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TREATMENT OF LIQUEFACTION SUSCEPTIBLE LOOSE SATURATED CLEAN SAND WITH MAGNESIUM OXIDE

TREATMENT OF LIQUEFACTION SUSCEPTIBLE LOOSE SATURATED CLEAN SAND WITH MAGNESIUM OXIDE

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ÖZET

Akma sıvılaşması statik ve dinamik etkilerle boşluk suyu basıncının hızlı gelişimi ile anlık efektif gerilme kaybı olarak granüler zeminin yumuşayarak şekil değiştirmesidir. Sıfır efektif gerilme altında zeminin direnci kaybolur ve sıvı gibi davranır. Sıvılaşmanın etkilerini azaltmak adına, zeminin doygunluğu düşürme, boşluklarını doldurarak daneleri birbirine bağlama amacıyla; kimyasal enjeksiyonu, sentetik lif güçlendirmesi, patlatarak sıkılaştırma gibi geleneksel ve çağdaş yöntemler önerilmiştir. Ancak, toksisite, çevresel örseleme, maliyetleri uygulanabilirliğini negatif etkiler. Alternatif olarak, magnezyum oksit(MgO) medikal, tarım ve inşaat endüstrilerinde yaygın kullanımı nedeniyle önerilebilir. Sıvılaşmayı önlemek adına, su içeriğini azaltabilen ve zemin daneleri birbirine bağlayabilen MgO hidrasyonu sonucu oluşan magnezyum hidroksit çökeltileri kullanılmıştır. Bu çalışmada, magnezyum oksitin sırasıyla %0.5, %1,%2,%4,%6 MgO dozları ile sıvılaşabilen ince ve tamamen doymuş temiz kumun kompaksiyon mukavemetine etkisi araştırılmıştır. Numuneler 23 ^{o}C ve %41 nem altında 3,7 ve 14 gün bekletilmiştir. Ardından, kontrollü gerinim altında tek eksenli serbest basınç deneyleri yapılmıştır. MgO katkısı ve zamanın, numunelerin saturasyonunu düşürerek sertleştirmiş ve böylece, numuneler daha erken kırılmıştır. Zamanın ve MgO miktarının artışı, zeminin kompaksiyon mukavemetini artırmış ve kırılma gerinimini düşürmüştür, böylece Elastik modulüsü artmış ve numuneler daha gevrekleşmiştir. Böylece sıvılaşma tabanlı etkilere karşı zeminin sünekliği azalmıştır. Sonuç olarak, zemin aşırı oturmalara ve aşırı saturasyona karşı mekanik olarak güçlendirilmiş, sıvılaşma riski azaltılmıştır.

*Anahtar **Kelimeler:** Liquefaction, Magnesium Oxide,Loose Sand*

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ABSTRACT

Static liquefaction is a strain-softening case of the granular soil, leading to sudden loss of effective stress due to quick increase in pore water pressure by static and dynamic actions. Under zero effective stress, soil strength is lost, so it behaves like a liquid. There have been traditional and recently developed improvement methods aganist liquefaction risk with the use of chemicals or synthethic fibers, lowering saturation degree, filling pores of soil and combining soil particles. However, some drawbacks such as toxicity and disturbance to ambiance, which are expensive and inapplicable for specific cases existed. Alternatively, magnesium oxide (MgO) was offered due to usage on medical, agricultural and constructional industries. To prevent liquefaction, the hydration mechanism of MgO, producing magnesium hydroxide precipitates was used to reduce water content and to connect soil grains. Under fully saturation, effects of MgO on the compressive strength of loose, fine, fully saturated liquefiable clean sand mixed with the doses of %0,5, %1, %2, %4, %6 of dry weight of sand, were seperately investigated. Treated cylindirical soil samples were cured under 23^{o}C and 41% humidity for 3, 7 and 14 days. Several unconfined compression tests (UCT) were made under strain-controlled case. Addition of MgO after curing periods diminished the saturation degree of soil, provided earlier failure and made samples stiffer and denser. Increase in MgO doses enhanced to compressive strength and reduced deformation capacity. Longer treatment also made samples more brittle with higher Elastic Modulus, so ductility of sample aganist liquefaction based actions was decreased. Eventually, liquefiable soil was improved mechanically aganist excessive deformation and heavy saturation. By this way, liquefaction possibility was decreased..

