KARYA ILHAM PUBLISHING
CONNECTING MINDS, BRIDGING IDEAS, INSPIRING READERS

Malaysian Journal on Composites Science and Manufacturing
Journal homepage:
https://karyailham.com.my/index.php/mjcsm/index
ISSN: 2716-6945

Synergistic Stabilization of Clay Soil Using Magnesium Chloride and Saw Dust Ash: A Strength Behavior Study

Bibi Zafirah Zaki[1], Nik Norsyahariati Nik Daud[1,*], Noor Azline Mohd. Nasir[1]

[1] Department of Civil Engineering, Faculty of Engineering, Universiti Putra Malaysia, Serdang 43400, Selangor, Malaysia

ARTICLE INFO

Article history:
Received 30 December 2025
Received in revised form 20 February 2026
Accepted 3 March 2026
Available online 31 March 2026

Keywords:

Clay soil stabilization; magnesium chloride; saw dust ash; synergistic effects; strength behavior

ABSTRACT

Soil stabilization remains a critical concern in geotechnical engineering particularly for clay soils exhibiting low shear strength and high compressibility. This study investigates the synergistic effects of magnesium chloride ($MgCl_2$) and saw dust ash (SDA) on the strength behavior of clay soil. An experimental program was conducted on clay soil samples treated with varying dosages of $MgCl_2$ (7%, 8%, and 9% by weight) combined with SDA (2%, 4%, 6%, 8%, and 10% by weight). Physical characterization included particle size distribution, Atterberg limits, specific gravity, linear shrinkage, and free swell index were determined according to British Standard (BS) and American Society for Testing and Materials (ASTM). Compaction characteristics were evaluated using standard proctor methods while strength behavior was assessed through California bearing ratio (CBR) which was conducted to measure a soil's ability to support loads. Unconfined compression strength (UCS) was carried out to determine the compressive strength of soil and direct shear box testing was conducted to determine the shear strength of soil. Together, they related to the soil's strength performance under different conditions. The 8% $MgCl_2$ treatment consistently outperformed both 7% and 9% treatment across all strength parameters. Results showed a very high correlation between CBR, UCS and cohesion. The analysis revealed a strong positive correlation with an R^2 value of 0.8296 (CBR=0.0114 and UCS=0.2235), 0.8728 (cohesion=0.0747 and UCS=-10.955) as well as 0.9153 (CBR=0.1495 and cohesion=1.9479). The study confirms that the cohesion shows the strongest and most consistent strength performance. Thereby, this practical approach is cost-effective and environmentally friendly.

1. Introduction

Soil stabilization could be defined as the improvement of soil properties through chemical or physical modification, which represents one of the most common solutions in geotechnical engineering practice. Traditional approaches, particularly cement, lime and fly ash stabilization, have demonstrated effectiveness but raise concerns regarding environmental sustainability and cost-effectiveness, as noted by Gudeta and Patel [1] and Alhakim *et al.*, [2]. Consequently, extensive research focuses on developing improved, sustainable, and affordable soil stabilization techniques,

---

[*] *Corresponding author.*
E-mail address: niknor@upm.edu.my

https://doi.org/10.37934/mjcsm.19.1.6085

particularly those utilizing locally accessible materials, to mitigate these risks, as reviewed by Ikeagwuani and Nwonu [3] as well as Gidebo *et al.*, [4]. Clay soils are characterized by high plasticity and low permeability, present challenges in foundation engineering and earthwork applications. The problems associated with clay soils include excessive settlement, low bearing capacity, high compressibility, and significant volume change upon moisture variation, as discussed by Mahdavian *et al.*, [5].

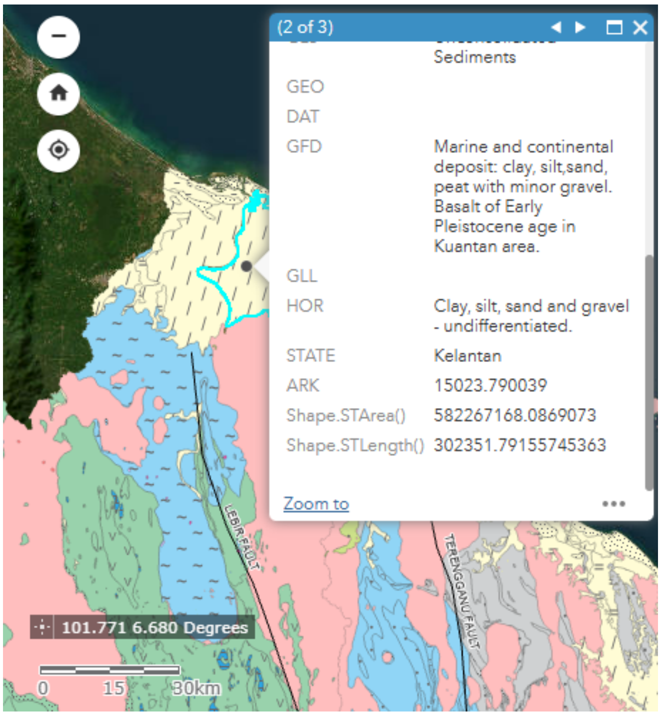
Magnesium chloride has emerged as a promising chemical stabilizer for clayey soils offering distinct advantages over conventional approaches. Recent studies have explored using $MgCl_2$ to enhance the physical and chemical properties of problematic soils. Furthermore, magnesium chloride offers greater economic efficiency for its performance level than either sodium chloride or calcium chloride, as highlighted by Sharma *et al.*, [6]. $MgCl_2$ is globally recognized as an environmentally friendly soil stabilizer due to its safe and anti-corrosive properties, according to Habibbeygi and Nikraz [7]. Research indicates that $MgCl_2$'s effectiveness as a stabilizer is concentration-dependent, as demonstrated by Latifi *et al.*, [8] and Muhammad *et al.*, [9]. Its mechanism involves reducing soil swelling by influencing osmotic pressure and promoting ion exchanges within clay structures, with efficiency tied to the soil's exchange capacity and cation characteristics, as explained by Hachichi and Fleureau [10]. Studies have also observed that the incorporation of $MgCl_2$ leads to an increase in the maximum dry density and a decrease in the optimum moisture content of treated soils, as reported by Waheed [11]. Additionally, other studies demonstrate that applying an $MgCl_2$ solution can reduce both the swell potential and dispersity of clay, as shown by Turkoz *et al.*, [12] and Vakili *et al.*, [13].

Agricultural waste has emerged as a promising, sustainable, and cost-effective alternative for soil stabilization. These materials address the crucial need to improve subgrade soil properties while simultaneously managing waste disposal issues that can harm the environment [14-18]. Agricultural wastes are favored for their innovative, user-friendly, and environmentally friendly nature, offering a viable substitute for more expensive and industrially intensive stabilizers like cement, which carry higher environmental risks [3,19-21]. Among these, saw dust ash (SDA), a readily available byproduct of the timber industry which is particularly effective due to its pozzolanic properties. Its silica content chemically reacts with moisture and soil components, enhancing soil strength and significantly improving mechanical properties like California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS), while also reducing shrinkage and cracks in expansive soils are taken from previous studies [17,18,22-24]. Although saw dust ash non-cementitious on its own, saw dust undergoes a chemical reaction with water to produce cementitious compounds. This process improves the soil engineering parameters, namely compressive strength and compressibility, according to Bunyamin *et al.*, [25]. Therefore, this study focused on the synergistic effects of clay soil mixed with varying percentages of magnesium chloride ($MgCl_2$) and saw dust ash (SDA) on the strength behavior.

2. Methodology

2.1 Sample Preparation

Soil samples were collected from a depth of 1.5 meters in Kota Bharu, Kelantan as shown in Figure 1 and stored in plastic bags. The sample exhibited a yellowish color. Following the BS1377-2:2022 standard, the soils were oven-dried at 110°C for 24 hours to remove moisture and then sieved through a 0.425 mm mesh. Based on the Unified Soil Classification System (USCS), the soil is classified as high plasticity clay (CH). The summary of soil properties of natural soil is tabulated in Table 1.



	Sediments
GEO	
DAT	
GFD	Marine and continental deposit: clay, silt,sand, peat with minor gravel. Basalt of Early Pleistocene age in Kuantan area.
GLL	
HOR	Clay, silt, sand and gravel - undifferentiated.
STATE	Kelantan
ARK	15023.790039
Shape.STArea()	582267168.0869073
Shape.STLength()	302351.79155745363

Fig. 1. Geological map of Kota Bharu, Kelantan [26]

Table 1
Soil properties of natural soil

Soil properties	Values
Grain size distribution	
Gravel	0%
Sand	45.54%
Fine material (Clay, Silt)	52.19%
Liquid limit	51.23%
Plastic limit	29.45%
Plasticity index	21.78%
Moisture content	37.16%
Specific gravity	2.72
pH	4.76
Linear shrinkage	13.33%
Free swell index	41.94%
Maximum dry density	1.38 g/cm^3
Optimum moisture content	23.58%

This study employed magnesium chloride ($MgCl_2$) as an environmentally sustainable stabilizing agent, recognized in the literature as a promising green stabilizer by Latifi *et al.*, [8]. The specific compound used was magnesium chloride hexahydrate ($MgCl_2 \cdot 6H_2O$), sourced from R&M Chemicals. This material typically appearing as white flakes was applied in a dissolved solution form. Saw dust for this research was sourced from a local sawmill in Kota Bharu, Kelantan. This material consists of fine wood particles and chips generated during wood cutting. To produce saw dust ash (SDA), the saw dust was burned in a furnace chamber at 600°C for three hours. The resulting SDA was then passed through a 0.425 mm sieve to remove any unburned material, lumps, or coarse particles.

This study was carried out the varying percentages such as 7%, 8% and 9% of magnesium chloride and 2%, 4%, 6%, 8% and 10% of saw dust ash. The soil and saw dust ash were first blended in a mixing container until uniformly combined. Subsequently, the magnesium chloride solution was introduced incrementally during continuous mixing to achieve a consistent and homogeneous mixture.

2.2 Geotechnical Properties

The geotechnical laboratory tests was performed following standardized methods such as particle size distribution, liquid limit was carried out using Casagrande apparatus, specific gravity was carried out using pycnometer method, pH test was conducted using pH meter and linear shrinkage were all conducted in accordance with BS 1377:2022; the free swell index was determined per ASTM D5890-1; Standard Proctor compaction test was carried out to determine the maximum dry density (MDD) and optimum moisture content (OMC), California bearing ratio (CBR), unconfined compression strength (UCS) and direct shear box testing was carried out to obtain cohesion and friction angle were followed as per BS 1377:2022.

3. Results and Discussion

3.1 Physical Properties

3.1.1 Particle size distribution

The particle size distribution curve presented in Figure 2 demonstrates that the soil sample is predominantly composed of fine-grained materials, with a relatively balanced composition between sand and fines materials. This reveals that fine materials (clay and silt) constitute 52.19% representing the dominant fraction in the sample. Sand particles make up 45.54% of the composition, which is nearly equivalent to the fine material content. Notably, gravel-sized particles are completely absent from the sample, accounting for 0%. Based on the Unified Soil Classification System (USCS), the soil sample is classified as SC (Clayey sand) with a high plasticity (CH).

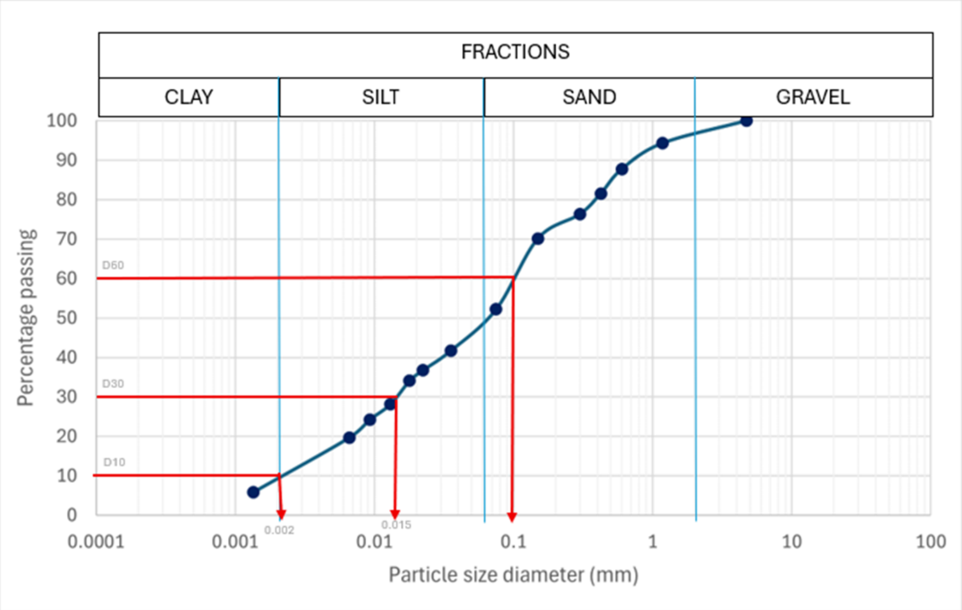


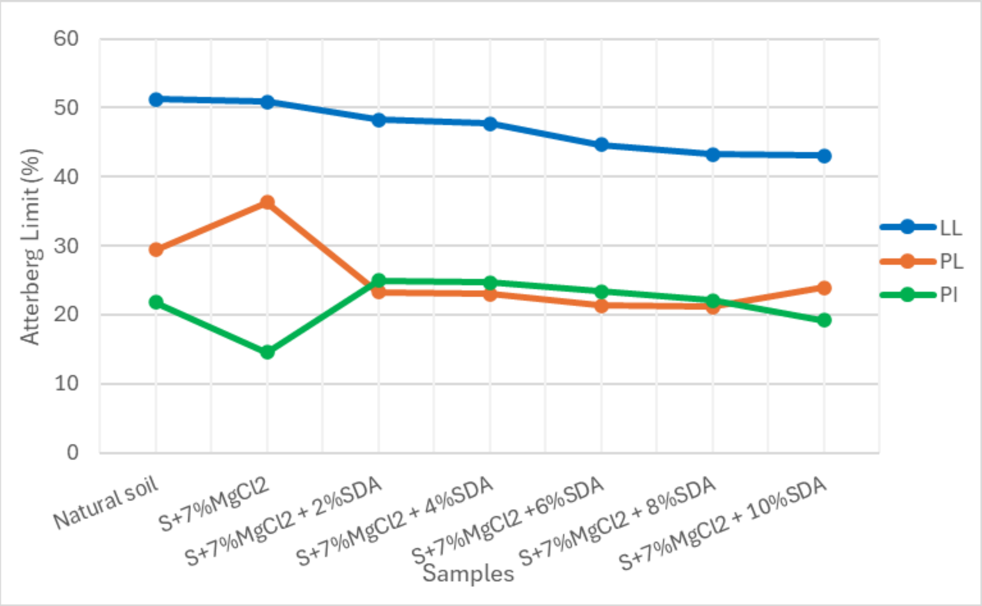
Fig. 2. Particle size distribution curve of soil sample

