International Journal of Sustainable Development and Planning
Vol. 17, No. 1, February, 2022, pp. 165-172
Journal homepage: http://iieta.org/journals/ijsdp

Using High Reactivity Attapulgite for Stabilizing Collapsible Gypseous Soil

Safaa A. Mohamada[1], Hadeel Ammar Mohammed[1], Hanan Adnan Hassan[1*], Mohammed Yousif Fattah[2]

[1] Highway and Transportation Department, Engineering College, Mustansiriyah University, Baghdad 46049, Iraq
[2] Civil Engineering Department, University of Technology, Baghdad 19006, Iraq

Corresponding Author Email: ghassan_hanan@uomustansiriyah.edu.iq

https://doi.org/10.18280/ijsdp.170116

Received: 25 October 2021
Accepted: 31 December 2021

Keywords:
gypseous soil, collapse, pozzolanic, improvement, attapulgite

ABSTRACT

The presence of gypsum in soil has a high effect on the mechanical and physical properties of soil. This effect depends fundamentally on the type and quantity of gypsum existent in the soil. The present study attempts to improve the physical and mechanical properties of gypseous soil using a new type of pozzolanic material discovered as a pozzolanic material from attapulgite clay. It is called "High Reactivity Attapulgite" HRA. The objective of this study is to investigate the ability of this material to be a moderate stabilizer material used for treating soil. The soil was obtained from one location at depth 1 m with 28% gypsum content. High Reactivity Attapulgite (HRA) was used as a replacement with soil in different percentage (5%, 10%, 20%, and 40%). Experimental tests included Atterberg limits, modified compaction, strength, unconfined compression and consolidation. Then all the tests were conducted on specimens with HRA content that was varied in the range 5-40%. The results showed the important effect of HRA on gypseous soil, as was seen from the reduction in the collapse potential by about 13-90%, and the increase in the unconfined compressive strength from 88 kPa to 271 kPa upon the addition of HRA by 5-40%.

1. INTRODUCTION

There are many types of problematic soils, some of the most noteworthy being swelling clay, dispersive soils, and collapsible soils that will be discussed subsequently. The present study focuses mainly on collapsible soils. Due to the wide extent of the salt – bearing soils in the middle east, they are used extensively in road construction both as general material in embankment and as sub-base material [1, 2].

Gypseous soils are defined as soils containing gypsum ($CaSO_4 \cdot 2H_2O$) in an amount enough to change or affect their engineering properties. These soils exist in arid regions and semi-arid regions and there are differences in origins and definitions for these soils. Gypseous soil can be defined and divided it into sub-groups as shown in Table 1 [3].

FAO [4], showed that there are one million km^2 (100 million ha) of gypseous soil distributed in arid and semi aird countries and rainfall of less than 500 mm and in Somalia, Spain Algeria, Australia, Syria, Argentina, Iraq, Libya and Sudan. Gypseous soils in Iraq cover about 20 to 30 % of its total land area and are concentrated primarily in the western desert and extend to the southern parts.

Nashat [5], demonstrated that the presence of gypsum in soil that leads to severe damage and large distress to man-made structures due to its detrimental behaviour, especially when accompanied by environmental changes in moisture content. There are many methods that can be used to improve the problematic soils such as gypseous soil to be used in construction without any problem. Al-Mufty and Nashat [6], showed that the gypseous soils can be treatment chemically or physically to decrease the effect of water and that leads to maintain safety and stability of the soil for the engineering structures.

Table 1. Gypseous soils classification [3]

Gypsum content (%)	Classification
0-0.3	Non-gypsiferous
0.3-3	Very slightly gypsiferous
3-10	Slightly gypsiferous
10-25	Moderately gypsiferous
25-50	Highly gypsiferous

2. COLLAPSIBLE SOIL IMPROVEMENT

Physical improvement strategies improve the soil properties using mechanical methods, such as compaction, stone columns, pre-wetting, and dynamic compaction [7, 8] while chemical strategies improve the soil properties modifying the composition of the soil through the incorporation of chemical additives, such as dehydrate calcium chloride, cement, lime, bentonite, cutback asphalt, and others [9]. Also soil improvement by reinforcement using geogrid is another method of improvement of stabilization fibers [10].

Soil mixing is a soil improvement technology used to treat soils in situ to improve strength and reduce their compressibility and collapsibility [5]. The choice of method is often based on design requirements, site conditions/restraints, economics, and the need was appeared for more applicable, durable and fast method to improve the collapsibility of gypseous soil. Abbeche et al. [11] studied the possibility to reduce the collapse potential Cp of the soil with chemical treatment by salts. They used potassium chloride KC1 and ammonium sulfate $(NH_4)_2SO_4$ with various concentrations under various compaction energies to get the acceptable level. They depend in their study on consolidation tests at variable levels of normal stress.