Keywords: *Liquefaction, Magnesium Oxide,Loose Sand*

1. INTRODUCTION

In 2008, there was an earthquake with magnitude 8.0 happened at Wenchuan. The consequences were very intense and shocking as much as an earthquake as resulted with 70,000 live losses, ground collapse, a number of fractures in the highways and buildings. It was thought that the main triggering point was due to liquefaction as as outcome of earthquake. As statistically, the liquefaction happened in the 62% of every fifty big earthquakes along with undertaking 15-30% of whole casulties. Liquefaction is defined as that the progressive or rapid loss of shear strength and stiffness of loose saturated granular soil, behaving like a liquid at the end due to sudden or continuous change in the stress conditions caused by large static and dynamic loadings (Rupam, 2020; Yu and Lin, 2016; Mingzhi et al, 2020; Naeini and Moayed, 2015; Toprak et al., 2019). It happens as two types as flow and cyclic liquefaction. Flow liquefaction occurs suddenly, when that steady-state strength of is less than driving shear stress within the slopes or foundations due to static or dynamic loadings such as extra loads on foundation and etc. It could be seen anywhere due to its mechanism where its damage may exceed to billion dollars. For liquefiable soil, clean sand near to ground surface under ground water level having low permeability, uniform gradation and rounded soil particles at very loose state together with newly deposited condition which is not subjected to seismic shaking before (Özaydın, 2007). In order to improve soil mechanical and dynamic properties, several traditional methods were suggested like vibro-compaction, blast densificaiton, permeation grouting. However, those had drawbacks in aspects of compatibility, applicability and feasilibilty over real cases. Thus, newly developed techniques were become vital need (Mathili, 2017; Sharma, 2010). On the other hand, recent techniques like usage of short synthetic fibers, MICPT, chemical injection like microfine cement, colloidal silica, laponite and bentonite and additives as fly-ash, zeolite, graphene oxide nano-sheet were seemed to be promising, but disadvantages still existed in terms of inapplicability, cost and disturbance to enviroment (Bao et al., 2019). Therefore, as an alternative method to reduce the civil, environmental, economic consequences of liquefaction, magnesium oxide (MgO) may be offered to increase soil condition weak against liquefaction.

In general, MgO as known as periclase is white solid mineral, which has very high melting (2800 ^{o}C) and boiling points (3600 ^{o}C) including two ions as Mg^{+2} and O^{-2} joining with ionic bonding, which was mostly produced from the calcination of magnesium carbonate, $MgCO_3$. Depending on the calcination temperature and time, specific surface area or activity degree of magnesium oxide was determined. From most active to lowest one, light (700-1000 ^{o}C as calcination temperature), hard (1000- 1500 ^{o}C) and dead-burnt (over 1500 ^{o}C) MgO exist as the types.

Magnesium oxide is also used in variable industries from nuclear area to medical and drug sectors involving chemical, medical and agricultural scopes along with reclamation of ground as an environmental benefit thanks to pH value (Hornak et al., 2018; Jandkhera, 2021). Also, it has an important role in civil engineering industry involved in Magnesium Oxychloride Cements as known as Sorel Cement, Reactive MgO cements, Magnesium Phosphate Cements and Magnesium Silicate Hydrate Cement (Walling and Provis, 2016). In soil, its effects on variable soils like fine loose sand, high and low plastic clay, silty sand, clayey silt are significant in terms of mechanical performance based on several studies. Especially, stiffness of soil, brittleness, strength capacity and hydraulic conductivity were enhanced when nano-size MgO was used in sandy soils (Ahmadi, 2019). Likewise, plasticity, swelling potential, liquidity and expansive actions were controlled by MgO addition in the clay through ion exchange between MgO and clay molecules (Salem et al., 2020; Taha et al., 2015). When MgO after hydration was exposed to CO_2, mechanical strength of silty sand was greatly increased, which exceeded to that of silty sand treated with Portland Cement under 28 days (Yi et al., 2013).

