

EFFECT OF MAGNESIUM OXIDE AND CARBONATION ON COLLAPSE POTENTIAL OF COLLAPSIBLE GYPSEOUS SOIL

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ABSTRACT: Gypseous soils are known as problematic soils from an engineering point of view. Many studies deal with collapsible soils and how to reduce the sudden collapse when the soil is soaked in water. The objective of this paper is to investigate the collapse potential when the collapsible gypseous soil is mixed with different percentages of Magnesium Oxide (0, 5, 10, and 15%) and carbonated with different carbonation periods (0, 1, 3, and 24 hours). The adequate Magnesium Oxide percentage was found to be 10% because its effect is close to that of 15% and the optimum carbonation period time is 3 hours. The 10% Magnesium Oxide used in treating the gypseous soil of relative density 35% without carbonation resulted in a reduction in collapse potential by 76% as compared with the natural soil. When the natural soil is carbonated at the relative density of 35% without adding Magnesium Oxide, the collapse potential decreased about 65% from no carbonation to 3-hour carbonation, but it decreased only 9% between the carbonation period of 3 hours and 24 hours. As for samples prepared at the relative density of 75%, the collapse potential decreased more than 77% from no carbonation to 3-hour carbonation, but it decreased only 8% between 3 hours and 24 hours.

Keywords: Collapsible soil, Gypseous soil, Magnesium oxide, Carbonation.

1. INTRODUCTION

The Gypseous soil is one of the problematic collapsible soils. According to the United Nations Food and Agriculture Organization [1], the gypseous soils cover about 1.5 million km² of the total area of the world. Many regions included gypseous soil and Iraq is one of the most countries that have gypseous soil which represents 30% of its total area [2].

If the foundations of a structure contain soluble minerals, then water seeping through them will create gaps. This causes loss of strength and collapsing to an unacceptable settlement, especially in important structures [3].

The collapse potential is defined as the percentage of collapsibility of the soil when water enters the soil and can be determined from the following equation. The collapsibility severity depends on the collapse potential value and the severity can be described as shown in Table 1 according to ASTM D5333 [4] and Jennings and Knight [5]:

In general, the treatment measures of gypseous soils can be summarized as follows:

- 1) Chemical treatment: in which the remedial materials recommended are primarily cement, lime, silica fume, nanomaterials, sodium chloride, and crude and/or west oil products [6].
- 2) Physical treatment: these measures are based upon the improvement of the geotechnical properties of gypseous soils to control the consequences of the dissolution of gypsum.

$$c_p = \frac{\Delta e}{1+e_0} \times 100 = \frac{\Delta h}{h_0} \times 100 \quad (1)$$

where; C_p : Collapse potential,
 Δe : Change in void ratio,
 e_0 : The initial void ratio,
 Δh : Change in the height of soil, and
 h_0 : The initial height of soil.

Several methods were used to minimize the collapse effect, like replacing the gypseous soil or through soil stabilization (grouting or soil improvement). For grouting, several materials were used, such as cement, bentonite, asphalt emulsion, and sodium silicate. Grouting is one of the several methods used to improve the strength of the soil. The main function of the grout is to provide a cemented bond between soil particles and to provide a waterproofing coat around the gypseous soil particles [7].

Razouki et al. [8] studied the effect of compacting effort (CE) and long-term soaking on the strength characteristics of clayey gypseous subgrade soil. To study the effect of CE and the long term soaking on the properties of the tested soil, various California bearing ratio soil samples were prepared and compacted at the optimum moisture content of the modified AASHTO compaction, but using four different chosen CEs of 12, 25, 56 and 70 blows/layer and then soaked for 0, 4, 7, 15, 30 and 120 days. The California bearing ratio (CBR) tests indicated that the CBR increases significantly in a nonlinear manner with increasing CE for all soaking periods, indicating improvement in soil strength with the increased compaction.

Fattah et al. [9] adopted a method for the treatment of collapsibility of gypseous soils by dynamic compaction. This was achieved by carrying out laboratory tests on three gypseous soils. It was found that the higher the gypsum content is, the more significant effect of compressibility will be. For soaked specimens treated by dynamic compaction, the variation in the void ratio progresses less than that of untreated specimens, which means the collapse potential is reduced. In terms of reduction in compression index (C_c) of soaked specimens, this was achieved when the soil specimens were subjected to 20 blows.