Mohamed and El-Gamalin [12], studied the effect of sulfur cement on soil as a treatment method, after preparing the specimens they were evaluated the mineralogical composition, microstructure, thermal, mechanical, physical, chemical and hydraulic properties. Then compressive strength test has been done on all the treated specimens and the results showed increase in strength of the treated soil about three times than the soils stabilized with normal Portland cement. Fattah et al. [13] investigated the gypseous soil treated by grouting with acrylate liquid and studied the strength of gypseous soil and collapsibility. The tests results shown reduction in compressibility and collapse potential of the GS by higher than 60-70% and 50-60%, respectively.

Investigation of the effect of using nanomaterials for improving and Stabilizing the gypseous soil was carried out by Hayal et al. [14]. The results of the experimental work showed significant modification in the geotechnical properties of the soil sample. The collapse potential decreases as soon as the used nanomaterials were increased until they reach a percentage after which the collapse potential will be increased. Thus, addition of nanomaterials, even at a low percentage, could improve the properties of gypseous soil. When adding the nano-silica to the soil, the collapse potential (CP) is decreased whenever the nano-silica increases until 1% of the added nanomaterials and then further stabilizer increases the (CP), the percent of decrease in CP is about 91% where the effect of the additive (nano-silica) changes the classification of severity of collapse from "moderate trouble" case to "no problem" case.

A new material was proposed in this study to improve the properties of gypseous soil by attapulgite lightweight pozzolanic material that was produced from attapulgite clay which is available in large amounts in Iraq. Late Miocene – Pliocene the Injana formation was found in Al-Najaf region and called Tar Al-Najaf. They are gray clay stones and bluish green with plants remains [15]. Attapulgite dominates clay mineral mudstones of the Injana formation in Al-Najaf and Karbala cities west Baghdad in Iraq. The distribution of attapulgite in Iraq is shown in Figure 1, and the attapulgite site in Al-Najaf region (Tar Al-Najaf) Injana formation is shown in Figure 2. The raw material of Attapulgite contains rocks ground in a manner of storming, transforming it to highly-refined powder for the purpose of making the most of their effectiveness. Large surface area and acidic properties of attapulgite with high silica content about 50% as fibrous silicate makes this type of clay most useful as an adsorbent and catalyst.

The presence of only small amount of pozzolanic material in the soil could influence significantly the physical and chemical behavior of soil due to a very high specific surface area of pozzolanic material, surface charges and their morphologic properties. In the limited investigation performed in this field, the effects of attapulgite lightweight pozzolanic material on the engineering properties of soil have been considered mainly in two major series of tests in addition to the classification tests. The objective of the present study is to investigate the effect of adding attapulgite lightweight pozzolanic material on the behavior of gepseous soil.

Figure 1. Distribution and deposits of Attapulgite in Iraq [15]

Figure 2. Attapulgite site in Al-Najaf Injana formation [15]

3. EXPERIMENTAL WORK

3.1 Soil

The soil used in this study is a disturbed natural gypseous soil that was brought from a location in Saladin governorate north of Baghdad city, and had a gypsum content of 28%. The soil was excavated from 1.0 m depth below the ground surface, and stored in double nylon bags. It was then air dried, pulverized, and mixed thoroughly. Classification, physical and chemical tests were performed according to the standard procedures. The grain size distribution using wet sieving was conducted according to ASTM. The grain size distribution curve of the soil sample showed that it is classified as ML (low plasticity silt) according to the Unified Soil Classification System (USCS). The chemical tests were carried out on the natural soil, these tests include: gypsum content using hydration method and sulphate content (SO_3). All results of chemical and physical properties of the soil used are listed in Table 2.

3.2 High reactivity attapulgite (HRA)

Attapulgite (or Palygoriskite) is a fibrous clay mineral. It is a form of crystalloid hydrous Magnesium - Aluminum silicate minerals, and includes chemically-absorbed water in its structure. Carroll [16] introduced the chemical form of Attapulgite as Si8Mg5O 20(OH)2 (OH)2 4. $4H_2O$; the actual composition of attapulgite varies due to the partial replacement of Magnesium byiron or Aluminum). Four silica ions are found in the structure of attapulgite tetrahedrals linked by magnesium ions in octahedral coordination [15]. Table 3 shows the chemical composition, physical properties and loss of ignition (LOA) of attapulgite before burning. The chemical analysis of attapulgite shows a high percentage of SiO_2 reaching more than 50% in its chemical composition. Oxides Al_2O_3, Fe_2O_3, CaO and MgO make more than 25% of the composition, and residual oxides form a low percentage from the mineral, like K_2O that reaches 1.8% present in the form of Illite [17].

