



Geotechnical Properties of Lime-Magnesium Slag Stabilized Clayey Sand: Experimental Study

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Abstract

Over the past decades, quite a few investigations have been carried out to utilize slags as a cementing agent in landfills, road construction, concrete, and mortars. However, a limited number of research studies investigated the use of magnesium slag as a soil stabilizer in geotechnical engineering projects. The manufacturing process of metallic magnesium produces a large volume of magnesium slag which is occasionally dumped in open areas. In this research, the potential use of magnesium slag as an additive agent to improve the properties of lime-stabilized soil was experimentally investigated. For this purpose, a number of different tests such as pH, Standard Proctor Compaction, Unconfined Compressive Strength, Indirect Tensile Strength, Toxicity Characteristic Leaching Procedure, X-ray diffraction, and Scanning Electron Microscopy were performed on the clayey sand containing 0%, 10%, 20%, 30%, 40% and 50% magnesium slag with 4% and 8% lime (by dry weight of the used soil). Samples were cured for 7, 28, and 56 days. The results of the study indicated that the addition of the maximum amount of magnesium slag (50%) at all curing days improved the geotechnical characteristics of soil samples containing 8% Lime. Generally, it was found that magnesium slag can be effectively applied in soil stabilization projects to improve the geotechnical properties and alleviate environmental repercussions.

Keywords Magnesium slag · Lime stabilized soil · Geotechnical properties · Compressive and tensile strength · Environmental issues

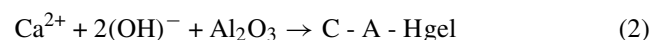
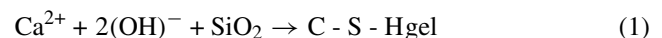
1 Introduction

Soil stabilization is one of the common methods used to improve the quality of the subgrade in road construction industry [1]. This method improves the geotechnical parameters of the materials at the project site and provides the required strength [2–5]. There are three main benefits of soil stabilization: (i) improving the quality of road pavement and embankment layers, (ii) reducing the thickness of pavement layers, and (iii) decreasing the operation costs [6]. Over the past few years, various additives have been used as soil stabilizing agents. The most important of these materials include different types of cement and lime. Nowadays, cement stabilization is not of great interest due to the environmental repercussions of carbon dioxide in the cement production

process [7–9]. Lime is one of the most traditional stabilizers that have been used to stabilize clayey soils to reduce plasticity index (PI) and shrinkage and increase strength and California bearing ratio (CBR) [9–11]. A large number of studies have been performed on the effects of lime and cement on the chemical and physical properties of the soils in the stabilization process [12–14]. The addition of lime causes pozzolanic reactions in the soils. During this process, additives create cation exchange, leading to particle flocculation and soil hardness. The results of the soil particle hardening are coarse-grained soils, lower plasticity, and higher durability [15–17]. Moreover, the soil pH increases due to the presence of OH⁻ ions, leading to the development and enhancement of pozzolanic reactions. The pozzolanic chemical equations are described as:

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The above reactions are the mechanism of soil stabilization by the occurrence of flocculation agglomeration. The Si and Al that exist within the mineral structure of the soil (or added by the stabilization agents) are combined with the available Ca^{2+} from the additives. This process results in cementitious compounds such as Calcium Silicate Hydrates (CSH) and Calcium Aluminate Hydrates (CAH). The formation of these compounds improves the resistance properties of the soils [18–20]. Additionally, these materials have been utilized as conventional stabilizers.

In recent years, a number of researchers have conducted many studies on the use of waste materials, especially mining wastes, as soil stabilizers. In addition to land occupation, these materials always cause various environmental problems [21–23]. Among these waste materials, some of the most common materials are listed as ground granulated blast furnace (GGBF), cement kiln ash, rice husks ash, coal ash, recyclable polymer additives, recycled glass, and fly ash. In addition to improving the geotechnical properties of soils, another purpose of investigating the effect of these materials is to reduce the environmental problems caused by the accumulation of these industrial wastes [24].

Magnesium slag is also another industrial waste that is produced after the Silicotherm reduction process for magnesium metal production. During the production of each ton of magnesium metal, about 5.5 tons of magnesium slag is produced. It is estimated that the accumulation of this waste material in the world was over 10 million tons by 2014. The chemical composition and physical properties of this material prove its potential for the hydration process [25–28]. Also, the results of previous investigations indicated that the physical, chemical and mineralogical characteristics of the magnesium slag and the Portland cement were occasionally similar [29]. The use of magnesium slag in soil stabilization projects has three advantages: (i) reduction of the use of cement, (ii) alleviation of the environmental problems caused by these industrial wastes, and (iii) protection of the natural resources [29]. The use of this material in the cement production process results in cement that requires less water and lower setting time than that of conventional Portland cement and provides a significant reduction in the kiln temperature, which leads to a reduction in energy consumption [30].

Xiao et al. [31] reported that the addition of magnesium slag and furnace slag with clinker in the cement production process improves the strength parameters of the obtained cement. In some studies, magnesium slag was found to be much more effective than furnace slag in terms of strength development of cementitious materials. The use of magnesium slag in combination with other materials for clinker production was also found to be effective in the production process of this material. In this way, the reduction in temperature is required for calcination of clinker, and the cement obtained from this clinker provided a higher strength [32].

Deng et al. [27] investigated the hydration mechanism of the magnesium slag as one of the main factors increasing the strength of the Portland cement and magnesium slag blends.

Amini and Ghasemi [33] investigated the effect of adding magnesium slag to cement-stabilized soil. They found that the magnesium slag increased pH and particle size of soil and enhanced compaction properties such as maximum dry density (MDD) and optimum moisture content (OMC). Also, up to 20% magnesium slag (by dry weight of soil) increased the uniaxial compressive strength of soil from 1.3 to 5.5 MPa, and by adding more magnesium slag, the compressive strength of the soil decreased. By adding 6% cement to the soil containing 20% magnesium slag, the compressive strength reached 14.3 MPa [33].

This study aims to reduce the environmental effects of magnesium slag and to investigate possibility of this waste material in soil improvement projects. In the present research, the authors evaluated the effect of magnesium slag on soil stabilization when lime is added. In this regard, some experiments such as pH, Laser Particle Size, Compaction Test, Uniaxial Compressive Strength (UCS) test, Indirect Tensile Strength (ITS), X-ray diffraction (XRD), scanning electron microscopy (SEM), and Toxicity Characteristic Leaching Procedure (TCLP) Test are carried out. These experiments simulate conditions within a landfill and determine whose contaminants, identified by the United States Environmental Protection Agency (EPA) [34]. These pollutants exist in the leachate as well as their concentrations.

