Proceedings of the 11th World Congress on New Technologies (NewTech'25)
Paris, France - August, 2025
Paper No. ICCEIA 129
DOI: 10.11159/icceia25.129

Chemical Stabilization of a Collapsible Soil

Tahar Ayadat[1]
[1]Prince Mohammad Bin Fahd University
P.O. Box 1664, Al-Khobar 31952, Saudi Arabia
tayadat@pmu.edu.sa

Abstract- In the event of soils collapsing under a specific load, their volumes can be reduced rapidly and dramatically following wetting. A collapsible soil beneath the foundation of an industrial or residential building can result in irreversible and significant damage to its supporting structures as a result of settlement. Stabilizing soil with chemicals improves its engineering properties by changing its characteristics. The objective of this experimental investigation is the development of a new stabilization method for collapsible soils using a mixture of chemical additives. The new method consists of mixing collapsible soils with a mixture composed of non-metallic by-product material and a non-traditional additive. The chemical additives consist of a mixture of ground granulated blast furnace slag (GGBS), Magnesium Oxide (MgO), and a Geopolymer (with a molar ratio z > 3). The results revealed that the new stabilization method is capable to dispose the collapse potential of soils, to reduce considerably soil settlement, and hence to improve soil strength and soil bearing capacity. The superlative of the chemical agents was noted to consist on a mixture of 10% ground granulated blast furnace slag (GGBS), 5% of magnesium oxide (MgO), and 20% of a Geopolymer. The magnesium oxide (MgO) is added or combined to the mix in order to activate the GGBS and consequently to achieve or acquire high performance of the stabilized soil. Furthermore, recycling of waste materials, used in the present stabilization technique, is one of the main ways of preserving the environment with a lower economic value.

***Keywords*:** Collapsible Soils, Chemical Stabilization, Blast Furnace Slag, Geopolymer

1. Introduction

Collapsible soils are prone to significant and rapid changes in volume when they become wet under a certain load. These soils typically exhibit a high initial void ratio, low saturation levels, high silt content, and quick softening (loss of cohesion) upon reaching moisture. When these soils settle after wetting, they can lead to serious and irreversible damage to the foundations of industrial or residential buildings. Chemical soil stabilization involves altering soil properties to improve its engineering characteristics. This is achieved by creating chemical interactions between soil particles, which enhances cohesion, shear strength, and overall structural stability [3, 4, 5, 6 and 7]. However, chemical stabilization materials have drawbacks, such as toxicity, alteration of soil pH, and potential contamination of groundwater and soils. Therefore, it is crucial to identify environmentally friendly and cost-effective alternatives for stabilizing collapsible soils [8].

The treatment approach varies based on the depth of the collapsible soil and the support needs of the intended structure. Various methods have been proposed to address this issue, including pre-collapse measures using driven piles, prewetting through ponding, dynamic and deep compaction, silt slurry injection, chemical treatments, grouting, and rolling. Future possibilities include heat treatment, ultrasonic methods, or electro-osmosis. The most straightforward solution is to extend the foundations to a depth where the collapse issue is minimal or non-existent, often achieved through piling. If the collapsible soil layer is relatively thin (less than 4 meters), it may be more economical and practical to excavate and replace it with a suitable, well-compacted soil. Ideally, the replacement material should be coarse, inorganic, and require minimal compaction effort. However, this method necessitates having the replacement material nearby, access to a large quantity of water (matching the optimal moisture content for the replacement soil), and sufficient compaction effort, all of which can increase project costs. Additionally, challenges may arise in arid and semi-arid regions due to limited water availability.

The aim of this experimental study is to create a new method for stabilizing collapsible soils using chemical additives. This method involves mixing the soil in place, specifically targeting a layer of collapsible soil. It employs soil mixers to thoroughly blend binders into the soil while it is undisturbed. The additives primarily consist of three chemicals: ground granulated blast furnace slag (GGBS), Magnesium Oxide (MgO), and a Geopolymer with a molar ratio greater than 3. The stabilization process utilizes soil mixers that can be easily attached to a standard excavator using pin mounts. These mixers are powered by the excavator's hydraulic system, transforming the excavator into an effective and adaptable mixing tool. The mixing drums can penetrate and blend various materials on-site, taking advantage of the excavator's mobility to access challenging or soft areas. Binders or chemical agents are delivered to the area with the highest mixing shear through an 80 mm diameter pipe and injected via a nozzle positioned between the mixing drums.