Attapulgite is converted into active pozzolanic material upon burning at a certain temperature, the appropariate burning degree was investigated by Al-Amide [15] who identified an optimum firing temperature of 750℃ attained at heating rate of 4℃/min and calcination time 30 min. Table 4 shows the chemical composition of Attapulgite after burning in 750℃ and calcination 30 min and loss on ignition [15]. The results of chemical analysis of attapulgite after burning show an increase in the content of SiO_2 and other oxides. This increase is caused by the absence of Loss on ignition (L.O.I.) after burning, where the L.O.I brews of water within clays and feldspar and CO_2 within calcite and dolomite [18].

Table 2. The soil physical and chemical properties

Soil properties	Value	Test Method
Specific gravity Gs	2.61	ASTM D854
Plastic limit P.L., (%)	24	
Liquid limit L.L., (%)	37	ASTM D4318
Plasticity index P.I., (%)	13	
Maximum dry unit weight, kN/m^3	17.4	ASTM
Optimum moisture content, %	20	D1557-99T
% fines (Passing sieve No. 200, (%)	93	
Classification of soil according to USCS	ML	ASTM D2487-00
PH	8.00	
SO_3 (%)	13.05	BS(1377)
T.S.S. (%)	17	BS(1377)
Gypsum content (%)	28	BS(1377)

Table 3. Physical and chemical analysis of Attapulgite before burning and after grinding

Oxide composition	Oxide content (%)
SiO_2	51.8
CaO	7.11
Al_2O_3	8.99
TiO_2	0.58
Fe_2O_3	4.88
MgO	5.52
Na_2O	1.01
K_2O	1.8
SO_3	0.68
Loss on ignition	18.65
Gs.	2.34
Specific Area, (m^2/ kg)	2109
Color	Bluish green

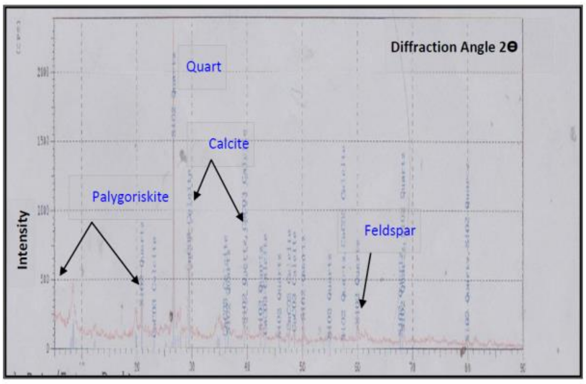
Table 4. The chemical analysis of attapulgite after burning in 750℃ and calcination time 30 min

Oxide composition	Oxide content (%)
SiO_2	60.48
CaO	8.46
Al_2O_3	13. 95
MgO	5.92
Fe_2O_3	6.07
K_2O	2.47
Na_2O	1.2
SO_3	0.54
Loss on ignation	0.01
Gs Specific area, (m^2/ kg)	2.2
Density, (kg / m^3)	2193

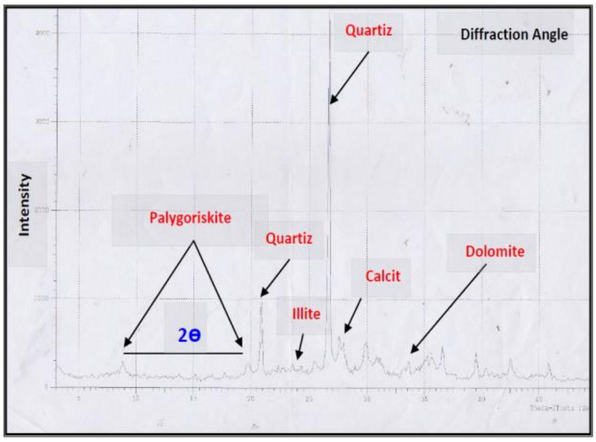
The ASTM C618 – 01 [18] specifications of the chemical requirements of pozzolan and the chemical analysis of attapulgite indicated that it comprises 80.5% of (SiO_2 + Al_2O_3 + Fe_2O_3) which conforms to the chemical requirements of the ASTM C618 – 01 Class N pozzolan as shown in Table 5. Figure 3 shows the X-ray diffraction (XRD) patterns of attapulgite. hydration method and sulphate content (SO_3).

Table 5. Chemical requirements of pozzolan [18]

Oxide composition	Pozzolan Class N	Attapulgite
SiO_2 + Al_2O_3 + Fe_2O_3 Min. percent	70	80.5
SO_3 Max. percent	4	0.45
Moisture Content Max. percent	3	-
Loss on Ignition Max. percent	10	0.1



a. Before burning



b. After burning

Figure 3. X-Ray diffraction analysis of attapulgite

4. RESULTS AND DISCUSSION

4.1 Grain size distribution

The distribution of grain size of untreated and treated soil specimens tested with various percentages of attapulgite (5%, 10%, 20%, and 40%) is shown in Figure 4. The results show the shifting of the grain size distribution curve for stabilized soils, which could be attributed to the pozzolanic reactions between the attapulgite and components of soil matrix and cation exchange process and that lead to flocculation of clay particles. It may also be due to the dispersion of colloidal properties of attapulgite in the liquid medium, to the extent that the individual needles become capable of independent motion relative to one another.

