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CHEMICAL INFLUENCE OF MAGNESIUM OXIDE ON THE ENGINEERING PROPERTIES OF CLAYEY SOILS USED AS ROAD SUBGRADE

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Abstract

This study investigates the effect of Magnesium Oxide (MgO) on the properties of clayey soils used as a road subgrade layer. A quantity of soil was collected from a work location in Baghdad city. The collected soil was mixed with different doses of MgO to investigate the changes in its engineering properties. The study included conducting laboratory tests to compare the properties of the pure soil and soil mixed with MgO. The California Bearing Ratio (CBR) test, swelling ratio, and triaxial compression test with repeated loading (this test determines the resilient modulus (Mr) of the soil) were applied on sample of pure soil and ones mixed with different doses of MgO. The results showed that CBR value of the pure soil sample is 3.37% whereas CBR values of the samples modified with 0.1%, 0.3%, 0.5%, 0.9%, 1.2%, and 1.5% of MgO are 7.2%, 15.6%, 26.5%, 36.0%, 35.5%, 30.0%, 22.0%, and 19.5% respectively. The results, also, showed that Mr value of the pure soil sample is 34 MPa whereas Mr values of the samples modified with the mentioned doses of MgO are 45, 88, 98, 147, 141, 129, 107, and 102 MPa respectively. In addition, the results showed that swelling ratio of the pure soil sample is 3.5% whereas the swelling ratios of the samples modified with the mentioned doses of MgO are 2%, 0.95%, 0.59%, 0.46%, 0.49%, 0.70, 0.95, and 1.55% respectively. Compared with a pure soil sample, CBR and Mr values increased in the samples mixed with the optimum MgO dose (which was found to be 0.7% from dry soil weight) by more than 10 times and 4 times respectively. The results also showed that adding that dose (0.7%) to the soil reduces its ability to swell by up to 13% of that recorded in the pure soil. Afterward, a pH test and X-ray energy dispersion spectroscopy (EDX) were performed to explore the chemical reactions that contributed to changing the properties of the soil. These tests exhibited a high enhancement in soil alkalinity when adding the optimum dose of MgO to it, as well as the presence of effective reactions that formed the Magnesium Silicate Hydrate compound that formed strong bonds among the soil particles and increased its tightness.

Keywords: CBR, Chemical influence, EDX, MgO, Subgrade properties.

1. Introduction

The earthworks, including the construction of the subgrade layer, are among the largest in terms of volume in road construction works [1]. Construction on poor subgrade require design of road-paving layers with a relatively large thickness to ensure the stability of these layers above such subgrade without significant deformations under the influence of traffic loads during its service life. In addition, subgrade with high swelling potential can cause severe damages in pavements structure [2].

In contrast, The preparation of a tight subgrade layer is an important matter in this field, as increasing the tightness of this layer [3]. It also increases the tightness of the overall pavements system [4], reduces the thickness of the remaining layers, and significantly reduces the total cost of the project [5] since most of the road projects cost is spent on constructing these layers [6]. There is no doubt that reducing the cost of road projects stimulates the construction of more of them and thus contributes to facilitating the movement of people and goods and leads to the prosperity of the economy of countries [7], especially the developing ones [8] where the population numbers are steadily increasing [9].

Several studies have used different materials to enhance the properties of this layer because of its importance [10], but the need to experiment with more additives is still urgent [11, 12]. In addition to the economic importance of using additives that improve the properties of the subgrade soils, they are important in the field of sustainable engineering such as reuse of waste materials [3] to preserve the environment and reduce pollution [13].

A literature review on the most recent domain studies was implemented and summarized in Table 1. The review involved 13 studies adopted MgO and other additives in soil stabilization. These studies applied a number of tests to investigate the effects of the additives on the properties of the soils. The results of the studies exposed the efficiency of the additives in soil improvements. Among the reviewed studies, 11 studies deal with the soil improvement in construction purposes. However, only two studies deals with soil as a subgrade for highway pavements [14, 15]. Nevertheless, the study in reference [14] adopted MgO as an additive to improve the properties of silt clay soil based on engineering tests only; the study did not provide chemical justifications. On the other hand, the study in reference [15] considered chemical influence but it adopted Nano-MgO as additives. Therefore, there is still a research gap in the literature and this study seeks to fill this gap.