3.1.2 Atterberg limit

Figure 3 presents Atterberg limit for natural soil and treated soils with $MgCl_2$ and SDA at varying dosages. Natural soil exhibited a high liquid limit (LL=51.23%) and plasticity index (PI=21.78%), classifying it as a highly plasticity soil. The liquid limit shows a consistent decreasing trend as saw dust ash content increases across all soil samples. Natural soil exhibits the highest LL value of 51.23%, indicating greater water absorption capacity. With 7% $MgCl_2$ stabilization, the LL decreases from 48.26% at 2% SDA to 43.10% at 10% SDA. Similarly, 8% $MgCl_2$ samples show a reduction from 46.13% to 38.64%, while 9% $MgCl_2$ samples decline from 49.16% to 38.48%. This downward trend suggests that this could be due to the effects of $MgCl_2$ on cation exchange, as suggested by Habibbeygi and Nikraz [7].

The plastic limit (PL) generally decreases as the amount of SDA increases across all $MgCl_2$ concentrations. For the natural soil, PL starts at 29.45%. Soil treated with 7% $MgCl_2$ addition, PL values range from 23.27% at 2% SDA to 23.89% at 10% SDA showing a general declining trend despite some fluctuation at 10%. The 8% $MgCl_2$ samples demonstrate a more consistent decrease starting at 26.11% and declining to 26.48%. The 9% $MgCl_2$ samples exhibit the most dramatic reduction in PL which beginning at 36.35% with 2% SDA and decreasing substantially to 25.95 at 10% ash indicating that higher $MgCl_2$ concentrations paired with increased SDA influence reducing plasticity.

The plasticity index (PI) shows a consistent declining trend compared to PL. The natural soil begins at 21.78% and this value drops significantly with $MgCl_2$ and SDA additions. The 7% $MgCl_2$ samples show PI values declining from 25.00% to 19.21%, while 8% $MgCl_2$ samples drop from 20.03% to 12.36%. Most notably, 9% $MgCl_2$ samples display the reduction which falling from 12.81% to just 12.54%. Overall, PI shows the most significant and consistent decrease across all combinations except for 7% $MgCl_2$ where it remains relatively high. This improvement could be attributed to the soil being enhanced as the addition of saw dust ash helps to remove some water from the saturated clay minerals, as noted by Oguche *et al.*, [27].



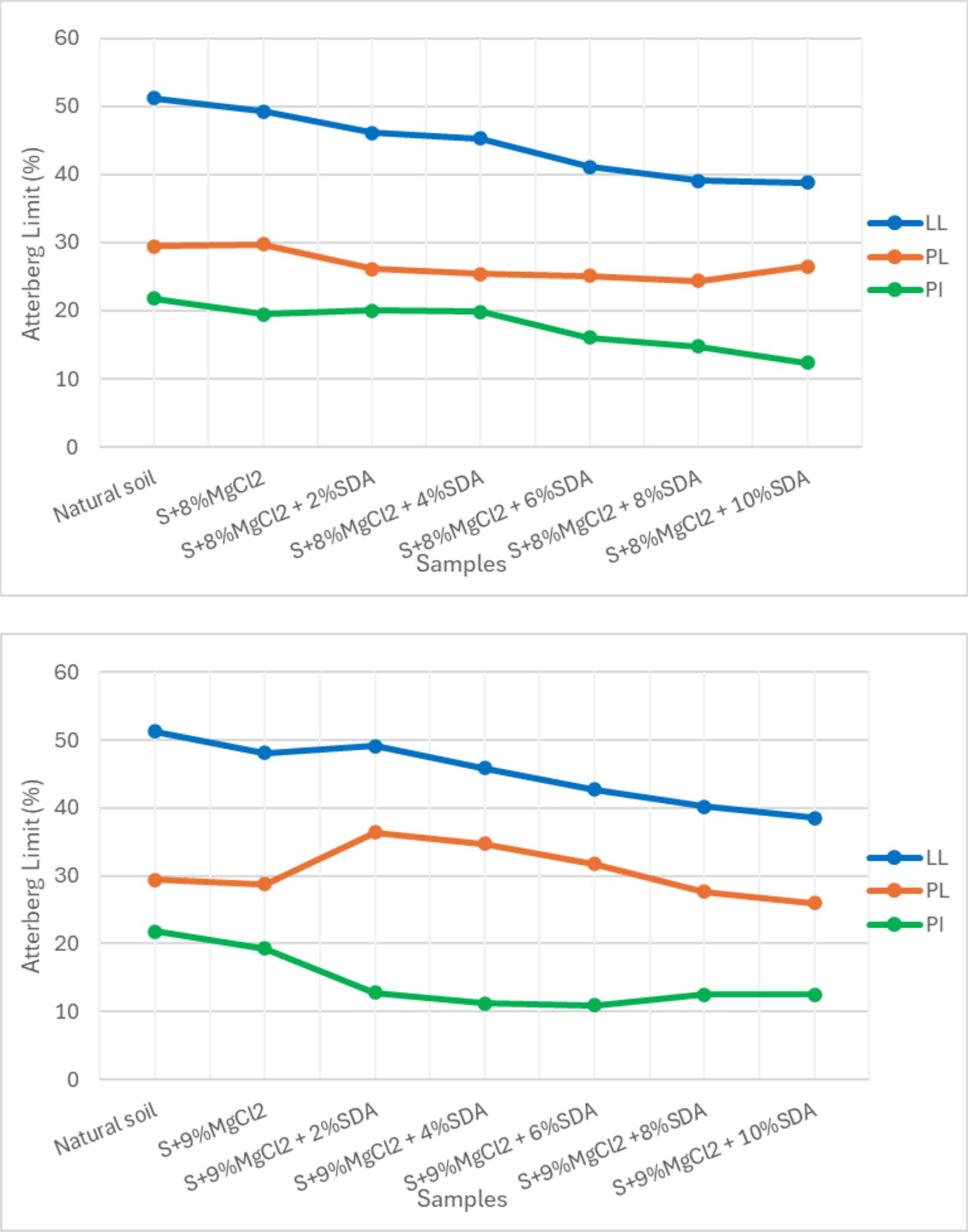
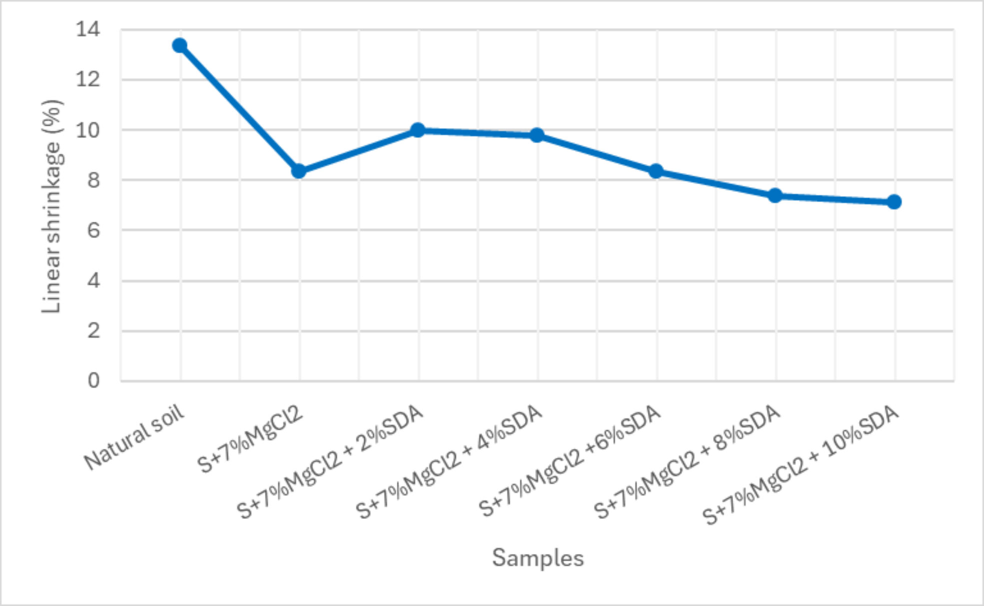


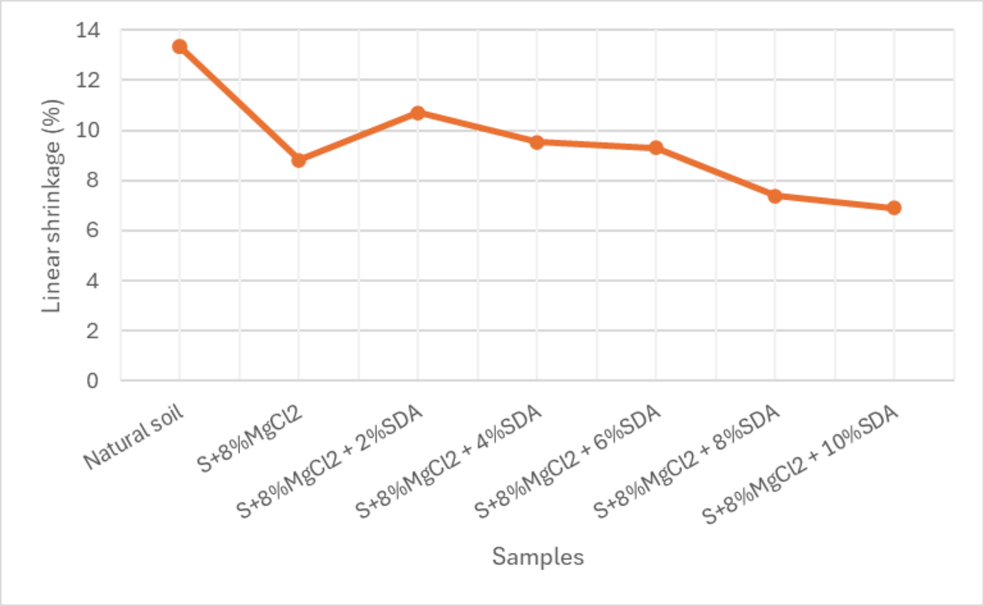
Fig. 3. Atterberg limit of stabilized soil

3.1.3 Linear shrinkage

The graph in Figure 4 shows a linear shrinkage of stabilized soil. The natural soil exhibited a linear shrinkage of 13.33%. The addition of $MgCl_2$ and SDA generally reduces linear shrinkage, indicating an improvement in soil stability. At 7% $MgCl_2$ with 2% SDA, the linear shrinkage decreased to 10.00%, declining further to 7.14% at 10% SDA. Soil treated with 8% $MgCl_2$ demonstrated similar trends, with linear shrinkage values decreasing from 10.71% at 2% SDA to 6.90% at 10% SDA. However, this could be due to the available silica from SDA, combined with Mg^{2+} from the salt, may promote the formation of magnesium-silicate-hydrate (M-S-H) type gels, which are stronger and more water-resistant than gels formed with SDA alone. This indicates fewer cracks when it dries out and enhances suitability for geotechnical construction projects, as reported by Blayi et al., [28].

In contrast, soil treated with 9% $MgCl_2$ shows a different trend which is linear shrinkage initially decreases with SDA but then increases at 8% and 10% SDA, reaching 9.05%. This suggests that 9% $MgCl_2$ may represent an overly high concentration where further SDA addition becomes less effective. Overall, the most effective combination for minimizing linear shrinkage in this experiment appears to be 8% $MgCl_2$ with 10% SDA, yielding the lowest recorded shrinkage of 6.90%.