Even though MgO extensively used from civil engineering industry to the investigation of treatment of soil had many advantages, there is a still lack of research about its effect on the liquefiable soils. Moreover, the question about how MgO influences mechanical and hydrological properties on a fully saturated sand with fine size and uniform gradation is unknown. To observe the impact of MgO on liquefiable soil at best, MgO additives should be mixed with saturated liquefiable sand without compaction. Finally, the effect of magnesium oxide on the static liquefaction performance of the clean liquefiable saturated sand was investigated in this study and the aims were sorted as removing water content through the hydration of MgO and connecting soil particles to each other by precipitation of magnesium hydroxide ($Mg(OH)_2$) so that saturated clean sand has no longer liquefaction risk and improved geotechnical properties thanks to MgO, which is very economical and safe for environment.

2. MATERIALS AND METHOD

For materials and preparation, clean sand was taken from the region located on the shore of Black Sea at Karaburun sieved for uniform gradation into the size between 0.420 mm to 0.0074 mm based on ASTM Mesh Size and Wentworth size class. Specific properties of sand were shown in Figure 1 and Table 1.

Table 1. General and state properties of pure sand.

Soil Properties	Results
Dry Density (g/cm^3)	1,382
Specific Gravity (G_s)	2,621
Void Ratio of Soil (e) at Lab. Condition	0,895
Maximum Void Ratio (e_{max})	0,941
Minimum Void Ratio (e_{min})	0,773
Relative Density (D_r) (%)	27
Saturated Water Content (%)	34.18
Coefficient of Uniformity (C_u)	1,95
Coefficient of Conformity (C_c)	0,97
USCS Classification of Soil	SP
Critical Friction Angle (°)	31

The properties were determined based on the ASTM Standards as sorted as Specific Gravity by Pycnometer Test by ASTM D854 B, Determination of Dry Density and Void Ratio by ASTM D7481-18, Maximum and Minimum Void Ratio with Relative Density Calculation by ASTM D4254-16M, Grain Size Distribution by Sieve Test by ASTM D422, Unconfined Compressive Strength test based on the procedures of ASTM D2166M-16. Also, the critical friction angle was measured based on Simplified Method, where angle of slope was the critical friction angle after cylinder filled with fully saturated sand sample was rotated about 60^0 and reversed into diagonal form to create slope known as critical friction angle (Santamarina and Cho, 2001).

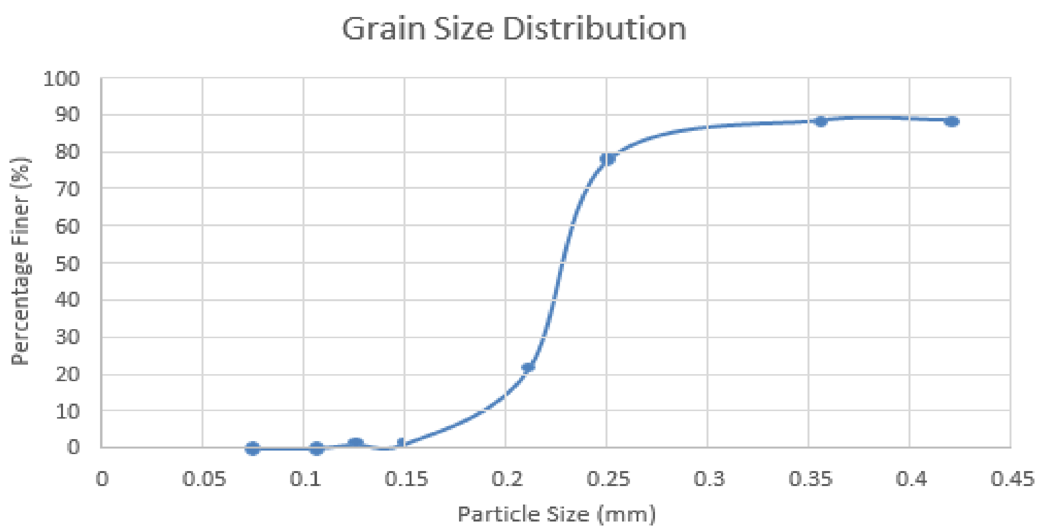

Figure 1. Grain size distribution of clean sand.