Table 1 Collapse potential severity.

Classification according to Jennings and Knight		Classification according to ASTM – D5333	
Cp (%)	Severity	Cp (%)	Severity
0 – 1	No problem	0	None
1 – 5	Moderate trouble	0.1 – 2	Slight
5 – 10	Trouble	2.1 – 6	Moderate
10 – 20	Severe trouble	6.1 – 10	Moderately severe
> 20	Very severe trouble	> 10	Severe

Alateya [10] conducted an experimental study to investigate the influence of three different types of additives on gypseous soil to improve its compaction properties. The additives used in the study were recycled fine asphalt pavement, recycled coarse asphalt pavement (RR), and Rice Husk Ash (RHA). The results showed that the best improvement is accomplished when samples were tested by adding a mix of (RR) and (RHA). Maximum dry density increases with the increase in the mixing content, while the optimum water content decreases.

Ibrahim and Schanz [11] studied the effect of adding silicone to the gypseous soil and the results showed that adding 4% silicone oil reduced the collapsibility of the gypseous soil.

In the work of Abbas and Al-Luhaibi [12], it was used 2-12% of melting furnaces and the results showed that the collapsibility decreased by about 91%.

A series of unconfined compression tests (UCTs) were conducted by [13] to investigate the effects of the content of reactive magnesia (MgO) and carbonation time on the engineering properties including apparent characteristics, a stress-strain relation, and deformation and strength characteristics of reactive MgO treated silt soils. The results demonstrated that the reactive MgO content and carbonation time have remarkable influences on the aforementioned engineering properties of soils. With the increase in reactive MgO content, the unconfined compressive strength

(q_u) increases at a given carbonation time (<10 h), whereas the water content and amounts of the crack of the soils decrease.

Cai et al. [14] investigated the apparent property, the mass change ratio, water content, dry density, pH, confined compressive strength and elasticity modulus as well as microstructural characteristics of reactive MgO carbonated silt after several drying-wetting cycles, and the ordinary Portland cement (PC) stabilized silt was used as a control sample for comparison. The results indicated that the maximum mass change ratio, water content, and soil pH of MgO carbonated silt are much lower than the corresponding values of PC stabilized silt. Both unconfined compressive strength and elasticity modulus of MgO carbonated silt were almost twice those of PC stabilized silt despite drying-wetting cycles.

Cai et al. [15] results indicated that compared with PC stabilized soils, the soundness ranks and pH of CO₂-carbonated MgO admixed clayey soils have varying degrees of decline after drying-wetting cycles and CO₂ carbonated MgO admixed clay has a higher mass change ratio and water content than carbonated MgO admixed silty clay. The residual strength ratios of carbonated MgO admixed and PC stabilized clay were 0.35 and 0.65, respectively, whereas the residual strength of carbonated MgO admixed silty clay still was higher than that of PC stabilized silty clay, although their residual strength ratios were above 0.8.

2. RESEARCH SIGNIFICANCE

The objective of the present study is to utilize Magnesium Oxide as a treatment material utilized for solving the collapse potential problem of gypseous soil with or without carbonation. Magnesium Oxide was added to a gypseous soil in different percentages and subjected to carbonation for different periods.

3. MATERIALS

3.1 Soil

The soil used in this research was a granular gypseous soil brought from Tikrit city north of Baghdad city in Iraq with a gypsum content 49%. Distilled water is normally used for specific gravity determination, but Kerosene is recommended instead of distilled water when the soil specimens contain a significant fraction of organic matter or gypseous material. The physical properties are illustrated in Table 2 and the grain size distribution is illustrated in Fig.1. To avoid dehydration and/or transformation of gypsum, the drying temperatures used herein were maintained to not exceed the range (45-50°C). According to the Unified Soil

Classification System, the soil is classified as poorly graded sand (SP). Soil samples were chemically analyzed to obtain the amount of gypsum by British Standards B.S. – 1377 [16]. The soil is prepared at two relative densities 35% and 75%.

3.2 Magnesium oxide

Indian Magnesium Oxide is used in this research and its properties are illustrated in Table 3. Magnesium Oxide is a lightweight white powder.

Table 2 Physical properties of the soil.