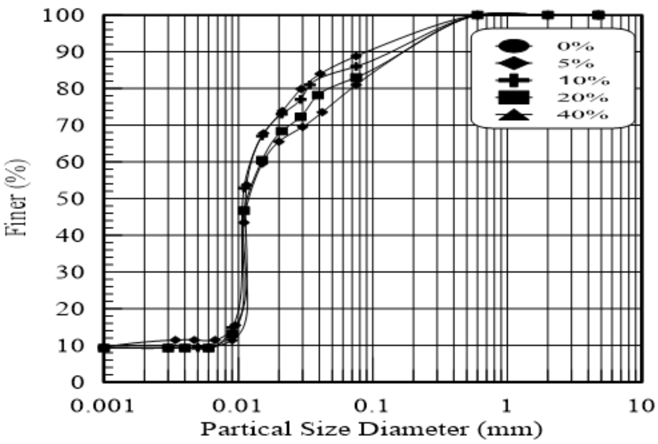


Figure 4. Grain size analysis of treated and untreated soil samples

4.2 Atterberg limits and specific gravity

Figure 5 shows the effect of the percentage of attapulgite on Atterberg limits (liquid limit L.L., plastic limit P.L. and plasticity index P.I.) of the soil samples. Clearly, the liquid and plastic limits increased with the increase in the attapulgite content, whereas P.I. decreased. The attapulgite clay behavior back to have highly L.L. and P.I. values and at higher valence of the exchange ions, with greater effectiveness at high than at low water contents. At low water contents, restraint is imposed by the apparent cohesion of attapulgite resulting from the presence of numerous capillary menisci as stated in ref. [19].

Figure 5 shows that there is very little change in the values of P.L. and P.I. when the percentage of HRA is increased until 20% HRA, which indicates that 20% of HRA is the optimum content to get the stabilize ML. Moreover, a slight increase appeared in L.L. about 10% at 40% HRA. Consequently, the P.I. decreases from 13% to 11%, which is attributed to the high adsorption capacity as a result of the high specific surface area.

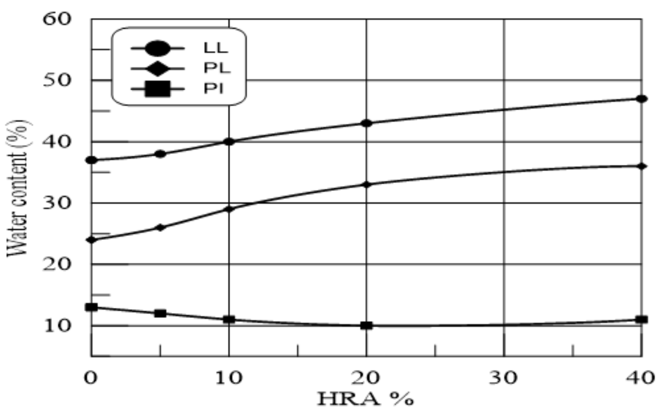


Figure 5. Variation of L.L., P.L. and P.I. with HRA%

Specific gravity Gs values of the treated soil mixtures increased with increase of the replacement percentage of HRA up to a 20% HRA, then the specific gravity slightly decreased as shown in Figure 6. HRA as a replacement material works as filler up to 20% HRA fill the voids in soil and that increased the density and Gs. But from another side, the low Gs and high specific area of HRA as shown in Table 3 the high percentage of HRA as a replacement above 20% case decreased in Gs of the soil which indicates that the 20% is the optimum HRA content to use for treating the soil.