Magnesium oxide, was supplied in white-powder form by OSA Dış Ticaret A.Ş, Istanbul. Chemical and physical properties were stated in Table 2 in below. XRF for Chemical Composition and BET Surface Area Analysis by Micromeritics Corp. Gemini VII 2390-t based on BS ISO 9277: 2010 were conducted on SARGEM Laboratory in Sakarya University. Required controls about liquefaction susceptibility of soil based on the results of critical friction angle, relative density, the parameters from grain size distribution, both geological and physical features of a soil and UCSC classification were carried out and results were compared with previously proposed data (Susilo et al., 2019), and soil gradation in Figure 1 was compared with limit curves as presented in Figure 2 for liquefaction susceptibility (Geotechnical Engineering Bureau, 2015).

Table 2. Chemical and physical properties of MgO

Chemical Composition	**Percentage (% by weight)**
MgO	88.19
SiO_2	5.28
CaO	2.61
Fe_2O_3	0.68
Loss on Ignition	3.04
Physical Properties	**Value**
Specific Surface Area (m^2/g)	18.33
Density (g/cm^3)	3.58
Appearance	White Powder
Average Particle Size (μ)	90/100
Melting Point (^oC)	2800
Boiling Point (^oC)	3600
Type	Hard-Burnt
Calcination Temperature Range (^oC)	1000-1500

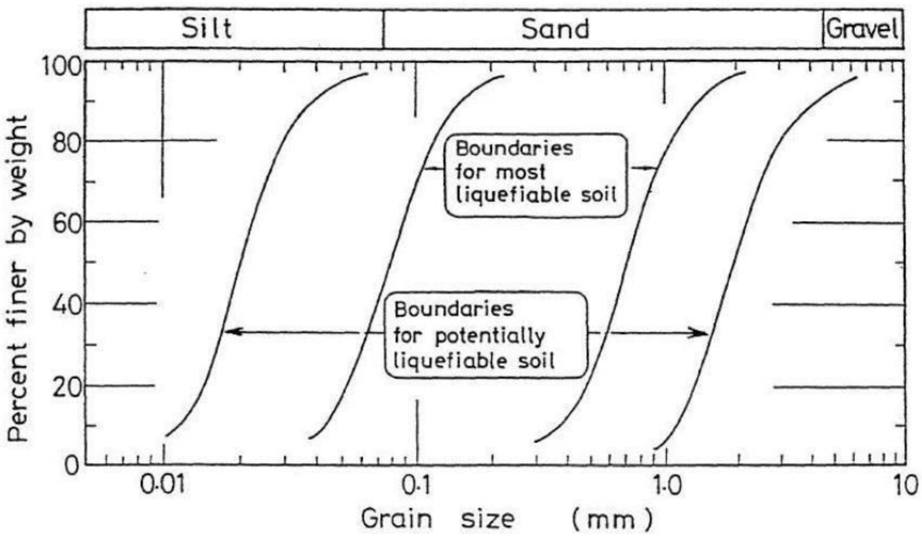

Figure 2. Gradation curves for liquefiable soils (Geotechnical Engineering Bureau, 2015).

At the end, the soil in this study come from marine-based deposits with uniformly graded fine sized, rounded particles having liquefaction risk.

Afterwards, void ratio and specific gravity under lab condition are determined. Water content (W) for fully saturated loose sand at lab condition was found by statement including e, Sr and Gs, which are successively void ratio of soil, degree of saturation and specific gravity as follows ;

$$Sr.e = Gs.\mathrm{W} \tag{1}$$

First, soil mixed with different MgO percentage as 0.5%, 1%, 2%, 4%, 6% of dry weight of soil under dry condition is poured into the certain amount water by wet-pluvation method to make loose state as much as possible as in Figure 3. Second, loose, fully saturated MgO-sand mixture in mold were formed without any compaction. By this way, the most critical situation for liquefaction was generated along with zero compaction case and the effect of magnesium oxide on the soil could be easily observed in terms of improvement against liquefaction.