The study aims to explore the effect of ordinary Magnesium Oxide on clay soils used as subgrade in road projects. For achieving the aim of the study, soil was collected from a work location in Baghdad and its physical and chemical properties were tested. Thereafter, a number of samples were prepared and mixed with different doses of Magnesium Oxide, and the selected doses were 0.1%, 0.3%, 0.5%, 0.9%, 1.2%, and 1.5% of the dry soil weight. These doses were selected based on literature review shown in Table 1. The nearest studies that select similar doses were found in references [14-18].

The treated specimens were packed in airtight bags to preserve their moisture content and left for 28 days to ensure that MgO interacted with the soil components. This procedure is similar to that adopted by reference [19]. Similar to soil improvement with lime or Portland cement, soil treatment in site must be applied in such a manner to ensure continues curing for the required time; the treated parts must be damped with water periodically as in concrete constructions.

Thereafter, a number of laboratory tests were implemented on the samples mixed with the mentioned doses of MgO to reveal the change in their engineering properties. These tests included CBR (bearing ratio and swelling) and a triaxial test with repeated loading. The results of those tests showed a remarkable enhancement in the properties of the collected soil. To understand these results, a pH test and a chemical composition test using EDX were applied.

Table 1 Summary of literature review.

Ref.	Soil Type	Additive	MgO%	Tests	Curing	I	RM
[20]	Silt	MgO	15	Density UCS, XRD SEM, MIP	3-6 h	1 2 3	R
[16]	Clayey sand	MgO GGBS	0.5-1	Density UCS HC	14, 28, 60, 90, 120 days	1 2 4	A
[17]	Marine soft clay	$MgSO_4$ PC, SF CaO MgO	0.2-1	UCS SEM, XRD UUTC, ODC	3, 5, 7, 9, 11, 14, 21, 28 days	1	R
[21]	Clay	CaO MgO) Na$_2$CO3	20%	pH, Porosity FTIR, XRD SEM, EDXR	7, 14, 28 days	1 5	R
[22]	Soft clay	GGBS BOFS CaO MgO	0.75-6	UCS SEM XRD	1, 28, 90 days	1 6	A
[15]	Soft clay	Nano MgO	0.20-2	CBR EDXR	28 days	7 8	R
[23]	Clay	MgO CaO FA	2-3	UCS SEM XRD	0.5-24h	1	R
[19]	Artificial clay sand	MgO CO2, PC	5	UCS XRD	28 days	1	R
[24]	Coastal soft soil	N-MgO PC	5-20	UCS SEM	12, 28 days	1	R
[18]	Kaolin	GGBS MgO	1.2-1.8	Density Porosity pH XRD	28 days	2 5	R
[14]	Soft silt clay	MgO	0.25-1.5	CBR CTC	3 days	7 8 9	R
[25]	Silt	MgO	10-30	UCS SEM	12h	1 6	A
[26]	Silt	MgO CS	2.5-5	UCS, SEM XRD	7,28,90 days	1	A

GGBS

CS: Carbide Slag, GGBS: Ground Granulated Blastfurnace Slag; PC: Portland Cement; SF: Silica fume; BOFS: Basic Oxygen Furnace Slag; Un: Unknown; UCS: Unconfined Compression Strength; SEM: Scanning Electron Microscopy; XRD: X-Ray Diffraction; MIP: Mercury Intrusion Porosimetry; 3-D XRI: Three-Dimensional X-Ray Imaging; HC: Hydraulic Conductivity EDXR: Energy-Dispersive X-Ray; CTC: Cyclic Triaxial Compression Test; FTIR: Fourier-Transform Infrared Spectroscopy