2 Materials and Methods

2.1 Materials

In this study, the soil sample was sourced from a depth of 1 m from Haft Bagh Alavi region (30.237394, 57.101819) in the south of Kerman city, Iran. In this research, soil samples that were used had an average particle size of 0.241 mm, liquid limit (LL) of 39%, plastic limit (PL) of 20%, the maximum specific gravity of 2.13 g/cm^3 , and optimum moisture content of 12%. Based on the Unified Soil Classification System and ASTM D2487 [35], the soil used in this study is classified as clayey sand (SC).

Soil characteristics and soil gradation curve are shown in Table 1 and Fig. 1, respectively. To investigate the minerals in the soil, XRD analysis was performed and its result is shown in Fig. 2. The soil contains quartz, albite, calcite, and phillipsite. Also, soil chemical composition was determined by X-Ray Fluorescence (XRF) analysis based on ASTM E1621 [40] and the result is presented in Table 2.

Two types of quick lime and hydrated lime are commonly used in soil stabilization projects. The quick lime is more voluminous and more effective in the stabilization process

Table 1 Geotechnical properties of soil

Properties	Standard test method	Value
Soil classification (USCS)	ASTM D2487-11, 2011 [35]	SC
Specific gravity (GS)	ASTM D854-92, 1994 [38]	2.33
Soil pH	ASTM D4972-13, 2007 [36]	8.36
Liquid limit (%)	ASTM D4318, 2010 [39]	39
Plastic limit (%)	ASTM D4318, 2010 [39]	20
Plasticity Index (%)	ASTM D4318, 2010 [39]	19
Maximum dry density (gr/cm ³)	ASTM D698, 2012 [37]	2.13
Optimum moisture content (%)	ASTM D698, 2012 [37]	12

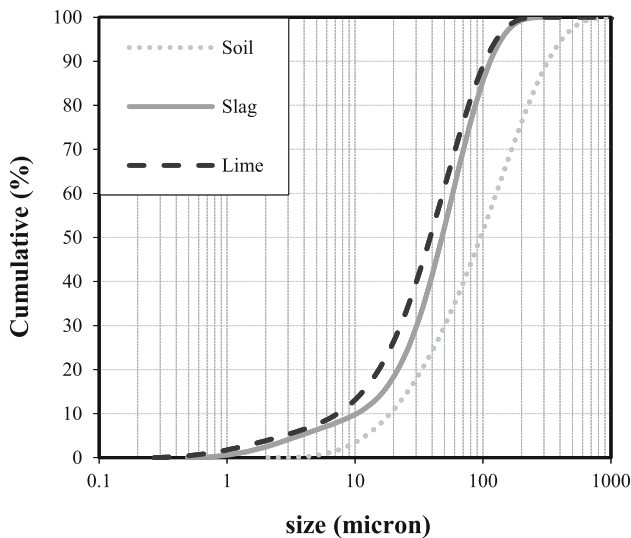
Table 2 Chemical composition of soil and studied additives

Compound	% by total weight		
	Soil	Lime	Mg Slag
Silicon dioxide (SiO ₂)	58.29	12.47	29.96
Alumina oxide (Al ₂ O ₃)	12.48	1.97	1.25
Ferric oxide (Fe ₂ O ₃)	4.93	1.84	4.17
Calcium oxide (CaO)	15.13	61.34	50.77
Magnesium oxide (MgO)	1.95	0.64	10.93
Loss on ignition (% by mass)	12.48	20.1	2.11

The quality of water can also affect the geotechnical characteristics of stabilized soils and cementitious materials [41–44]. Therefore, in the current research, distilled water was used for both characterization tests and sample preparation [45–48].

2.2 Sample Preparation

All the samples were prepared at 95% compaction energy. Dry soil, lime, and magnesium slag were mixed. Distilled water was then gradually added to the mixture and the mixing procedure was continued for one minute until a homogeneous mixture was obtained. The samples were pounded in three layers in a steel mold with a diameter of 50 mm and a height of 100 mm. After demolding, the samples were placed in plastic bags and cured for 7, 28, and 56 days at 20 ± 1 °C. To ensure the accuracy of test results, four replicate samples were prepared for each test, and the average values were calculated.

**Fig. 1** GSD Curves for base soil, lime and slag

than the hydrated lime. However, during the experiments, due to the smaller volume change of hydrated lime than quick lime, hydrated lime was utilized to eliminate the shrinkage and creep.

The lime gradation curve used is shown in Fig. 1. The chemical composition of the lime can also be seen in Table 2. Magnesium slag was obtained from a magnesium metal production factory in Ferdows city, Iran (33.954294, 58.203146). Magnesium slag with a specific gravity of 3.19 g/cm^3 was formed as a bright gray powder and its gradation curve is shown in Fig. 1.

The chemical composition of magnesium slag is also presented in Table 2. Particles of raw materials which include soil, lime, and magnesium slag can be seen in SEM micrographs. These SEM micrographs illustrate that the particles have sharp edges with non-uniform shapes (Fig. 3).

3 Laboratory Tests

To investigate the effects of adding magnesium slag and lime on the alkalinity of the soil, the pH test was performed based on ASTM D4972 [36]. Also, laser radiation was used to compare grain size distribution (GSD) curves for the soil samples before and after the addition of Stabilizing material in the same way that was used by Sol-Sánchez et al. [18]. The dispersion unit used (analysette 22 NanoTec) is capable to detect the particle size in the range of 0.02–2000 μm . The standard Proctor compaction test was performed based on ASTM D698 [37]. Uniaxial compressive strength test was carried out following ASTM D2166 [49], and additionally, tensile strength test was performed according to ASTM D3967 [50] on the samples. TCLP) Toxicity Characteristic Leaching Procedure (test was performed to analyze the contamination of groundwater resources with heavy metals from stabilized layers. Accordingly, 10 g of the sample was added

to 200 mg of deionized water and acetic acid, and then the mixture was vibrated at 20 rpm for 18 h at 20 °C. The samples were placed on a fiberglass filter, and the acetic acid solution was added to the water of the sample to bring the pH of the water to less than 2. The resulting solution was examined by the spectrometer and the concentration of heavy metals was measured. Figure 4 shows a schematic description of the experimental process performed in this study.

4 Results and Discussion

4.1 pH Test

The pH is an important indicator to indicate the effectiveness of lime treatment [51]. In the beginning, the initial pH of the soil, lime, and magnesium slag were 8.36, 13.09, and 12.97,

respectively. Figures 5, 6 and 7 illustrated the results of the pH test on the samples treated with 10%, 20%, 30%, 40%, and 50% magnesium slag and 0%, 4%, and 8% lime after 7, 28, and 56 days of curing, respectively.