Figure 3. Preparation, pluviation by funnel and moulding of sand-MgO mix

Third, all samples were tripled and cured for 3, 7 and 14 days separately under room condition as 23 ^oC temperature with 41% humidity. Finally, specimens were analyzed on Unconfined Compression Test (UCT) under strain-controlled case with 0.7 mm/mins. UCT lasted until the failure of the treated samples having specific type of slip surface. Totally, there are 45 samples involving magnesium oxide waited for different curing periods. Accordingly, change in maximum compressive strength (UCS), strain capacity and saturation of sample through physical observation were obtained and discussed depending on MgO amount and curing periods.

3. DISCUSSION AND RESULTS

Unconfined Compressive Strength (UCS) values and correspoding strain values(%) for all treated samples under 3 days, 7 days and 14 days curing were shown in Figure 4, Figure 5 and Figure 6. Under same curing periods, rise in MgO contents increased mechanical resistance of samples. For 3-days of curing, unlike 6%-MgO specimen, samples with lower MgO contents from 0.5% to 4%, increase in MgO was not significant on UCS and failure strain results. After 4% level, UCS was obviously enhanced along with lower failure strain.

Likewise, UCS values for samples under 7 and 14-days of curing were considerably increased beyond 1% MgO level and strain values at failure were gradually decreased. Increment in MgO contents under 14-days had maximum influence on UCS and strain values at failure. Rise in MgO content generated more $Mg(OH)_2$ particles within pores between sand grains, resulted with more powerful cementation of sand particles, greater uniaxial resistance and lower deformation capability.

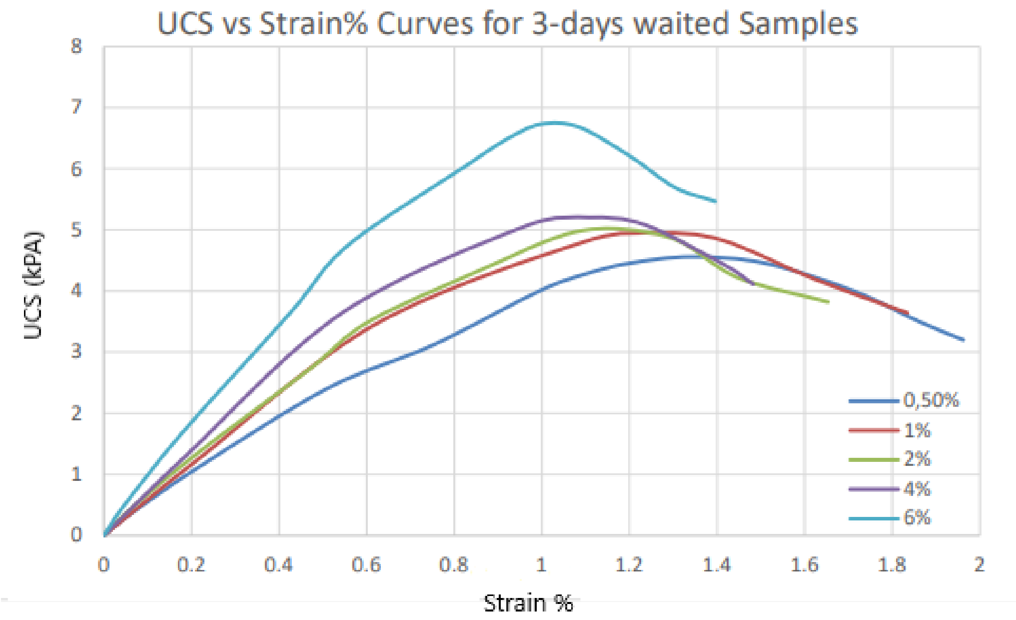

Figure 4. The stress-strain curves for 3-days waited samples.