I: Improvement; 1= Strength: increased; 2= Density: increased; 3= Freezing/thawing Resistance: increased; 4= Hydraulic conductivity: decreased; 5= Porosity: decreased; 6= Compressibility: decrease; 7= CBR: increased; 8= Swelling: decreased; 9= Mr: increased

RM: Role of MgO; A: Activator; R: Reactive

2. The Materials Used

A quantity of soil was collected from a work location in Baghdad for testing before and after mixing with MgO. The study included conducting a number of tests to identify soil properties, as revealed in Table 2. MgO was purchased from a specialized company (the Central Drug House (P) Ltd). The main physical and chemical properties of MgO used in this study were obtained from the manufacture manual as presented in Table 3. Figure 1 illustrates pictures for the soil and MgO.

Table 2. Properties of the pure soil.

Physical and Engineering Properties	
Colour	Brownish
Passing Sieve #200	100%
Liquid Limit (L.L.)	42%
Plastic Limit (P.L.)	26%
Plasticity Index (P.I.)	16%
AASHTO Classification	A-7-6
Specific Gravity	2.77
Max. Dry Density	1889 kg/m^3
Optimum Moisture Content	%14.7
CBR	3.37%
Swelling Ratio	3.5%
Resilient Modulus	34 MPa
Chemical Properties	
SiO_2	62.05%
Al_2O_3	29.78%
Fe_2O_3	4.66%
TiO_2	1.23%
K_2O	0.61%
MgO	0.57%
SO_3	0.19%
CaO	0.17%
Others	0.50%
pH	5.2

Table 3. Properties of MgO.

Physical Properties	
Colour	White
Form	Powder
Average particles size	0.5-2 μm
Purity	99.64%
Solubility in dilute acid	96.5-100 %
Loss on ignition (at 900 C)	8%
Substances insoluble in acetic acid	0.15%
Chemical Compounds	
MgO	99.64%
Chloride (Cl)	0.11%
Sulphate and Sulphate (as SO_4)	0.1%
Arsenic (As)	0.0004%
Calcium (Ca)	0.1%
Iron	0.05%
Heavy metals (as Pb)	0.002%

(a) Soil. **(b) MgO.**

Fig. 1. Materials used.

3. Testing Program

In addition to the laboratory tests carried out to determine the properties of the materials used (pure soil and MgO), a number of samples were prepared as modified ones. The specimens were prepared according to the procedure explained in reference [26]. First, predetermined quantities of dry soil and dry MgO were mixed and homogenized for 10 minutes using a mechanical mixer rotates for 300 rpm. Second, a predetermined quantity of water was added to the mixture and the mixing was continued for extra 10 minutes. Optimum moisture content and maximum dry density were kept the same for all samples (the original and the modified ones) to exclude the effect of the density on the results and to distinguish the effect of MgO as a modifier. The samples were kept in waterproof bags and left for 28 days under wet treatment. The curing period was selected based on the literatures stated in Table 1. Among the thirteen studies included in Table 1, three studies adopted carbonation for 0.5-24 hours. Whereas eight out of the remaining ten studies adopted twenty-eight days as one of the curing periods.

Therefore, this study adopted this period. The chemical reaction occurred. Thereafter, a number of engineering and chemical tests were performed on these samples. The same tests were also performed on pure soil. Table 4 summarizes the testing program. Some testing details are presented in the following subsections.

Table 4. Testing Program.

Test	Purpose	ASTM
CBR	Determination of the values of the California bearing ratio (%) that showed the ability of the subgrade soil to withstand traffic loads	D 4429
Swelling Ratio	Determination of the swelling ratio in the soil (%), which shows the volumetric changes occurring in the road subgrade	D 4429
Triaxial Test by Repeated Loading	Determination of the soil resilient modulus (Mr), which indicates the ability of the soil to withstand traffic loads and also determines the design thickness of the paving layers	D 4123
pH Test	Determination of the pH value that reflects the catalysis of the materials for a chemical reaction	D 4972
EDX	Determination of the concentrations of elements in the substance, which reflects the changes in the chemical composition of the substances after the reaction	E 1508

3.1. CBR test

CBR test was conducted on samples (each include three specimens) of the original soil and others improved with different doses of magnesium oxide for showing the change in soil properties after treatment with MgO.

