figure 3.3 a) MgO and b) MgCl₂

3.2 Soil Characterization

A comprehensive suite of standardized laboratory tests was conducted to fully characterize the geotechnical properties of the native marl soil prior to stabilization. All testing procedures strictly adhered to relevant ASTM standards to ensure methodological rigor and result reproducibility. The soil classification was performed according to the Unified Soil Classification System (USCS) following ASTM D2487-17 [54], which involved a systematic evaluation of particle size distribution and plasticity characteristics.

The particle size distribution analysis was conducted through a two-stage process: (1) dry sieve analysis (ASTM D6913 [55]) for coarse fractions ($>75\ \mu\text{m}$), and (2) hydrometer testing (ASTM D7928 [56]) for fine particle quantification. This combined approach accurately determined the relative proportions of sand, silt, and clay fractions, providing critical data for soil classification and subsequent stabilization design.

The Atterberg limits testing included determination of the liquid limit (ASTM D4318 [57]) using the Casagrande cup method, plastic limit testing via the thread-rolling technique, and calculation of the plasticity index. These tests characterized the soil's water content-dependent behavior and provided essential parameters for evaluating its engineering performance.

Additionally, compaction characteristics were established through Standard Proctor testing (Figure 3.4) to determine the optimum moisture content and maximum dry unit weight - fundamental parameters for sample preparation in stabilization experiments. The compaction curve analysis also provided insights into the soil's workability and potential response to stabilization.

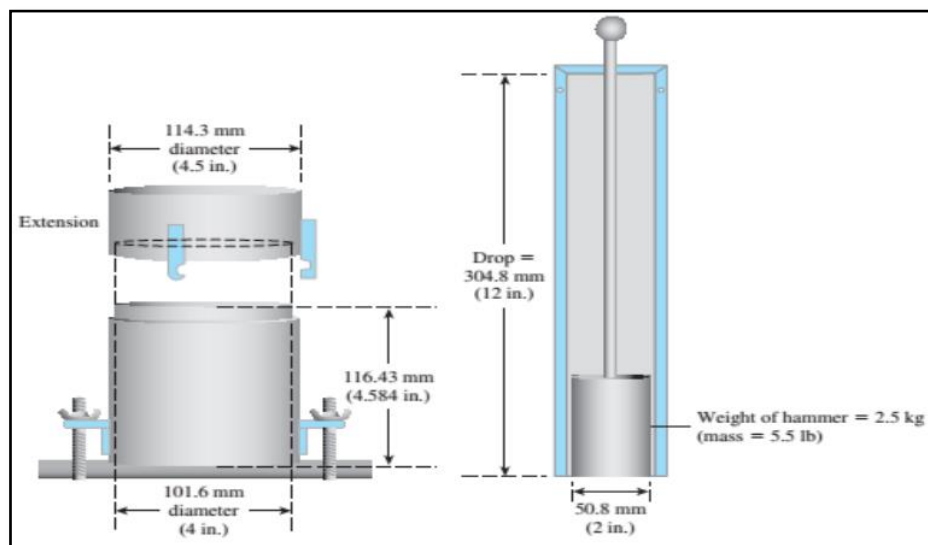


Figure 3.4 Standard Proctor testing [58].

This thorough characterization established a reliable baseline for evaluating stabilization effectiveness and ensured proper interpretation of subsequent mechanical test results. The data obtained not only facilitated accurate soil classification but also informed the selection of appropriate binder types and dosages for the stabilization experiments.

The compaction characteristics, including the optimum moisture content (OMC) and maximum dry unit weight (MDD), were obtained using the Proctor compaction test as per [59] (Standard Proctor). These tests collectively provided a comprehensive understanding of the soil's engineering properties, enabling accurate classification and predicting its behavior under varying conditions. Table 3-1 shows testing conditions and sample nomenclature.

Table 3-1. Testing conditions and sample nomenclature

Binder Type	Dosages (%)	Curing Condition	Sample Nomenclature	Example
Reactive Magnesia Cement (RMC)	2.5, 5.0, 7.5, 10.0	Ambient (3, 7, 14 days)	M [dosage]	M5
Magnesium Oxychloride Cement (MOC)	2.5, 5.0, 7.5, 10.0	Ambient (3, 7, 14 days)	MOC [dosage]	MOC7.5
Ordinary Portland Cement (CEM 7.5)	7.5 only	Ambient (3, 7, 14 days)	CEM [dosage]	CEM7.5

3.3 Sample Preparation

The preparation of stabilized marl soil samples followed a systematic approach to evaluate the effectiveness of different binder types and dosages. Control samples consisting of untreated marl soil (0% binder content) were prepared as a baseline reference. For

conventional stabilization, samples were mixed with 7.5% Ordinary Portland Cement (OPC) by dry soil weight - an intermediate dosage selected based on extensive literature review [5],[60],[61],[62] demonstrating that 5-10% OPC content optimally improves marl soil's engineering properties while maintaining economic feasibility.

The experimental design incorporated a comprehensive evaluation of magnesia-based binders, with Reactive Magnesia Cement (RMC) tested at four incremental dosages (2.5%, 5%, 7.5%, and 10% by soil weight) to establish a performance-dose relationship. Similarly, Magnesium Oxychloride Cement (MOC) stabilization employed the same percentage range, with careful control of the chemical formulation - maintaining a $\text{H}_2\text{O}/\text{MgCl}_2$ molar ratio of 15 and MgO/MgCl_2 ratio of 5:1 to ensure consistent cementitious reactions.

All mixtures underwent rigorous homogenization using a mechanical mixer to achieve uniform binder distribution throughout the soil matrix. The Standard Proctor compaction method (ASTM D698 [59]) was employed to prepare cylindrical specimens (50 mm diameter $\times$ 100 mm height) at optimum moisture content, ensuring consistent density across all samples. Visual inspection (Figure 3.6) confirmed proper specimen after compaction. Following preparation, samples were cured under controlled ambient conditions to simulate typical field environments, with curing periods aligned with standard testing protocols for stabilized soils. This meticulous preparation methodology enabled a reliable comparison of mechanical performance across different stabilization approaches.



Figure 3.5 Sample Extruder Machine

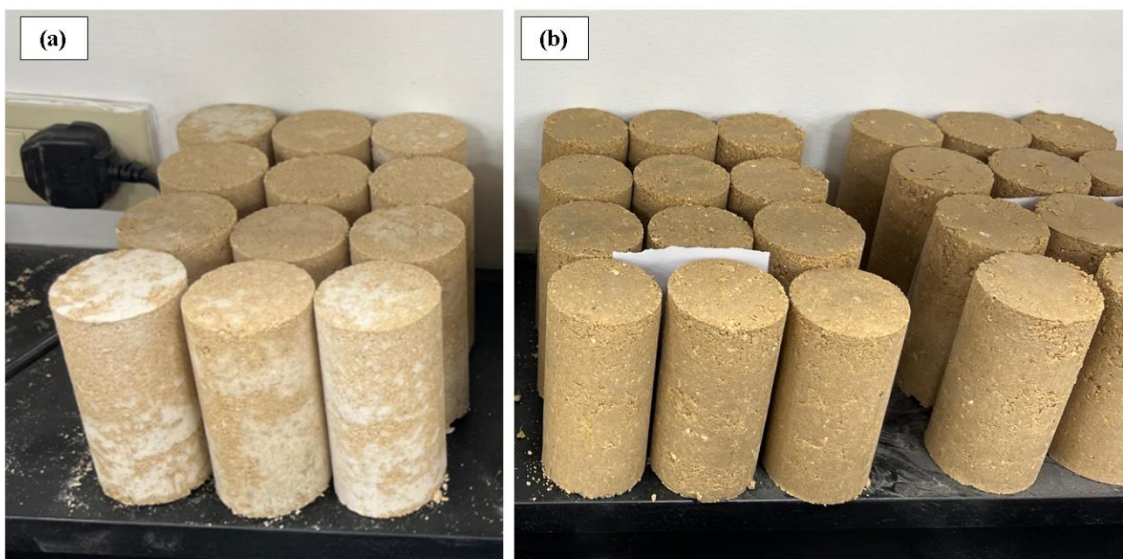


Figure 3.6 a) RMC and b) MOC stabilized Marl soil

3.4 Experimental Methods

3.4.1 Unconfined Compressive Strength (UCS) Tests

The UCS tests were conducted to evaluate the peak compressive strength of stabilized marl soil specimens under axial loading without lateral confinement, following ASTM D2166 [63] standards. Cylindrical samples (50 mm diameter $\times$ 100 mm height) were loaded at a constant strain rate of 1.25 mm/min until failure. The automated testing machine continuously recorded axial load and displacement, calculating the maximum stress (UCS) as the highest attained stress prior to failure, determined by dividing the peak load (P_{max}) by the initial cross-sectional area (A) of the specimen ($\sigma_{max} = P_{max}/A$). This maximum stress value serves as the primary indicator of each binder's effectiveness in enhancing soil strength, with higher values reflecting better stabilization performance. The test conditions ensured uniform stress distribution and minimized end effects, while the automatic stopping criterion at 15% post-peak load drop guaranteed consistent failure detection across all samples. The resulting UCS values were then used to compare the relative performance of OPC, RMC, and MOC stabilization methods at different curing periods.

3.4.2 Failure Strain (ϵ_f)

Failure strain (ϵ_f) represents the axial deformation at which the stabilized soil specimen reaches its peak strength. It is calculated as the percentage ratio of the axial displacement at failure (ΔL_f) to the original specimen height (L_o). The testing machine records the displacement continuously at the prescribed rate of 1.25 mm/min until the load drops to 15% of the peak value (automatic stopping criterion). Mathematically, $\epsilon_f = (\Delta L_f/L_o) \times 100\%$, where ΔL_f is determined from the peak stress point on the stress-strain curve. This parameter indicates the material's ductility, with higher values suggesting greater deformation capacity before failure. For marl soils, ϵ_f is particularly important as it reveals whether stabilization has improved the typically brittle nature of the untreated soil.



Figure 3.7 UCS Testing Machine

3.4.3 Secant Modulus (E_{50})

The secant modulus (E_{50}) quantifies the stiffness of stabilized soil at 50% of its peak strength. It is derived from the stress-strain curve by drawing a line connecting the origin to the point corresponding to half of the maximum UCS ($0.5q_u$). The slope of this line gives E_{50} , calculated as $E_{50} = (0.5q_u)/\epsilon_{50}$, where ϵ_{50} is the strain at 50% peak stress. This value represents the "effective stiffness" during early loading stages and is crucial for evaluating how the stabilized soil will behave under working loads. The automated UCS testing system typically identifies these reference points digitally from the continuous stress-strain data, ensuring precise modulus calculations for comparative analysis between different binder treatments.

3.4.4 Toughness (T)

Toughness (T) measures the energy absorption capacity of stabilized soil up to failure, calculated as the total area under the stress-strain curve from zero strain to failure strain (ϵ_f). The numerical integration is performed using the trapezoidal rule: $T = \Sigma[0.5(\sigma_i + \sigma_{i+1}) \times (\epsilon_{i+1} - \epsilon_i)]$, summing all incremental areas between consecutive data points. Modern UCS equipment with digital data acquisition automatically performs this calculation by processing the continuous load-displacement recordings. Toughness is expressed in units of energy per volume (kJ/m^3) and provides critical insight into the material's ability to withstand deformation energy, a key parameter for applications where the stabilized soil may experience cyclic or impact loads. Higher toughness values indicate better performance in scenarios requiring ductility and crack resistance.