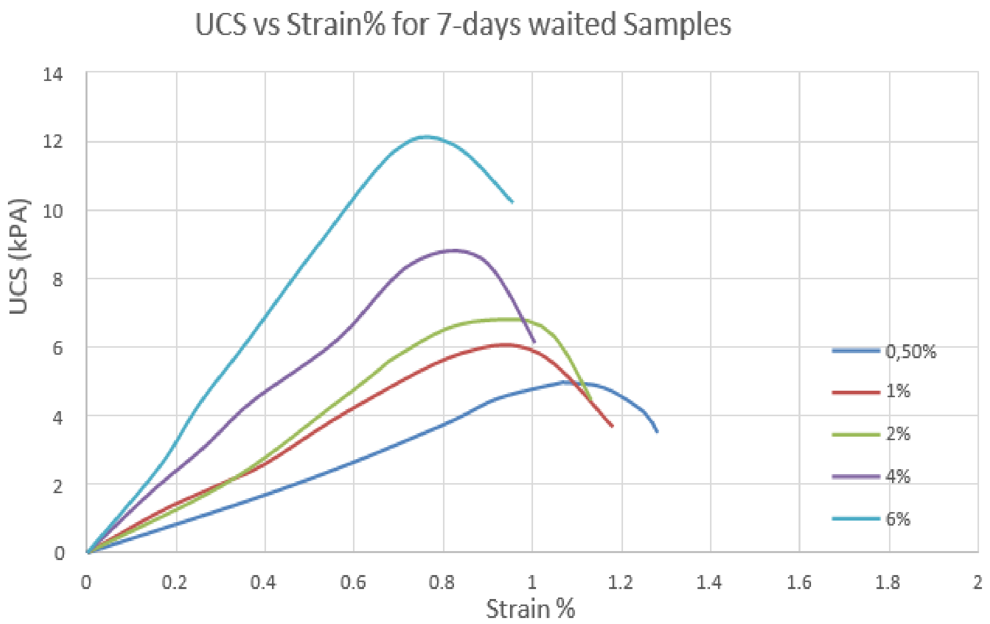

Figure 5. The stress-strain curves for 7-days waited samples.

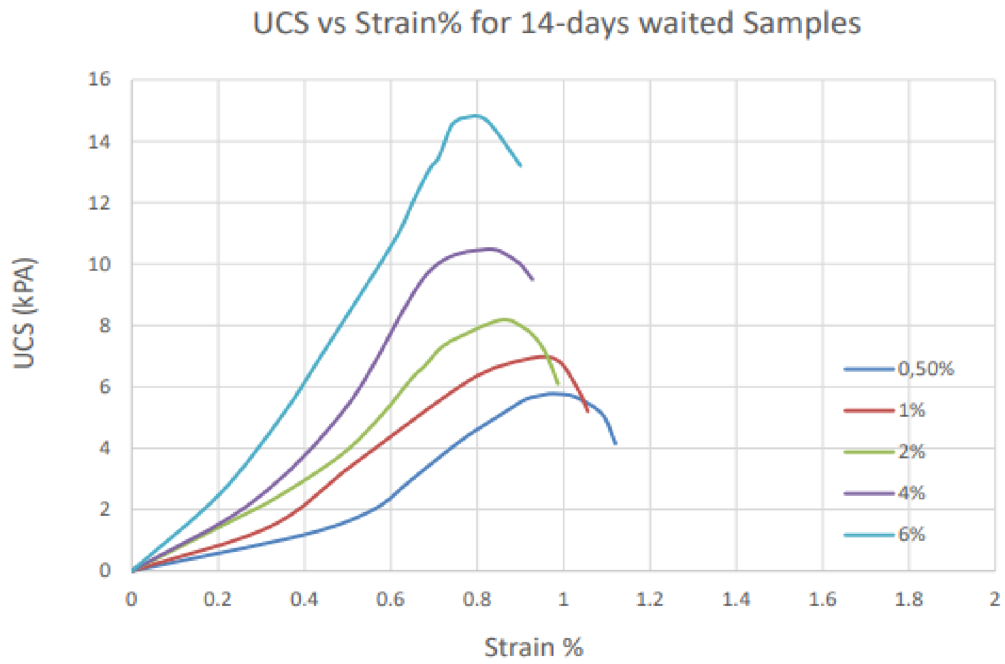

Figure 6. The stress-strain curves for 14-days waited samples.