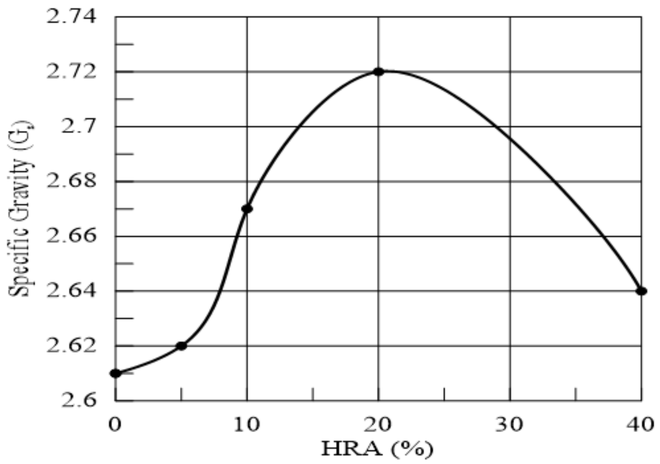


Figure 6. Variation of specific gravity (Gs) with HRA content

4.3 Compaction characteristics

Treated soil samples with different replacement percentage of HRA (5%, 10%, 20%, and 40%) were tested by modified Proctor test and compared with untreated soil samples. The maximum dry density MDD and the optimum moisture content OMC were found for all samples of the gypseous soil as shown in Figure 7 which illustrates that with increasing the water content, the dry density increases until reaching the OMC, after which it decreases for the selected cases. Figure 8 presents the variation in the MDD with the percentage of HRA. According to the results, increasing the replacement percentage of HRA in the soil mixture decreased the MDD of soil mixture and increased the OMC as shown in Figure 9.

Such behavior was expected, due to silt being the major component of the mixtures [20] or due the changes of soil structure from dispersed to flocculated structure. The high percentage of silica in HRA increased the chemical pozzolanic reaction between the mixture content and increased the speed process. The high chemical pozzolanic reaction needs high water demand, and due to the high specific area of HRA led the mixture needs to increase the water content [21, 22].

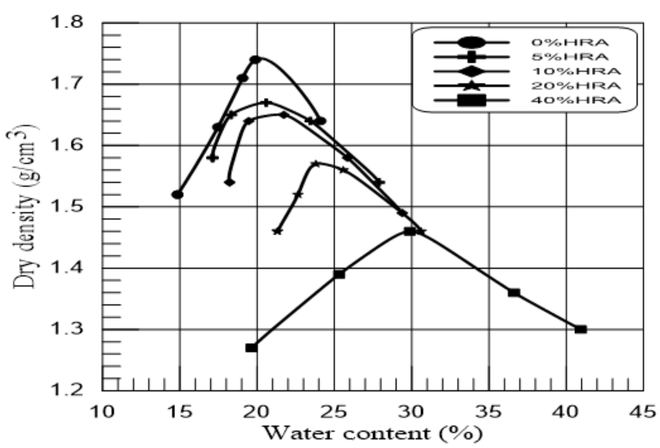


Figure 7. Compaction curves for different HRA content

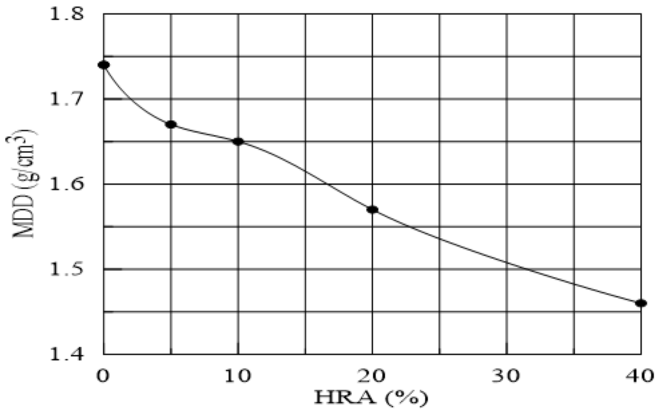


Figure 8. The relation between MDD and HRA content

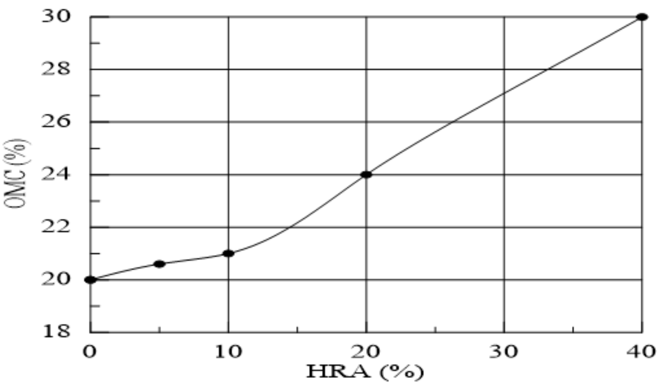


Figure 9. The relation between OMC and HRA content

4.4 Collapsibility characteristics (consolidation test)

Single consolidation test was carried out using an oedometer cell and following the procedures indicated by Mohamed et al. [23], and Jennings and Knight [24] to determine the collapse potential of the samples. The sample in this test is loaded in a dry state without any water according to the standard consolidation test. The applied stress of 200 kPa on samples is left for 24-hour duration, then water is added to the cell and left for another 24 hours. The changes in thickness (ΔH) were recorded. According to conventional consolidation test, the remaining of the tests were performed [25].