Furthermore, results related to the addition of magnesium slag to the soil show an increase in the soil pH. Results obtained after 7 days of curing show that 8% of lime alone raised the soil pH to 12.8, and increased to 13.75 with the addition of magnesium slag 50%. This increase is due to the high ratio of CaO in magnesium slag (50.7%) which increases the amount of calcium ions in the sample.

CaO, Fe₂O₃, and Al₂O₃ are the most important compounds that increase soil pH to facilitate pozzolanic reactions. At the high levels of pH, soil minerals dissolve more rapidly, and then the secondary minerals (e.g., hydrated calcium silicate and hydrated calcium aluminate) are formed, and additionally, the soil particles become more stable [33].

Fig. 2 XRD results for the soil

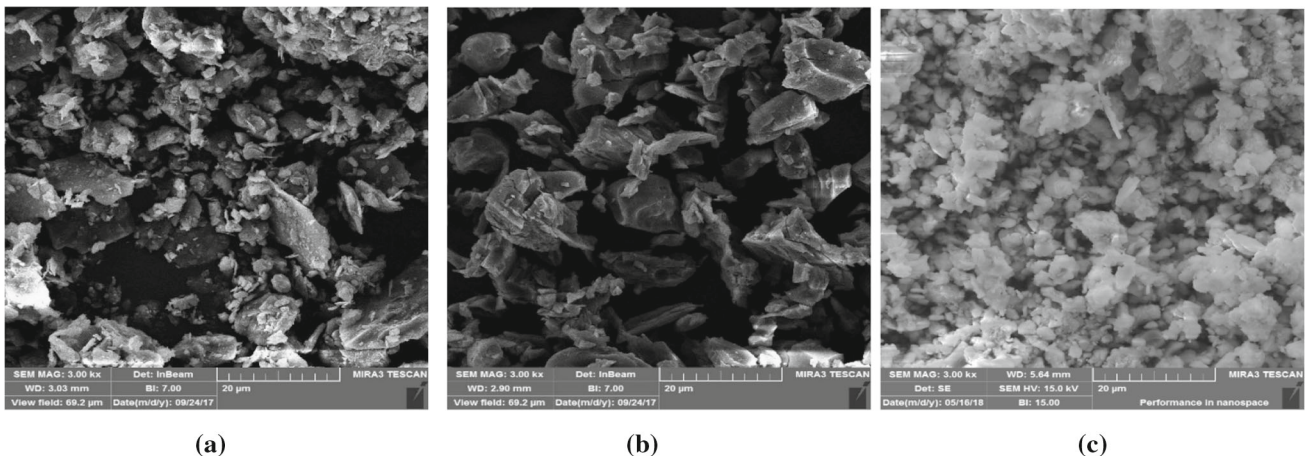
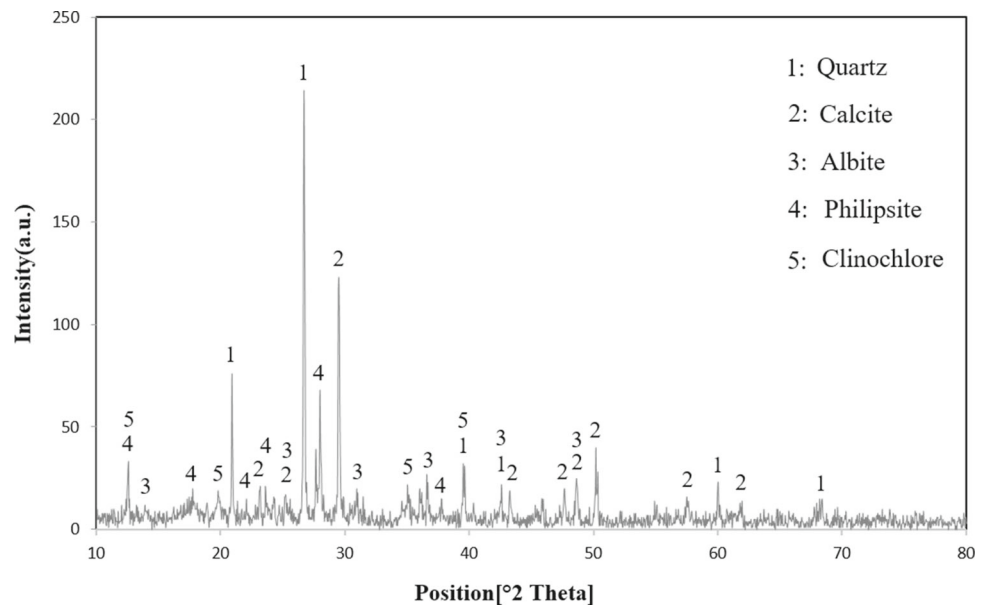