3.4.5 Phase Transformation Analysis through X-Ray Diffraction (XRD)

XRD analysis was employed to investigate the phase transformations and hydration products formed during the stabilization of marl soil with RMC and MOC binders. The technique was particularly valuable for identifying the crystalline phases resulting from hydration reactions and chemical interactions between the binders and soil minerals. The XRD data were analyzed using MATCH! Software, which enabled phase identification through comparison with the International Centre for Diffraction Data (ICDD) database. The software's pattern-matching algorithms helped distinguish overlapping peaks and quantify the relative abundance of crystalline phases. This analysis provided insights into the reaction kinetics of different binders, explaining the strength development trends observed in mechanical testing. By correlating XRD findings with mechanical test results, this study established a direct relationship between phase formation and the engineering performance of stabilized soils, enhancing the understanding of stabilization mechanisms in marl soils.

3.4.6 Microstructural Characterization

This study conducted detailed microstructural analysis of RMC and MOC-stabilized marl soils using SEM to investigate how these binders modify soil fabric at microscopic levels and correlate these changes with mechanical property improvements. Specialized sample preparation was implemented to preserve delicate hydrated phases: samples were dried in a vacuum desiccator with silica gel beads for 72 hours at room temperature to gradually remove moisture without microstructural distortion, followed by gold sputter coating to ensure proper conductivity during SEM imaging. The vacuum desiccation method proved particularly effective for preserving the morphology of hydration products compared to conventional oven drying, while the gold coating provided optimal imaging quality without charging effects. These microstructural observations directly explained the mechanical performance trends of RMC and MOC stabilized soil samples. This micro-scale evidence substantiates the superior performance of magnesia-based binders for marl soil stabilization, providing critical insights into their strengthening mechanisms.

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Soil Characterization

Table 4-1 summarizes the basic properties of the soil and Table 4-2 shows the main chemical constituents of the soil, while Figure 4.2 is the XRD analysis of Marl soil. Table 4-3 and Figure 4.3 present the MDD and OMC of Marl soil stabilized with cement, RMC, and MOC at different dosages. The results demonstrate how varying stabilizer percentages influence the compaction characteristics of the soil.

Table 4-1. Index Properties of Marl Soil

Properties	Values	Testing Standards
Liquid limit (%)	40.2	ASTM D4318 [57]
Plastic limit (%)	23.5	
Plasticity index (%)	16.7	
Gravel (%)	0.0	ASTM D2487[54]
Sand (%)	38	
Silt (%)	43	ASTM D7928 [56]
Clay (%)	19	
Specific Gravity	2.64	ASTM D854 [64]
Soil Classification (USCS)	Sandy lean clay (CL)	ASTM D2487[54]
Soil Classification (AASHTO)	A-7-6	AASHTO M 145 [65]

Table 4-2. Chemical constituents (%) of the Marl Soil

MgO	Al ₂ O ₃	SiO ₂	SO ₃	CaO	TiO ₂	Fe ₂ O ₃	SrO	K ₂ O
8.26	4.46	28.68	1.29	53.39	0.36	2.36	0.14	0.75

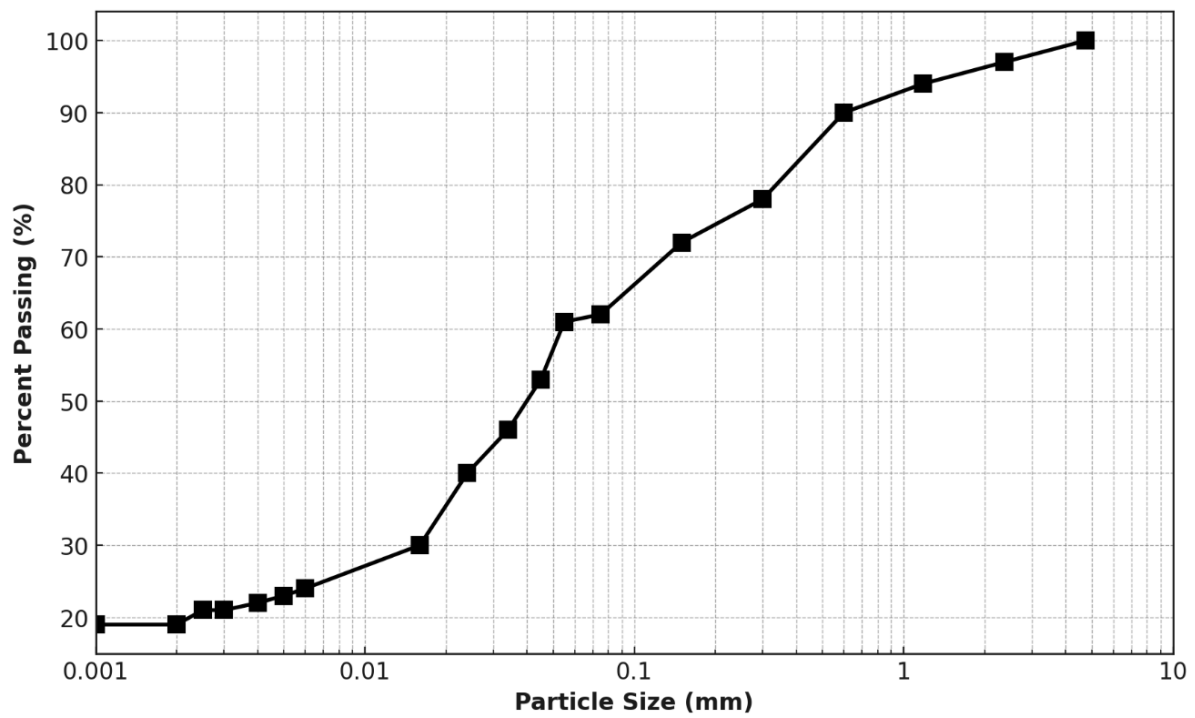


Figure 4.1 Gradation Curve of the soil

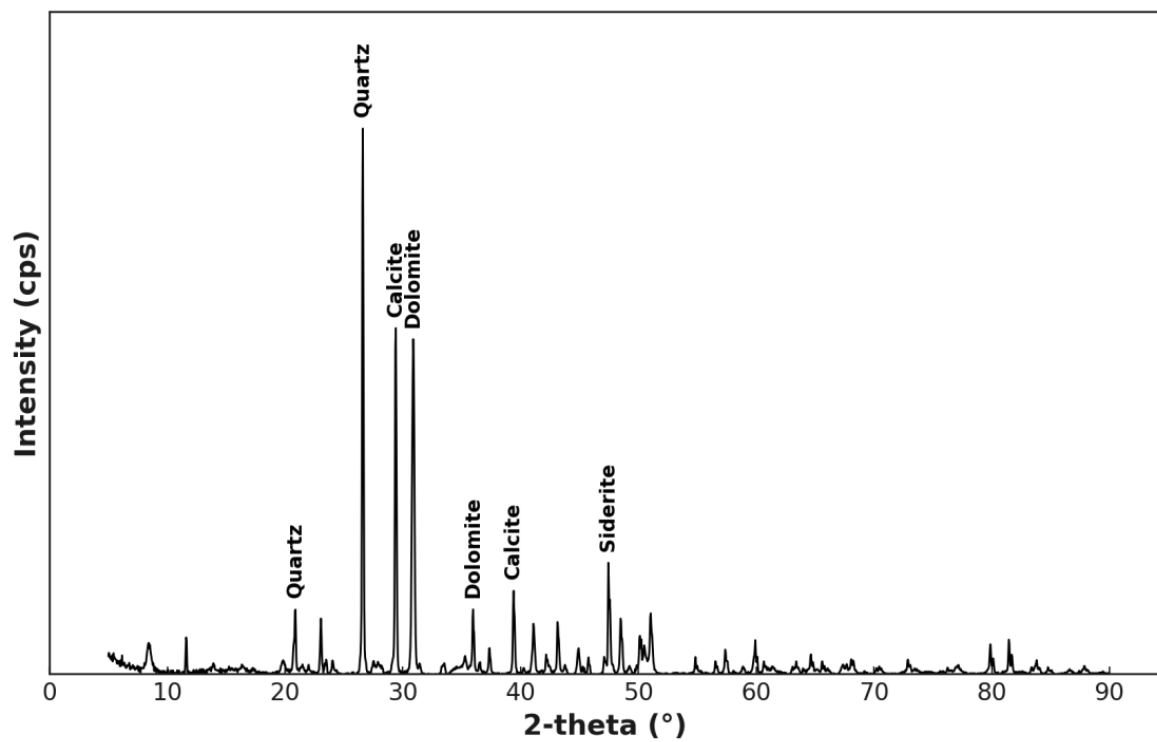


Figure 4.2 X-Ray diffraction analysis of Marl soil.