Physical properties	Value
Gypsum content (%)	49
Specific gravity (Gs)	2.41
Liquid limit (L.L) (%)	26
Plastic limit (P.L) (%)	N.P
Gravel %	0
Sand %	96
Fines (Silt + clay) %	4
D ₆₀ (mm)	0.4
D ₃₀ (mm)	0.2
D ₁₀ (mm)	0.11
Uniformity coefficient (Cu)	3.64
Curvature coefficient (Cc)	0.91
Optimum moisture content (O.M.C) (%)	12
γ _{dry max.} (kN/m ³)	17.45
γ _{dry min.} (kN/m ³)	12.12
Classification	SP

SP: Poorly graded sand.

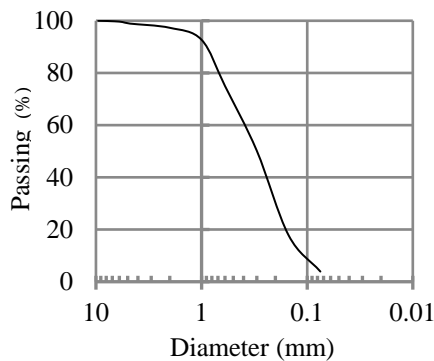


Fig.1 Grain size distribution of the soil.

Table 3 Properties of Magnesium Oxide.

Property	Value
Water-soluble matter (%)	2
Chloride (cl) (%)	0.15
Sulphate (%)	0.5
Heavy metals (Pb) (%)	0.002
Iron (Fe) (%)	0.05
Bulk density	10 g/100 ml

3.3 Carbonation

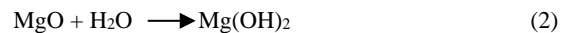
The carbonation was made by using the carbon dioxide CO₂ pressure and carbonation apparatus. The apparatus consists of several parts, as illustrated in Fig. 2. The main purpose of carbonation in the present study is to stabilize the improvement of Magnesium Oxide for the soil. The carbonation curing apparatus was used to apply a low pressure of pure carbon dioxide gas on soil samples. The major components of the set-up include a compressed gas tank, pressure vessel, thermocouple, data acquisition, vacuum and pressure transducer [17]. The carbonation curing apparatus is shown pictorially in Fig.2.



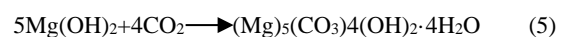
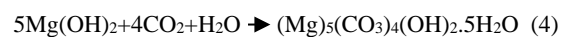
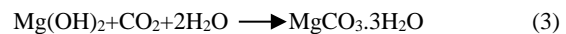
Fig.2 Carbonation apparatus.

4. CHEMICAL REACTIONS

The carbonation of any structure was provided with enough carbon dioxide to penetrate through its pores and reactive Magnesium Oxide hydrates by this equation, as described by [18] and [19]:



Brucite has a very limited binding ability [20]. However, under appropriate conditions, brucite will carbonate to form one or more of the following hydrated magnesium carbonates:



5. TESTING PROGRAM

There are many tests conducted in this research, depending on several factors. Two types of collapse testing were used: a single oedometer test and double oedometer test, and different percentages of Magnesium Oxide (0, 5, 10 and 15%) with different periods of carbonation (0, 1, 3 and 24 hours) were utilized.

5.1 Single oedometer test (SOT)

In this test, the soil sample is incrementally loaded at initial water content until the vertical stress reaches 200 kPa. Then, the sample is soaked with water for 24 hours. The additional settlement is recorded at a pressure of 200 kPa, indicating a collapse. The collapse potential (CP) is calculated using eq. (1).

5.2 Double oedometer test (DOT)

This test can be conducted by using two identical samples. The first sample is tested at its natural water content until the end of the test, while the other sample is soaked at the beginning of the test. The procedure for testing the two samples was the same as in the conventional consolidation test procedure. The difference between the two curves of void ratio - pressure ($e - \log \sigma_v$) represents the soil collapse at any given pressure.

5.3 Test preparation

To prepare the soil for testing, the following steps were followed:

- 1) The soil was mixed with a percentage of Magnesium Oxide carefully.
- 2) The mix was placed in the carbonation container if the test needed carbonation.
- 3) The valve of the vacuum was opened and the vacuum was allowed to deflate the air from the soil and container.
- 4) The valve of the vacuum was then closed and the valve of carbon dioxide was opened till reaching the same previous pressure.
- 5) The carbon dioxide valve was closed and the curing was maintained for some time.
- 6) The mix was extracted and the sample was prepared for the oedometer mold and the test started according to SOT or DOT.