Fig. 3 SEM micrographs for **a** Soil, **b** Mg slag, **c** Lime

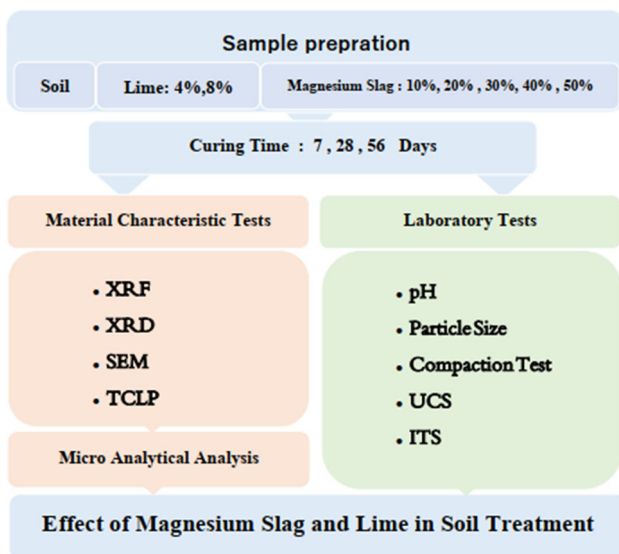


Fig. 4 Schematic representation of the experimental program

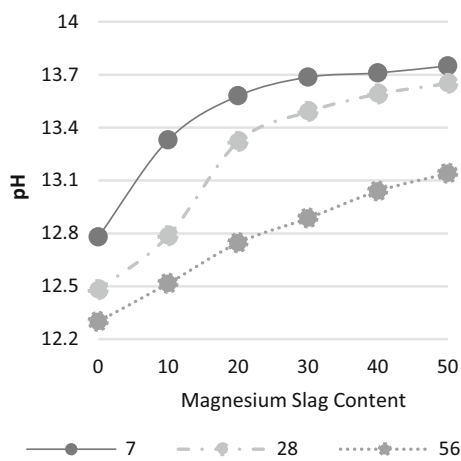


Fig. 5 pH results measured for samples treated with 0% Lime

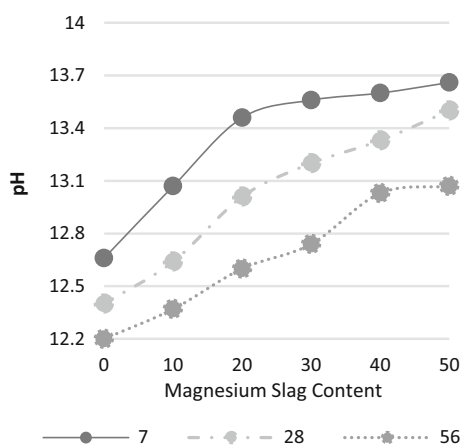


Fig. 6 pH results measured for samples treated with 4% Lime

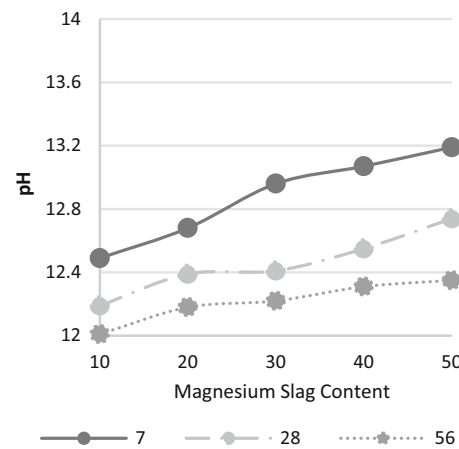


Fig. 7 pH results measured for samples treated with 8% Lime

Higher mechanical strength was obtained at higher pH values because alkali activator concentration was higher [52–54]. From Figs. 5, 6 and 7, it was inferred that the pH of the soil composition decreases with an increase in the curing time. Several reactions such as the mineral dissolution, formation of C–S–H phases, and the carbonation of Ca(OH)₂ consume OH⁻ groups, resulting in a decrease in the pH with an increase in the curing period [55]. The main result of this experiment shows the positive effect of lime and magnesium slag on increasing the soil pH, indicating an improvement in the geotechnical properties of soil samples.

4.2 Soil Particle Size Distribution

One of the physical effects of additives on soil properties is a significant change in the particle size distribution. Increasing the particle size of the soil after the addition of stabilizers often leads to improved soil geotechnical properties. This increase in size is due to the flocculation of the soil particles, which is the result of cation exchange due to the soil hydration by stabilizing additives.

The increase in particle size can be seen by comparing the soil gradation curve before and after the addition of stabilizers. The amount of change in soil particle size decreases over time. Sol-Sánchez et al. [18] considered the 28-day curing period to be the appropriate time to evaluate and compare soil particle size after the addition of stabilizing agents. In the present research, another result was the positive effect of hydrated lime on increasing the particle size of soil in this processing period.

This period which seems to be appropriate to complete the change in soil particle size is consistent with another recent study [56]. Compared with the gradation curves, Fig. 8 illustrates the variations in the particle size of the studied soil with the addition of 8% lime and various amounts of magnesium slag after 28 days of the curing period. Soil particle size

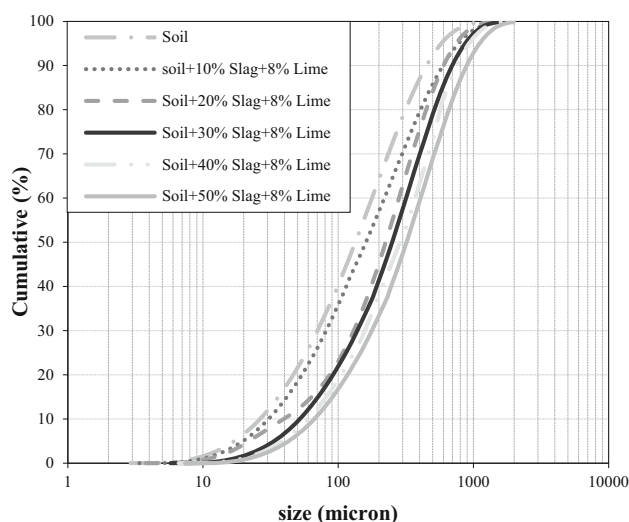


Fig. 8 GSD Curves for the soil samples with 8% of lime and different percentage of slag

increases with the addition of magnesium slag and additionally, the gradation curve tends to the right due to the addition of magnesium slag to the soil.

According to Fig. 8, the average size of soil particles without stabilizing materials was 241 microns, which increased to 367 microns by adding stabilizing materials up to 50% magnesium slag and 8% lime. The addition of stabilizing materials to the soil causes the particles to become more granular, which reduces the plasticity of the soil, increases the permeability and bearing capacity of the soil [33, 57].

The main result of this experiment indicates the positive effect of adding different percentages of magnesium slag to the soil treated with lime, which increases the particle size and improves soil geotechnical properties.

4.3 Standard Proctor Compaction Test

Table 3 demonstrated changes in maximum dry density (MDD) and optimum moisture content (OMC) after the addition of different percentages of lime and magnesium slag. The results of this experiment indicate an increase in soil MDD and OMC due to the addition of magnesium slag (A1–A6). The increase in MDD depends on the particle size and specific gravity of the additives and soil.

Magnesium slag, due to the difference in gradation with the soil, fills the voids among the soil particles and as a result, increases the specific gravity to 2.8 g/cm^3 . An increase in specific gravity indicates the improvement of soil geotechnical properties [58–61]. The addition of lime also reduces the specific gravity of the soil, which could be due to the lower specific gravity of the lime and a large amount of calcium hydroxide in the soil–lime composition.

In this case, the initial reactions could also occur rapidly, which increase the soil resistance to compaction and reduce the MDD of the stabilized soil [62]. Also, another reason for reducing the maximum specific gravity of soil in the lime addition state can be due to the replacement of soil particles in a certain volume with lime particles with lower weight. Despite the difference in the trend of changing the maximum dry density of soil with the addition of each magnesium slag and lime, the addition of both stabilizers up to 50% magnesium slag and 8% lime caused this parameter to reach 2.64 g/cm^3 . Table 3 shows that both stabilizers increase the dependence of soil on water. Adding lime and magnesium slag to the soil increases the optimum moisture content.