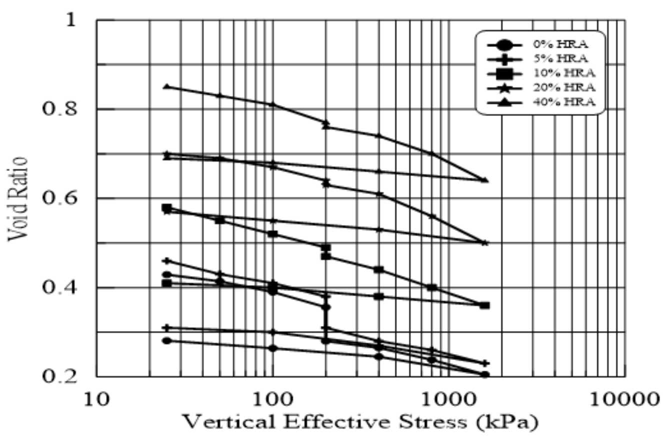


Figure 10. Variation in void ratio with applied stress for different HRA contents in single oedometer test

Figure 10 shows the relation between the vertical stress and void ratio plotted on a log scale according to single-oedometer test. The results show the reduction in the void ratio due to the applied pressure for each percentage of HRA. The results also show the increase in the void ratio with the increase in the HRA content. This can be attributed to the decrease in the dry density and specific gravity of the soil mixture.

The collapse potential (Cp) is calculated using Eq. (1):

$$Cp=\Delta e/(1+e_o) \quad (1)$$

where:

Cp is the collapse potential,

Δe is the difference in void ratio, and

e_o is the initial void ratio.

Table 6 shows the severity of the problem of collapse potential. The collapse potential decreased from 5.1% to 0.53% as the HRA content increased from 0% to 40% as shown in Figure 11. This behavior is attributed to the high surface area of attapulagite and pozzolanic activity that affected the particle orientation and acts as a cohesive bond between soil particles and to provide a water proofing coat around the GS particles.

Table 6. The collapse potential severity at 200kPa stress level [24]

Value of collapse potential, %	Severity of problem
0	No problem
0.1-2	Slight
2.1-6	Moderate
6.1-10	Moderately severe

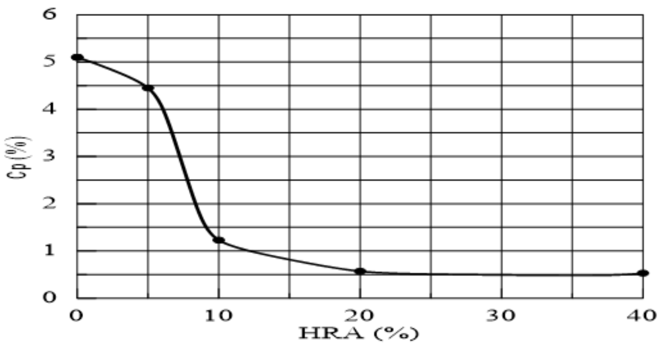


Figure 11. Variation of Cp with HRA content

4.5 Shear strength characteristics (unconfined compression test)

The unconfined compression strength UCS tests were conducted on all the samples of the soil (untreated and treated) with different replacement percentages of HRA prepared at the MDD and the OMC. The soil samples were prepared with 80 mm height and 38 mm diameter, and by controlling the mass and volume of samples the desired density was obtained. The sample height was divided into four layers, 20 mm for each layer.

This test was applied according to ref. [19], and the rate of load was fixed at 0.5 mm/min. Figure 12 shows the results. The UCS improved gradually as the HRA content increased up to 5%. The UCS significantly increased from 88 to 271 kPa in the content range between 5% and 40%. Based on the classification of the unconfined compressive strength presented by Das and Sobhan [26], the untreated soil is medium consistency and when adding 5% to 40% of HRA the consistency of soil becomes very stiff. This may be attributed to the increase in SiO_2 content and enhancement in the strength up to the pozzolanic reaction, or may be attributed to the increase in particle-to-particle contact those results from the degree of springiness imparted to the crystals [20]. Table 7 shows the effect of HRA on the properties of the gypseous soil.

Table 7. Effect of HRA on properties of gypseous soil

HRA (%)	L.L. (%)	P.L. (%)	P.I. (%)	G_s	MDD (g/cm^3)	OMC (%)	C_p (%)	UCS (kPa)
0	37	24	13	2.61	1.74	20	5.1	79.12
5	38	26	12	2.62	1.67	20.6	4.45	87.57
10	40	29	11	2.67	1.65	21	1.23	123.99
20	43	33	10	2.72	1.57	24	0.57	171.46
40	47	36	11	2.64	1.46	30	0.53	270.42