The chemical agents consist of a blend of 10% ground granulated blast furnace slag (GGBS), 5% magnesium oxide (MgO), and 20% Geopolymer (with a molar ratio of $z > 3$). The addition of magnesium oxide (MgO) activates the GGBS, enhancing the performance of the stabilized soil. It's important to highlight that GGBS is utilized as an additive in this process to modify the mineralogy of collapsible soil, alter its fabric structure, increase particle size, and reduce silt content. GGBS serves as an effective binder that improves the stabilization of collapsible soils. Additionally, the Geopolymer functions as both a binder and a stabilizing agent, featuring a more linear structure that provides adhesive properties, thus promoting soil stabilization. This innovative stabilization technique is expected to eliminate the potential for soil collapse, enhance soil strength and bearing capacity, minimize settlement, and significantly lower soil permeability. The treated collapsible soil, with these chemical additives, solidifies and gains strength within a few days. Moreover, it transforms the soil foundation into a more advanced composite ground, ultimately reducing geotechnical project costs.

This method is considered effective because it addresses waste disposal and supports environmental protection. The use of ground granulated blast furnace slag (GGBS) and Geopolymer in stabilizing collapsible soils should be further developed and encouraged to eliminate significant amounts of stored GGBS. Additionally, Geopolymer offers several benefits as a binder, including affordability, wide availability, strong physical properties, good chemical compatibility, and ease of processing. Collapsible soil treated with Geopolymer can effectively support dynamic loads, such as those from highways and railways. The combination of GGBS and Geopolymer for stabilizing collapsible soils is superior to traditional methods, providing quicker early strength gain, reduced shrinkage, lower thermal conductivity, greater durability, and excellent adhesion. The additives used in this approach enhance ongoing efforts to achieve sustainability in geotechnical applications.

2. Experimental Investigation

The collapsible soil examined in this study was recreated or reconstituted in a laboratory using a blend of 85% concrete sand and 15% brown-red clay, which is typically used in brick manufacturing. Distilled water was utilized for mixing the soil. Figure 1 illustrates the particle size distribution of the collapsible soil, while its characteristics are detailed in Table 1. According to the Unified Soil Classification System (USCS), this soil is categorized as clayey sand (SC). All tests were conducted in a consolidation cell (oedometer) with a diameter of 50mm under specified conditions. The samples, measuring 200mm in thickness, were saturated from the bottom center of the cell using a plastic filter that is 50mm in diameter and 5mm thick.

All samples were tested at four different densities: 35%, 55%, 75%, and 95% of the optimum maximum dry density (ρ_{dmax}). For each density, four initial water contents were tested: 20%, 40%, 60%, and 80% of the optimum moisture content (w_{opt}). The samples were placed in an oedometer cell, and the testing procedure followed that of Ayadat and Hanna [9]. Standard consolidation collapse tests were performed at specific relative densities and initial water contents, with the load gradually increased to 200 kPa, as recommended by Jennings and Knight [10] and Luteneger and Saber [11]. After this loading, the specimen was saturated with water, allowed to sit for 24 hours, and then the consolidation test was conducted up to the maximum loading limit. The untreated/treated soil was placed in the cell in three layers using dynamic compaction with an impact hammer designed to provide the necessary energy per unit volume of the compacted soil. The hammer used was similar to that described by Ayadat and Hanna [12]. A Linear Variable Differential Transformer (LVDT) with a 10 V power supply and a maximum travel of 100 mm was installed on top of the specimen to measure vertical displacement.