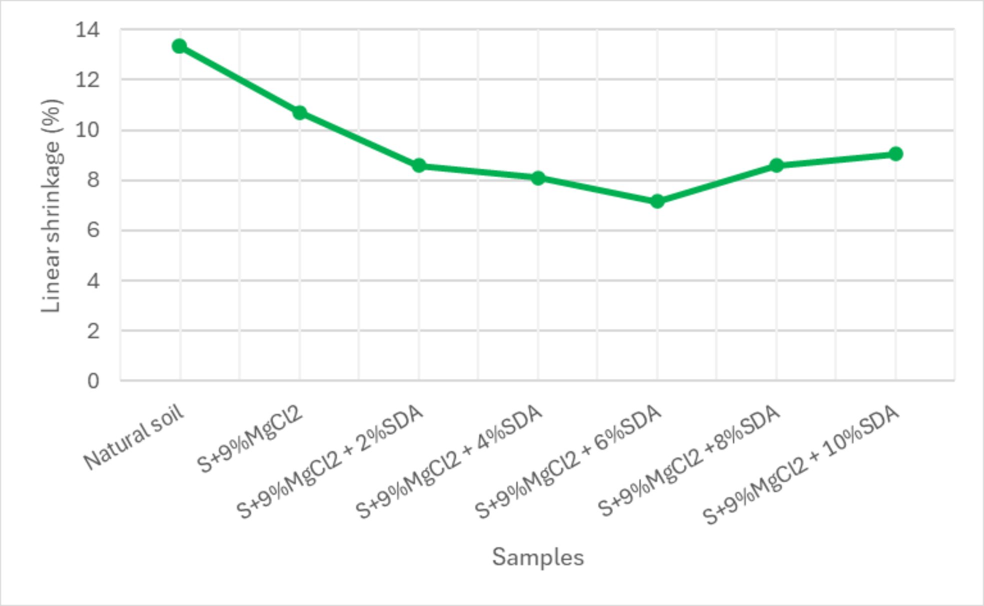
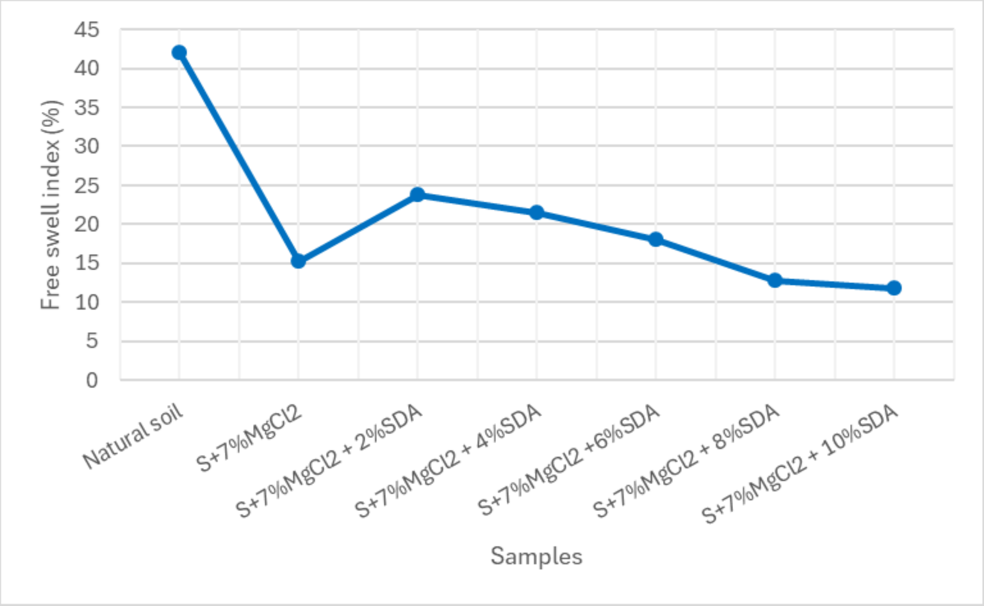


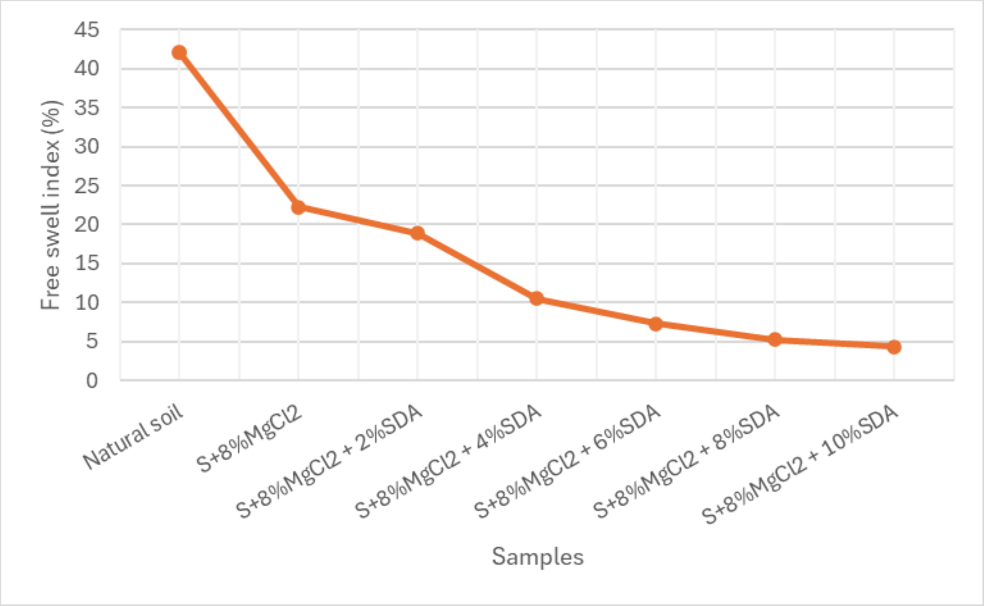
Fig. 4. Linear shrinkage of stabilized soil

3.1.4 Free swell index

As shown in Figure 5, the graph illustrates the free swell index of stabilized soil. The natural soil exhibited a free swell index of 41.94%, indicating significant swelling potential. The application of magnesium chloride dramatically reduced this swelling characteristic. At 7% $MgCl_2$, the free swell index decreased to 23.81% (2% SDA), declining further to 11.76% at 10% SDA, representing an 71% overall reduction. The 8% $MgCl_2$ treatment produced even more substantial swelling reduction, with free swell index values declining from 18.92% (2% SDA) to 4.35% (10% SDA). Notably, the 9% $MgCl_2$ treatment demonstrated variable performance, with values ranging from 21.95% (2% SDA) to 22.58% (10% SDA), suggesting that 9% $MgCl_2$ concentration may exceed optimal conditions for swelling reduction.

The dramatic reductions in free swell index indicate that the swelling index of clay decreases when clay particles clump together, as explained by Arasan *et al.*, [29]. The maximum reduction of 90% was achieved with 8% $MgCl_2$ and 10% SDA combination, resulting in free swell index of only 4.35%. These substantial improvements in swelling characteristics indicate that the treated soils would demonstrate best performance in moisture-variable environments and would be suitable for construction applications previously precluded due to excessive swelling potential.


Free swell index (%)
45
40
35
30
25
20
15
10
5
0
Natural soil
S+7%MgCl2
S+7%MgCl2 + 2%SDA
S+7%MgCl2 + 4%SDA
S+7%MgCl2 +6%SDA
S+7%MgCl2 + 8%SDA
S+7%MgCl2 + 10%SDA
Samples


Free swell index (%)
45
40
35
30
25
20
15
10
5
0
Natural soil
S+8%MgCl2
S+8%MgCl2 + 2%SDA
S+8%MgCl2 + 4%SDA
S+8%MgCl2 + 6%SDA
S+8%MgCl2 + 8%SDA
S+8%MgCl2 + 10%SDA
Samples

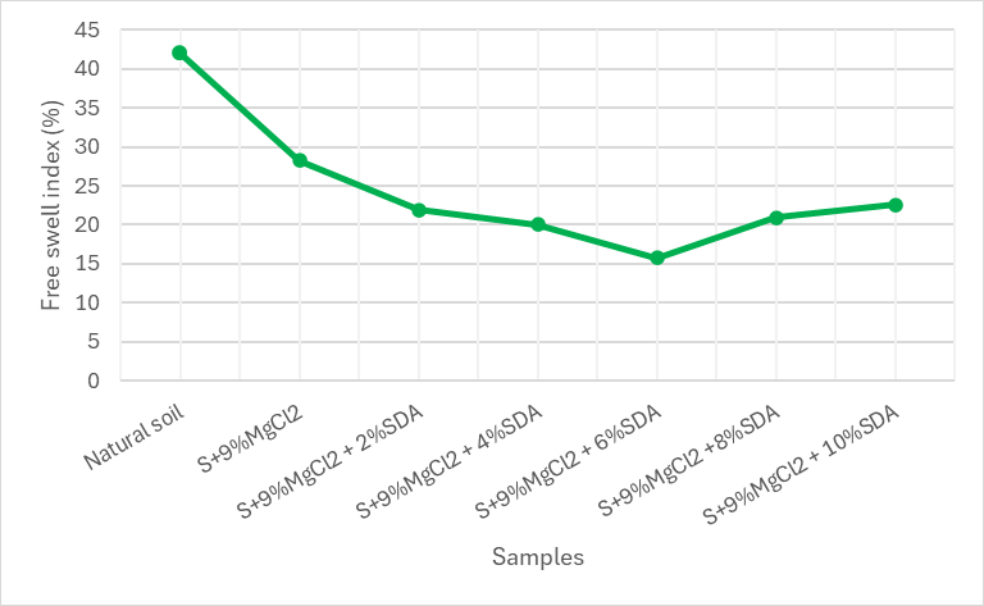


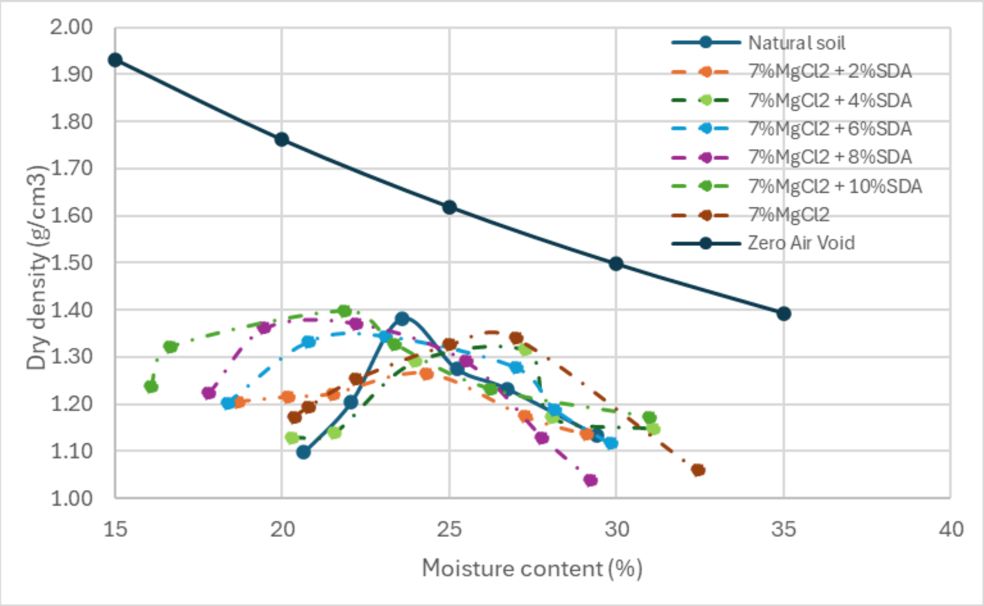
Fig. 5. Free swell index of stabilized soil

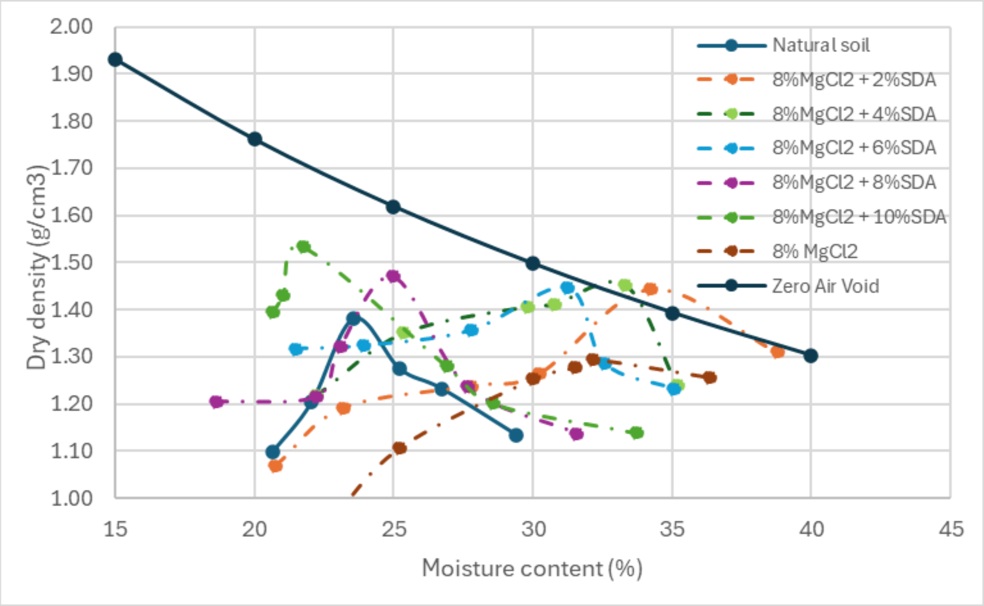
3.2 Compaction Characteristics

As depicted in Figure 6, the compaction curve displays the relationship between moisture content and dry density for natural soil and treated soil samples and the variation of MDD and OMC of stabilized soil were illustrated in Figure 7. The addition of $MgCl_2$ as a soil stabilization significantly affected the compaction curves of the soil samples. The natural soil exhibited a maximum dry density of 1.38 g/cm^3 and an optimum moisture content of 23.58%.