The samples were prepared according to the standard method and using the optimum water ratio, and then they were wrapped in airtight bags to preserve the water content in them and left for 28 days to ensure that the reaction took place. After the end of the treatment period, the samples were immersed in water for 4 days, and then the swelling percentage in the soil was measured according to the standard method (Fig. 2).

(a) Specimens merged in water. **(b) Loaded specimen.**

Fig. 2. CBR specimens.

After that, a standard piston penetration test was applied for calculating the CBR value. The average value of each three specimens was considered as the CBR value of one sample. This test gives relative values, as the California bearing ratio is the value of the stress recorded when penetrating the soil with a standard piston by 2.5 mm divided by that stress recorded for standard rock in California for the same penetration. This value reflects the ability of the subgrade soil to bear the traffic loads and consequently determines the thickness of the pavement's layers. Therefore, increasing this value means a decrease in the thickness of those layers.

In addition, the swelling ratio gives an idea of the volume change of subgrade soil in water-saturated media. The lower the swelling ratio, the more suitable the soil as a subgrade as subgrade swelling causes severe damage to the stable pavement's layers above it, which increases the cost of maintenance and reduces the service life of the pavements. The optimal MgO content was determined by testing results.

3.2. Cyclic triaxial compression test

A series of cyclic triaxial compression tests were conducted in accordance with (AASHTO T-307) on a number of original and modified soil samples prepared under conditions same as those adopted in CBR test. Figure 3 shows sample testing. This test is adopted to determine the values of resilient modulus (Mr) of subgrade soils. Mr is the capability of subgrade to recover strain under repeated loads. This test included fifteen sequences; each includes three confining pressures.

Fig. 3. Cyclic triaxial compression testing.

3.3. pH test

In addition to measuring the pH value of the original soil, pH value of the soil improved with the optimum content of MgO was measured after the wet treatment for knowing the change in it before and after improving with MgO. This value is considered in the interpretation of the chemical reactions taking place between soil particles and MgO.

3.4. XRD test

This test was conducted on samples of the original soil and soil improved with MgO after wet treatment according to the optimum water content and for a period of 28 days for showing the change in the concentrations of the basic elements included in the soil composition before and after improvement and wet treatment.

4. Results

Based on original soil properties shown in Table 1, the following points can be stated. First, all soil particles are finer than 0.075mm. Second, the values of liquid limit and plasticity index are 42% and 16% respectively. Consequently, the soil can be classified as A-7-6 according to AASHTO classification system; this class is rated as poor subgrade (AASHTO M145). Therefore, improvement of this soil is required to improve its properties to be relevant as pavements subgrade. Otherwise, road-paving layers should be designed with a relatively large thickness to ensure the stability of these layers above such subgrade without significant deformations under the influence of traffic loads during its service life.

This finding is supported by the soil CBR value (3.37%), which is relatively small. In addition, the swelling value of the soil (3.5%) showed that the original soil has a medium capacity to swell in the presence of moisture, which may lead to severe damage to the pavement system, especially under water-saturated conditions. In light of these results, it becomes clear the necessity to improve the properties of the soil to increase its efficiency and serviceability. The following subsections show the results obtained from the aforementioned tests.

4.1. Results of CBR test

The results of the pure soil tests showed that CBR value was 3.37%, as previously mentioned. The results of the tests also showed that the CBR values for the soil mixed with MgO are higher than that recorded for the pure soil as shown in Fig. 4.

The highest CBR value reached more than 10 times that of the pure soil when adding 0.7% of MgO. This increase in soil strength can be attributed to the bonds among the particles created by the chemical reactions between the soil and MgO as described in subsections 4.3 and 4.4. Afterward, the CBR values begin to decrease with increasing doses. This may be attributed to the decrease in chemical reaction due to consumption of the limited amount of curing water leaving extra amount of MgO that weaken the soil structure. The CBR values were (7.2%, 15.6%, 26.5%, 36.0%, 35.5%, 30.0%, 22.0%, and 19.5%) with addition of (0.1%, 0.3%, 0.5%, 0.7%, 0.9%, 1.1%, 1.3, and 1.5%) of MgO respectively (Fig. 4). The results were in line with those stated in references [14-16].