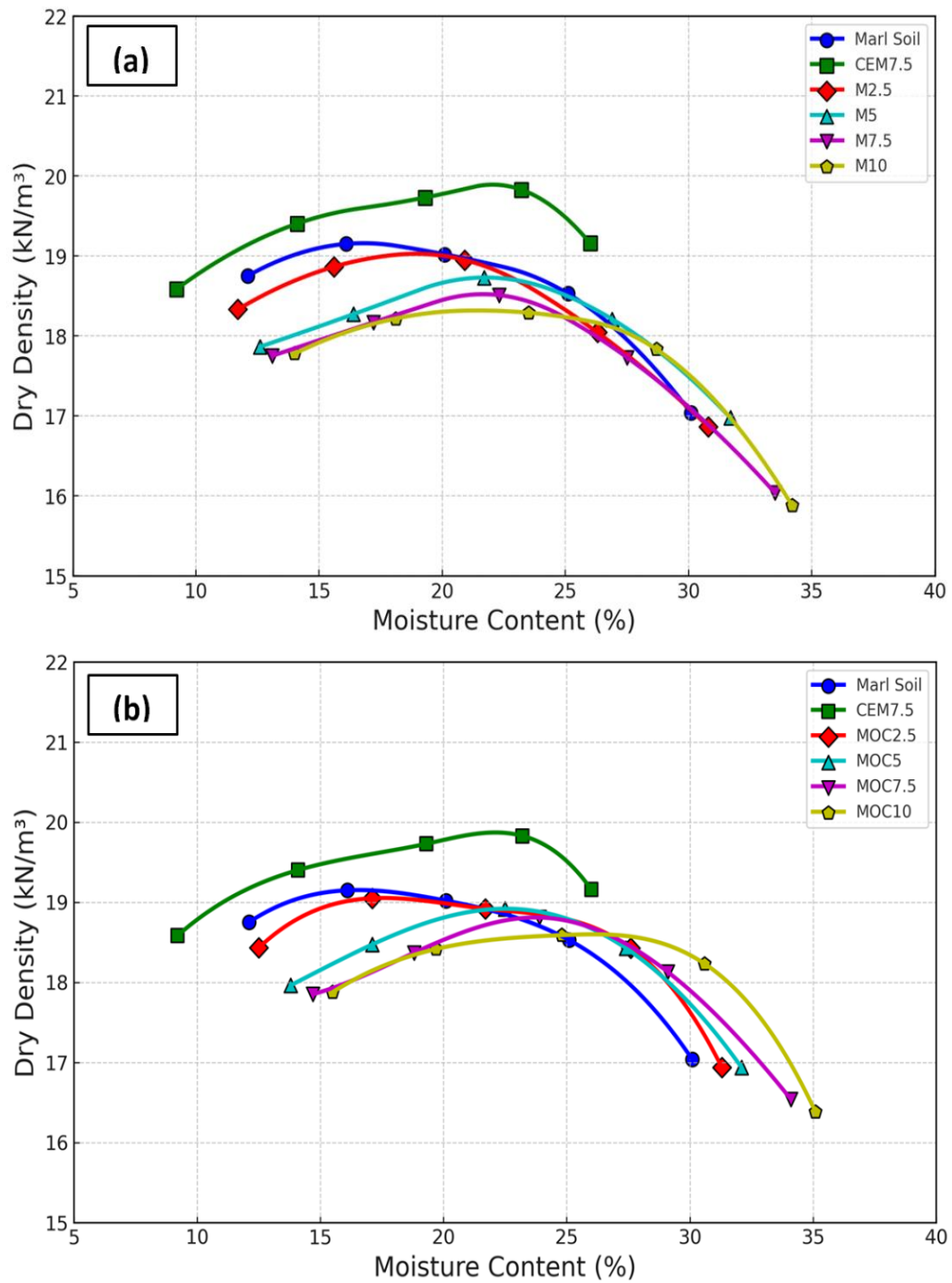


Figure 4.3 MDD and OMC for Marl Soil Stabilized with Cement, RMC, and MOC

Table 4-3. MDD and OMC for Marl Soil Stabilized with Cement, RMC, and MOC

Material	MDD (kN/m³)	OMC (%)
Marl Soil	19.15	16.10
CEM7.5	19.83	23.20
RMC (Reactive Magnesia Cement)		
2.50%	18.95	20.90
5%	18.73	21.70
7.50%	18.51	22.30
10%	18.29	23.50
MOC (Magnesium Oxychloride Cement)		
2.50%	19.05	17.10
5%	18.92	22.50
7.50%	18.81	23.90
10%	18.59	24.80

4.2 Mechanical Properties

4.2.1 UCS test results of RMC-stabilized soil

Figure 4.4 demonstrates the (UCS) performance of stabilized soil samples over 3, 7, and 14 days is illustrated in the two graphs. Marl, used as the untreated control, showed minimal strength gains, increasing from 603.4 kPa at 3 days to 1130 kPa at 7 days, and reaching 1152 kPa at 14 days, a 69.7% total increase. Beyond 7 days, no major chemical reactions occur in unstabilized soil. As a result, strength development plateaus, and no significant further improvement is observed after 7 days. In contrast, M2.5 steadily improved from 1080 kPa on day 3 to 2014 kPa by day 14, achieving an 86.5% increase. M5, starting at 1784 kPa on day 3, reached 2747 kPa by day 14, reflecting a 54% increase. M7.5 began at day 3 752 kPa, rose rapidly to 1939 kPa by day 14, showing the largest percentage increase of 157.8% among all mixes. M10 demonstrated moderate gains, starting at 865 kPa on day 3 and reaching 1592 kPa by day 14, an 84% increase.

By day 14, M5 achieved the highest strength (2747 kPa), followed by M2.5 (2014 kPa), M7.5 (1939 kPa), and M10 (1592 kPa), with the unstabilized soil showing the lowest strength (1147 kPa). This behavior can be attributed to excess unreacted MgO in the soil matrix. Magnesium oxide (MgO) requires sufficient moisture to hydrate and form magnesium hydroxide $[Mg(OH)_2]$, which contributes to strength through particle bonding and matrix densification. However, at higher dosages (7.5%–10%), the available water in the soil may be insufficient to fully hydrate all the MgO, resulting in unreacted particles. These unhydrated MgO particles can introduce weak interfaces within the soil matrix, ultimately reducing the overall strength gain. When compared to a previous study that stabilized soil using 5% cement, achieving a strength of 1600 kPa at 28 days [60].

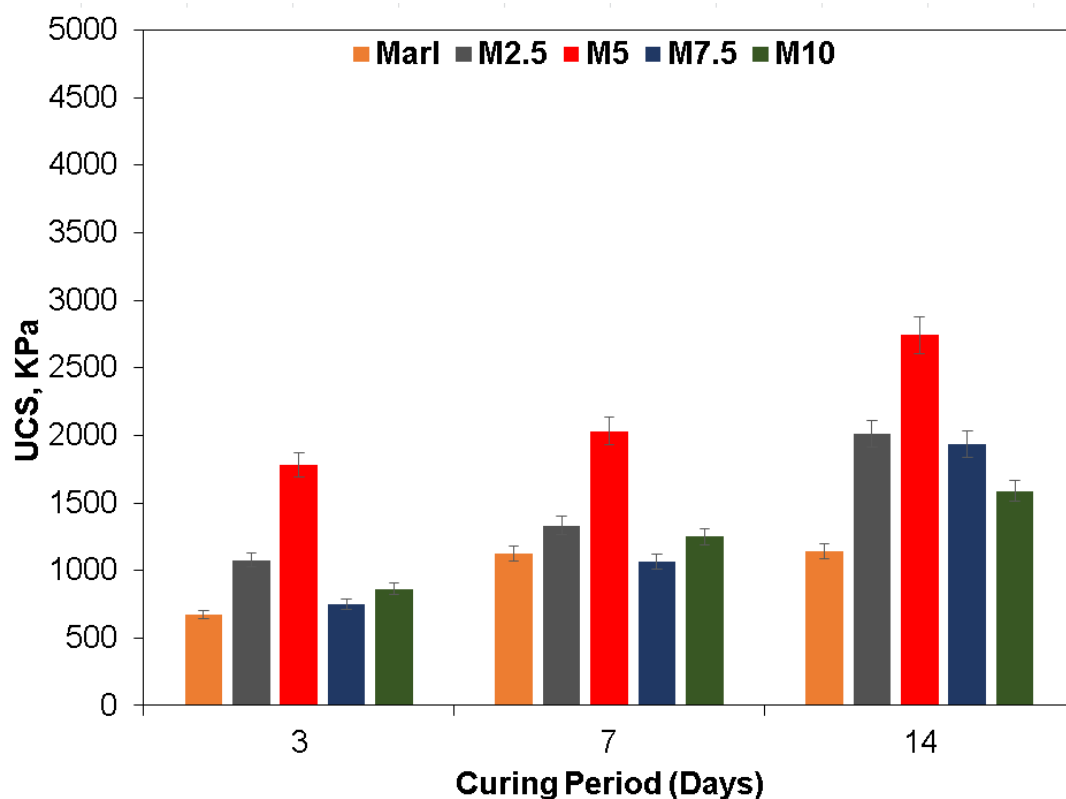


Figure 4.4 Effect of Curing Period and Binder Dosage on the UCS of Soils Stabilized with RMC

These results highlight that all MgO-stabilized mixes significantly outperformed the unsterilized soil. While M5 achieved the highest 14-day strength, M7.5 demonstrated the largest percentage improvement, indicating its potential for applications requiring rapid strength gains. Overall, stabilization markedly enhances soil strength compared to the unsterilized sample.

4.2.2 UCS test results of MOC-Stabilized soil

Figure 4.5 shows the UCS test results for MOC-stabilized soil samples (MOC2.5, MOC5, MOC7.5, and MOC10) compared to the unstabilized soil reveal significant strength improvements over time are shown in **Error! Reference source not found.** Marl Soil, used as the untreated control, exhibited the lowest UCS values across all curing periods, increasing from 676 kPa to 1147 kPa over 14 days. In contrast, MOC-stabilized mixes demonstrated substantial strength gains. MOC2.5 steadily improved from 706 kPa on day 3 to 1646 kPa by day 14, a 133% increase. MOC5 showed a higher initial strength of 818 kPa, reaching 2010 kPa by day 14, with a 145.7% increase. MOC7.5 started stronger at 1309 kPa on day 3, achieving 2937 kPa by day 14, marking a 124.3% increase. MOC10 exhibited the highest strength throughout, starting at 2601 kPa on day 3 and reaching 4618 kPa by day 14, with a 77.5% increase. By day 14, MOC10 achieved the highest strength (4618 kPa), over 300% stronger than the unsterilized soil, while MOC7.5 demonstrated the largest percentage strength improvement over its initial value. Overall, all MOC mixes outperformed the unsterilized soil, with MOC10 being the best-performing mix based on its superior 14-day strength.

While MOC10 exhibited the highest UCS among all samples, reaching 4618 kPa and demonstrating a 303% improvement over Marl Soil, it cannot be conclusively stated as the optimal dosage without testing higher concentrations such as MOC15. However, it's worth

noting that continued increases in binder content may lead to higher strength but also significantly increase material costs. Thus, among the tested dosages, MOC10 appears to offer the best performing dosage, balancing strength gain with practical considerations.

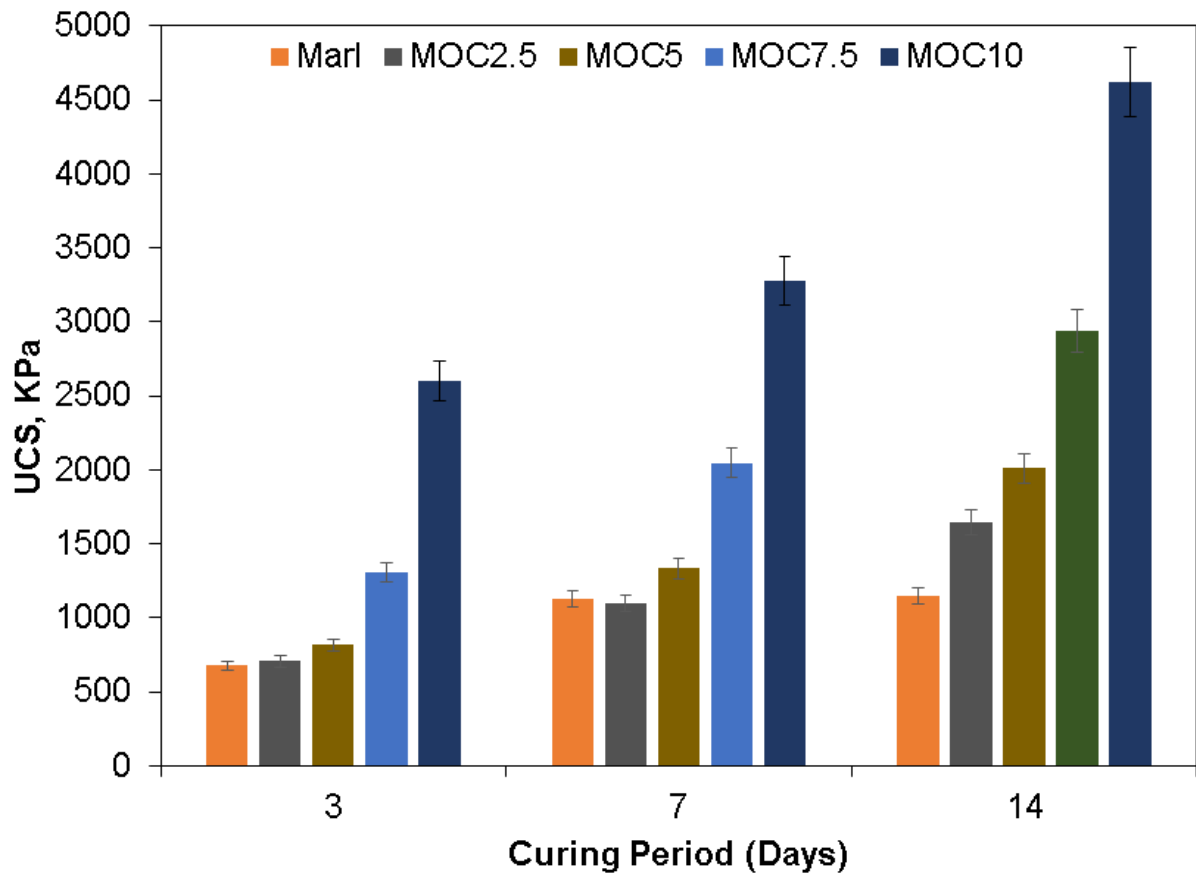


Figure 4.5 Effect of Curing Period and Binder Dosage on the UCS of Soils Stabilized with MOC.