The samples treated with 7% $MgCl_2$ combined with varying percentages of show remarkably different compaction curves. The treatments with 4% to 10% SDA additions produce peak dry densities from 1.32 to 1.40 g/cm^3 at 27.27 to 21.88% moisture content. The zero-air void line shows the dry density could be all air voids were eliminated at given moisture contents. The gap between actual compaction curves and this line represents the minimum air void ratio achievable. The treatment of 8% $MgCl_2$ with 2% to 10% SDA show improved compaction curves compared to natural soil which with the treated materials achieving higher densities across most moisture ranges. The 8% $MgCl_2$ with 10% SDA treatment reaches the highest density peak at approximately 1.53 g/cm^3 at 21.77% moisture content which suggesting optimal stabilization at lower moisture levels. The zero-air void curve showed at full saturation which is no air voids. Besides, the 9% $MgCl_2$ treatment demonstrated increase values in MDD from 1.28 to 1.39 g/cm^3 which closely to the natural soil while the OMC for 9% $MgCl_2$ treatment showed the behavior with a peak of 30.95% (at 2% SDA). However, the 9% $MgCl_2$ with 10% SDA illustrated the lines peak at high densities which is 1.39 g/cm^3 at 24.14% OMC.

Interestingly, increasing SDA percentages generally led to decreased OMC values across all $MgCl_2$ concentrations which suggesting that higher SDA dosages progressively reduced the moisture retention capacity of the stabilized soil. Therefore, this suggests that 8% $MgCl_2$ concentrations appeared as the optimal stabilization level for maximize the soil density particularly at higher SDA dosages caused MDD increased steadily compared to other treatments. This trend attributed to the particle flocculation and aggregation, according to Yeganeh Rikhtehgar and Teymür [30].


Dry density (g/cm3)
2.00
1.90
1.80
1.70
1.60
1.50
1.40
1.30
1.20
1.10
1.00
15
20
25
30
35
40
Moisture content (%)
Natural soil
7%MgCl2 + 2%SDA
7%MgCl2 + 4%SDA
7%MgCl2 + 6%SDA
7%MgCl2 + 8%SDA
7%MgCl2 + 10%SDA
7%MgCl2
Zero Air Void


Dry density (g/cm3)
2.00
1.90
1.80
1.70
1.60
1.50
1.40
1.30
1.20
1.10
1.00
15
20
25
30
35
40
45
Moisture content (%)
Natural soil
8%MgCl2 + 2%SDA
8%MgCl2 + 4%SDA
8%MgCl2 + 6%SDA
8%MgCl2 + 8%SDA
8%MgCl2 + 10%SDA
8% MgCl2
Zero Air Void

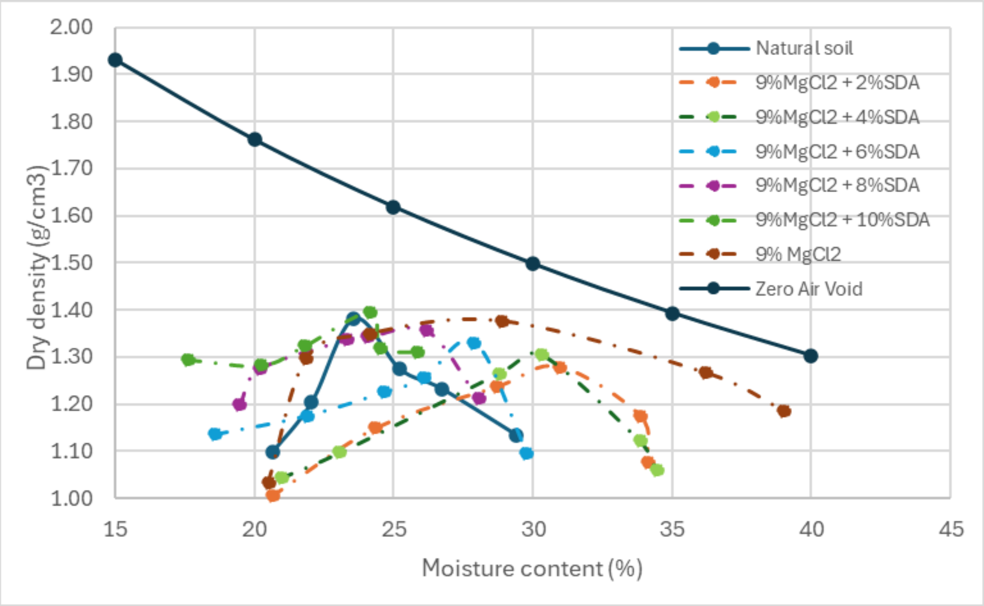


Fig. 6. Compaction curves of stabilized soil

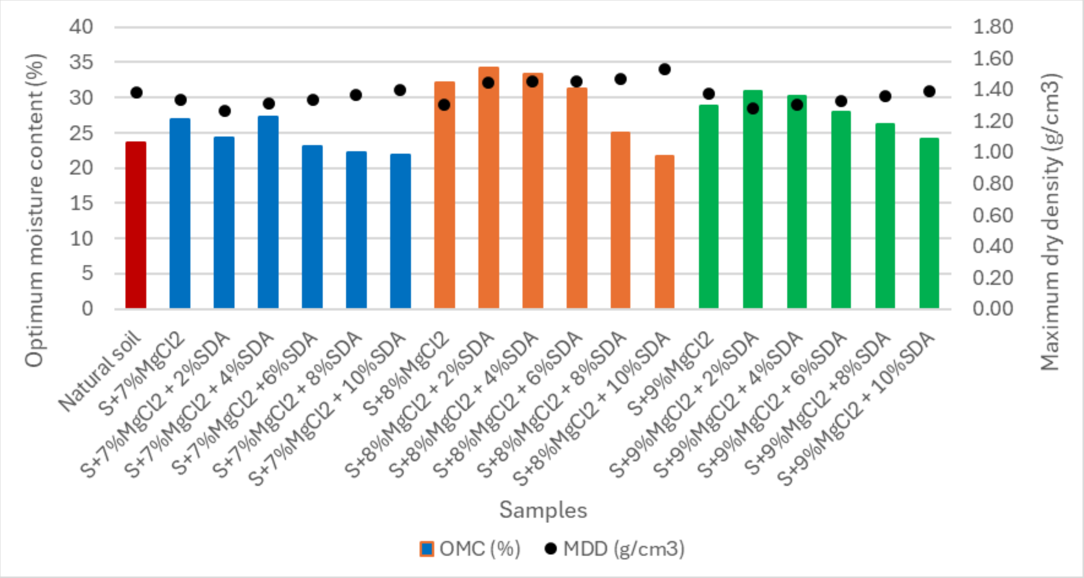


Fig. 7. Variation of MDD and OMC of stabilized soil

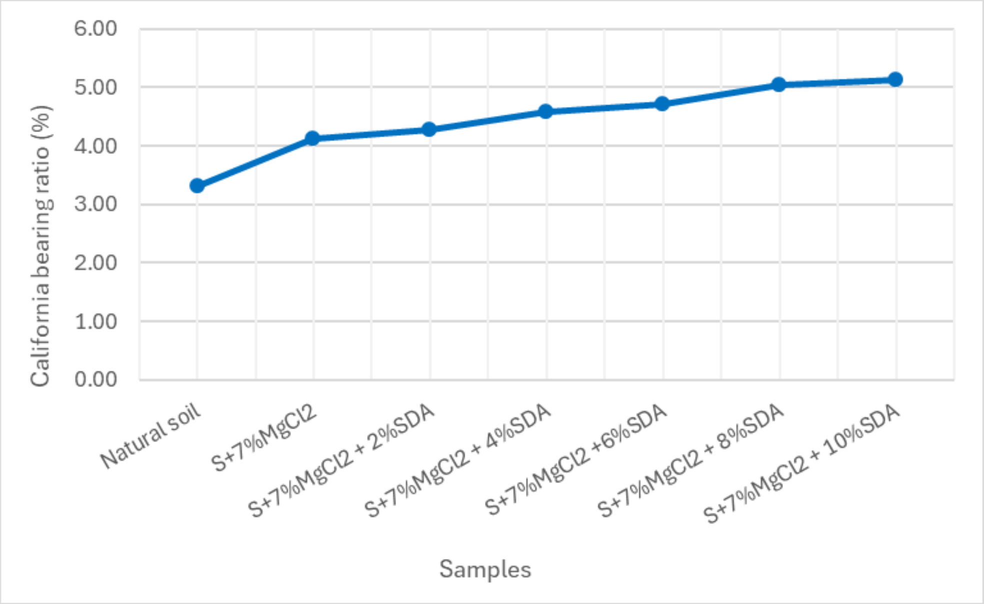
3.2 Strength Behavior

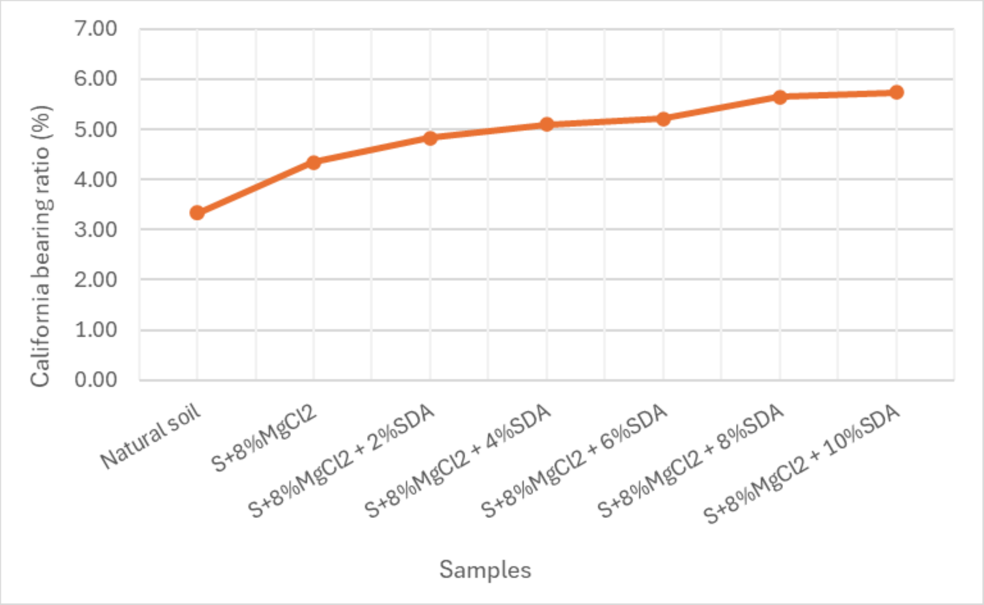
3.2.1 California bearing ratio

Based on the graph in Figure 8, it shows the California bearing ratio of stabilized soil. The California bearing ratio test revealed substantial improvements in bearing capacity consequent to stabilization treatment. The natural soil exhibited a CBR value of 3.32%, indicating poor bearing capacity. The 7% $MgCl_2$ treatment with 2% SDA increased the CBR to 4.27%, with further improvements to 5.14% achieved at 10% SDA.

The 8% $MgCl_2$ treatment proved substantially more effective, with 2% SDA producing a CBR of 4.83%, increasing progressively to 5.73% at 10% SDA. This represents an increase of 73% compared to the natural soil. The 9% $MgCl_2$ treatment produced comparable but slightly lower results, with CBR values reaching a maximum of 4.18% at 8% SDA.

The CBR improvements demonstrate that the combined $MgCl_2$-SDA stabilization substantially enhances soil bearing capacity. The optimal performance was achieved with the 8% $MgCl_2$ and 10% SDA combination, yielding a CBR of 5.73%, which represents a practical improvement. The improvement mechanisms are likely to involve due to the reduction of plasticity, as noted by Sefene [31] and the SDA particles act as filler within the pores and voids of the soil, according to Blayi et al., [28].