6 DISCUSSION OF TEST RESULTS

The samples were first not mixed with Magnesium Oxide. Fig.3 and 4 illustrate some of the single oedometer tests and double oedometer test results and the potential collapse values are summarized in Table 4.

Upon wetting, there is an increase in collapsibility due to the removal of bonding between cementing particles as a result of stress release and leaching of soil during water infiltration, resulting in softening due to the rearrangement of soil particles.

In double oedometer tests, it is difficult to set both specimens to the same initial void ratio. In addition, the friction that develops between the oedometer ring and soil specimen under equal external stress will be different in dry and wet specimens, resulting in different “true” compressive stresses applied to dry and wet specimens.

The collapse may be caused by the break-down of the inter-particle bonds under high loads. It can be seen that for soil samples, the same rate of collapse increases takes place at all stress levels. On the other hand, a continuous increase in the potential collapse rate occurs when the stress level increases.

In the second stage, the samples were mixed with Magnesium Oxide of 5% by weight. Collapse potential values are presented in Table 4.

A certain amount of water was only used for the hydration of MgO-stabilized gypseous soil, but plenty of water also gets consumed in CO₂ carbonation besides the initial consumption in MgO hydration, causing a great decrease of water content compared to MgO-stabilized gypseous soil.

The soil particles are bonded closely and coated by the carbonation products of nesquehonite and dypingite/ hydromagnesite, producing fewer or less interconnected pores among the soil particles.

The collapse caused by the loose structure is held together by the small contents of water-softening or water-soluble salts, such as gypsum, chlorine, and calcium carbonate. The presence of water dissolves or softens the bonds between the silt grains and permits them to take a denser arrangement under any form of the applied loading.

In the third stage, samples were mixed with Magnesium Oxide of 10%. Fig.7 and 8 illustrate some results of the single oedometer test and the double oedometer test and the collapse potential values are shown in Table 4.

The huge difference in dry density between MgO carbonated silt and MgO-stabilized gypseous soil is due to the mass growth of MgO stabilized specimens resulting from large amounts of CO₂ absorption and the pore-filling from carbonation products. The relatively constant dry density of MgO stabilized gypseous soil is related to the stable appearance and water content, while the slight decline of dry density of MgO carbonated gypseous soil is mainly due to the desquamation phenomenon of specimens.

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In the third stage, samples were mixed with Magnesium Oxide of 10%. Fig.5 and 6 illustrate some results of the single oedometer test and the double oedometer test and the potential collapse values are shown in Table 4.

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In the fourth stage, samples were treated with Magnesium Oxide 15% by weight. The potential collapse values are shown in Table 4.

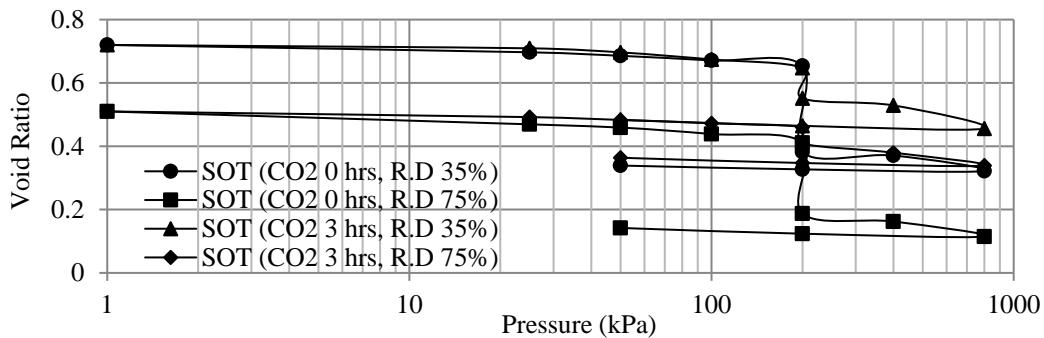


Fig.3 SOT results for untreated soil with carbonation period time = 0 and 3 hours.