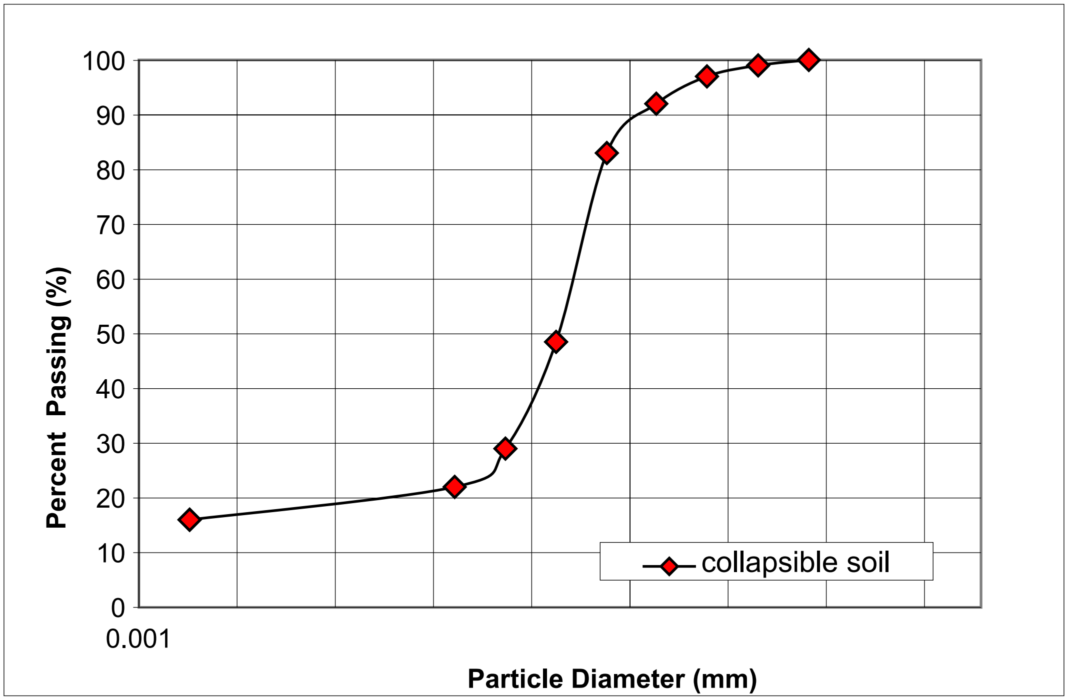

Figure 1. Particle size distribution of the collapsible soil

Table 1. Properties of the reconstituted collapsible soil

Material	Proprieties	Value
Collapsible soil	Specific gravity (G_s)	2.67
	D_{50} (mm)	0.3
	Maximum dry density (ρ_{dmax}, kN/m^3)	20.2
	Optimum moisture content (w_{opt}, %)	9.5
	Liquid Limit, *LL* (%)	22
	Plastic Limit, *PL* (%)	14

The soil treatment chemical agents were composed of a blend of 10% ground granulated blast furnace slag (GGBS), 5% magnesium oxide (MgO), and 20% Geopolymer (with a molar ratio of z > 3). GGBS is a by-product from iron production in blast furnaces, primarily made up of silicate and alumino-silicate of melted calcium that needs to be periodically extracted. Its particles are smaller than 45 µm, with a surface area ranging from 400 to 600 m^2/kg. GGBS is a hydraulic material that can harden when mixed with water, mainly containing calcium oxides (CaO), silica (SiO2), and alumina (Al_2O_3), along with trace amounts of other oxides.

Magnesium oxide (MgO), also known as magnesia, is a naturally occurring white hygroscopic mineral that appears as periclase and serves as a source of magnesium. Its chemical formula is MgO, consisting of a lattice structure formed by Mg^{2+} and O^{2-} ions bonded ionically. Historically, magnesium oxide was referred to as magnesia alba to distinguish it from magnesia negra, a black mineral that contains what is now recognized as manganese.