When these stabilizers are added to the soil, air cavities form among the particles due to the instantaneous reaction of cation exchange and flocculation of soil particles, creating a porous media with the lower maximum dry density. Hence, a higher volume of water is needed to fill the pores. The main result of compaction experiments indicates the positive effect of stabilizing additives in improving the compaction properties of the studied soil, which is one of the most important geotechnical properties of the soil.

4.4 Compressive and Tensile Strength Tests

The effects of adding magnesium slag on the uniaxial compressive strength of unstabilized and stabilized soils with 4% and 8% lime after different curing days of 7, 28, and 56 are shown in Figs. 9 and 10, respectively. The effect of the mentioned factors on indirect tensile strength can also be seen in Figs. 11 and 12, respectively.

Figures 9 and 11 show the effect of adding lime and magnesium slag along with an increase in the curing period, compressive strength and the tensile strength of the stabilized soil also increases. This physical behavior is due to the change in the particle size of the stabilized soils (described in Sect. 4.2) and an increase in the cation exchange between the soil and the stabilizers. Also, the increase in resistance over the passage of the curing time may be due to a decrease in pH level as a result of calcium ion consumption. This subject is also discussed in Sect. 4.1. Another reason leading to the increase in resistance is the high percentage of CaO in magnesium slag, which leads to the production of Ca(OH)_2 after mixing with water. Ca(OH)_2 reacts with SiO_2 (found in soil and additives) and produces CSH gel. As the hydration process of Ca(OH)_2 production continues, a large volume of C–S–H gel is formed, leading to the formation of strong and resistant soil masses. Additionally, C–S–H gel has a strong positive effect on the compressive strength of soil composition [63]. In the state of the strength of soil samples with 0% lime, Figs. 9a and 11a show compressive and tensile strengths increased with the replacement of magnesium slag

Table 3 Compaction properties of different mix proportions

Mix name	Lime (%)	Mg Slag (%)	Maximum dry density (gr/cm ³)	Optimum moisture content (%)
A1	0	0	2.13	12
A2	0	10	2.28	13.5
A3	0	20	2.41	14.5
A4	0	30	2.54	16
A5	0	40	2.68	17
A6	0	50	2.8	18
B1	4	0	2.06	12.5
B2	4	10	2.2	14
B3	4	20	2.34	15.5
B4	4	30	2.46	16.5
B5	4	40	2.59	17.5
B6	4	50	2.73	19
C1	8	0	1.94	13.5
C2	8	10	2.09	15
C3	8	20	2.25	16.5
C4	8	30	2.37	17.5
C5	8	40	2.51	19
C6	8	50	2.64	21.5