Comparing these results with previous studies, a soil stabilized with 5% cement achieved a strength of 1600 kPa at 28 days [60],[62], significantly lower than all MOC-stabilized mixes at just 14 days. Additionally, a study incorporating 5% cement and 5% fuel oil fly ash reported a 28-day strength of 2151 kPa [60], which remains substantially lower than MOC10 at 14 days and is even outperformed by MOC7.5 (3061 kPa at 14 days). These comparisons emphasize the superior early-age performance of MOC stabilization, indicating its

effectiveness in rapidly improving soil strength compared to conventional cement-based stabilization techniques.

4.2.3 14 Days strength Comparison of Cement, RMC and MOC stabilized soil.

After 14 days, the UCS test results reveal significant differences in strength among the mixes, attributable to the distinct chemical reactions and binding mechanisms of the stabilizers used. The untreated marl exhibited the lowest strength at 1147 kPa due to its naturally weak structure and lack of cementation. The CEM7.5 mix reached 1953 kPa, showing a 70.2% strength increase over the untreated soil. This improvement is primarily due to the hydration of cement, producing calcium silicate hydrate (C–S–H) and other cementitious compounds that enhance interparticle bonding and reduce voids. The M5 mix achieved 2747 kPa—a 139.5% improvement. This can be attributed to the formation of magnesium hydroxide (brucite) and other potential reaction products, which fill pores and contribute to early strength through densification and chemical bonding. Additionally, the fine particle size and high reactivity of RMC accelerate its interaction with the soil matrix. MOC10 exhibited the highest strength at 4618 kPa, representing a 302.4% increase over the untreated soil. MOC superior performance is due to its rapid-setting behavior and the formation of crystalline binding phases such as Phase 3 and Phase 5, which create a strong, interlocked structure. These phases significantly enhance the early mechanical strength and stiffness of the soil-binder matrix. Based on these 14-day results, MOC10 is the best-performing mix, followed by M5, CEM7.5, and the untreated soil, as shown in Figure 4.6.

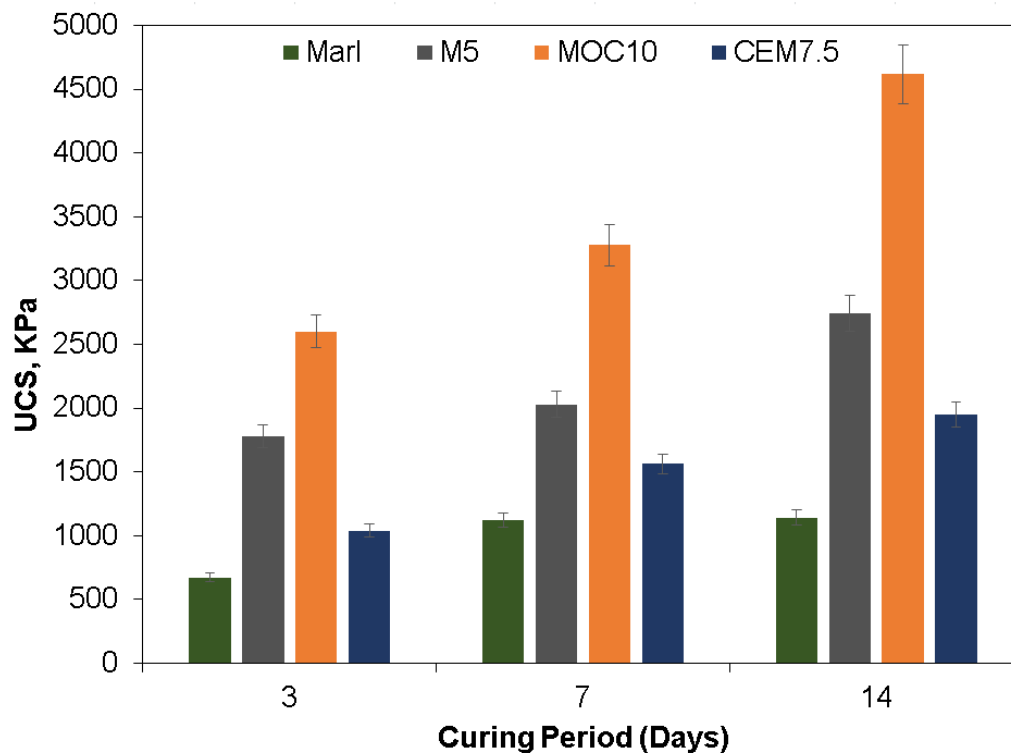


Figure 4.6 Strength Comparison of Cement, RMC and MOC stabilized soil at 14 Days.

4.2.4 Effect of RMC and MOC on stress-strain relationship

Figure 4.7a illustrates the stress–strain behavior of untreated marl soil and soils stabilized with various dosages of RMC and CEM7.5. The untreated marl exhibits a gradual increase in stress with strain, indicating a relatively ductile response and limited strength. As the stabilizer content increases, the stress–strain curves become steeper and broader, reflecting enhanced stiffness and greater resistance to deformation. The M2.5 and M5 mixes show significantly stiffer responses than the untreated soil, highlighting improved bonding and densification of the soil matrix. The M7.5 curve maintains a smooth and extended profile, suggesting a favorable balance between strength and ductility, while the M10 mix shows a sharper drop after peak stress, indicating a potential increase in brittleness at higher binder contents. The CEM7.5 curve demonstrates a moderately stiff response with a more gradual peak and post-peak behavior compared to RMC blends. This suggests that while Portland

cement enhances strength, it also contributes to a more ductile failure mode, likely due to the slower hydration kinetics and different microstructural development compared to magnesia-based binders. Overall, the curves reveal that the addition of stabilizers substantially improves the mechanical behavior of Marl Soil, with each mix showing distinct characteristics suitable for varying geotechnical applications.

Figure 4.7b shows the stress–strain behavior of marl soil and its stabilized counterparts using different concentrations of MOC, alongside CEM7.5 for comparison. The untreated marl soil exhibits a steady rise in stress with strain, reflecting a relatively ductile behavior and limited strength capacity. Introducing MOC into the soil matrix significantly enhances its mechanical performance, as evident from the curves for MOC2.5, MOC5, MOC7.5, and MOC10. As the MOC content increases, the mixtures display greater stiffness and strength. MOC5 and MOC7.5 show a balanced performance, combining improved load capacity with ductility. Notably, MOC7.5 demonstrates a smooth and gradual post-peak decline, indicating a favorable balance between strength and deformation capacity. MOC10, while exhibiting the highest stress response, shows a steeper drop after peak stress, suggesting increased brittleness at higher dosages. The CEM7.5 curve, carried over from Fig. 26a for comparison, presents a moderate improvement in strength relative to the untreated soil, with a more gradual peak and softer post-peak response compared to MOC mixes. This reflects the slower hydration and more ductile failure behavior typical of OPC-based stabilization. Overall, the use of MOC enhances the load-carrying capacity of marl soil, with moderate concentrations yielding more ductile and stable behavior compared to higher concentrations, which tend to be more brittle.

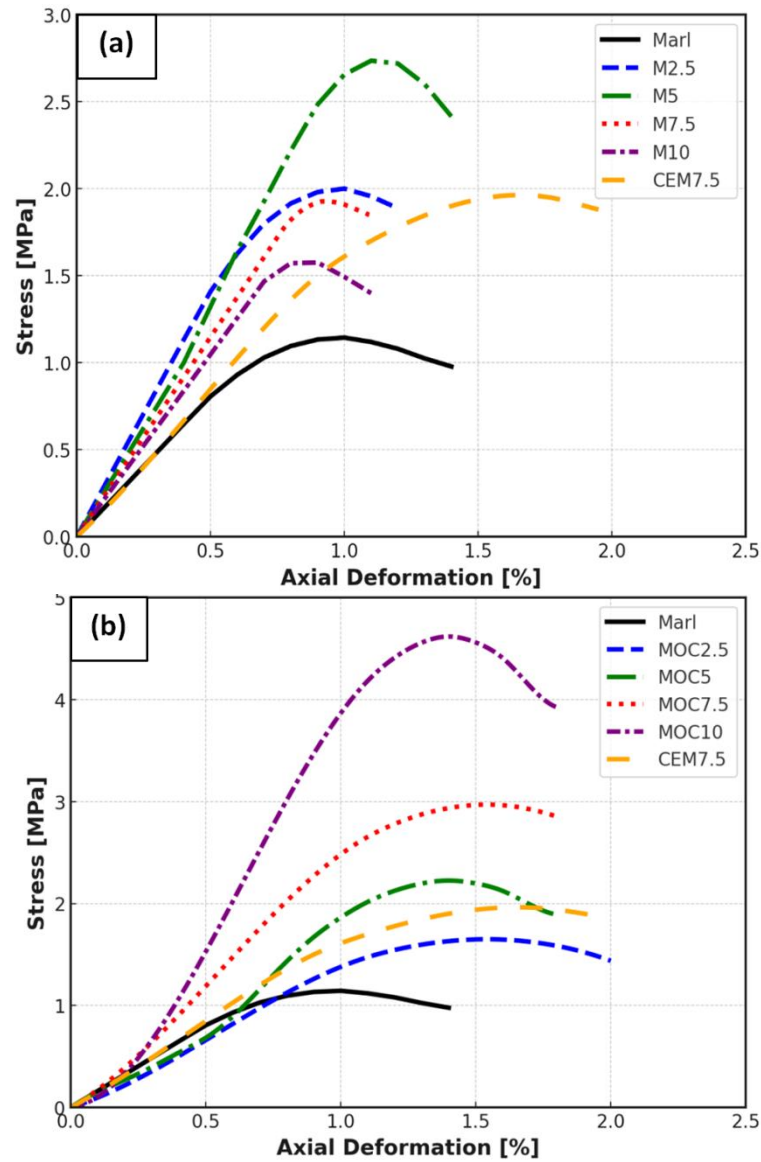


Figure 4.7 Stress-Strain relationship of a) MgO stabilized Soil and b) MOC stabilized soil at 14 days.

4.2.5 Effect of Stabilization and Curing Time on Elastic Modulus (E_{50}) of the Soil

Figure 4.8a presents the development of E_{50} (MPa) over 3, 7, and 14 days for untreated marl soil and soils stabilized with varying percentages of Reactive Magnesia Cement (RMC)—specifically M2.5, M5, M7.5, and M10. The untreated marl soil shows a steady increase in stiffness from 44 MPa at 3 days to 143.3 MPa at 14 days. M2.5 starts at 40 MPa on day 3 but increases to 109 MPa by day 14, indicating modest improvement. M5 stands out with the

highest stiffness among the RMC mixes, increasing from 116 MPa to 227.9 MPa over 14 days, suggesting that this dosage provides an optimal balance of reactivity and pore-filling capacity. M7.5 and M10 follow with values of 126 MPa and 112 MPa at 14 days, respectively. The CEM7.5 mix, shown for comparison, demonstrates a stiffness increase from 108 MPa at 3 days to 162 MPa at 14 days. While CEM7.5 outperforms M2.5 and is comparable to M7.5 and M10 by day 14, it falls short of M5, confirming that moderate RMC content (e.g., M5) is more effective in enhancing stiffness than OPC at the same dosage. This is attributed to the formation of magnesium hydroxide (brucite) and densification of the soil matrix.