These results reflect a tremendous enhancement in the properties of the subgrade soil and an effective increase in its ability to withstand high traffic loads as higher CBR value refer to tight subgrade [27]. This leading to a significant reduction in the thickness of the paving layers, which in turn leads to a significant reduction in the construction cost. An example with predetermined values obtained from reference [3] for a pavement design showed that the overall thickness could be decreased to about 60% by modifying the CBR from 3.37% to 36%. Accordingly, the cost can be decreased to about 60%.

The results of the pure soil tests showed that the swelling ratio is 3.5%, as previously mentioned. The results of the tests also showed that the swelling ratios of the soil mixed with MgO are less than that recorded for the pure soil, as shown in Fig. 5. It is noticed from the figure that the swelling rate decreases with increasing the doses of MgO and reaches its lowest at the dose of 0.7% (reaching about 13% of that of the pure soil). The results were in line with those stated in references [14, 15].

This decrease in soil swelling can be attributed to the bonds among the particles created by the chemical reactions between the soil and MgO as described in subsections 4.3 and 4.4. Afterward, it starts to increase with increasing doses. This behavior may be attributed to the swelling of the extra (non-reacted) MgO. The swelling ratios were (2%, 0.95%, 0.59%, 0.46%, 0.49%, 0.70, 0.95, and 1.55%) with the addition of (0.1%, 0.3%, 0.5, 0.7%, 0.9%, 1.1%, 1.3, and 1.5%) of MgO respectively.

This significant decrease in swelling indicates a significant enhancement in the ability of the soil to resist the volumetric changes under partial or full saturation conditions. As it decreases from medium swelling potential which may cause severe damaged or distortions [28, 29] such as heaving, waving, and rutting in pavements [30] to low swelling potential which is relatively safe [31]. This leads to ensuring the safety of the paving layers from damage due to swelling action, and thus a significant reduction in the cost of maintenance, as well as a significant increase in the service road life.

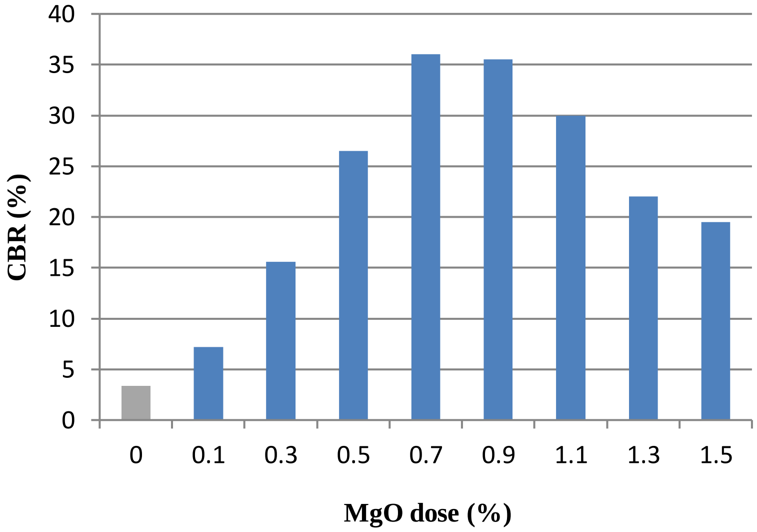


Fig. 4. CBR values for pure samples and samples mixed with different doses of MgO.