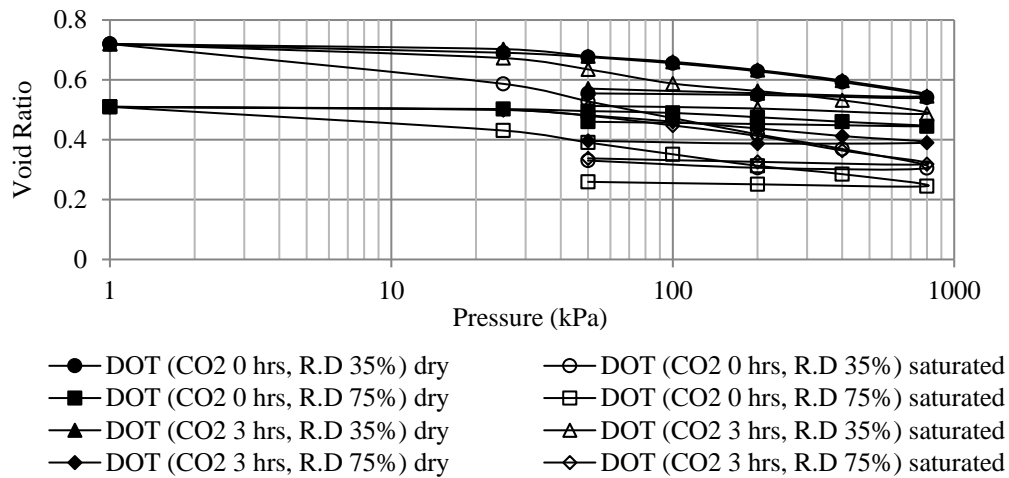


Fig.4 DOT results for untreated soil with carbonation period time = 0 and 3 hours.

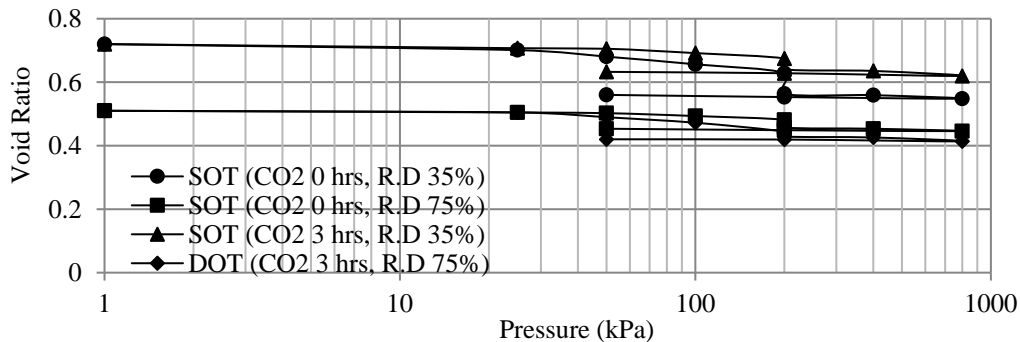


Fig.5 SOT results for soil mixed with 10% MgO with carbonation period time = 0 and 3 hours.

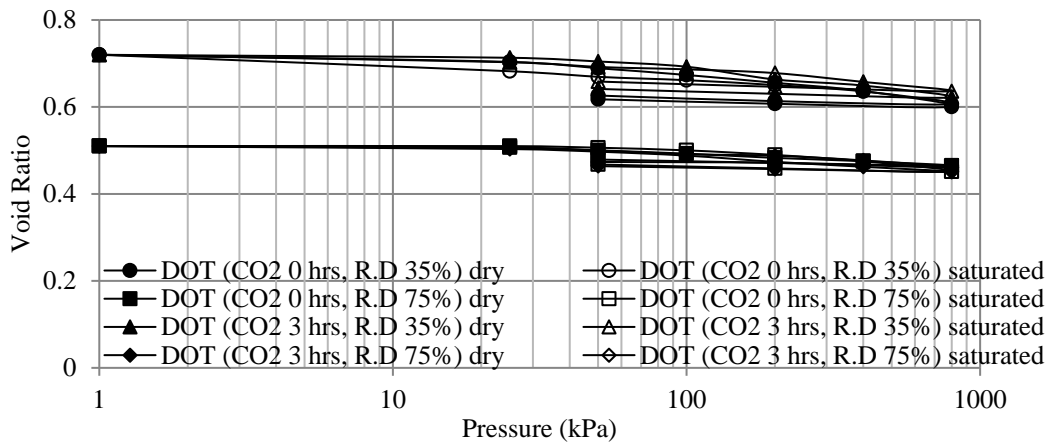


Fig.6 DOT results for soil mixed with 10% MgO with carbonation period time = 0 and 3 hours.