Figure 4.8b illustrates the E_{50} evolution for Magnesium Oxychloride Cement (MOC)-stabilized soils—MOC2.5, MOC5, MOC7.5, and MOC10—alongside the untreated soil and again, CEM7.5 for comparison. MOC-stabilized soils exhibit significantly higher stiffness values compared to both the untreated and cement-treated soils. MOC2.5 increases from 67.6 MPa at day 3 to 164.6 MPa at day 14, slightly exceeding CEM7.5 at the same age. MOC5 advances to 179 MPa, and MOC7.5 and MOC10 reach 245 MPa and 352 MPa, respectively, by day 14. In direct comparison, CEM7.5 shows lower stiffness than all MOC mixes except MOC2.5 at early ages, and is significantly outperformed by MOC5 and higher. The superior performance of MOC is due to the rapid formation of strong, stable crystalline phases (e.g., Phase 3 and Phase 5), which create a dense and well-bonded structure within the soil. Overall, both figures demonstrate that MOC binders provide the most substantial improvement in soil stiffness, especially at higher dosages and with longer curing. RMC-stabilized soils offer notable gains, particularly at moderate dosages like M5, while CEM7.5 shows moderate effectiveness, making it less competitive than magnesia-based binders in terms of stiffness development. These results highlight the importance of binder selection and dosage optimization for maximizing the mechanical performance of stabilized marl soil.

When compared to previous studies [4], [62], a soil stabilized with 7% cement achieved an elastic modulus of only 165 MPa at 28 days [62]. In contrast, both M5 and MOC10 exhibited significantly higher stiffness at an earlier stage, underscoring their superior performance in enhancing soil rigidity. Notably, MOC10 outperformed all other mixes, achieving nearly three times the modulus of the cement-stabilized soil within a much shorter curing period. These findings suggest that MOC-based stabilization not only accelerates strength development but also enhances soil stiffness more effectively than traditional cement-based approaches.

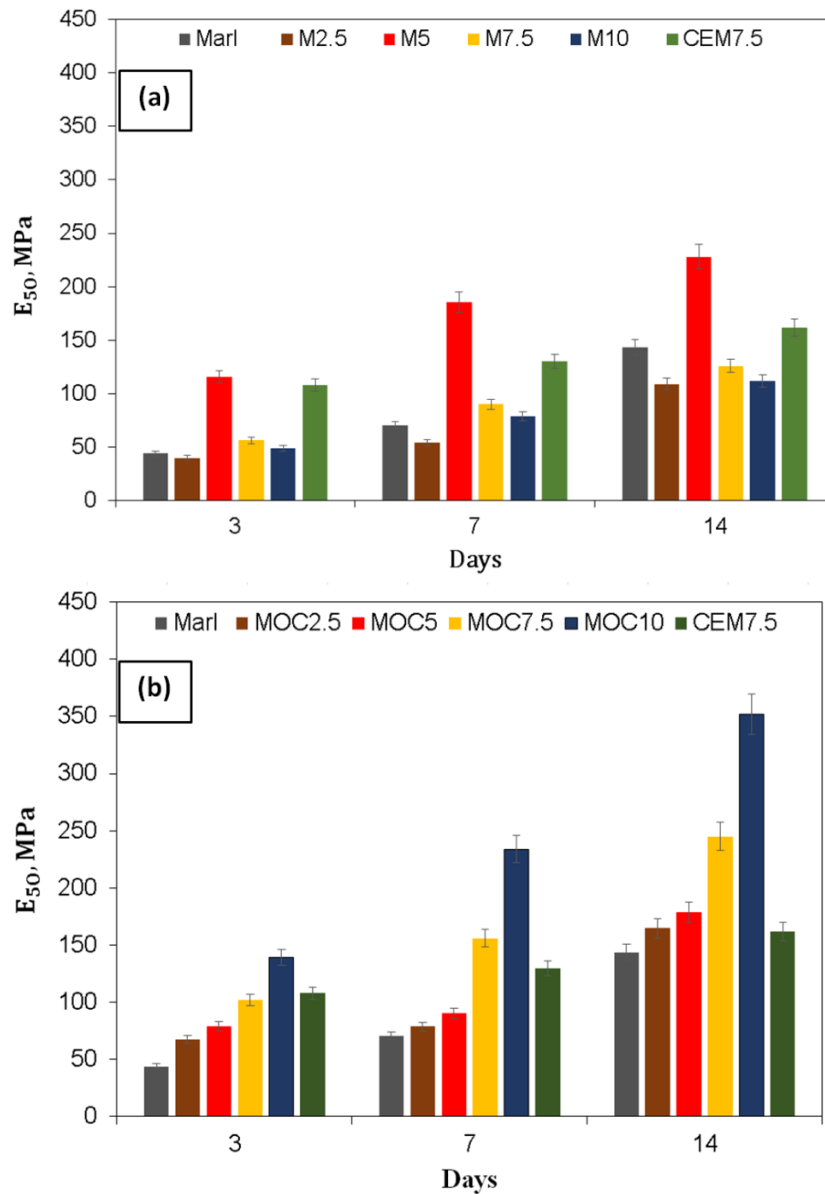


Figure 4.8 Effect of a) RMC and b) MOC Stabilization and Curing Time on E50 of Soil

4.2.6 Effect of RMC and MOC on the Toughness of the Soil

Figure 4.9a illustrates the toughness of marl soil treated with different dosages of RMC and CEM7.5. The untreated soil shows a baseline toughness of 11.5 kPa, which increases to 16.5 kPa with 2.5% RMC and peaks at 24.04 kPa for 5% RMC (M5). However, toughness decreases at higher RMC dosages—13.16 kPa for M7.5 and 11.6 kPa for M10—likely due to over-stiffening, which limits the soil's energy absorption and ductility. In comparison,

CEM7.5 achieves the highest toughness at 26.1 kPa, outperforming all RMC mixes. This suggests that cement stabilization better preserves ductile behavior, offering a more balanced improvement in both strength and deformability. This downward trend in toughness beyond the initial dosage can be attributed to the increased stiffness introduced by higher RMC content. While stiffness may benefit compressive strength, excessive rigidity in the soil matrix tends to reduce energy absorption capacity and deformability, which are key contributors to toughness. The stiffer matrix likely restricts the ductile behavior needed to withstand dynamic or tensile stresses, resulting in a brittle response under loading conditions. Therefore, while low RMC content improves soil toughness, higher dosages may inadvertently reduce it due to over-stiffening effects.

Figure 4.9b presents the toughness development in marl soil treated with increasing dosages of MOC, alongside CEM7.5 for comparison. Unlike the RMC-stabilized mixes, MOC-treated samples show a consistent increase in toughness—from 22.0 kPa (MOC2.5) to 24.89 kPa (MOC5), 34.3 kPa (MOC7.5), and peaking at 53.4 kPa (MOC10). This trend highlights MOC's ability to enhance both strength and ductility through the formation of strong crystalline phases (e.g., Phase 5), which improve structural integration without overly stiffening the soil. CEM7.5, with a toughness of 26.1 kPa, performs better than MOC2.5 and MOC5, but falls short of MOC7.5 and MOC10. This continuous enhancement reflects the superior bonding and structural integration offered by MOC, likely due to the formation of a denser matrix and strong gel phases such as Phase 5 ($5\text{Mg}(\text{OH})_2 \cdot \text{MgCl}_2 \cdot 8\text{H}_2\text{O}$), which contribute to high load-bearing capacity and improved ductility. The absence of excessive stiffness allows the soil to retain its deformation capacity while gaining strength, resulting in a tougher, more resilient composite. Hence, MOC proves more effective than RMC for improving soil toughness, especially at higher binder dosages.

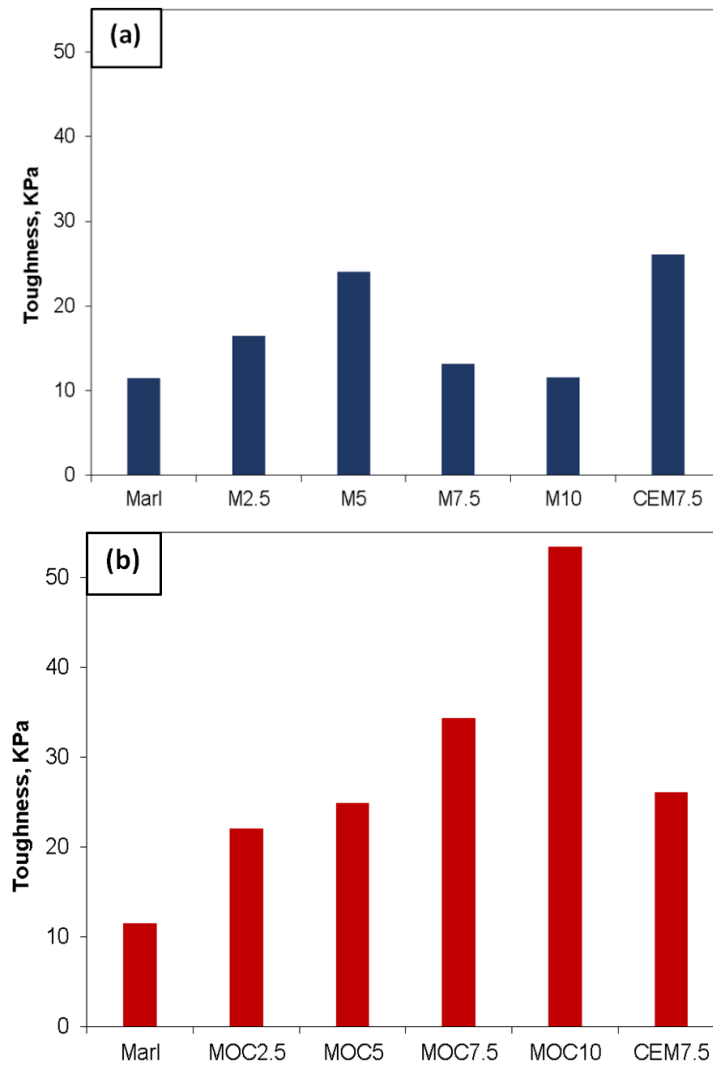


Figure 4.9 Effect of a) RMC and b) MOC Stabilization on Toughness of the Soil

4.2.7 Effect of RMC and MOC on the Peak/Failure Strain of the Soil

5 Figure 4.10a presents the strain at peak and failure points for marl soil treated with varying dosages of RMC, including a comparison with CEM7.5. The untreated marl shows moderate strain values at both peak and failure. M2.5 and M5 exhibit slightly increased peak and failure strains, with M5 showing the highest ductility among the RMC mixes. However, both M7.5 and M10 display reduced strain values, indicating increased brittleness at higher RMC contents. In contrast, CEM7.5 shows the highest failure strain

and one of the highest peak strains, suggesting that cement treatment maintains better deformability and post-peak ductile behavior compared to RMC at similar or higher.