Geopolymer is an inorganic substance that has emerged as a novel eco-friendly binder for the stabilization of challenging soils. It consists of a network of alumina-silicates formed from alumina (AlO_4) and silica (SiO_4). The basic molecular formula can be expressed as $\{M_n\text{-}(SiO2)_z\text{-}AlO_2\text{-}\}_n$, where *M* represents alkali cations (such as Na+ or K+), *n* indicates the degree of polymerization, and z denotes the Si/Al molar ratio. When z > 3, the Geopolymer exhibits a more linear structure, which provides adhesive qualities that enhance soil stabilization.

3. Test Results

As indicated previously, the objective of this experimental investigation is the development of a new stabilization method for collapsible soils using a mixture of chemical additives. The new method consists of mixing collapsible soils with a mixture composed of non-metallic by-product material and a non-traditional additive. A preliminary testing program was conducted on treating the reconstituted collapsible soil using different combination of the chemical additives. Based on the results of this preliminary testing program, a mixture of 10% ground granulated blast furnace slag (GGBS), 5% of magnesium oxide (MgO), and 20% of a Geopolymer was retained for this investigation.

Typical consolidation test results obtained for untreated and treated collapsible soil at a density of 35% of ρ_{dmax} and 20% of w_{opt} are shown in Figure 2. It can be noted from this figure that the wetting-induced collapse strain was reduced from 19.7% to 2.3%. According to the classification of Jennings and Knight, the state of the soil changed from severe trouble to moderate trouble. The wetting-induced collapse strain (ε_c) was calculated using the following equation:

$$\varepsilon_c = \frac{\Delta e_c}{1 + e_o} \quad (1)$$

Where:

Δe_c: change in the void ratio due to inundation,

e_o: initial void ratio.

The variations of the wetting-induced collapse strain with the dry density for untreated and treated soils are illustrated in Figures 3 and 4, respectively. It is confirmed from these figures that the collapse strain is inversely proportional with the density. Furthermore, the treatment of the collapsible soil with the chemical additives decreases drastically the collapse stain. Practically, the soil collapse behaviour was eliminated (i.e. $\varepsilon_c \leq 1$) by the actual chemical treatment under certain conditions of density and moisture content. These different conditions are illustrated in Figure 5 and summarized in Table 2.

Table 2. Values of Moisture Content and dry Density which Eliminate Collapse for Treated Soil

Collapse Strain	Moisture Content (w)	Dry Density (ρ_d)
$\varepsilon_c \leq 1\%$	20 % of w_{opt}	66% of ρ_{dmax}
	40 % of w_{opt}	58% of ρ_{dmax}
	60 % of w_{opt}	50% of ρ_{dmax}
	80 % of w_{opt}	40% of ρ_{dmax}