The main reason was higher amount of $Mg(OH)_2$ and better distribution over sand at greater concentrations. When quantity of MgO was incremented, more interaction between MgO and water happened, so number of $Mg(OH)_2$ in the soil pores were increased. Moreover, due to the closer sizes between MgO particles and uniform fine clean sand (252 µ as D_{50}), MgO solid (95 µ) might easily distribute over voids, enhancing contact points between soil grains. Therefore, soil grains were adhered to each other well depending on the amount of $Mg(OH)_2$, supporting soil relative density. Through wider spreading of $Mg(OH)_2$ within all pores, better morphology and well-connected network in terms of micro-particular arrangement within sample may be occurred.

On the other hand, even if MgO content is enough, shorter curing (3-days) in system may restrict strength development and brittleness due to uncompleted hydration and insufficient cementation since at earlier period of hydration, water consumption was lower compared to other curing periods, which breaks up $Mg(OH)_2$-based bonds between soil grains and inner support system was not properly established. In such cases, samples became more ductile and duration of straining extended. In contrast, longer period of hydration (7-days) provided completion of hydration, so unconsumed amount was diminished, ensuing more uniform, denser and homogenous internal texture in the samples. Hence, load on such samples may be transmitted more properly, resulted with earlier failure strain or higher brittleness. Thus, longer curing developed strength gaining and brittleness thanks to completed hydration and well-established inner support system. Additionally, if duration of curing was extended to 14-days, several interactions between $Mg(OH)_2$ particles and other chemicals like sulfate, aluminum, silicate within sand may be possible, which promotes UCS and earlier failure (Walling and Provis, 2016).

Based on these, mechanical behaviour of samples was compared by the results of Young's modulus, calculated by UCS over strain at failure, according to on MgO content and curing period as presented in Figure 7.