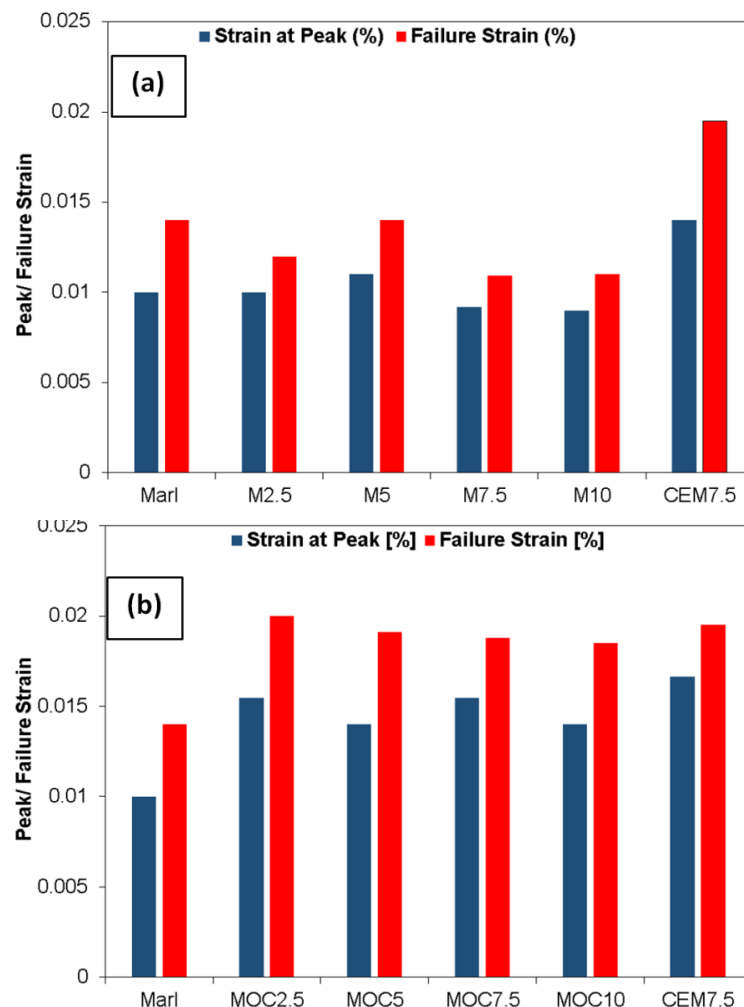


Figure 4.10 Effect of a) RMC and b) MOC on the Peak/Failure Strain of the Soil

In contrast, Figure 4.10b illustrates the strain behavior for soils stabilized with Magnesium MOC. All MOC-treated samples demonstrate higher peak and failure strains than untreated marl, indicating improved ductility and energy absorption capacity. Notably, MOC2.5 and MOC5 show well-balanced strain behavior, while MOC7.5 and MOC10 maintain high values despite their higher strength levels, suggesting that MOC enhances both strength and ductility. CEM7.5, included for comparison, exhibits peak and failure strain values similar to

MOC10, highlighting that MOC can match or exceed the ductility benefits of OPC while delivering greater strength improvements.

4.2 Phase Transformation Analysis

The XRD analysis, presented in Figure 4.11a, is RMC stabilized soil that reveals the presence of key mineral phases, including brucite ($\text{Mg}(\text{OH})_2$), calcite (CaCO_3), and dolomite ($\text{CaMg}(\text{CO}_3)_2$). Brucite, formed through the hydration of MgO , plays a crucial role in enhancing the stability and durability of the stabilized soil. Calcite, identified at $\sim 29.4^\circ$ 2-theta, is a prominent phase contributing to the binding properties of the matrix. Dolomite, observed at $\sim 30.8^\circ$ 2-theta, is indicative of the interaction between magnesium and calcium components, further reinforcing the stabilized soil structure. Additionally, quartz (SiO_2), with a peak at $\sim 26.7^\circ$ 2-theta, remains as a dominant phase, providing structural support. The presence of these mineral phases confirms the effectiveness of RMC in modifying the soil's mineralogical composition, leading to improved strength and durability.

The XRD analysis, presented in Figure 4.11b, confirms the successful stabilization of soil with MOC, as evidenced by the presence of key hydration products such as $\text{Mg}_3(\text{OH})_5\text{Cl}\cdot 4\text{H}_2\text{O}$ (Phase 5 of MOC), which plays a crucial role in strength development and long-term stability. The detection of MgO (Magnesium Oxide) and $\text{Mg}(\text{OH})_2$ (Brucite) suggests that some magnesium oxide remains unreacted, indicating a gradual hydration process that can continue enhancing the material's properties over time. Additionally, the presence of CaCO_3 (Calcite) and $\text{CaMg}(\text{CO}_3)_2$ (Dolomite) suggests the retention of calcium-based compounds, which can contribute to improved durability. The detection of SiO_2 (Silica), likely originating from the soil, confirms that native minerals are still present and may influence further interactions within the stabilized matrix. These findings highlight the

formation of stable phases, ensuring that the MOC-stabilized soil exhibits improved mechanical properties and long-term performance.

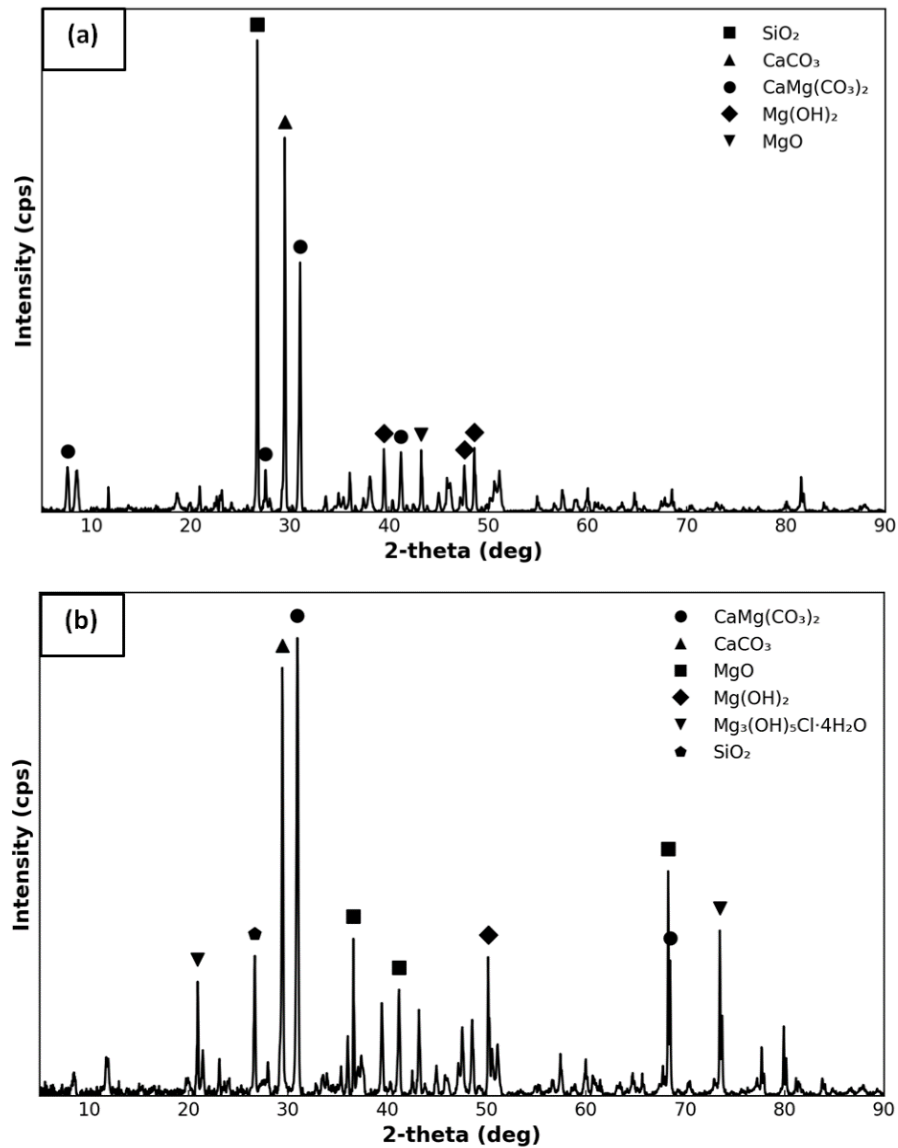


Figure 4.11 X-Ray diffraction analysis of a) RMC stabilized Soil at 5% and b) MOC stabilized soil at 10%.

4.3 Microstructural Characterization

The SEM image (Figure 4.12a) of the RMC-stabilized soil provides a detailed microstructural view, highlighting the presence of brucite ($\text{Mg}(\text{OH})_2$) and dolomite ($\text{CaMg}(\text{CO}_3)_2$) as key mineral phases contributing to soil stabilization. The brucite appears as flake-like structures,

which result from the hydration of MgO, enhancing the bonding and cohesion within the soil matrix. These thin, plate-like formations contribute to improved stability by filling voids and binding soil particles together. The dolomite, on the other hand, is observed as prismatic crystals, indicating well-defined growth and crystallization due to the interaction between magnesium and calcium components. These prismatic formations play a crucial role in strengthening the stabilized matrix by providing rigidity and structural reinforcement. Additionally, the image reveals voids, which are regions of incomplete densification that may influence the material's porosity and water retention capacity.

The SEM image (Figure 4.12b) of the RMC-stabilized soil reveals a complex microstructure characterized by distinct mineral formations contributing to the material's stability and mechanical performance. The presence of nesquehonite, observed as needle-like or fibrous crystalline structures, suggests the formation of hydration products that enhance the cohesion within the soil matrix. Additionally, hydro-magnesite appears as plate-like aggregates, indicating the development of secondary mineral phases that contribute to structural integrity.

The combination of these mineral phases plays a crucial role in improving the overall strength and durability of the stabilized soil by refining its microstructure and enhancing particle bonding. The observed formations suggest a well-developed mineralization process, leading to a denser matrix with reduced porosity and improved mechanical properties. The microstructural analysis confirms that RMC stabilization significantly alters the soil's composition, promoting mineral transformations that enhance its mechanical performance and structural integrity.

The SEM image (Figure 4.13a) of the MOC-stabilized soil highlights the presence of Phase 5, brucite ($\text{Mg}(\text{OH})_2$), and dolomite ($\text{CaMg}(\text{CO}_3)_2$) as key mineral phases. Phase 5, appearing as needle-like structures, is a characteristic hydration product of MOC, contributing to the

reinforcement and mechanical strength of the stabilized soil. These elongated formations play a crucial role in binding the soil particles together and enhancing the overall durability of the matrix. The brucite, observed as flake-like structures, results from the hydration of magnesium components, further aiding in the stabilization process by filling voids and improving the cohesion of the soil. Additionally, the dolomite, present as prismatic crystals, suggests the interaction between magnesium and calcium ions, leading to the formation of a stable matrix that enhances the structural integrity of the soil.

The SEM image (Figure 4.13b) of the MOC-stabilized soil reveals a well-developed microstructure with distinct mineral phases contributing to its stabilization. The presence of hydro-magnesite, identified as clustered formations with a plate-like morphology, indicates the development of secondary hydration products that enhance the integrity and bonding of the matrix. Additionally, unreacted MgO is observed as isolated particles within the structure, suggesting incomplete hydration or excess MgO content in the system. The distribution of these phases plays a significant role in influencing the mechanical properties of the stabilized soil by promoting matrix densification and improving interparticle cohesion. The overall microstructure exhibits a combination of fibrous and dense formations, indicative of the transformation processes occurring during MOC hydration and stabilization.