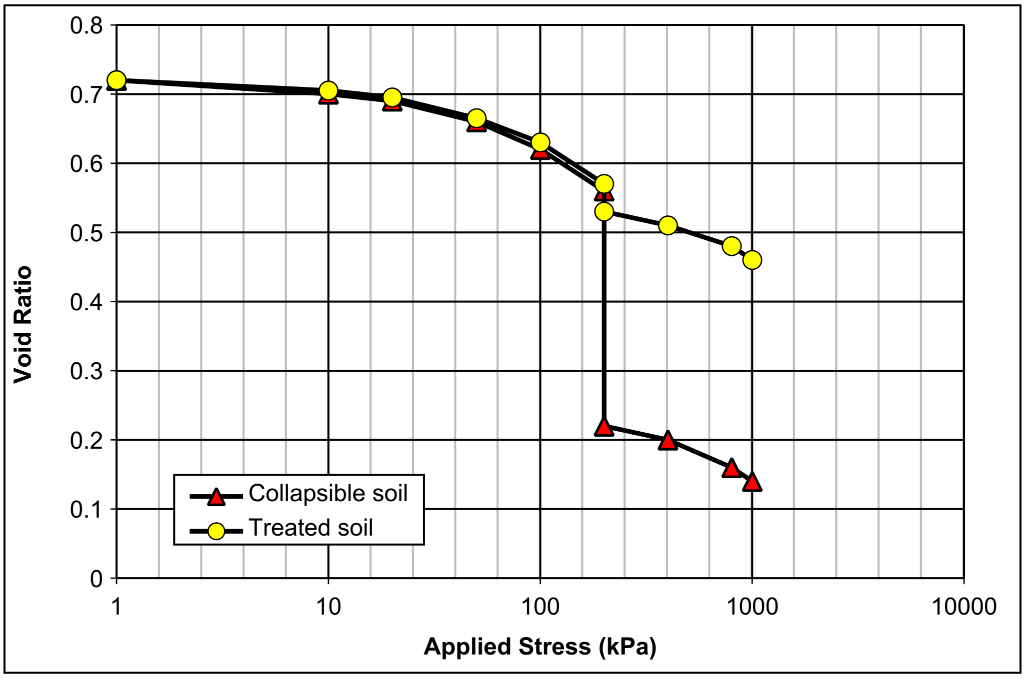

Figure 2. Consolidation test results of untreated/treated collapsible soil at 35% ρ_{dmax} and 20% w_{opt}

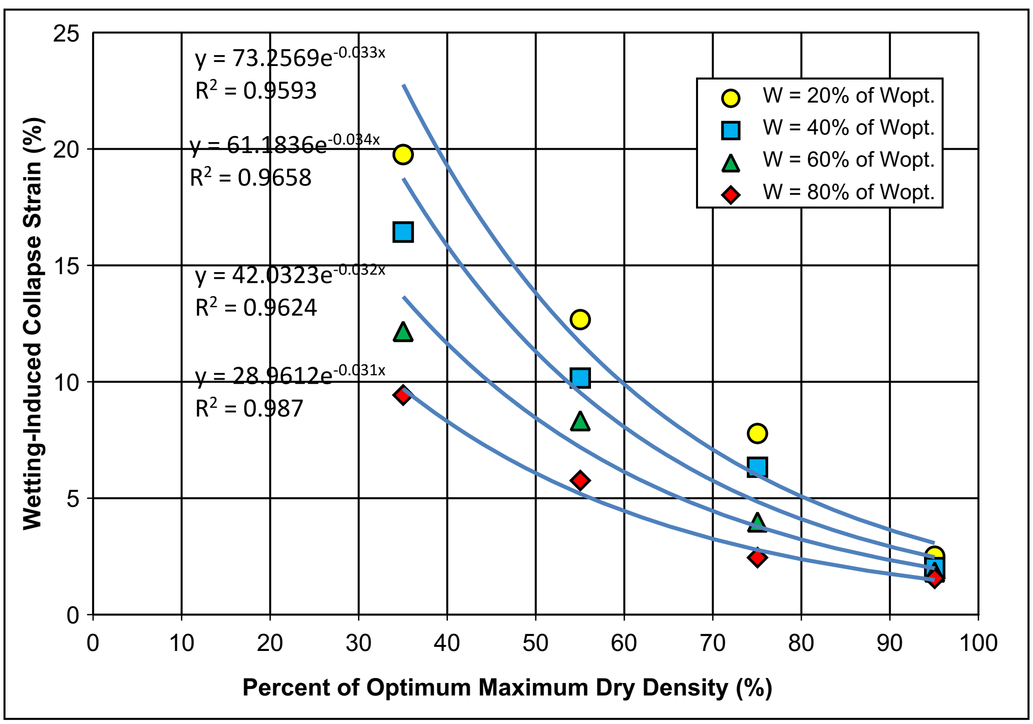

Figure 3. Variation of Wetting-Induced Collapse Strain with Dry Density for untreated soil