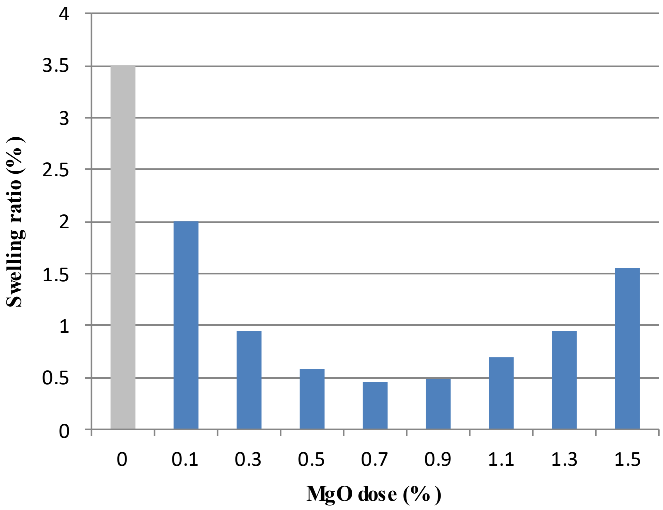


Fig. 5. Swelling ratios for pure samples and samples mixed with different doses of MgO.

4.2. Results of triaxial compression test

Through this test, the values of the resilient modulus (Mr) of the subgrade soil were determined for the pure sample and the samples mixed with MgO as shown in Fig. 6. It is evident from the figure that the samples show a similar behavior to that in the case of CBR test as expected, as the resilient modulus of the soil reflects its tightness and its ability to withstand traffic loads. The maximum value of Mr was (147) MPa for the soil mixed with 0.7% of MgO. This value is more than 4 times that of the pure soil, which is 34 MPa. The results were in line with those stated in references [14, 15]. This behavior can be justified by causes similar to those stated for CBR behavior.

Through the results of this test and the CBR test, as well as the swelling ratio test, the dose of 0.7% of MgO can be considered as the optimum dose that is recommended to be used to enhance this type of weak soil for the purposes of its use in the road subgrade layer. This enhancement in soil properties can be attributed to the formation of strong bonds among the soil particles through the chemical reaction between Magnesium Oxide and the soil components by curing with water. For explaining the chemical reaction, the pH test and EDX were adopted as shown in the following subsections.

4.3. pH test results

The results of this test showed that the value of the pH of the soil mixed with the optimum dose of MgO after wet treatment is 10.3, which is much higher than that of the pure soil, as its value was 5.3. This change in pH value indicates an increase in the alkalinity of the modified soil, which could be responsible for dissolving some soil components, stimulating chemical reactions, and contributing to the formation of interconnected compounds that increased the strength of the soil [31]. In addition, increasing the pH value helps soil particles to agglomerate, which improves their structural composition, which increases their tightness as well [15, 21].

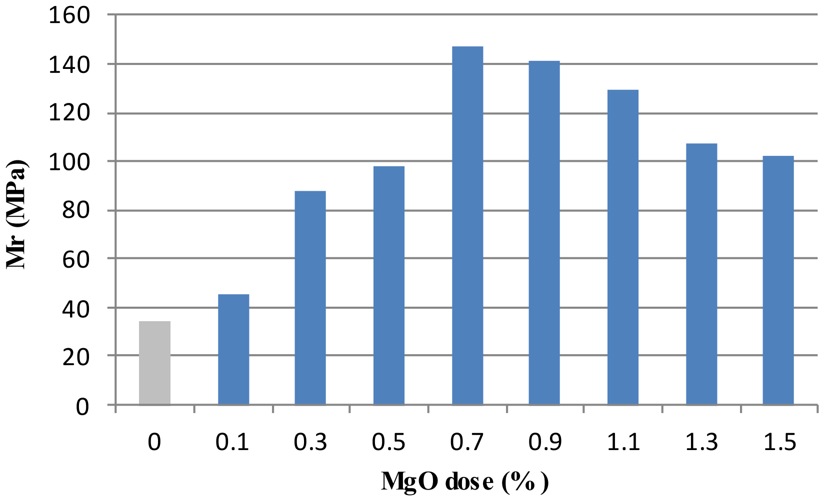


Fig. 6. Mr values for pure samples and samples mixed with different doses of MgO.