The combined presence of these phases confirms the mineralogical transformations occurring in MOC-stabilized soil, leading to improved strength, durability, and resistance to environmental degradation.

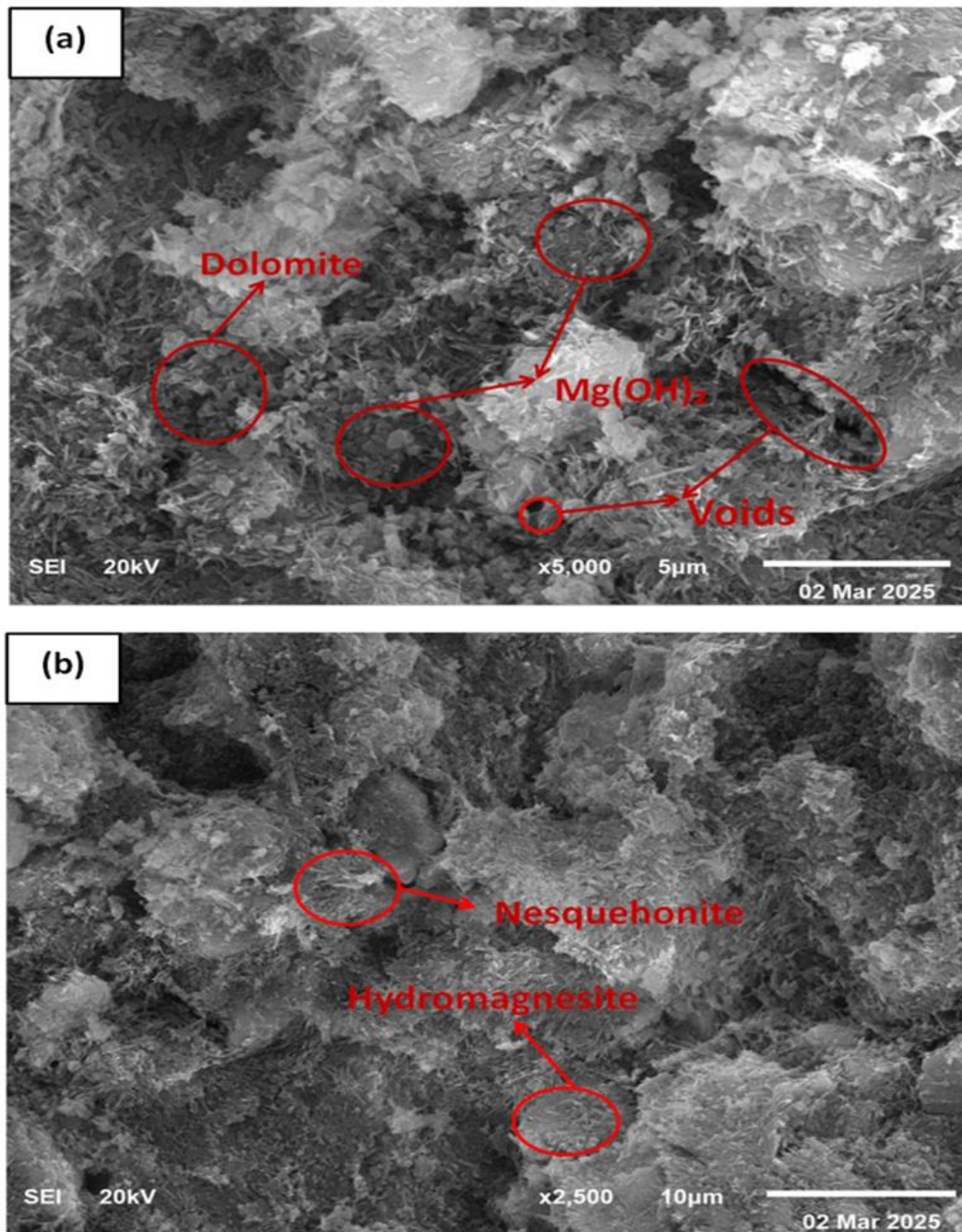


Figure 4.12 SEM analysis of RMC-stabilized Soil at 5%

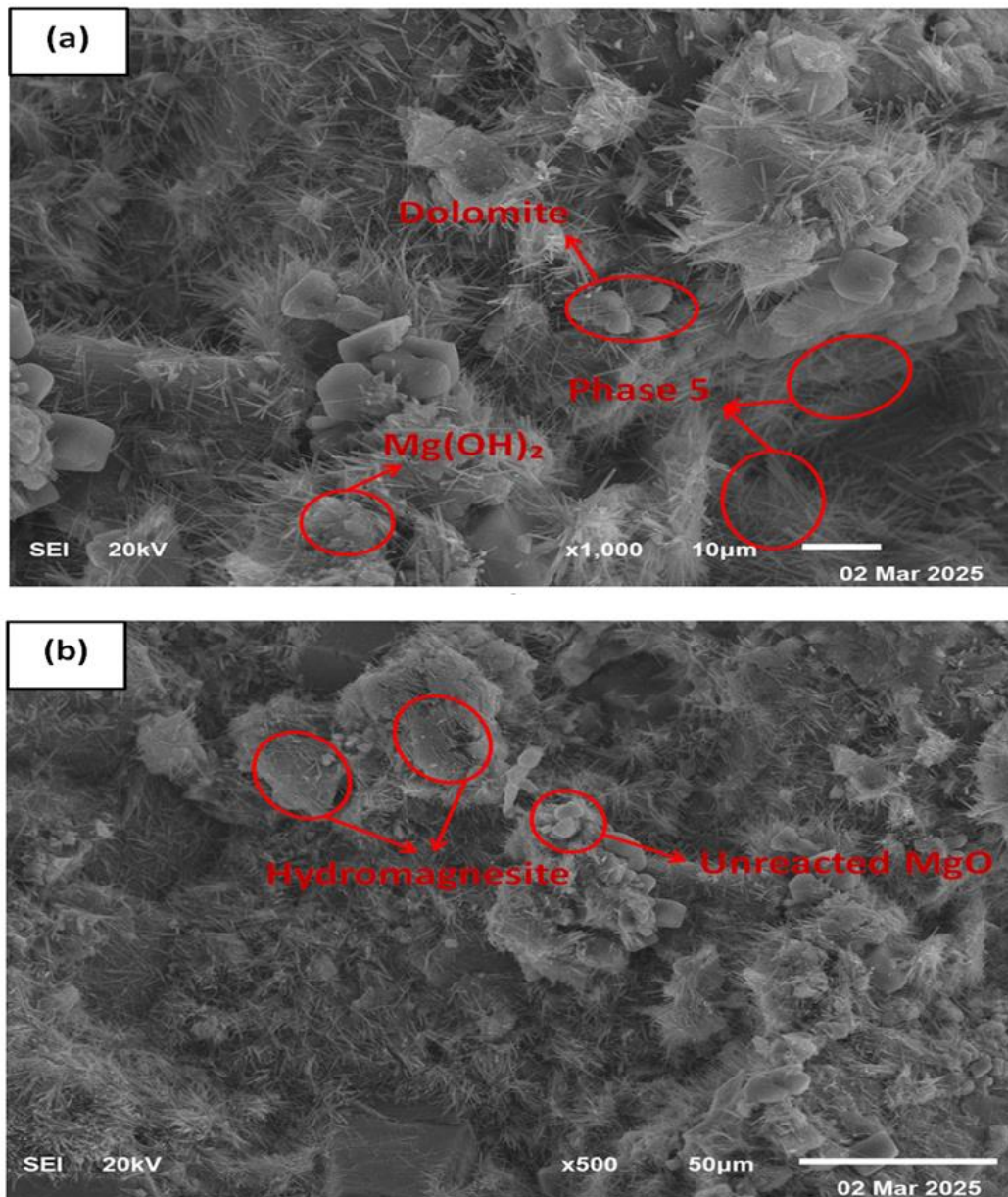


Figure 4.13 SEM analysis of MOC-stabilized Soil at 10%

4.4 Comparison with existing studies

When compared with earlier studies, soil treated with 5% cement attained a compressive strength of approximately 1600 kPa at 28 days [60],[62], which is substantially lower than the strength values achieved by all MOC-stabilized samples within just 14 days. Furthermore, even when cement was combined with 5% fuel oil fly ash, resulting in a 28-day strength of 2151 kPa [60], the outcome still fell short compared to the 14-day performance of MOC10,

and was surpassed by MOC7.5, which recorded a strength of 3061 kPa. These results clearly reflect the superior early-age strength development provided by MOC, highlighting its potential to rapidly improve soil mechanical properties in comparison to conventional cement-based stabilizers.

In addition to MOC performance, the RMC-stabilized marls also demonstrated notable strength improvements. By day 14, M5 achieved the highest strength among the RMC mixes (2747 kPa), followed by M2.5 (2014 kPa) and M7.5 (1939 kPa). Although RMC mixes generally developed strength more gradually than MOC, their 14-day strengths still exceeded those of cement-treated marls at 28 days, underscoring their effectiveness in long-term soil stabilization.

Similarly, in terms of stiffness, prior research showed that soil stabilized with 7% cement exhibited an elastic modulus of only 165 MPa at 28 days [4], [62]. In contrast, both M5 and MOC10 demonstrated notably higher elastic moduli at much earlier ages, reinforcing their effectiveness in increasing soil rigidity. MOC10, in particular, delivered an elastic modulus nearly three times greater than the cement-treated sample, all within a significantly shorter curing period. This indicates that MOC not only accelerates strength gain but also substantially enhances stiffness, offering performance advantages over traditional cement stabilization methods.

4.5 Cost Comparison of OPC, RMC and MOC Stabilized soil

From a cost standpoint, Ordinary Portland Cement (OPC) remains the most widely used and cost-effective soil stabilizer, with an average market price ranging from \$90 to \$120 per ton, depending on location and supply chain factors. Its widespread production and availability contribute to its relatively low cost. In comparison, Reactive Magnesia Cement (RMC) typically costs between \$180 and \$250 per ton, owing to the need for high-purity MgO and

its lower production volumes. Despite the higher upfront cost, RMC offers advantages such as lower calcination temperatures (around 750°C vs. 1450°C for OPC) and CO₂ absorption during carbonation, which can translate to carbon credits and environmental savings in sustainability-driven projects. Magnesium Oxychloride Cement (MOC) tends to be the most expensive among the three, with costs ranging from \$280 to \$350 per ton, primarily due to the high price of magnesium chloride (MgCl₂), a key component that is not always readily available in all regions as shown in Table 4-4. However, MOC's superior early-age strength and shorter curing time can reduce labor costs and accelerate project timelines, potentially offsetting part of its material cost. Therefore, while OPC remains the most affordable in terms of direct cost, RMC and MOC offer competitive advantages in terms of environmental performance and construction efficiency, especially in contexts where sustainability, rapid strength development, or reduced curing times are prioritized.