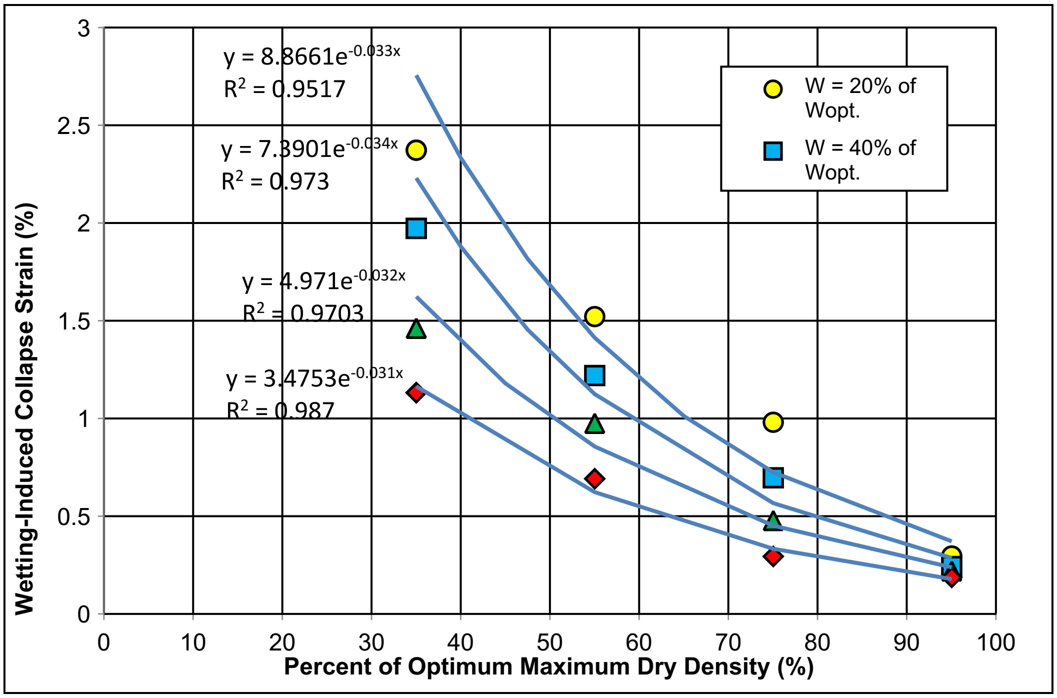

Figure 4. Variation of Wetting-Induced Collapse Strain with Dry Density for treated soil

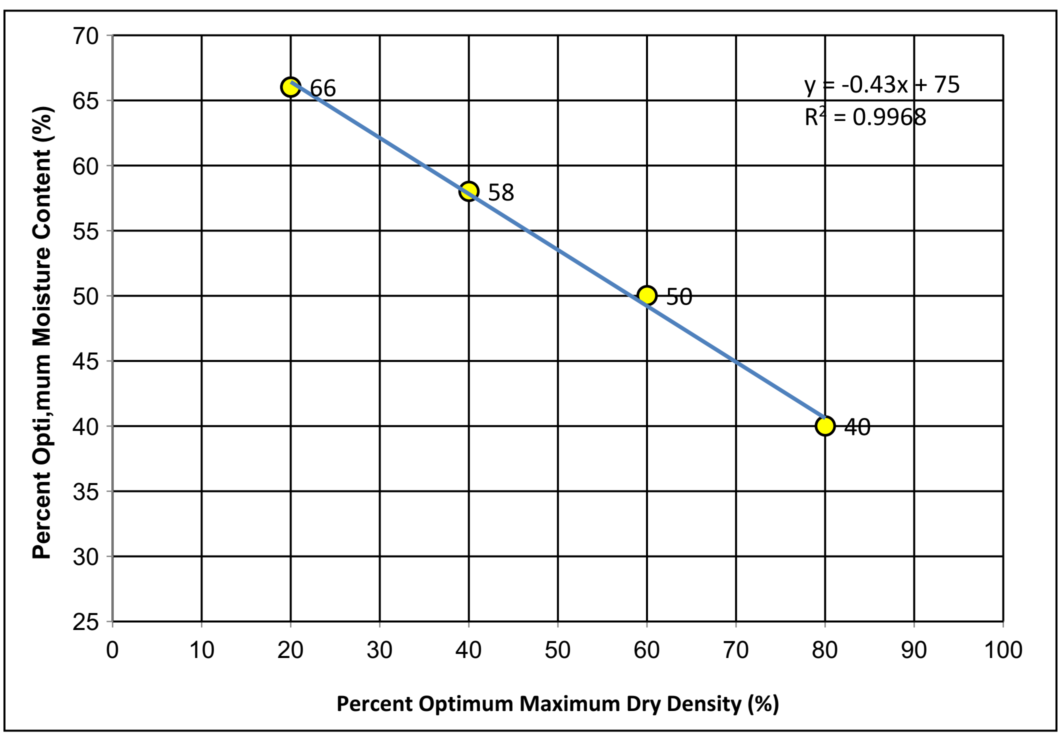

Figure 5. Values of Soil Moisture Content and Dry Density of Treated Soil which eliminate Soil Collapse