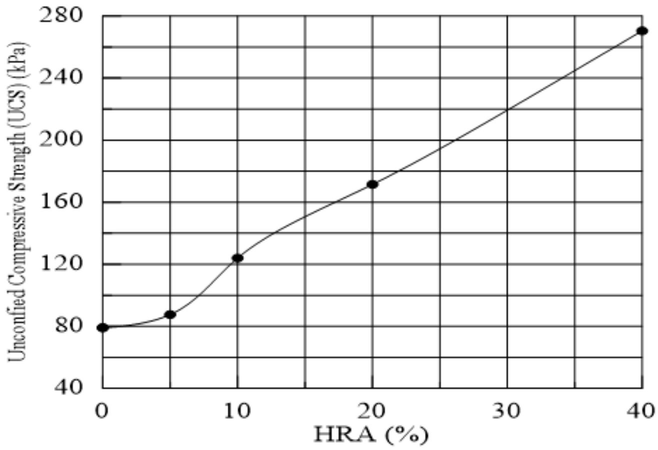


Figure 12. Variation of the USC with different HRA contents

5. CONCLUSIONS

1. Local attapulgite material is converted into active pozzolanic material (HRA) upon burning at a certain temperature, the approparіate burning degree of 750ºC attained at heating rate of 4°C/min and calcination time of 30 min and used as stabilizer material to improve the properties of gypseous. Compared to previous studies, the (HRA) materials were not used with the technique of pozzolonia materials for the purpose of improving the engineering properties of gypseous soil.

2. The grain size distribution curve shifted downward for HRA-treated soils as the sand content increases by about 90%, while the clay content and silt content were reduced by about 38% and 11%, respectively, for HRA content between 5% and 40%.

3. The plasticity index decreased by about 7% to 18% with the increase in the HRA % from 5% to 20% which is attributed to the high adsorption capacity as a result of the high specific surface area, the results also indicate that 20% HRA is more effective on the plasticity index.

4. The specific gravity of the treated soil mixture increased by about 4.2% with the addition of HRA to the soil with content ranging between 5% and 20%. Above 20% HRA caused a decrease in the specific gravity due to low Gs and high specific area of the HRA with the high percentage of

HRA as a replacement.

5. The maximum dry density MDD of the treated soil mixture decreased, whereas the optimum moisture content OMC of the mixture increased by adding HRA to the soil mixture. This is beneficial in humid climate due to the high water demand for samples and that cased as a result of pozzolanic reaction of soil which caused the chemical reaction process. The chemical reaction process needs high water content.

6. The collapse potential decreased by about 13% to 90% as the HRA increased from 0% to 40%, due to the effect of the specific surface area of HRA after burning.

7. The unconfined compressive strength increased from 88 kPa to 271 by adding 5% to 40% of HRA and based on the classification of unconfined compressive strength the soil change from medium to very stiff soil consistency. The incorporation of 10% of High-Reactivity Attapulgite (HRA) as a partial replacement by weight of gypseous soil leads to increases in the unconfined compressive strength by about 56%.

8. Based on the obtained results, the optimum percentage of HRA needed for the stabilization of gypsiferous soil was determined between 20% to 40%.

ACKNOWLEDGMENT

The authors are grateful to Mustansiriyah University (www.uomustansiriyah.edu.iq) and the staff of the soil mechanics laboratory of the Department of Civil Engineering for providing assistance in this research.

REFERENCES

[1] Fookes, P.G., Sweeney, M., Manby, C.N.D., Martin, R.P. (1985). Geological and geotechnical engineering aspects of low-cost roads in mountainous terrain. Engineering Geology, 21: 1-152. https://doi.org/10.1016/0013-7952(85)90002-X

[2] Subhi, R.K. (1987). Properties of salt contaminated soils and their influence the performance of roads in Iraq. Ph.D. Thesis, Queen Mary College, University of London.

[3] Al-Barzanji, A.F. (1973). Gypsiferous soils of Iraq. Ph.D. Dissertation, State University of Ghent, Belgium.

[4] FAO. (1990). Management of gypsiferous soils. FAO Soils Bulletin, No.62.

[5] Nashat, I.H. (1990). Engineering characteristics of some gypseous soils in Iraq. Unpublished Ph.D. thesis, Civil Eng. Dep., University of Baghdad, Baghdad Iraq.

[6] Al-Mufty, A.A., Nashat, I.H. (2000). Gypsum content determination in gypseous soils and rocks. 3rd International Jordanian Conference on Mining, pp. 500-506.

[7] Al-Nouri, I., Saleam, S. (1994). Compressibility characteristics of gypseous sandy soils. Geotechnical Testing Journal (GTJ), 17(4): 465-474.