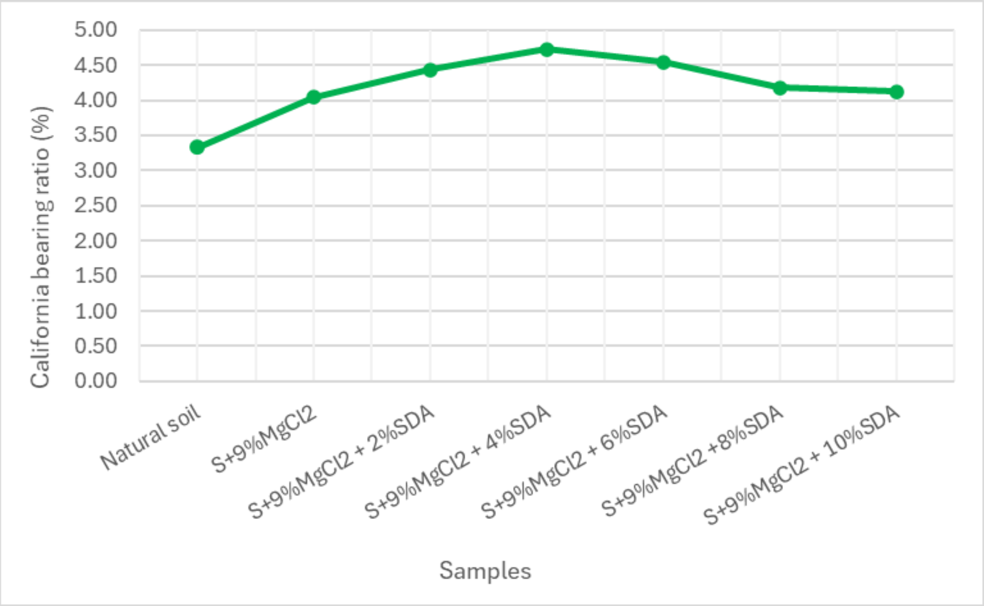


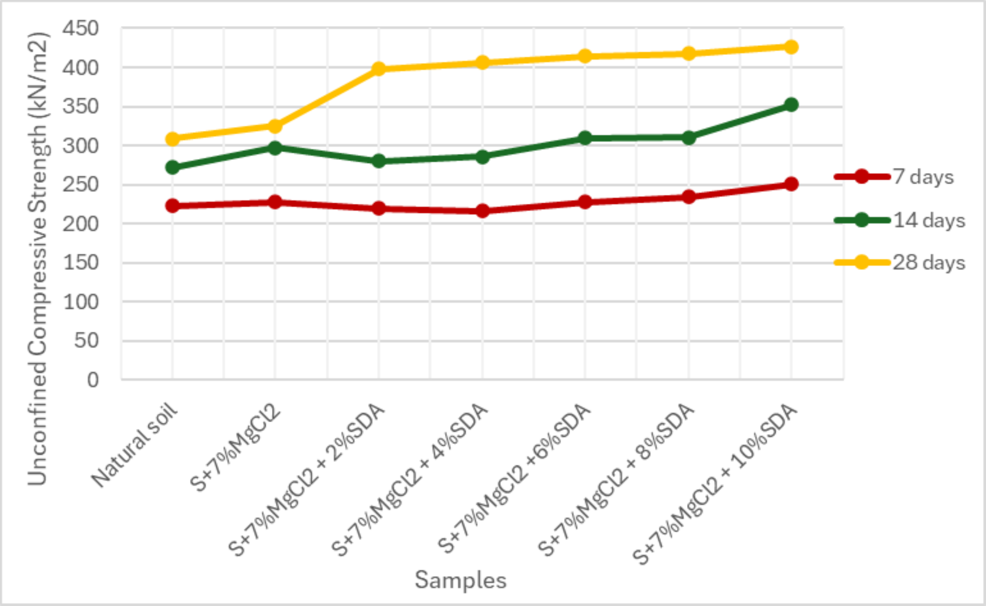
Fig. 8. California bearing ratio of stabilized soil

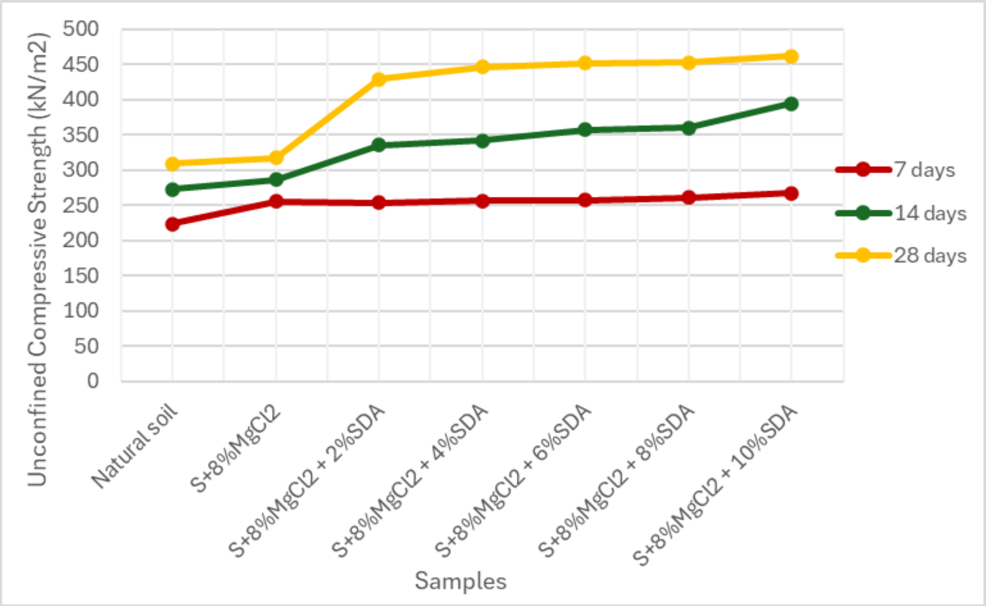
3.2.1 Unconfined compression strength

The graph in Figure 9 shows the unconfined compression strength of stabilized soil. The unconfined compression strength testing was conducted at 7, 14, and 28-days curing periods to assess both initial strength development and long-term strength evolution. The natural soil exhibited a 7 days UCS of 223.07 kPa, increasing modestly to 271.96 kPa at 14 days and 308.63 kPa at 28 days. The 7% $MgCl_2$ treatment with 2% SDA produced a 7 days UCS of 220.02 kPa, which is slightly lower than the natural soil, suggesting that the initial stabilization effect may require longer curing periods to exist. However, by 28 days this combination achieved 398.27 kPa, exceeding the natural soil strength.

The 8% $MgCl_2$ treatment demonstrated more substantial early strength development, with 7 days UCS values ranging from 253.63 kPa (2% SDA) to 266.87 kPa (10% SDA). By 28 days, these values had increased from 428.83 kPa (2%) to 461.42 kPa (10%) which represents improvements of 39% and 50% compared to the natural soil. The optimal strength performance was achieved with the 8% $MgCl_2$ and 10% SDA combination, which produced a 28-day UCS of 461.42 kPa nearly 50% higher than the natural soil. The strength development across all time periods was consistent with a curing curve with accelerated strength gain observed between 7 and 14 days and 28 days.

The 9% $MgCl_2$ treatment exhibits a clear negative effect, particularly at early curing stages and higher SDA values. It produced more slight results with 7 days UCS values of approximately 246.50 to 259.74 kPa, increasing to 302.52 to 304.56 kPa at 14 days and 417.62 to 433.92 kPa at 28 days at 4% and 2% SDA. These results confirm that the 8% $MgCl_2$ concentration provides best strength performance compared to both 7% and 9% $MgCl_2$ concentrations. The consistent strength improvements across all curing periods confirm that the stabilization mechanisms are durable and progressive. This improvement is typically attributed to the pozzolanic reaction, where the Al_2O_3 and SiO_2 in the soil react with the CaO from the ash to form cementing gels (hydrates), thereby causing the soil particles to agglomerate, as described by Salahudeen *et al.*, [32].


Unconfined Compressive Strength (kN/m2)
450
400
350
300
250
200
150
100
50
0
Natural soil
S+7%MgCl2
S+7%MgCl2 + 2%SDA
S+7%MgCl2 + 4%SDA
S+7%MgCl2 +6%SDA
S+7%MgCl2 + 8%SDA
S+7%MgCl2 + 10%SDA
Samples
7 days
14 days
28 days


Unconfined Compressive Strength (kN/m2)
500
450
400
350
300
250
200
150
100
50
0
Natural soil
S+8%MgCl2
S+8%MgCl2 + 2%SDA
S+8%MgCl2 + 4%SDA
S+8%MgCl2 + 6%SDA
S+8%MgCl2 + 8%SDA
S+8%MgCl2 + 10%SDA
Samples
7 days
14 days
28 days

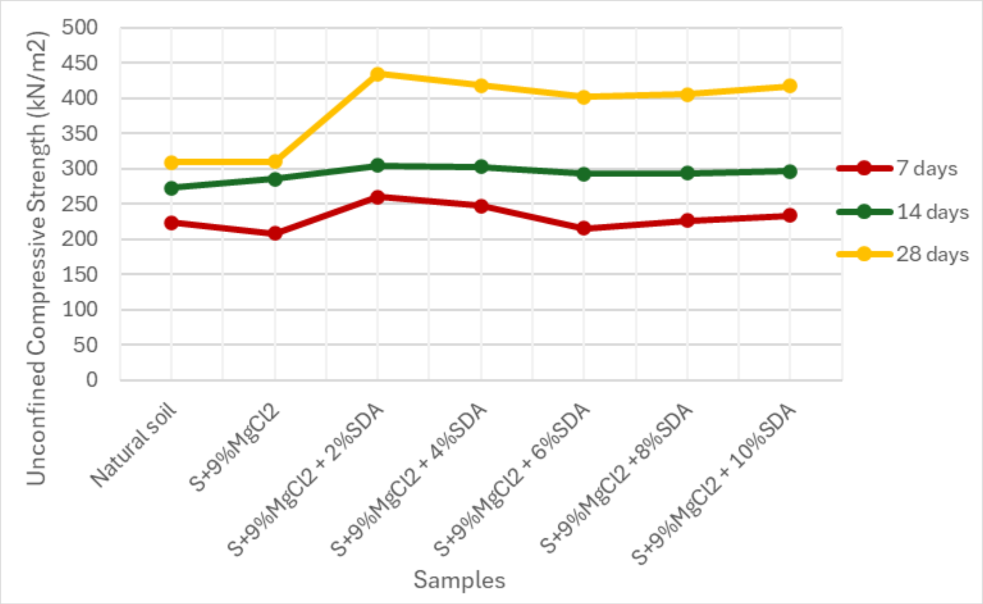


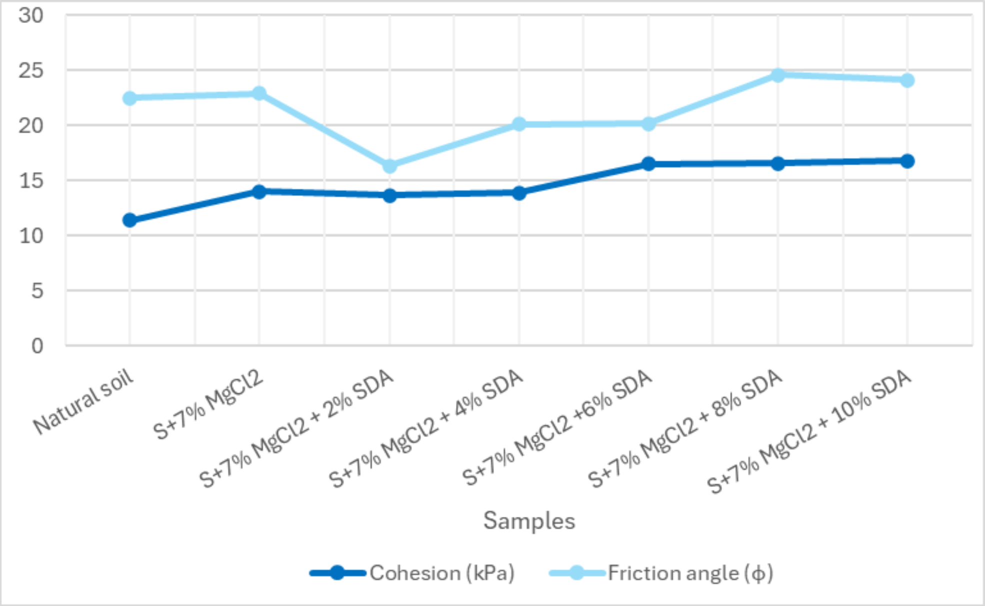
Fig. 9. Unconfined compression strength of stabilized soil

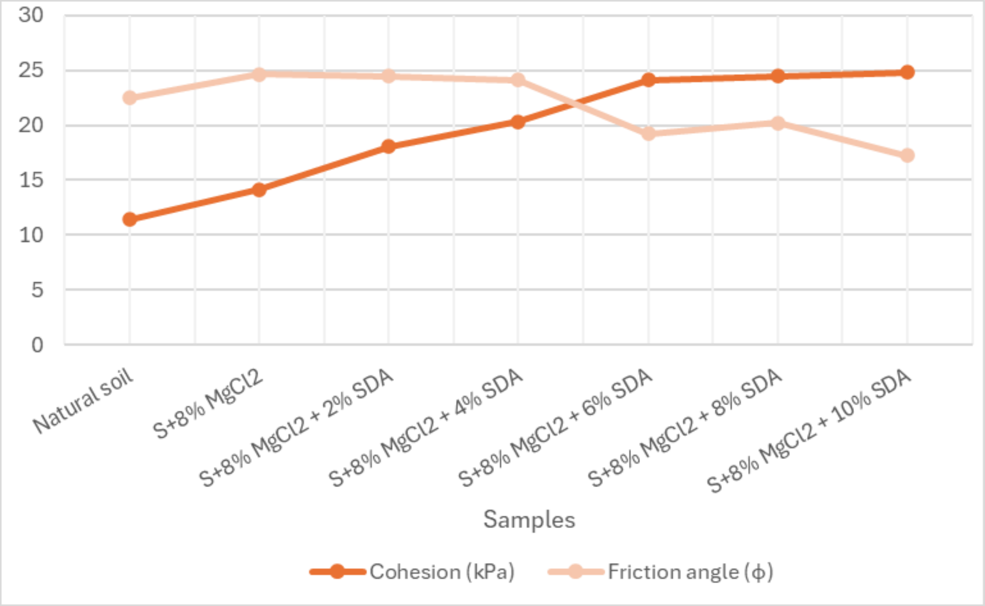
3.2.2 Shear strength

Figure 10 reveals a clear trend where $MgCl_2$ concentration with SDA significantly influences soil behavior. The direct shear box testing results demonstrated substantial improvements in shear strength parameters consequent to $MgCl_2$ and SDA stabilization. The natural soil exhibited a cohesion of 11.40 kPa and a friction angle of 22.50°. The application of 7% $MgCl_2$ with 2% SDA resulted in cohesion increasing to 13.67 kPa and friction angle decreasing to 16.34°. Increasing the SDA dosage to 10% with 7% $MgCl_2$ produced cohesion of 16.82 kPa with a friction angle of 21.12°.