The results shown in Figures 3 and 4 indicate that the collapse strain varies exponentially with the density. This relationship can be expressed by the following equation:

$$\varepsilon_c = A \times e^{-0.03 \frac{\rho_d}{\rho_{d\max}}} \qquad (2)$$

Where:

A = A parameter which depend on the soil moisture content

$\frac{\rho_d}{\rho_{d\max}}$ = ratio between soil dry density and optimum maximum dry density (expressed in percentage).

The variation of the parameter A with the soil moisture content (w) for untreated and treated soil is shown in Figure 6. The correlations between the parameter A and the ratio $\frac{w}{w_{opt}}$ (expressed in percentage) can be approximated by the following equations:

- For untreated soil: $$A = -0.67 \frac{w}{w_{opt}} + 89.36$$

- For treated soil: $$A = -0.093 \frac{w}{w_{opt}} + 10.82$$

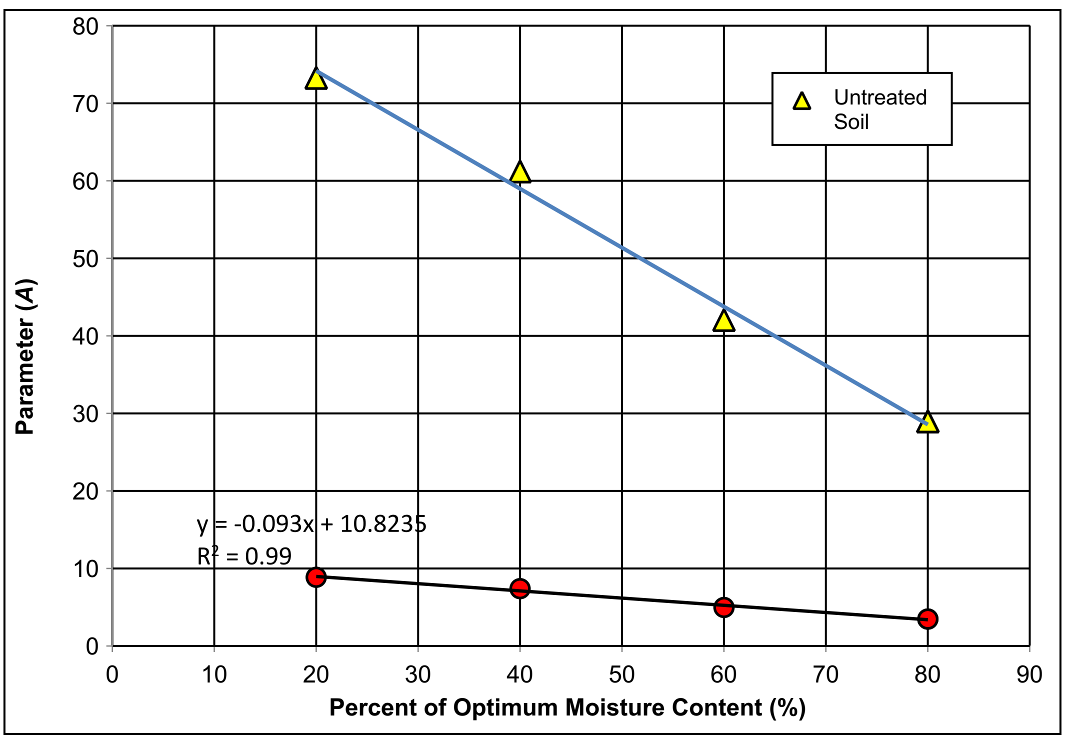

Figure 6. Variation of parameter A with the Soil Moisture Content for Treated/Untreated Soil