4.4. Results of EDX

Figures 7 and 8 show the results of those tests for pure soil and soil mixed with the optimum dose of MgO. The results show a remarkable change in the concentrations of the main elements of the soil before and after addition, as shown in Fig. 9. By comparing the two figures (Fig. 9(a) for pure soil and Fig. 9(b) for enhanced soil), it is evident that there is an effective increase in the concentrations of Oxygen and Magnesium compared to a decrease in the concentrations of Aluminum and Silicon, and this is clear evidence of a chemical reaction between Magnesium Oxide and soil components, as the reaction of Magnesium Oxide and water formed a Magnesium Hydroxide compound.

Increasing the alkalinity of the mixture after wet treatment, which was proven by the pH test previously mentioned, emphasizes this conclusion. Afterward, portions of Aluminum and Silicon were dissolved in the Hydroxide solution, and their dissolution decreased their concentration in the mixture. Consequently, the concentrations of Magnesium and Oxygen increased.

In addition to the increase in the Oxygen concentration due to the decrease in the concentrations of Aluminum and Silicon, there is an additional increase in the Oxygen concentration due to the interaction of Magnesium Oxide with water, as this reaction added another Oxygen atom originating from the water. These results are in line with those found in references [2, 15, 18, 26].

These reactions can create the Magnesium Silicate Hydrate compound, which is formed by the reaction of Magnesium Hydroxide with the Silica present in the original soil and is a compound responsible for creating strong bonding forces between the soil particles. This reaction is similar to the reaction of Portland cement with clay soils, which form the Calcium Silicate Hydrate compound [15, 18].

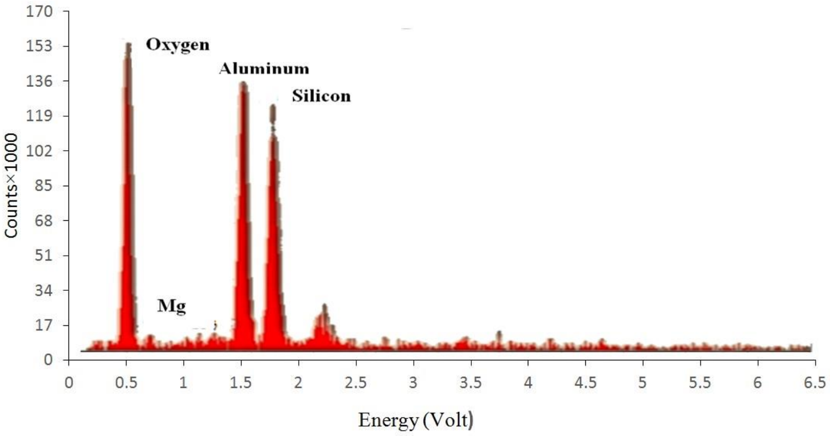


Fig. 7. EDX results for pure soil.

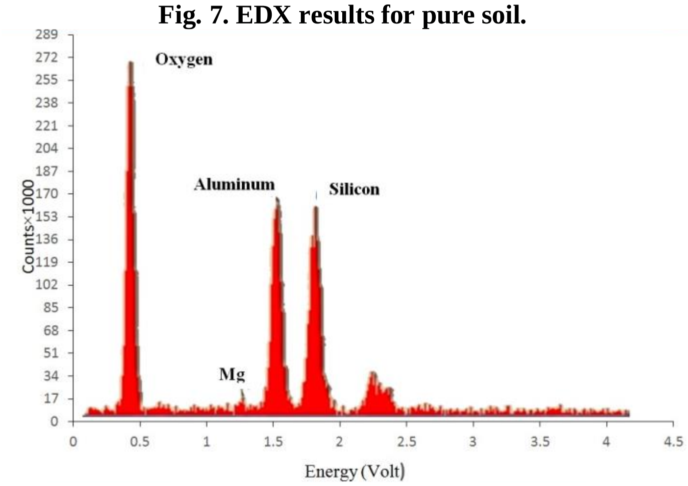
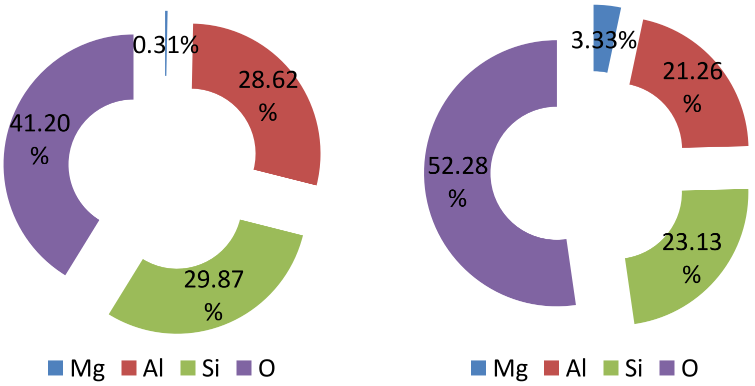