The 8% $MgCl_2$ treatment proved highly effective, with 2% SDA producing cohesion of 18.08 kPa and friction angle of 24.44°. Maximum cohesion improvement was achieved at 8% $MgCl_2$ with 8% SDA, yielding cohesion of 24.46 kPa with friction angle of 20.19°. Further SDA increase to 10% resulted in cohesion of 24.79 kPa, representing a 117% increase compared to the natural soil with friction angle of 17.25°. The 9% $MgCl_2$ treatment demonstrated more variable results, with cohesion values ranging from 16.65 kPa (2% SDA) to 10.55 kPa (10% SDA), suggesting that 9% $MgCl_2$ concentration may constitute excessive dosage with diminishing stabilization effectiveness.

The 8% $MgCl_2$ concentration with 8% to 10% SDA appears optimal for maximizing overall shear strength which primarily through a substantial boost in cohesion. This indicates that soil shear strength improves initially due to the results from the pozzolanic reaction that generates a strong matrix to bind particles together to strengthen the soil structure and combined with the soil particles flocculation and agglomeration, as reported by Fawaz *et al.*, [33]. Thus, the synergistic effect between $MgCl_2$ and SDA is clearly evident in the superior cohesion improvements achieved with combined treatment compared to individual stabilizer application.


30
25
20
15
10
5
0
Natural soil
S+7% MgCl2
S+7% MgCl2 + 2% SDA
S+7% MgCl2 + 4% SDA
S+7% MgCl2 +6% SDA
S+7% MgCl2 + 8% SDA
S+7% MgCl2 + 10% SDA
Samples
Cohesion (kPa)
Friction angle (ϕ)


30
25
20
15
10
5
0
Natural soil
S+8% MgCl2
S+8% MgCl2 + 2% SDA
S+8% MgCl2 + 4% SDA
S+8% MgCl2 + 6% SDA
S+8% MgCl2 + 8% SDA
S+8% MgCl2 + 10% SDA
Samples
Cohesion (kPa)
Friction angle (ϕ)

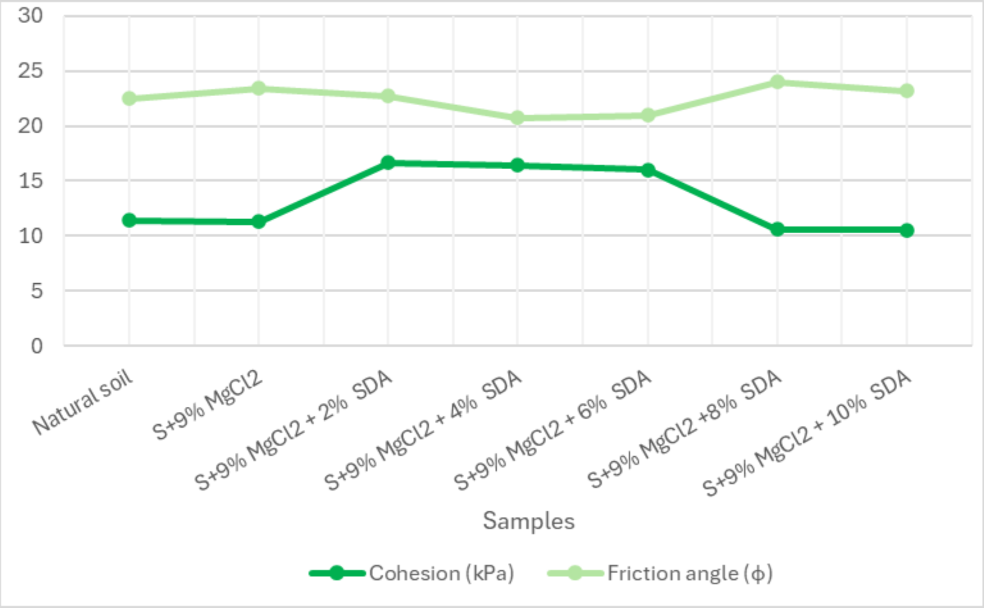


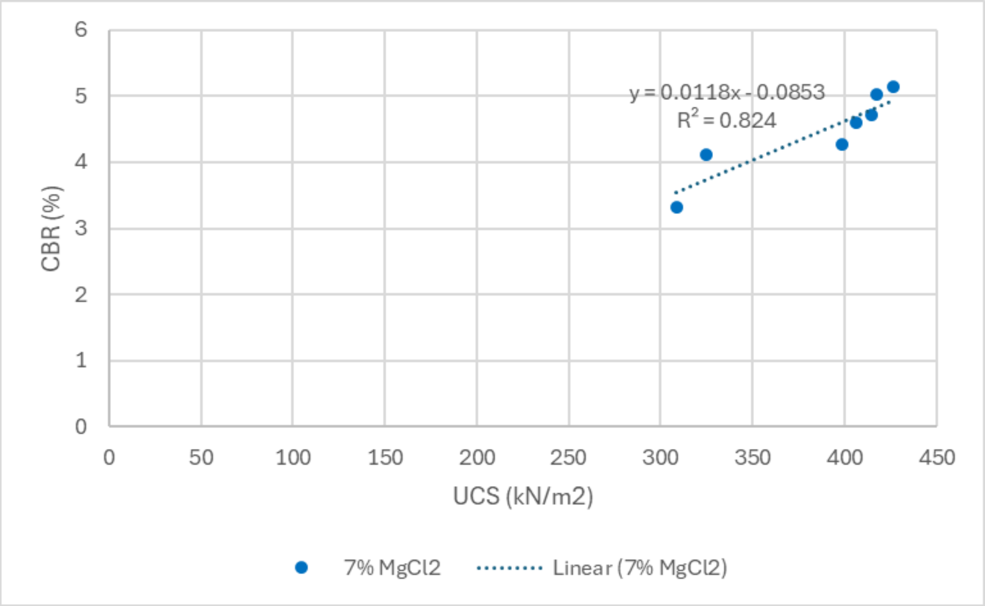
Fig. 10. Shear strength of stabilized soil

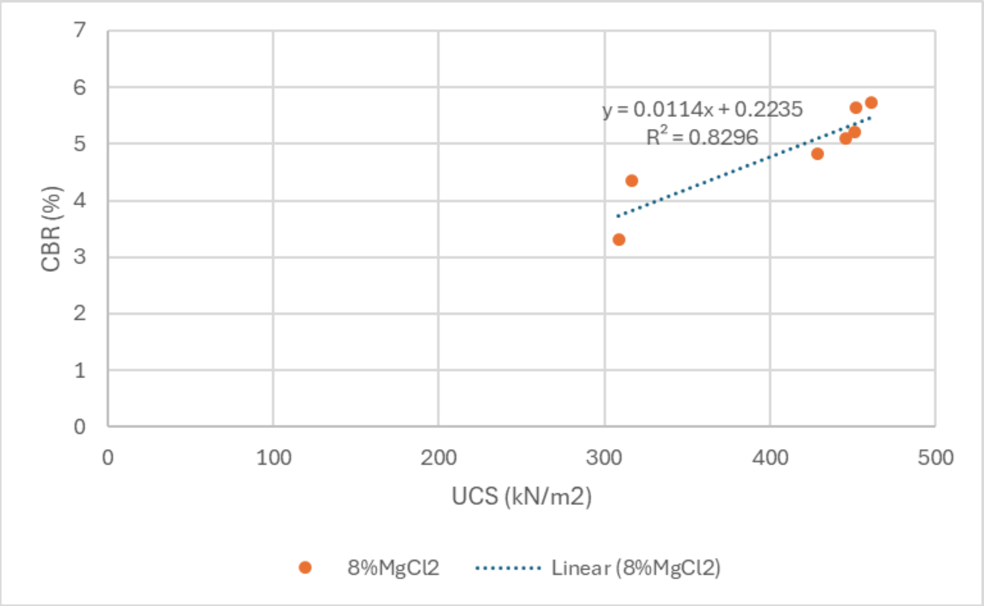
3.2.3 Regression model analysis of strength behavior

The graphs show in Figure 11 were the relationship between unconfined compressive strength (UCS) and California bearing ratio (CBR) of stabilized soil with all 7% $MgCl_2$. As UCS increases, CBR also tends to increase which indicating that higher compressive strength corresponds to improved bearing capacity. The regression equation $y = 0.0118x - 0.0853$ demonstrates that CBR increases proportionally with UCS with a slope of 0.0118. The coefficient of determination $R^2 = 0.824$ signifies a strong linear correlation explaining about 82.4% of the variability in CBR through UCS. This demonstrates that UCS can serve as a reliable predictor of CBR in $MgCl_2$-stabilized soil under the tested conditions.

For all soil treated with 8% $MgCl_2$, the trend shows clear positive linear relationship between UCS and CBR. This relationship is quantified by the linear regression equation $y = 0.0114x + 0.2235$, with an R^2 value of 0.8296 indicating that approximately 83% of the variance in CBR can be explained by UCS. CBR increases by approximately 0.0114%. Compared to the 7% $MgCl_2$ treatment, the 8% mixture demonstrates a marginally stronger correlation and a slightly different intercept with underscoring the influence of stabilizer dosage on the strength of bearing capacity relationship.

For soil stabilized with all 9% $MgCl_2$, a positive but comparatively weaker linear trend is observed, as indicated by the equation $y = 0.0066x + 1.6598$ where the slope of 0.0066 is notably lower than those for the 7% and 8% treatments. This suggests that increases in UCS result in smaller corresponding gains in CBR at this higher stabilizer dosage. The coefficient of determination $R^2 = 0.5782$ reveals that only about 57.82% of the variation in CBR is explained by UCS which indicating a moderate correlation and greater data scatter around the trend line.


y = 0.0118x - 0.0853
R² = 0.824
CBR (%)
UCS (kN/m2)
0
1
2
3
4
5
6
0
50
100
150
200
250
300
350
400
450
● 7% MgCl2
Linear (7% MgCl2)


y = 0.0114x + 0.2235
R² = 0.8296
CBR (%)
UCS (kN/m2)
0
1
2
3
4
5
6
7
0
100
200
300
400
500
● 8%MgCl2
Linear (8%MgCl2)

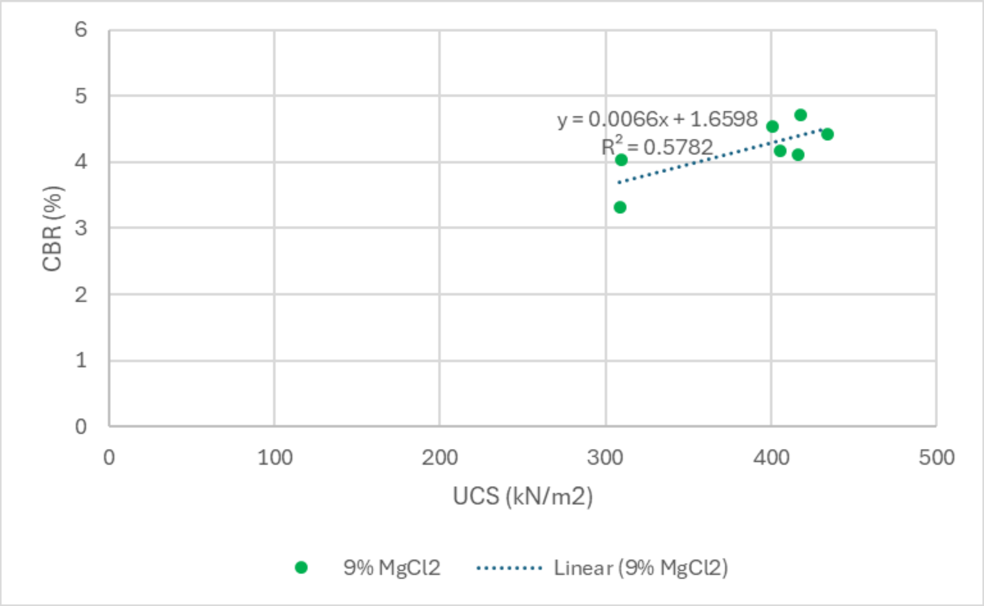
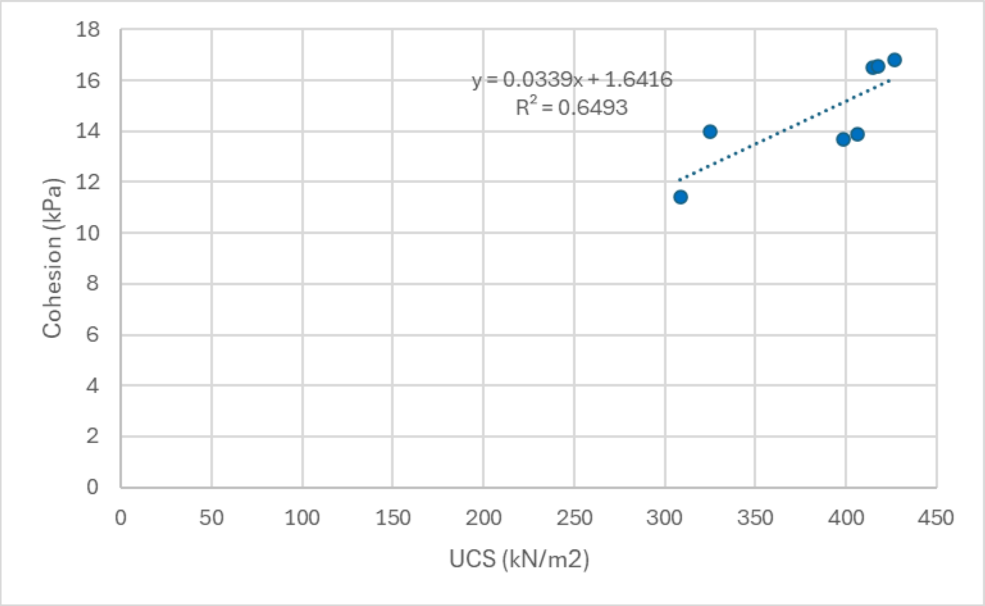