4. Conclusion

In this investigation a new stabilization method for collapsible soils using a mixture of chemical additives was developed. The new method consists of mixing collapsible soils with a mixture composed of non-metallic by-product material and a non-traditional additive. The results revealed that the new stabilization method is capable to dispose and eliminate the collapse potential of soils, to reduce considerably soil settlement, and hence to improve soil strength and soil bearing capacity. The superlative of the chemical agents was noted to consist on a mixture of 10% ground granulated blast furnace slag (GGBS), 5% of magnesium oxide (MgO), and 20% of a Geopolymer. Moreover, it was noted that the collapse strain for treated and untreated soils is inversely proportional with the density according to an exponential correlation. It should be pointed that recycling of waste materials, used in the present stabilization technique, is one of the main ways of preserving the environment with a lower economic value

Acknowledgements

I am expressing my deepest gratitude and appreciation for the assistance and support received throughout the completion of this research paper. I want to take this opportunity to acknowledge the contributions of Mr. Soudani Djillali who have played a significant role in successfully completing this research investigation.

References

[1] Tahar Ayadat, F Bellili (1995). Sols susceptibles d'affaissement: identification, mécanismes et traitement, Algérie-Équipement, 20, 18-23.
[2] Tahar Ayadat (2021). Assessment and identification of three types of difficult soils, Acta Geodynamica et Geomaterialia 18 (2), 209-231.
[3] M. Amrani, Y. Taha, A. Elghali, M. Benzaazoua, A. Kchikach, R. Hakkou (2021). An experimental investigation on collapsible behavior of dry compacted phosphate mine waste rock in road embankment, Transp. Geotech., 26, 100439, 10.1016/j.trgeo.2020.100439.
[4] S.M. Haeri, A. Valishzadeh (2021). Evaluation of Using Different Nanomaterials to Stabilize the Collapsible Loessial Soil, Int. J. Civ. Eng., 19 (2021), pp. 583-594, 10.1007/s40999-020-00583-8.
[5] S. Adjabi, M.S. Nouaouria, W. Djebabla (2021). Treatment of Collapsible Soils with Granulated Blast Furnace Slag and Calcined Eggshell Waste, Civ. Environ. Eng. Reports., 31 (2021),, pp. 138-162, 10.2478/ceer-2021-0024.
[6] Mohammad Ali Khodabandeh, Gábor Nagy, Ákos Török (2023). Stabilization of collapsible soils with nanomaterials, fibers, polymers, industrial waste, and microbes: Current trends Construction and Building Materials, Volume 368, 130463.
[7] Altameemi, Z. A., Shafiqu, Q. S. M., and Al-Taie, A. J. (2023. Evaluation of Tikrit dune sand soil enhanced with CKD. In E3S Web of Conferences (Vol. 427, p. 01008). EDP Sciences
[8] Tahar Ayadat, M. Dahili, K.MH. Ahmed (1998). Traitement d'un sol effondrable par un liant hydrocarboné, Revue française de géotechnique, 57-64.
[9] Tahar Ayadat and Hanna, A.M. (2007). Identification of collapsible soil using the Fall Cone apparatus. Geotechnical Testing Journal, ASTM, 30(4). DOI: 10.1520/GTJ14193
[10] Jenning, J.E. and Knight, K. (1975). A guide to construction on or with materials exhibiting additional settlement due to 'collapse' of grain structure. Proc. of the 6th Regional Conf. for Africa on SMFE, Durban, South Africa, 1, 99–105. DOI: 10.1016/0148-9062(75)91203-6
[11] Lutenegger, A.J. and Saber, R.T. (1988). Determination of collapse potential of soils. Geot. Testing Jnl, GTJODJ, ASTM. 11(3), 173–178.
[12] Tahar Ayadat, T. And Hanna, A. M. (2007). Prediction of collapse behaviour in soil. European Journal of Civil Engineering, 11(5). DOI: 10.1080/17747120.2007.9692947