Table 4-4 Cost Comparison of OPC, RMC and MOC Stabilized soil

Stabilizer	Cost Range (USD/ton)	Key Cost Factors	Advantages
OPC	\$90 – \$120	High availability, widespread production	Most affordable, widely available
RMC	\$180 – \$250	High-purity MgO, lower production volume	Lower calcination temp (~750°C), CO ₂ absorption (carbon credits), environmentally friendly
MOC	\$280 – \$350	High cost of MgCl ₂ , limited regional availability	Superior early-age strength, shorter curing time, potential labor cost savings

4.6 Cost estimation of 1 cubic meter of OPC, RMC and MOC Stabilized Marl

The cost estimation of 1 cubic meter of stabilized marl was calculated by determining the amount of binder required per cubic meter of soil based on the specified dosage percentages. This was followed by multiplying the required binder mass (in kg/m³) by the unit cost of each binder (in USD/ton), and then converting the mass to cost per cubic meter. The formula used is:

$$\text{Estimated Cost } \left(\frac{\text{USD}}{\text{m}^3} \right) = \left(\frac{\text{Binder Required (kg/m}^3\text{)}}{1000} \times \text{Cost (USD/ton)} \right)$$

As shown in the table, Ordinary Portland Cement (OPC) at a 7.5% dosage requires 127.5 kg/m³ and results in the lowest estimated cost of 13.39 USD/m³, due to its lower unit cost. Reactive Magnesia Cement (RMC) at 5% dosage requires 85 kg/m³, costing 18.28 USD/m³, while Magnesium Oxychloride Cement (MOC) at the same dosage has a slightly lower binder price but results in the highest cost of 26.2 USD/m³, primarily due to its higher unit price and similar binder quantity. This comparison highlights the economic considerations in selecting a stabilizer, where OPC remains the most cost-effective, while MOC, despite its superior performance, incurs a higher material cost.

Table 4-5 Cost estimation of 1 cubic meter of OPC, RMC and MOC Stabilized Marl

Stabilizer	Dosage (%)	Binder Required (kg/m ³)	Cost (USD/ton)	Estimated Cost (USD/m ³)
RMC	5	85	215	18.28
MOC	5	85	157.5	26.2
OPC	7.5	127.5	105	13.39

4.7 Comparative Evaluation of OPC, RMC and MOC Binders in Terms of

E n e r g y D e m a n d a n d C O E m i s s i o n s

In the pursuit of sustainable construction practices, the selection of cementitious binders plays a pivotal role in minimizing environmental impacts, particularly with respect to energy consumption and carbon emissions. Cement production is widely recognized as a significant contributor to global greenhouse gas (GHG) emissions, with Ordinary Portland Cement (OPC) being the most commonly used but also the most carbon-intensive. As concerns about climate change and resource depletion intensify, alternative binders such as Reactive

Magnesia Cement (RMC) and Magnesium Oxychloride Cement (MOC) have garnered attention due to their potential to reduce both energy demands and production-related CO₂ emissions.

This section presents a comparative evaluation of OPC, RMC, and MOC based on their energy requirements and carbon dioxide emissions during the production phase. By quantifying these parameters for the production of one metric ton of each binder, the analysis provides a clearer understanding of the environmental trade-offs associated with their use. The results serve as a basis for identifying more sustainable alternatives to OPC and inform recommendations for greener material choices in the construction industry.

4.7.1 OPC

CO₂ Emission:

- $\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$ (44% CO₂ by mass)
- 1.25 tons of limestone required $\rightarrow$ 1 ton OPC
- CO₂ from calcination = $1.25 \times 0.44 = 550$ kg
- Fuel combustion adds ~ 350 kg $\rightarrow$ Total ≈ 900 kg CO₂

Energy Consumption:

- Kiln (thermal) = ~ 3600 MJ
- Grinding = ~ 900 MJ $\rightarrow$ Total ≈ 4500 MJ

4.7.2 RMC

CO₂ Emission:

- $\text{MgCO}_3 \rightarrow \text{MgO} + \text{CO}_2$ (52% CO₂ by mass)
- 1.6 tons magnesite $\rightarrow$ 1 ton MgO

- CO₂ from calcination ≈ 0.83 tons but averaged at 300 kg for brine-based routes

Energy Consumption:

- Low calcination temp ($\sim 750^\circ\text{C}$)
- Energy = $2.0 \text{ MJ/kg} \times 1000 = 2000 \text{ MJ}$

4.7.3 MOC

CO₂ Emission:

- From MgO = $\sim 300 \text{ kg}$
- From MgCl₂ production = $\sim 50 \text{ kg} \rightarrow \text{Total} \approx 350 \text{ kg CO}_2$

Energy Consumption:

- MgO: 2.0 MJ/kg
- MgCl₂: $\sim 0.8 \text{ MJ/kg}$
- Total $\approx 2.8 \text{ MJ/kg} \times 1000 = 2800 \text{ MJ}$

Table 4-6. Comparative Evaluation of OPC, RMC and MOC Binders in Terms of Energy Demand and CO Emission

Binder	Derived From	Calcination Temp	CO from Calcination (kg)	CO from Fuel (kg)	Total (kg)	Total Energy (MJ)
OPC	CaCO ₃	$\sim 1450^\circ\text{C}$	550	350	900	4500
RMC	MgCO ₃ or Desalination brine	$\sim 750^\circ\text{C}$	200–400	~ 100	400	2000
MOC	MgO + MgCl ₂	$\sim 750^\circ\text{C}$ (MgO)	300 (MgO)	50 (MgCl ₂)	350	2800

CHAPTER 5: CONCLUSION

This study evaluated the stabilization of marl soil using Reactive Magnesia Cement (RMC) and Magnesium Oxychloride Cement (MOC) to enhance its mechanical properties. The findings demonstrate that both stabilizers significantly improve soil strength, stiffness, and microstructural composition, with MOC exhibiting superior performance. The following conclusions are drawn from obtained results

5.1 Key Findings

5.1.1 Mechanical Properties

The experimental results clearly demonstrate that stabilization with both RMC and MOC significantly enhances the mechanical properties of marl soil in terms of unconfined UCS and E50. The untreated marl soil exhibited minimal strength gains, plateauing at 1152 kPa by day 14, while RMC-treated samples, particularly M5, reached a peak UCS of 2747 kPa—a 138% improvement over the control highlighting its potential for applications requiring rapid strength development. In contrast, MOC-stabilized soils achieved even greater improvements. MOC10 recorded the highest UCS of 4618 kPa at 14 days, over 300% higher than the untreated soil, emphasizing the efficiency of MOC in accelerating strength development. In terms of stiffness, both RMC and MOC mixes outperformed untreated soil, which reached only 143.3 MPa at 14 days. M5 achieved the highest E50 among the RMC formulations at 227.9 MPa, whereas MOC10 demonstrated a remarkable stiffness of 352 MPa by day 14. Although CEM7.5 achieved a UCS of 1953 kPa, confirming its reliability as a conventional stabilizer, it was consistently outperformed by MOC and RMC in both strength and stiffness. These findings confirm that

both binder type and dosage significantly influence the mechanical behavior of marl soil, and that curing time further enhances performance. While MOC10 delivered the highest overall mechanical improvement, considerations regarding cost-effectiveness and material availability may influence the choice of optimal dosage for field applications.

5.1.2 Phase Transformation Analysis:

XRD analysis confirmed the formation of key phases responsible for strength and durability. In RMC-stabilized soil, brucite ($\text{Mg}(\text{OH})_2$), calcite (CaCO_3), and dolomite ($\text{CaMg}(\text{CO}_3)_2$) were identified, with M5 showing the most distinct mineral transformations contributing to its improved strength. For MOC-stabilized soil, Phase 5 ($\text{Mg}_3(\text{OH})_5\text{Cl}\cdot 4\text{H}_2\text{O}$) was the dominant hydration product, playing a crucial role in structural reinforcement, with MOC10 demonstrating the most pronounced mineral formations.

5.1.3 Microstructural Analysis:

SEM analysis revealed distinct morphological features that contributed to strength development. In RMC-stabilized samples, flake-like brucite and prismatic dolomite structures were observed, improving cohesion and particle bonding, with M5 showing the densest matrix formation. MOC-stabilized soil exhibited needle-like Phase 5 structures and flake-like brucite, significantly reinforcing the soil matrix. MOC10 displayed the most interconnected and well-defined structures, confirming its superior performance in reducing porosity and enhancing mechanical stability.

The marked improvements in strength and stiffness observed in both RMC- and MOC-stabilized soils highlight their suitability for a wide range of geotechnical engineering projects, including road subgrades, embankments, and foundation support in weak marl deposits. The rapid strength development of MOC, in particular, offers advantages in time-sensitive construction, while RMC

presents a promising balance between performance and sustainability. These results provide a strong foundation for advancing the use of magnesia-based binders in field-scale soil stabilization

5.1.4 Cost Comparison

While OPC remains the most cost-effective stabilizer at \$90–\$120 per ton, RMC and MOC, despite their higher prices (\$180–\$250 and \$280–\$350 per ton, respectively), offer notable sustainability and performance benefits. RMC provides lower calcination energy and potential CO₂ absorption, while MOC delivers high early strength and faster curing. These advantages make RMC and MOC viable alternatives in projects prioritizing environmental impact reduction and construction efficiency.

5.1.5 Embodied Carbon and Energy Comparison

The comparative analysis of energy consumption and CO₂ emissions among OPC, RMC, and MOC highlights the significant environmental advantages of alternative binders. While OPC production remains energy-intensive and emits approximately 900 kg of CO₂ per ton, RMC and MOC demonstrate considerably lower emissions at 300 kg and 350 kg CO₂ per ton, respectively. Additionally, their lower thermal processing requirements contribute to substantial energy savings. These findings support the potential of RMC and MOC as sustainable alternatives for reducing the carbon footprint in construction and soil stabilization applications.

The marked improvements in strength and stiffness observed in both RMC- and MOC-stabilized soils highlight their suitability for a wide range of geotechnical engineering projects, including road subgrades, embankments, and foundation support in weak marl deposits. The rapid strength development of MOC, in particular, offers advantages in time-sensitive construction, while RMC presents a promising balance between performance and sustainability. These results provide a

strong foundation for advancing the use of magnesia-based binders in field-scale soil stabilization.

5.2 Limitations and Future Directions

While this study offers valuable insights into the stabilization of marl soil using RMC and MOC, several limitations must be acknowledged. The experiments were conducted under controlled laboratory conditions, which may not fully replicate field conditions characterized by environmental stressors such as cyclic wetting-drying and freeze-thaw effects. Additionally, the study focused on short-term curing periods, which may not fully capture the long-term behavior of binders. The economic analysis was limited to material costs and did not factor in large-scale logistical considerations such as regional binder availability or transport distances. To address these gaps, future research should incorporate comprehensive life cycle assessments (LCA) that evaluate cradle-to-gate energy use and comparative environmental impacts of RMC/MOC versus OPC systems. Moreover, extended durability testing simulating realistic environmental exposures and phase stability monitoring through techniques such as XRD and SEM over one to five years is essential. Finally, the integration of circular economy approaches—such as the use of industrial by-products (e.g., slag, biomass ash) and renewable energy solutions like solar curing—may further enhance the sustainability of soil stabilization practices.

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Publication

Title	Type	Status
Magnesia-based binders for stabilizing and improving soft soils	Chapter: Computer Aided Chemical Engineering	Published
Reactive Magnesia and Magnesium Oxychloride Cement Treatments for Mechanical Enhancement of Marl Soil	Journal: Results in Engineering	Under review
Influence of bonded mortar on recycled aggregate concrete properties: A review	Journal: Construction and Building Materials	Published
Marine Resilience: Understanding the durability and effects on concrete structures – a comprehensive review	Journal: Arabian Journal of Science and Engineering	Under Review
Design considerations and remedial measures for reinforced concrete building structures in marine environment: A resilience perspective	European Journal of Environmental and Civil Engineering	Under Review