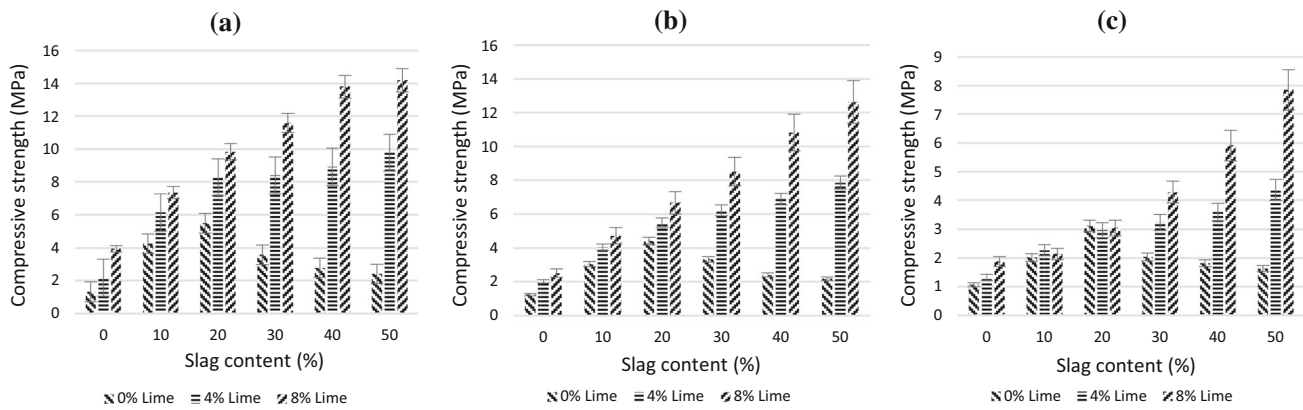


Fig. 9 Compressive strength for curing ages of **a** 7, **b** 28, **c** 56 days

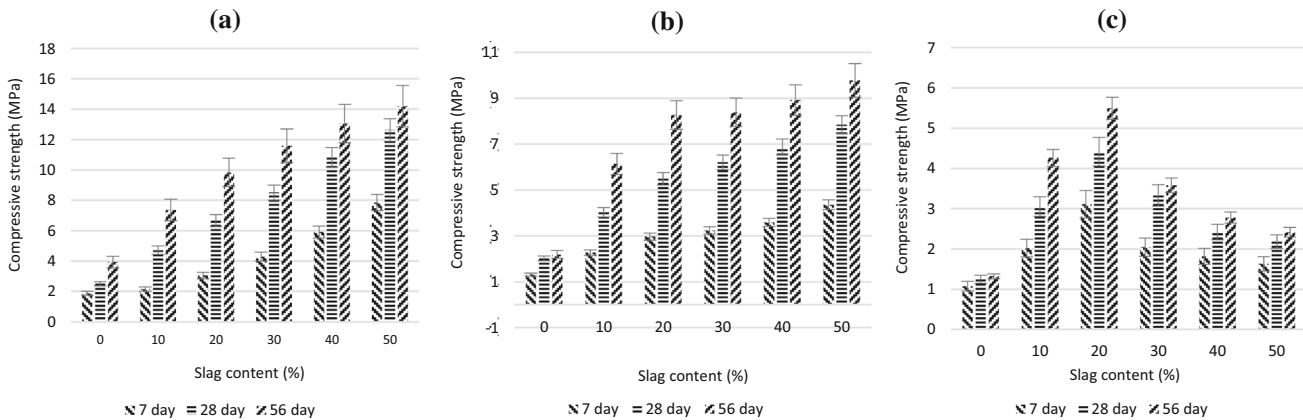


Fig. 10 Compressive strength of Samples with **a** 0%, **b** 4%, **c** 8% Lime

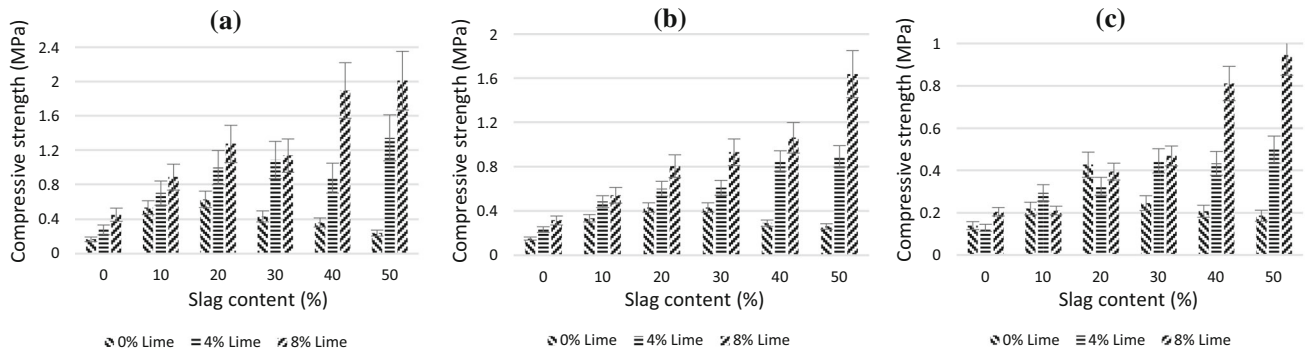


Fig. 11 Indirect tensile strength for curing ages of **a** 7, **b** 28, **c** 56 days

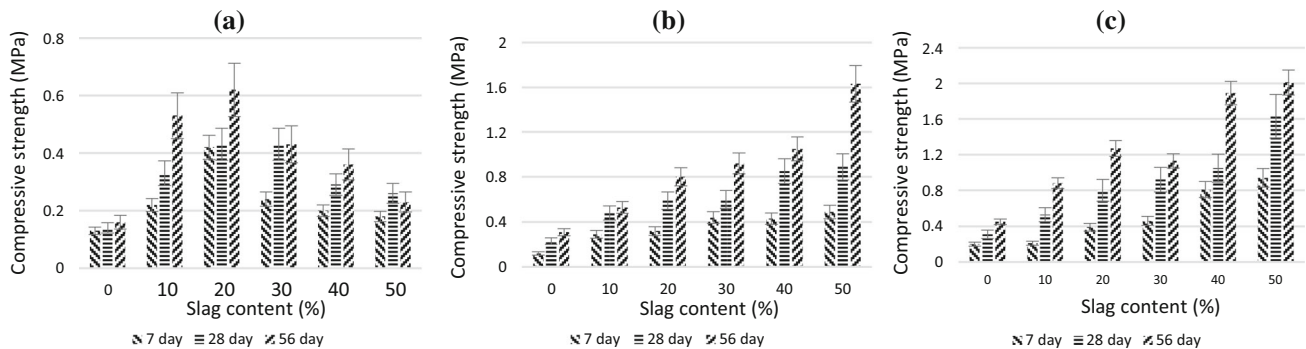


Fig. 12 Indirect tensile strength of Samples with **a** 0%, **b** 4%, **c** 8% Lime

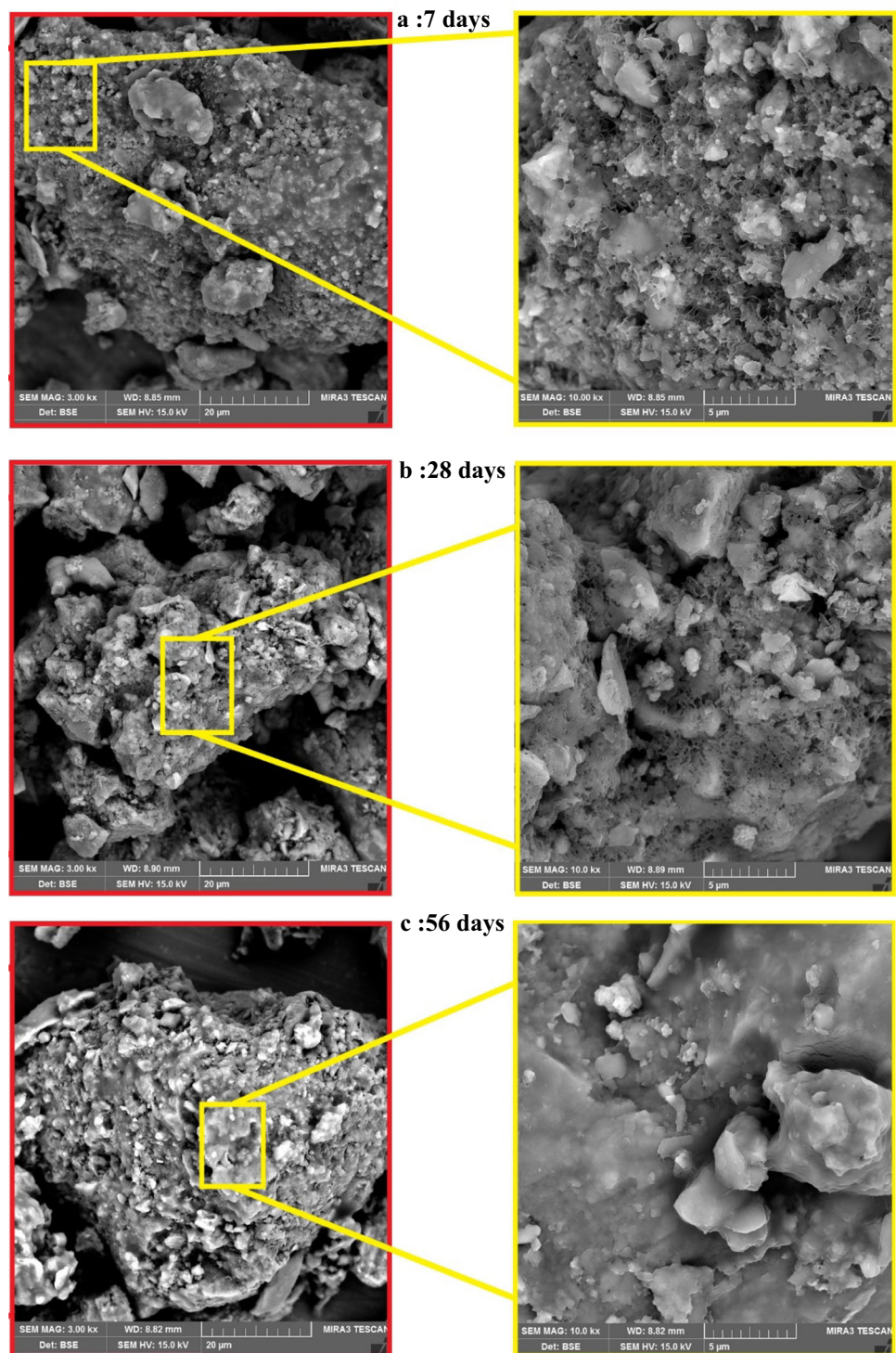
up to 20% of soil weight. But, for larger amounts of magnesium slag, the compressive and tensile strengths were on the decrease. The reason for this decrease in resistance at percentages higher than 20% of magnesium slag can be due to the high percentage of MgO. The high content of MgO in the chemical composition of magnesium slag increases the volume and thus reduces the strength of the sample [33]. Magnesium slag is suitable if the amount of MgO is less than 8% [27]. In this study, magnesium slag contains 10% magnesium oxide (MgO), which can cause swelling and reduce resistance to high percentages of magnesium slag in the soil [33]. Then, Figs. 9b,c and 11b,c illustrated that the strength of the samples increased with the addition of lime. Lime neutralizes the effect of an increase in the sample volume due to the high percentage of magnesium slag and additionally, the strength of samples with 50% magnesium slag significantly increased. Therefore, the sample treated with 50% magnesium slag and 8% lime achieved a compressive strength of 14.19 MPa and a tensile strength of 2 MPa after 56 days of curing period, showing the positive effect of the combined use of lime and magnesium slag in reducing the swelling potential of soil. Adding lime to the soil with high swelling capability increased the compressive strength and decreased the swelling of this type of soil. Similar results have been reported by Kumar et al. [64].