The summary of all test results can be described as the collapse potential of each test. Fig.7 illustrates the change in collapse potential as the carbonation period time increases at zero Magnesium Oxide. Fig.8 displays the change in collapse potential as the carbonation period time increases at 5% Magnesium Oxide. Fig.9 shows the change in collapse potential as the carbonation period time increases at 10% Magnesium Oxide, while Fig.10 presents the change in collapse potential as the carbonation period time increases at 15% Magnesium Oxide.

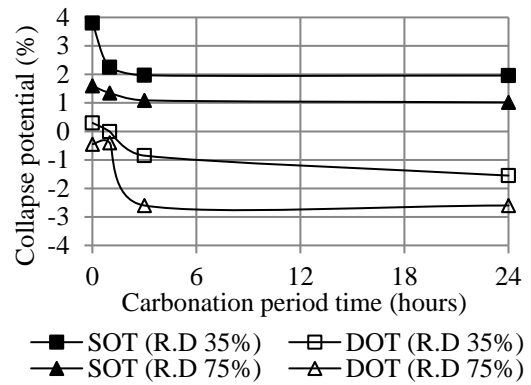


Fig.9 Change in Cp with different carbonation times for samples treated with 10% MgO.

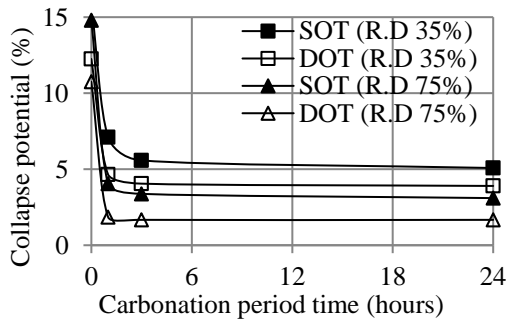


Fig.7 Change in Cp with different carbonation times for samples subjected to carbonation only.

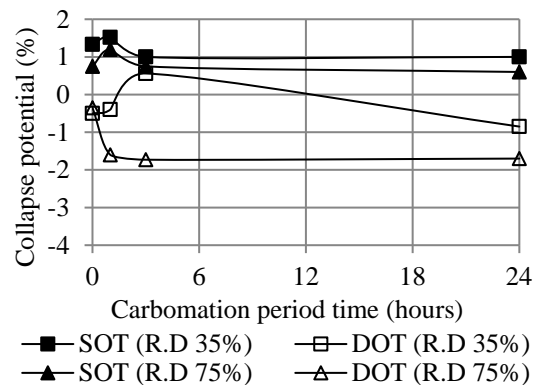


Fig.10 Change in Cp with different carbonation times for samples treated with 15% MgO.

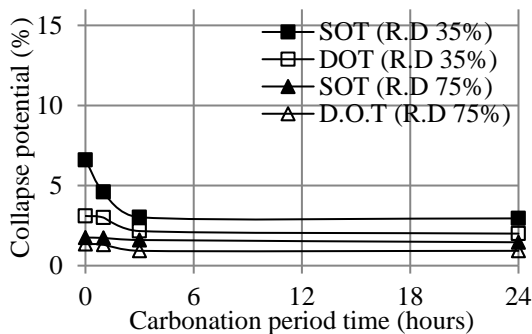


Fig.8 Change in Cp with different carbonation times for samples treated with 5% MgO.

The main points of collapse potential in this research can be summarized as follows:

- 1- It can be seen that the collapse potential for samples tested in the double oedometer test is greater than those obtained from the collapse test at the stress level of 200 kPa. This may be caused by sample preparation, in addition to high gypsum content, which may prevent more dissolution of gypsum.