Fig. 8. EDX results for sample mixed with optimum dose of MgO.



(a) Pure soil. **(b) Soil+MgO after curing.**

Fig. 9. The concentrations of the main elements in pure sample and sample mixed with optimum dose of MgO.

5. Conclusion

The present study adopted a laboratory-investigation approach to determine the chemical influence of adding different doses of MgO to clayey soils used as a road subgrade. The following conclusions were addressed from the study:

- The use of Magnesium Oxide significantly enhances the soil properties of the road subgrade soil, which increases its tightness. The maximum enhancement in soil properties was achieved by adding 0.7% of MgO. Therefore, this dose can be considered as the optimum dose in enhancing this type of subgrade soils.
- MgO decreases the swelling potential of the subgrade soil from medium level, which can cause severe damages and distortions in pavements to low level, which is not harmful.
- Adding Magnesium Oxide to clay soil reduces its acidity and increases its alkalinity, as indicated by the pH test, as the pH value increased from 5.3 in the pure soil to 10.3 for the soils mixed with MgO. Increasing the alkalinity of the soil enhances the dissolution of its components and helps the interaction of those components with MgO, which forms new chemical compounds, as indicated by the results of the EDX test. The formation of new compounds leads to the formation of bonding forces between the soil particles and helps in agglomeration, thus improving its engineering properties and increasing its tightness.

6. Future Work

Similar to other studies, this study included some limitations due to limited available time and resources. These limitations can be considered in the future work. Therefore, a number of proposals are recommended for future work as show in the following:

- Investigating the effects of different curing periods.
- Investigating the effects of different water contents.
- Investigating the effect of soluble salts on the subgrade soils modified by MgO.
- Applying similar studies on different types of soil especially clayey soils.

Nomenclatures

Al_2O_3	Aluminum Oxide
CaO	Calcium Oxide
CO_2	Carbon Dioxide
CS	Carbide Slag,
Fe_2O_3	Iron Oxide
HC	Hydraulic Conductivity
K_2O	Potassium Oxide
L.L	Liquid Limit
MgO	Magnesium Oxide
$MgSO_4$	Magnesium Sulfate
Mr	Resilient modulus
Na_2CO_3	Sodium carbonate
P.I	Plasticity Index
P.L	Plastic Limit
pH	potential of Hydrogen

SiO_2	Silicon Dioxide
SO3	Sulfur Trioxide
TiO_2	Titanium Dioxide
Un	Unknown

Abbreviations

3-D XRI	Three-Dimensional X-Ray Imaging
AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
BOFS	Basic Oxygen Furnace Slag
CBR	California Bearing Ratio
CTC	Cyclic Triaxial Compression Test
EDX	X-ray energy dispersion spectroscopy
EDXR	Energy-Dispersive X-Ray
FTIR	Fourier-Transform Infrared Spectroscopy
GGBS	Ground Granulated Blastfurnace Slag
MIP	Mercury Intrusion Porosimetry
PC	Portland Cement
PEN	Periodicals of Engineering and Natural Sciences
SEM	Scanning Electron Microscopy
SF	Silica fume
UCS	Unconfined Compression Strength
XRD	X-Ray Diffraction

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