Amini and Ghasemi [33] indicated that the maximum compressive strength in the sample with 20% magnesium slag and 6% cement reached 14.3 MPa after 56 days of curing time. Although the result of the compressive strength test (14.19 MPa) is in good agreement with the study performed by the authors' (14.3 MPa), the present research has a subtle superiority in two ways. The first is due to an increase in the percentage of magnesium slag while utilizing lime instead of cement, which can reduce the accumulation of this industrial waste and the related environmental concerns. Meanwhile, this increase in the percentage of magnesium slag can be due to the low percentage of silica and alumina in lime compared to cement, which leads to the use of more pozzolanic materials to improve soil behavior. The second one is the potential usability of lime instead of cement, which in turn results in lower costs and environmental pollution.

5 Microstructural Analysis

Lime and magnesium slag contain aluminosilicates, hence; they can be considered as soil stabilizers. In Evan's report [65], it has been mentioned that aluminosilicate compounds in unstabilized soil composition are the cause of cementitious calcium materials for performing the long-term pozzolanic reactions. On the other hand, according to the results of this

Fig. 13 SEM micrographs for stabilized soil specimens at various curing times



study, some other pozzolanic materials in lime and magnesium slag were very useful for soil stabilization. SEM and XRD images of the samples with 8% lime and 50% magnesium slag in 7, 28, and 56 days of curing were used to observe soil changes after stabilization with these additives.

As shown in Fig. 13a, after 7 days of curing time, the soil structure has become denser and has reduced soil porosity in

comparison with Fig. 3a. The pozzolanic reactions between soil and additives result in greater density and stronger cohesion among soil particles, ultimately; reduced soil porosity. An increase in density and a decrease in soil porosity increase the compressive strength of the stabilized lateritic soil [66]. After the curing time, more dense masses are formed and the soil structure becomes more cohesive. As illustrated in

Fig. 14 X-ray diffraction patterns of stabilized specimens at various curing times

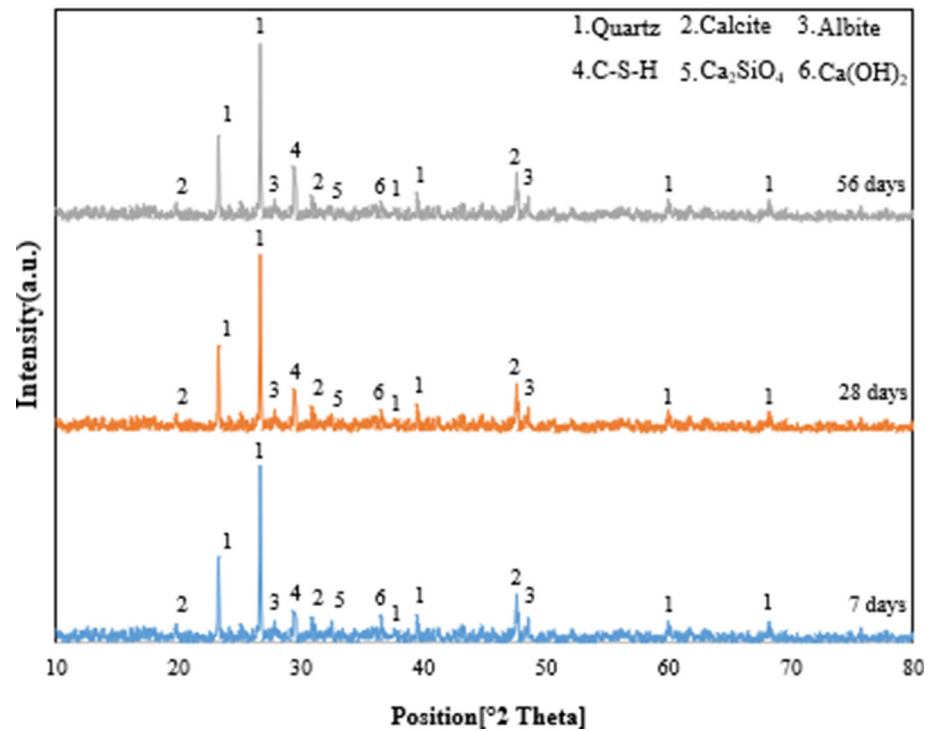


Fig. 13c, the soil particles are completely surrounded by gel of the compounds such as CSH, leading to an increase in soil strength. This result is consistent with the results obtained from the uniaxial compressive strength and tensile strength.

Figure 14 shows the diffraction peaks of the hydrated calcium silicate) C–S–H (obtained by X-ray diffraction and then, the diffraction peaks became higher at various extensions of curing time. The diffraction peaks for C–S–H and $\text{Ca}(\text{OH})_2$ were observed at of 29.4° and 36.5° , respectively. Higher peaks of $\text{Ca}(\text{OH})_2$ were detected at the extension of shorter curing times. At the curing times of 28 and 90 days, the diffraction peaks at various diffraction angles were reduced. Calcium hydroxide ($\text{Ca}(\text{OH})_2$) produces stronger hydration with an increase in the reaction time. Calcium hydroxide can also react with soil aluminosilicates or additives (lime and magnesium slag). These pozzolanic reactions can produce hydrated calcium silicate and hydrated calcium aluminate. The C_2S was also associated with a decrease in reflection intensity after 56 days of curing time. In general, it can be concluded that the decrease in C_2S and $\text{Ca}(\text{OH})_2$ is due to the growing process of hydration which produces more CSH. Hence, Ca^{2+} reacts with aluminosilicates to produce calcium silicate and hydrated calcium aluminate. This means that the additives were able to compact the soil particles.