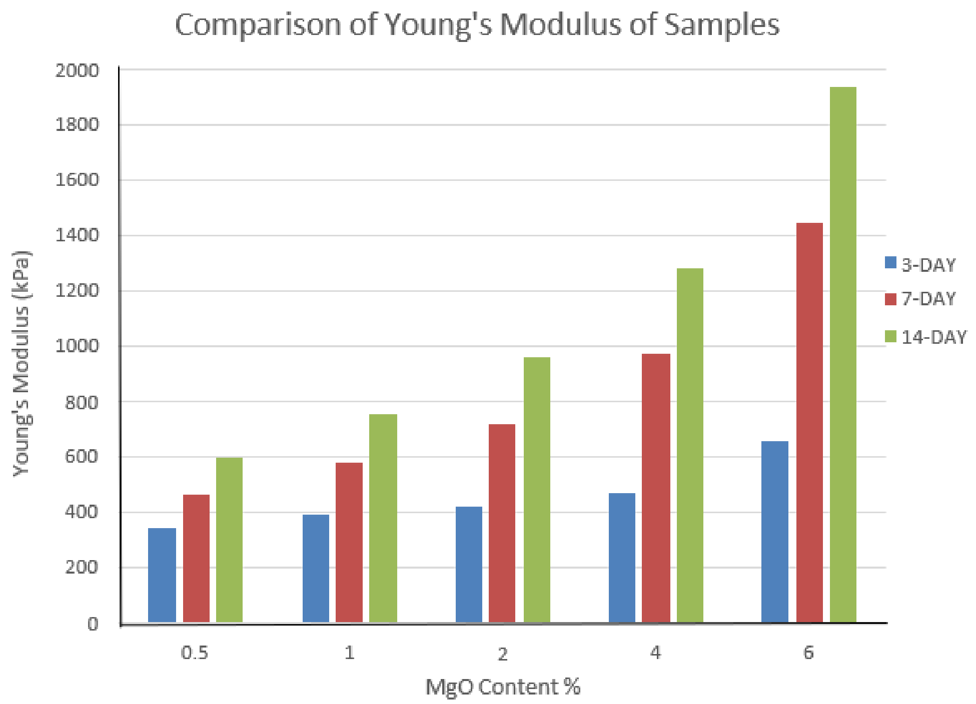

Figure 7. Comparison for Young's Modulus of Sample with varying MgO contentunder 3,7 and 14 days of curing.

According to the results, both increase in MgO and extension of period provided the completion of hydration reactions, better early and post hydrations products, provided to better interconnection between soil grains, which supported to UCS development and earlier failure. Hence, Young's Modulus became greater, which made samples more brittle gradually. In more details, change in Young's Modulus was seen more clearly for the samples under 7 days and 14-days. For samples waited for 3-days, Young's Modulus was increased much more at 6% MgO level, whereas significant development in Young's Modulus started from 1% level of MgO for samples cured for 7 and 14-days. As the reason mentioned before, the distribution of higher amount of MgO over sand became wider, ensuing better cementation for soil grains after formation of $Mg(OH)_2$ on voids. While hydration continues with the extension of curing period, samples start to have more integrated network and denser formation depending on adequate time required for completion of hydration. Therefore, loads were easily conveyed over sample due to more regular micro-texture, which lessened deformation capacity and increased UCS results. By this way, Young's Modulus enhanced, and the behavior of samples turned to be more brittle against loading. Finally, increase rate of Young's Modulus by MgO addition reached at maximum level at 14-days, as possible reactions between $Mg(OH)_2$ solid with surrounding chemicals in the system such as phosphate, aluminum, silicate, sulphate which might be formed after 7 and 14-days, but more efficiently in 14 days.

4. CONCLUSION

In this study, the best results were attained with the sample having 6% MgO waited for 14 days. Under this case, mechanical, hydrological, physical properties and durability properties of loose saturated liquefiable sand was substantially developed by decreasing water content level, supporting maximum UCS value, and providing more brittle behavior.

The addition of magnesium oxide on fully saturated liquefiable loose clean sand was important to diminish saturation after adequate time, to constitute well-connected and strong-bonded network in the complex, to improve elastic structure by making soil more brittle, to develop deformation properties by providing lower strain value at failure, to enhance mechanical uniaxial compressive strength.

Moreover, longer period of treatment supported to lower axial deformation at failure, strength- gaining, reduction of saturation, cementation of soil particles, stiffness and elasticity, since hydration reactions between MgO and water particles required enough time to form $Mg(OH)_2$ precipitates and further products formed from interactions among $Mg(OH)_2$ and other chemicals on the system.

In future, there would be development about how magnesium oxide should be implemented to soil underground surface. The most economical and practical solution could be offered to utilize the effect of magnesium oxide on all liquefiable soil. As the novel study, this encouraging chemical exhibits its importance for geotechnical engineering and more comprehensive efforts are still needed.

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SYMBOL LIST

Symbol	**Explanation**
Al_2O_3	Aluminium Oxide
c	Cohesion
C_c	Coefficient Of Conformity
C_u	Coefficient Of Uniformity
CaO	Calcium Oxide
$Ca(OH)_2$	Calcium Hydroxide
CO_2	Carbon Dioxide
Dr	Relative Density
e	Void Ratio
e_{max}	Maximum Void Ratio

e_{min}	Minimum Void Ratio
e_o	Void Ratio of Soil
Ea	Axial Strain
Fe_2O_3	Iron(III) Oxide
Gs	Specific Gravity
$MgCl_2$	Magnesium Chloride
$MgCO_3$	Magnesium Carbonate
MgO	Magnesium Oxide
$Mg(OH)_2$	Magnesium Hydroxide
SiO_2	Silicon Dioxide
Sr	Degree Of Saturation
W	Water Content
ϕ	Friction Angle
μ	Micron