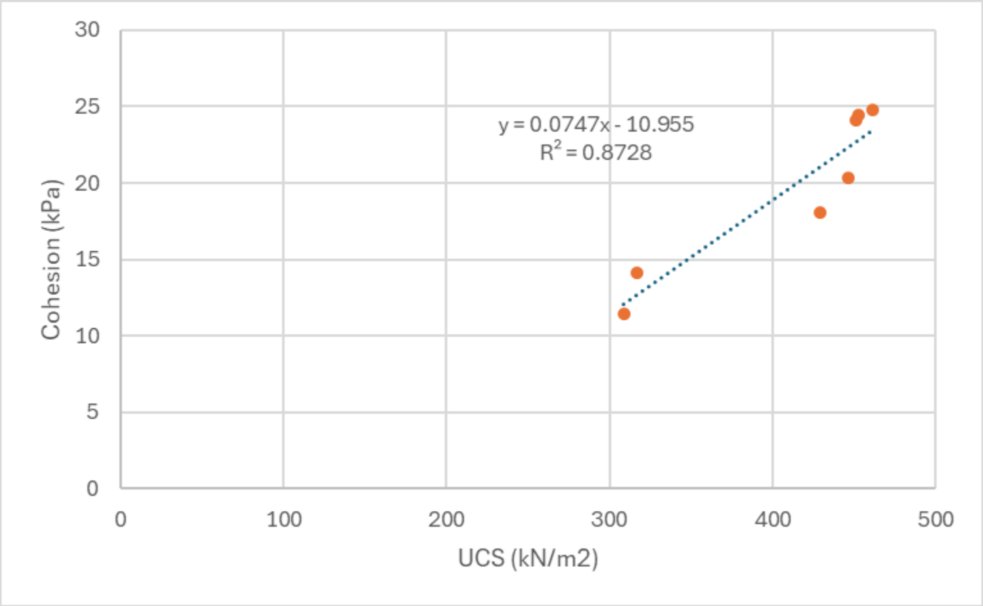
Fig. 11. Relationship between UCS and CBR

The relationship between UCS and cohesion were demonstrated in Figure 12. For all soil treated with 7% $MgCl_2$, the linear trend line indicates a positive correlation between UCS and cohesion represented by the equation $y = 0.0339x + 1.6416$ which demonstrates that cohesion increases proportionally with UCS values by approximately 0.0339 kPa. However, the coefficient of determination R^2 value of 0.6493 suggesting that approximately 65% of the variance in cohesion can be explained by changes in UCS.

Based on the regression graph for soil treated with 8% $MgCl_2$, the analysis shows a strong positive linear relationship between UCS and cohesion. The linear equation $y = 0.0747x - 10.955$ quantifies this relationship indicating that cohesion increases by approximately 0.0747 kPa. The regression line exhibits an R^2 value of 0.8728 demonstrates that around 87.28% of the variability in cohesion is explained by UCS which reflecting a much stronger and more reliable correlation compared to the 7% treatment.

The regression graph for 9% $MgCl_2$ treatment reveals a markedly weaker relationship between UCS and cohesion compared to the 7% $MgCl_2$ and 8% $MgCl_2$ treatment. While the linear equation $y = 0.0279x + 2.5306$ indicates a positive relationship where cohesion increases by only approximately 0.0279 kPa. Most notably, the R^2 value of 0.2555 indicates that only about 25.55% of the variation in cohesion can be explained by changes in UCS which demonstrating a notably weaker correlation.


Cohesion (kPa)
0
2
4
6
8
10
12
14
16
18
UCS (kN/m2)
0
50
100
150
200
250
300
350
400
450
y = 0.0339x + 1.6416
R² = 0.6493


Cohesion (kPa)
0
5
10
15
20
25
30
UCS (kN/m2)
0
100
200
300
400
500
y = 0.0747x - 10.955
R² = 0.8728

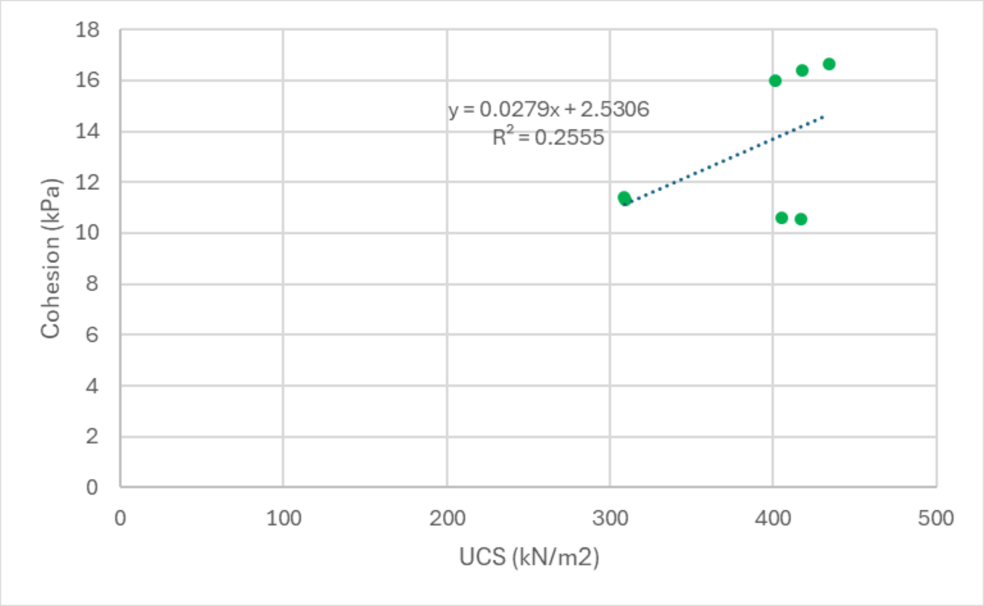
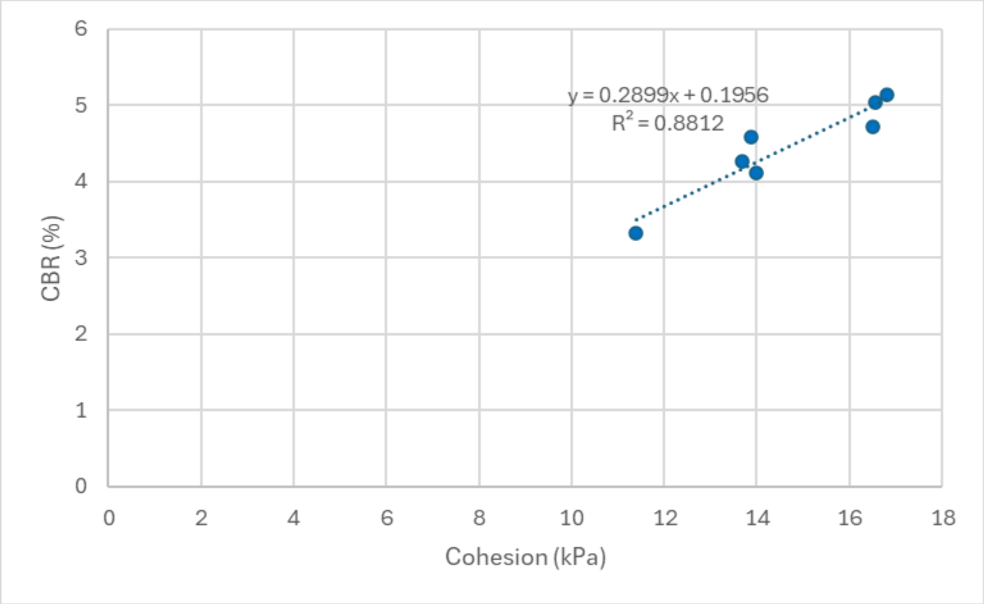


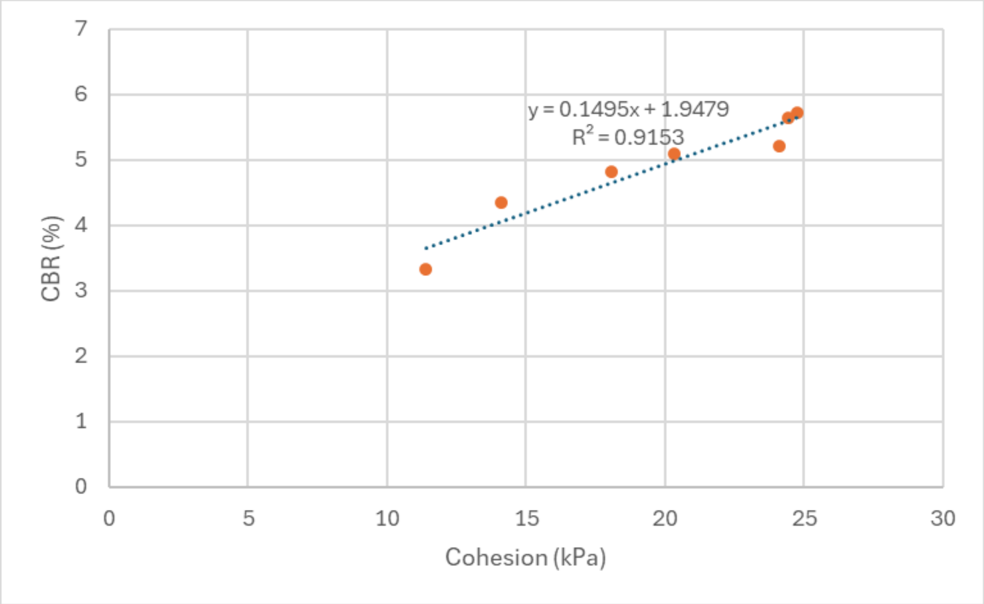
Fig. 12. Relationship between UCS and cohesion

As shown in Figure 13, the graph shows the relationship between cohesion and CBR. This demonstrates a strong positive linear for all soil treated with 7% $MgCl_2$ as indicated by the regression equation y = 0.2899x + 0.1956 and a high coefficient of determination R^2 value of 0.8812. This relationship shows that CBR increases consistently with increasing cohesion. The CBR increases by approximately 0.29%. The very high R^2 value indicates that approximately 88.12% of the variability in CBR can be explained by changes in cohesion which suggesting that cohesion is a reliable and dominant predictor of CBR within the tested range.

The regression graph illustrates the relationship for all the 8% $MgCl_2$ treatment shows a strong and highly reliable positive linear correlation between the cohesion and CBR. The trendline is defined by the equation y = 0.1495x + 1.9479 where the CBR increases by approximately 0.15%. With an R^2 value of 0.9153, these explains approximately 91.53% of the variation in CBR is accounted for by changes in cohesion.