[8] Fattah, M.Y., Al-Ani, M.M., Al-Lamy, M.T.A. (2015). Wetting and drying collapse behaviour of collapsible gypseous soils treated by grouting. Arabian Journal of Geosciences, 8(4): 2035-2049. https://doi.org/10.1007/s12517-014-1329-7

[9] Dimitrova, R.S., Yanful, E.K. (2011). Factors affecting the shear strength of mine tailings/clay mixtures with varying clay content and clay mineralogy. Engineering Geology, 125(27): 11-25. https://doi.org/10.1016/j.enggeo.2011.10.013

[10] Abdulrahman, S.M., Fattah, M.Y., Ihsan, E.A. (2021). Influence of plastic fiber on the geotechnical properties of gypseous soil. International Journal of Engineering, IJE TRANSACTIONS B: Applications, 34(2): 367-374. https://doi.org/10.5829/ije.2021.34.02b.08

[11] Abbeche, K., Bahloul, O., Ayadat, T., Bahlou, A. (2010). Treatment of collapsible soils by salts using the double consolidation method. In: Experimental and Applied Modeling of Unsaturated Soils, Geotechnical Special Publications, GeoShanghai, pp. 69-78. https://doi.org/10.1061/41103(376)10

[12] Mohamed, A.M.O., El-Gamalin, M.M. (2012). Treatment of collapsible soils using sulfurcement. International Journal of Geotechnical Engineering, 6(1): 65-77. https://doi.org/10.3328/IJGE.2012.06.01.65-77

[13] Fattah, M.Y., Al-Ani, M.M., Al-Lamy, M.T. (2014). Studying collapse potential of gypseous soil treated by grouting. Soils and Foundations, 54(3): 396-404. https://doi.org/10.1016/j.sandf.2014.04.008

[14] Hayal, A.L., Al-Gharrawi, A.M.B., Fattah, M.Y. (2020). Collapse problem treatment of gypseous soil by nanomaterials. International Journal of Engineering, IJE TRANSACTIONS C: Aspects, 33(9): 1737-1742. https://doi.org/10.5829/ije.2020.33.09c.06

[15] Al-Amide, S.H.M. (2012). Some properties of concrete containing fired local attapulgite clay. MSc. Thesis, University of Technology - Iraq.

[16] Carroll, D. (1970). Clay Minerals: A Guide to their X-ray identification. Geol. Soc. Am. Spec. Pap. 126. https://doi.org/10.1130/SPE126

[17] Al-Obaidey S.J.K. (2015). Fresh and some hardened properties of lightweight self consolidating concrete containing attapulgite. MSc. Thesis, University of Technology.

[18] Brown, G. (Ed.) (1961). Palygorskite. In The X-ray Identification and Crystal Structure of Clay Minerals, 2nd Ed. Mineral. Soc. London, pp. 343-335. https://www.amazon.com/dp/090305602X.

[19] ASTM Book of standards, American Society for Testing and Materials, Annual Book of ASTM.

[20] Edelbert, V., Hans, F.W. (2013). Engineering properties of several pure clays as functions of mineral type, exchange ions and phase composition. Paper Sponsored by Committee on Physico-Chemical Phenomena in Soils and Presented at the 46th Annual Meeting, pp. 55-65.

[21] Al-Rawas, A.A., Yahia, E.A.M., Al-Shabibi, A.S., Al-Katheiri, S. (2006). Sand–attapulgite clay mixtures as a landfill liner. Geotechnical and Geological Engineering, 24: 1365-1383. https://doi.org/10.1007/s10706-005-2214-7

[22] Alireza, S.G., Mohammad, M.S., Hasan, B.M. (2013). Application of nanomaterial to stabilize a weak soil. Seventh International Conference on Case Histories in Geotechnical Engineering. http://scholarsmine.mst.edu/icchge.

[23] Mohamed, S.A., Al-Hamad, R.K.H.S., Khaled, T.T. (2020). Investigating the effect of elevated temperatures on the properties of mortar produced with volcanic ash. Innovative Infrastructure Solutions., 5(25). https://doi.org/10.1007/s41062-020-0274-4

[24] Jennings, J.E., Knight, K. (1975). A guide to construction

on or with materials exhibiting additional settlement due to collapse of grain structure. Proceedings of the 6th Regional Conference for Africa on Soil Mechanics and Foundation Engineering, Durban, South Africa, 1: 99-105. https://doi.org/10.1016/0148-9062%2875%2991203-6
[25] ASTM D5333-03. (2003). Standard test method for measurement of collapse potential of soils, Book of ASTM Standards, Vol. 04.08. ASTM International, West Conshohocken, PA.
[26] Das, B.M., Sobhan, K. (2014). Principles of Foundation Engineering. Eighth Edition, Cengage Learning.

NOMENCLATURE

CP	Collapse potential
e_0	Initial void ratio
G_s	Specific gravity
HRA	High reactivity attapulgite
LL	liquid limit
PL	Plastic limit
PI	Plasticity index
MDD	Maximum dry density
OMC	Optimum moisture content
UCS	Unconfined compressive strength