5.1 TCLP Analysis

Using the toxicity characteristic leaching procedure (TCLP) test, the concentration of heavy metals (i.e., Zn, Cu, As, Hg,

Table 4 Results of TCLP test

	Regulatory level	Magnesium Slag	C6 Sample
Zn(mg/l)	25	0.39	0.19
Cu(mg/l)	25	0.87	0.41
As(mg/l)	5	4.18	0.57
Hg(mg/l)	0.2	0.17	0
Ni(mg/l)	25	7.62	0.69
Pb(mg/l)	5	5.2	0.56
Cr(mg/l)	5	5.49	0.75
Cd(mg/l)	1	1.87	0.04

Bold underline values indicate the amounts of the three elements Pb, Cr and Cd related to magnesium slag are higher than the Regulatory level, while they are not dangerous for use in the environment after combining with lime

Ni, Pb, Cr, and Cd) of the samples of magnesium slag and C₆ (50% magnesium slag and 8% lime) sample which had the highest compressive and tensile strength in the whole periods of the curing time, were determined. The results of this test are presented in Table 4 along with Regulatory levels. Regulatory levels are the maximum amount of heavy metal concentrations that have been defined by this institute for non-hazardous material [34].

According to Table 4, the concentrations of Pb, Cr, and Cd related to the magnesium slag are higher than permissible levels. The result of this test on the magnesium slag shows that if the material is stored, groundwater pollution in the depot

Table 5 Comparison the TCLP test results

Samples	Sample with 20% Mg Slag and 6% Cement	Sample with 50% Mg Slag and 8% Lime
	Previous study [33]	Present study
<i>Compressive Strength (MPa) (After 56 Days)</i>	14.3	14.1
Zn(mg/l)	0.32	0.19
Cu(mg/l)	0.35	0.41
As(mg/l)	0.61	0.57
Hg(mg/l)	0	0
Ni(mg/l)	0.74	0.69
Pb(mg/l)	1.52	0.56
Cr(mg/l)	0.84	0.75
Cd(mg/l)	0.16	0.04

for a long time is seen. The combination of magnesium slag with soil as a stabilizer produced different results. The test results on the C6 sample showed that the concentration of all heavy metals decreased significantly and was within the specified standard range. Furthermore, a single-point test such as TCLP often estimates potentially toxic elements release under leaching conditions that are unlikely to occur in actual situations [67]. This indicates the positive impact of using magnesium slag as a soil stabilizer from an environmental perspective. Amini and Ghasemi [33] also performed this test on the sample with the highest compressive strength containing 20% magnesium slag and 6% cement (relative to the dry weight of soil). Quantitative comparisons of the present results with the result of C₆ of the present study was given in Table 5.

This comparison aims to compare the status of the two samples and select the best sample in terms of environmental parameters. Due to the same conditions of the two samples in terms of the type of primary soil and the combined magnesium slag, the difference in the amount of magnesium slag and the choice of the second stabilization material (between cement and lime) is important. Furthermore, there is small difference between the compressive strength of the two specimens. Despite the fact that magnesium slag in the sample with lime was more than 2 times as much as in the sample with cement, the concentration of heavy metals in the sample with lime is less than the concentration reported in the sample with cement. If the solution to the environmental problems is prioritized, the selection of a sample with lime has a good priority. This sound priority is due to the cement whose production process causes air pollution will not be used. Also, more magnesium slag is used to minimize

environmental damage caused by the depot of this industrial waste material.

6 Conclusions

In this research, the influence of the combined use of magnesium slag and lime on soil improvement was evaluated. According to the results, the following main conclusions were drawn:

1. By increasing the percentages of either lime or magnesium slag or their combination, the pH of clayey sand soil increases. The combination of lime and magnesium slag raises the pH of the stabilized soil more than when the stabilizers are separately used. The pH of the stabilized soil decreased gradually with an increase in the curing time due to the chemical reactions.
2. Both magnesium slag and lime increased the soil particle size. Also, between the particle size distribution of soil and the results of the pH test, a relationship was observed that can be used to evaluate the variations in physical properties during soil stabilization. This result was due to the relatively identical changes in the process of soil particle size change with the trend of pH changes in the same time intervals. Changes in these parameters were higher in the first days of curing and then decreased by an increase in the curing times.
3. 3-By adding magnesium slag to the soil, the maximum dry density and optimum moisture content increased. While adding lime to the soil-magnesium slag composition slightly reduced MDD and increased OMC to 2.64 gr/cm³ and 21.5%, respectively.
4. By analyzing the tensile and compressive strengths of the samples with magnesium slag in all curing times, up to 20% slag, these two parameters increased and then decreased by increasing the amount of magnesium slag. By adding lime to this composition, different results can be obtained. The tensile and compressive strengths increased with an increase in the percentage of lime and magnesium slag in all curing times. The highest compressive and tensile strengths were obtained in samples with 50% magnesium slag and 8% lime. At 7, 28, and 56 days of curing, compressive strength values of 7.8, 12.6, and 14.1 MPa and tensile strength of 0.9, 1.6, and 1.98 MPa were recorded, respectively.
5. Microscopic analysis showed that the addition of lime and magnesium slag to the soil caused a change in soil morphology. XRD test results showed that CSH is an effective factor in increasing the strength of samples stabilized with lime and magnesium slag. An increase in the intensity of CSH gels along with increasing the curing time and compressive and tensile strengths, as well



as the results of SEM images, indicated positive effect of CSH on improving soil properties. These cementitious phases induced significant improvements in the engineering properties of the soil such as workability, compaction, and strength.

6. TCLP test results showed the necessity of using magnesium slag to avoid its deposition and the resulting environmental issues due to the presence of heavy metals. The results of this test on the sample with the highest amount of tensile and compressive strengths were within the specified standard range and thus do not pose a risk of groundwater contamination.

It seems that the usability of lime and magnesium slag to stabilize the subgrade in road construction can be considered as an economic and ecological solution since magnesium slag is a waste material and can reduce CO₂ emissions when compared to other cementitious agents such as cement.

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