- 2- Carbonation without Magnesium Oxide for the natural soil showed a noticeable decrease in collapsibility.
- 3- In the double oedometer test, the saturated test showed that the addition of water to samples treated with 10% and 15% Magnesium Oxide revealed a very strong material as compared with the dry test. This difference showed a negative collapse potential and it can be considered that no collapse takes place.
- 4- Carbonation period time, for all percentages of Magnesium Oxide, affected the collapse. When the time was increased from 0 to 3 hours, there was a good reduction in collapse potential, but there was no noticeable reduction in collapse potential when the carbonation time was increased from 3 hours to 24 hours. These results agree with those of Cai et al., (2019a) who found that using Magnesium Oxide with 3 hour carbonated period time in silty soil was better than 6 hours.
- 5- When 15% Magnesium Oxide was added to the soil, the unit weight of the soil became lower than its natural unit weight because of the Magnesium Oxide lightweight. Therefore mixing between the soil and Magnesium Oxide and sample preparation for the oedometer cell became harder than other percentages, as well

as the potential collapse value, was close to 10% Magnesium Oxide.

- 6- The specific carbonation time of peak strength is dependent on the extreme value of the corresponding equation for different-content reactive MgO-treated soil. The strength difference is likely to result from the effects of CO₂, water, and new carbonate crystals derived from the carbonation reaction.

Fattah et al. [21] found that the fibers of gypsum are well defined and partially dissolved gypsum particles cumulated on sand particles; the gypsum crusts remain covering the particles of sand, which need more presence of wetting to react and dissolve binding agents. However, larger voids between particles as compared with soil before leaching thereby increasing both the solubility rate and compressibility as the leaching periods increase.

Cai et al. [13] found that the reactive MgO content has obvious effects on the unconfined compressive strength Q_u of reactive MgO treated specimens at different accelerated carbonation periods. Undoubtedly, the combined action of reactive MgO addition and accelerated carbonation in the CO₂ atmosphere had more or less enhanced the strength of reactive MgO-treated soil.

Table 4 Collapse potential for treated and untreated samples.

R.D 35%											
CO ₂ =0 hour			CO ₂ =1 hour			CO ₂ =3 hours			CO ₂ =24 hours		
MgO %	SOT %	DOT %	MgO %	SOT %	DOT %	MgO %	SOT %	DOT %	MgO %	SOT %	DOT %
0 %	15.8	12.25	0	7.1 %	4.65	0	5.58	4.05	0	5.08	3.9
5 %	6.6	3.1	5	4.6	3	5	3.02	2.16	5	2.95	2
10 %	3.8	0.3	10	2.25	-0.005	10	1.97	-0.85	10	1.96	-1.55
15 %	1.33	-0.85	15	1.52	0.56	15	1	-0.4	15	1	-0.5

R.D 75%											
CO ₂ =0 hour			CO ₂ =1 hour			CO ₂ =3 hours			CO ₂ =24 hours		
MgO %	SOT %	DOT %	MgO %	SOT %	DOT %	MgO %	SOT %	DOT %	MgO %	SOT %	DOT %
0 %	14.8	10.75	0	4.05	1.85	0	3.38	1.67	0	3.1	1.67
5 %	1.75	1.35	5	1.73	1.31	5	1.6	0.925	5	1.46	0.925
10 %	1.6	-0.45	10	1.35	-0.4	10	1.09	-2.6	10	1.02	-1
15 %	0.75	-0.35	15	1.2	-1.6	15	0.75	-1.73	15	0.6	-1.5

7 CONCLUSION

From all the above results, it can be concluded that:

- The adequate Magnesium Oxide percentage was found to be 10% because its effect is close to that of 15% and the optimum carbonation period time is 3 hours.
- The 10% Magnesium Oxide used for the treatment of gypseous soil of relative density of 35% without carbonation resulted in the reduction in collapse potential of 76% as compared with the natural soil.
- When the natural soil was carbonated at a relative density of 35% without adding

Magnesium Oxide, the collapse potential decreased about 65% from no carbonation to 3-hour carbonation but it decreased only 9% between the carbonation period 3 hours and 24 hours. For the samples prepared at a relative density of 75%, the collapse potential decreased more than 77% from no carbonation to 3-hour carbonation but it decreased only 8% between 3 hours and 24 hours.

- For the samples treated with 5% and 10% Magnesium Oxide without carbonation, the decrease in collapse potential ranged between 58% and 89% as compared with natural soil. The collapse potential decreased about 81% to

93% when the mixed soil was carbonated for 3 to 24 hours.

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