For all the 9% $MgCl_2$ treatment reveals a weak positive linear relationship which described by the equation y = 0.1103x + 2.7306. While an increase in cohesion corresponds to a slight rise in CBR approximately 0.11%. The predictive strength is notably lower than that observed in other treatments. This is indicated by the coefficient of determination R^2 value of 0.4945 meaning that only about 49.46% of the variation in CBR can be attributed to changes in cohesion.


y = 0.2899x + 0.1956
R² = 0.8812
CBR (%)
0
1
2
3
4
5
6
0
2
4
6
8
10
12
14
16
18
Cohesion (kPa)


y = 0.1495x + 1.9479
R² = 0.9153
CBR (%)
0
1
2
3
4
5
6
7
0
5
10
15
20
25
30
Cohesion (kPa)

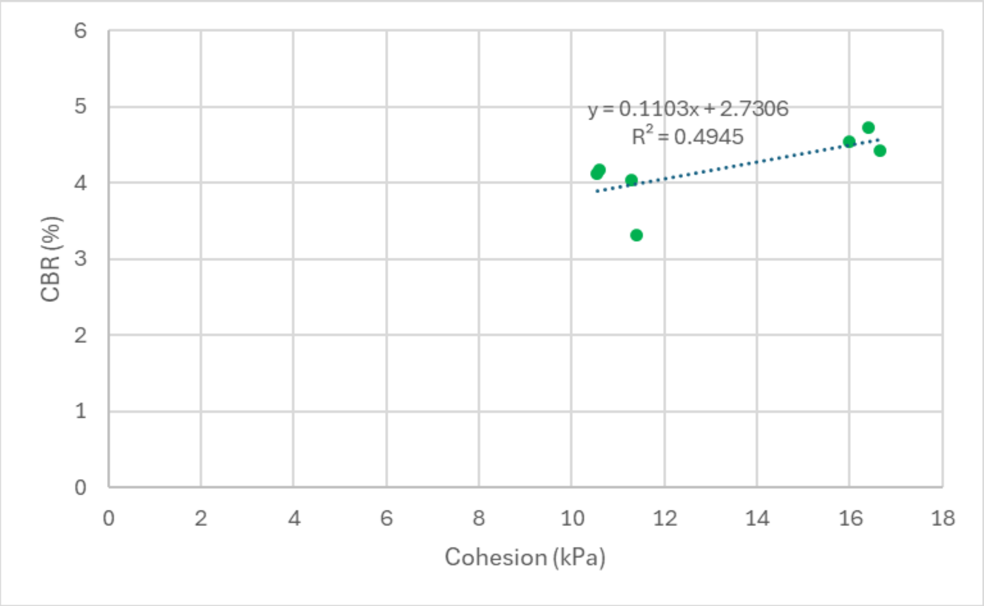


Fig. 13. Relationship between cohesion and CBR

4. Conclusions

In conclusion, this research investigated the synergistic effects of combined $MgCl_2$ and SDA stabilization on clay soil strength behavior across varies mechanical properties and curing periods which demonstrating that the interaction between both stabilizers produces enhanced performance substantially exceeding individual treatment approaches. California Bearing Ratio testing revealed that combined stabilization significantly improves soil bearing capacity with the optimal 8% $MgCl_2$ and 10% SDA combination achieving a 73% increase compared to natural soil while unconfined compression strength results showed consistent and progressive strength development with nearly 50% improvement in 28 days UCS at the same optimal dosage. Direct shear box testing confirmed these trends with an increase in value of cohesion which establishes that soil shear strength improvements are driven primarily through pozzolanic reactions that create strong binding matrices between soil particles.

Overall, the research clearly establishes that 8% $MgCl_2$ concentration combined with 10% SDA represents the optimal proportion for maximizing soil strength behavior. Based on the regression analysis, the relationship between cohesion and CBR for all the 8% $MgCl_2$ treatment demonstrates the strongest correlation which is the highest R^2 value of 0.9153 (91.53%). This indicates that cohesion is a more reliable predictor of CBR than UCS. The consistent strength development across all testing methods and curing periods confirms that the stabilization mechanisms are durable and sustainable which offers practical benefits for geotechnical engineering by pointed specific proportions that maximize strength with minimal material usage and providing a pathway for cost-effective, environmentally responsible soil stabilization that reduces material consumption while maintaining superior mechanical properties. Future research should explore the effect of adding natural or synthetic fibers such as polypropylene or coir to the $MgCl_2$-SDA stabilized soil to improve ductility and reduce brittleness.

Acknowledgement

This research was supported by financial assistance from Universiti Putra Malaysia through their Geran Putra Inisiatif program (Grant No.: 9795100). We acknowledge the Faculty of Engineering at Universiti Putra Malaysia in Selangor for granting access to the laboratory equipment and infrastructure necessary to conduct this work. We also wish to recognize the contributions of the technical assistant and faculty members who provided expert guidance and assistance during all stages of the research.

References

[1] Gudeta, Alemu Diribsa, and Patel AV. "A critical review on soil stabilization using different industrial wastes and admixtures." *Int Res J Eng Technol (IRJET)* 4, no. 12 (2017): 1674-1678.

[2] Alhakim, Ghida, Oussama Baalbaki, and Lina Jaber. "Effects of incorporation of cement and metakaolin on the mechanical properties of poorly graded sand." *Arabian Journal of Geosciences* 15, no. 24 (2022): 1777. https://doi.org/10.1007/s12517-022-11080-8

[3] Ikeagwuani, Chijioke Christopher, and Donald Chimobi Nwonu. "Emerging trends in expansive soil stabilisation: A review." *Journal of rock mechanics and geotechnical engineering* 11, no. 2 (2019): 423-440. https://doi.org/10.1016/j.jrmge.2018.08.013

[4] Gidebo, Frehaileab Admasu, Hideaki Yasuhara, and Naoki Kinoshita. "Stabilization of expansive soil with agricultural waste additives: a review." *International Journal of Geo-Engineering* 14, no. 1 (2023): 14. https://doi.org/10.1186/s40703-023-00194-x

[5] Mahdavian, Soroush, Navid Rashidi, Ali Raeesi Estabragh, and Jamal Abdolahi. "Effect of magnesium chloride solution on the improvement of a clay soil." *Journal of Engineering Geology* 19, no. 1 (2025): 60-83.

[6] Sharma, Sukanya, Vijay Kumar, and Ajay Bindlish. "Enhancing the engineering properties of black cotton soil by using magnesium chloride." In *Ground Improvement and Reinforced Soil Structures: Proceedings of Indian Geotechnical Conference 2020 Volume 2*, pp. 79-90. Singapore: Springer Singapore, 2021. https://doi.org/10.1007/978-981-16-1831-4_8

[7] Habibbeygi, Farzad, and Hamid Nikraz. "Compression behaviour of highly expansive clays stabilised with a green stabiliser of magnesium chloride." *GEOMATE Journal* 14, no. 45 (2018): 144-150. https://doi.org/10.21660/2018.45.10697

[8] Latifi, Nima, Ahmad Safuan A. Rashid, Sumi Siddiqua, and Suksun Horpibulsuk. "Micro-structural analysis of strength development in low-and high swelling clays stabilized with magnesium chloride solution—A green soil stabilizer." *Applied Clay Science* 118 (2015): 195-206. https://doi.org/10.1016/j.clay.2015.10.001

[9] Muhammad, Nurmunira, Sumi Siddiqua, and Nima Latifi. "Solidification of subgrade materials using magnesium alkalinization: A sustainable additive for construction." *Journal of Materials in Civil Engineering* 30, no. 10 (2018): 04018260. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002484

[10] Hachichi, A., and J. M. Fleureau. "Characterization and stabilization of a few expansive soils from Algeria." *Revue française de geotechnique* (1999): 37-51. https://doi.org/10.1051/geotech/1999086037

[11] Waheed, Muhanned Qahtan. "A laboratory evaluation of stabilization of silty clay soil by using chloride compounds." *Engineering & Technology Journal* 30, no. 17 (2012): 3054-3064. https://doi.org/10.30684/etj.30.17.8

[12] Turkoz, Murat, Hasan Savas, Aykut Acaz, and Hasan Tosun. "The effect of magnesium chloride solution on the engineering properties of clay soil with expansive and dispersive characteristics." *Applied Clay Science* 101 (2014): 1-9. https://doi.org/10.1016/j.clay.2014.08.007

[13] Vakili, Amir Hossein, Mohammad Kaedi, Mehdi Mokhberi, Mohamad Razip bin Selamat, and Mahdi Salimi. "Treatment of highly dispersive clay by lignosulfonate addition and electroosmosis application." *Applied Clay Science* 152 (2018): 1-8. https://doi.org/10.1016/j.clay.2017.11.039

[14] Afolayan, O. D., O. M. Olofinade, and I. I. Akinwumi. "Use of some agricultural wastes to modify the engineering properties of subgrade soils: A review." In *Journal of Physics: Conference Series*, vol. 1378, no. 2, p. 022050. IOP Publishing, 2019. https://doi.org/10.1088/1742-6596/1378/2/022050

[15] Yuriz, Yasmin, Tuan Noor Hasanah Tuan Ismail, and Nik Normunira Mat Hassan. "An overview of waste materials for sustainable road construction." *International Journal of Sustainable Construction Engineering and Technology* 11, no. 1 (2020): 215-229.

[16] Atahu, M. K., F. Saathoff, and A. Gebissa. "Strength and compressibility behaviors of expansive soil treated with coffee husk ash." *Journal of rock mechanics and geotechnical engineering* 11, no. 2 (2019): 337-348.https://doi.org/10.1016/j.jrmge.2018.11.004

[17] Barišić, Ivana, Ivanka Netinger Grubeša, Tihomir Dokšanović, and Berislav Marković. "Feasibility of agricultural biomass fly ash usage for soil stabilisation of road works." *Materials* 12, no. 9 (2019): 1375. https://doi.org/10.3390/ma12091375

[18] Sankar, V. Siva, P. D. A. Raj, and S. J. Raman. "Stabilization of expansive soil by using agricultural waste." *Int J Eng Adv Technol* 8, no. 3 (2019): 154-157.

[19] Munirwan, R. P., D. Sundary, Munirwansyah, and Bunyamin. "Study of coffee husk ash addition for clay soil stabilization." In *IOP Conference Series: Materials Science and Engineering*, vol. 1087, no. 1, p. 012016. IOP Publishing, 2021. https://doi.org/10.1088/1757-899X/1087/1/012016

[20] Ramdas, Veshara Malapermal, Prisha Mandree, Martin Mgangira, Samson Mukaratirwa, Rajesh Lalloo, and Santosh Ramchuran. "Review of current and future bio-based stabilisation products (enzymatic and polymeric) for road construction materials." *Transportation Geotechnics* 27 (2021): 100458. https://doi.org/10.1016/j.trgeo.2020.100458

[21] Adedokun, S. I., and J. R. Oluremi. "A REVIEW OF THE STABILIZATION OF LATERITIC SOILS WITH SOME AGRICULTURAL WASTE PRODUCTS." *Acta Technica Corviniensis-Bulletin of Engineering* 12, no. 2 (2019).

[22] Raheem, A. A., and A. I. Ige. "Chemical composition and physicomechanical characteristics of sawdust ash blended cement." *Journal of Building Engineering* 21 (2019): 404-408 https://doi.org/10.1016/j.jobe.2018.10.014

[23] Malongweni, Siviwe Odwa, Yasutaka Kihara, Kuniaki Sato, Takeo Tokunari, Tabhorbayar Sobuda, Kaya Mrubata, and Tsugiyuki Masunaga. "Impact of agricultural waste on the shrink–swell behavior and cracking dynamics of expansive soils." *International Journal of Recycling of organic waste in Agriculture* 8, no. 4 (2019): 339-349. https://doi.org/10.1007/s40093-019-0265-7

[24] Naranagowda, M. J., N. S. Nithin, K. S. Maruthi, and D. S. Mosin Khan. "Effect of saw dust ash and fly ash on stability of expansive soil." *International Journal of Research in Engineering and technology* 4, no. 7 (2015): 83-86.

[25] Bunyamin, B., R. P. Munirwan, M. Ridha, and N. Hendrifa. "Utilization of wood processing dust as a substitute for a part of cement in concrete." In *IOP Conference Series: Materials Science and Engineering*, vol. 1087, no. 1, p. 012004. IOP Publishing, 2021. https://doi.org/10.1088/1757-899X/1087/1/012004

[26] Department of Minerals and Geosciences Malaysia. (2025). MyGEMS - Malaysian Minerals and Geosciences Geospatial Information System. https://mygems.jmg.gov.my/

[27] Oguche, Joan O., Joseph B. Adeyeri, Olugbenga O. Amu, and O. F. Joseph. "STABILIZATION OF EXPANSIVE CLAY SOILS USING SAW DUST ASH." *JOURNAL OF INNOVATION SCIENCE AND TECHNOLOGY* 2, no. 1 (2022).

[28] Blayi, Rizgar A., Bashdar Omer, Aryan Far H. Sherwani, Rawen M. Hamadamin, and Hawnaz K. Muhammed. "Geotechnical characteristics of fine-grained soil with wood ash." *Cleaner Engineering and Technology* 18 (2024): 100726. https://doi.org/10.1016/j.clet.2024.100726

[29] Arasan, Seracettin, R. Kagan Akbulut, Temel Yetimoglu, and Gonca Yilmaz. "Swelling pressure of compacted clay liners contaminated with inorganic salt solutions." *Environmental & Engineering Geoscience* 16, no. 4 (2010): 401-409. https://doi.org/10.2113/gseegeosci.16.4.401

[30] Yeganeh Rikhtehgar, Amin, and Berrak Teymür. "Effect of magnesium chloride solution as an antifreeze agent in clay stabilization during freeze-thaw cycles." *Applied Sciences* 14, no. 10 (2024): 4140. https://doi.org/10.3390/app14104140

[31] Sefene, Sinodos S. "Determination of effective wood ash proportion for black cotton soil improvement." *Geotechnical and Geological Engineering* 39, no. 1 (2021): 617-625. https://doi.org/10.1007/s10706-020-01508-x

[32] Salahudeen, Anigilaje Bunyamin, Nana Sunday Kpardong, and Patience Mark Francis. "Enhancement of kaolin clay soil for civil engineering application using rice husk ash and sawdust ash geopolymer cements." *Nigerian Journal of Technological Development* 20, no. 1 (2023): 44-55. https://doi.org/10.4314/njtd.v20i1.1232

[33] Fawaz, Alaa, Ghida Alhakim, and Lina Jaber. "The stabilisation of clayey soil by using sawdust and sawdust ash." *Environmental Technology* 45, no. 26 (2024): 5712-5722.https://doi.org/10.1080/09593330.2024.2304674