AbouKhadra et al., *Cogent Engineering* (2018), 5: 1517577
https://doi.org/10.1080/23311916.2018.1517577

cogent engineering

CIVIL & ENVIRONMENTAL ENGINEERING | RESEARCH ARTICLE

Experimental evaluation of strength characteristics of different Egyptian soils using enzymatic stabilizers

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Received: 02 October 2017
Accepted: 26 August 2018
First Published: 04 September 2018

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Reviewing editor:
Felipe Villalobos, Universidad Catolica de La Santisima Concepcion, Chile

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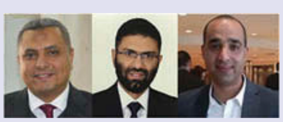
Abstract: Soils with poor bearing capacities represent a challenge to construction engineers, therefore continuous investigation of different additives and stabilizers is sought in order to improve such weak soils and reduce the cost of replacement. In this paper, an experimental program is adopted to investigate the effect of environmentally friendly material based on enzymes on the soil performance. The effect of different dosages of two commercial enzymatic preparations on the soil strength, maximum dry density and permeability of five different soils was examined. Besides, California Bearing Ratio (CBR) and unconfined compressive strength (UCS) were conducted to investigate the enhancement in soil strength. X-ray fluorescence (XRF) analysis showed a slight increase in the silica ion content in the treated soils. It is inferred from the results that using the enzymatic preparations significantly increased the strength of fine soil, the rate of improvement was found to be proportional to the clay content in the soil.

Subjects: Materials Science; Nanobiotechnology; Civil, Environmental and Geotechnical Engineering

Keywords: soil stabilization; enzyme; CBR; soil permeability

1. Introduction

Roads are crucial in the economic development for any country, the cost of construction is influenced by different factors including the properties of the soil present in the construction



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Dr. Abdullah AbouKhadra is assistance professor (Lecturer) at Faculty of Engineering, Beni-Suef University and is head of the Road Research Laboratory. He is currently collaborating with Dr. Ahmed Zidan, Associate professor, Faculty of Engineering, BSU and Dr. Yasser Gaber, Associate professor, Microbiology Department, Faculty of Pharmacy, BSU. The collaboration is funded by ASRT, Egypt, research project entitled “Low Cost Technology for Roads Construction”, PI Dr. Yasser Gaber. The project aims to develop, cheap, effective and green materials to be used in roads construction. Investigation of biologically derived material is considered such as enzymes, bacteria and biopolymers.

PUBLIC INTEREST STATEMENT

Improving soil characteristics to meet the criteria of road construction requires sometimes transportation of sand and or gravel from distant areas; this poses an additional cost to the overall process. New methods of road construction that can reduce or eliminate the process of sand and gravel replacement will be advantageous in terms of economy. The current research provides an investigation on the use of a biologically derived material that is safe to humans, and environment in the process of roads construction. This will lead to economic and safe applications of the road construction process. The current investigation is the first to our knowledge to be conducted on Egyptian soils. The project is running and more publications including new experiments are to be released within the coming year.

site, sometimes, there is a need to replace the soil present due to poor engineering properties. Various techniques are used to increase the soil strength, reduce compressibility, permeability, shrinkage and swelling of soil, including: surface compaction, drainage methods, soil reinforcement, grouting and injection and chemical stabilization (Bryson & El Naggar, 2013; Guido, Chang, & Sweeney, 1986; Hamidi, Nikraz, & Varaksin, 2009). Since few decades ago, enzymes as soil stabilizers have been used to improve the strength of subgrades due to its wide applicability and low cost compared to the conventional methods of soil stabilization.

Stabilization of soil with enzymatic preparations has been investigated by a number of researchers (Khan & Taha, 2015; Malko, Brazetti, Casagrande, & Silva, 2015; Tingle & Santoni, 2003; Velasquez, Marasteanu, & Hozalski, 2006; Visser, 2007). Enzymes are protein in structures that are usually found as catalysts in biological systems (Katz et al., 2001). They are known to speed the reaction speed without being involved in the products. It is known that the properties of soil particles, specifically the clay soil, are greatly influenced by the water layer adhering their surfaces (Terzaghi, Peck, & Mesri, 1996). This layer thickness relates directly to the compressibility and swelling properties of the soil. Reduction of such water layer would improve the soil engineering performance (Tingle, Newman, Larson, Weiss, & Rushing, 2007). Many research projects are carried out to study the effect of commercial preparations claimed to be enzymatic in nature and found in the market under different brand names i.e. Terrazyme, Earthzyme and Permazyme as soil stabilizers. Depending on enzymes and soil types as well as the curing time, their results showed varying effects that ranged from modest to significant improvement (Khan & Taha, 2015; Layrea, 2003; Rajoria & Kaur, 2014).

Peng, Su, Zhang, and Wang (2011) studied the effect of curing conditions on three types of soils stabilized with quicklime and enzyme. The tested samples were cured in two different conditions up to 60 days i.e. air-drying and in a sealed container. They found that the soil stabilized with the enzymatic preparation improved as monitored by an increase in the unconfined compressive strength values in the air-drying curing. Rauch, Harmon, Katz, and Liljestrand (2002) measured the performance of five different soils treated with three different liquid stabilizers: ionic stabilizer, enzyme stabilizer, and polymer stabilizer, an obvious improvement in the bearing capacity, soil density and lower soil permeability were observed.

Marasteanu, Hozalski, Clyne, and Velasquez (2005), conducted triaxial tests and determined the resilient modulus for two types of soils (Soil-1 and Soil-2) that were treated by two different enzymatic preparations (Enzyme-A and Enzyme-B). Soil-1 had 96% of fines (75% of clay) and Soil-2 had 60% of fines (14.5% of clay). The chemical analysis was only done for Enzyme-1. The analysis included: pH, total organic carbon concentration, inorganic anion concentrations and metal concentration. The pH was 4.77 and it had a very high concentration of potassium and moderate to high concentration of calcium, sodium and magnesium. The triaxial tests were performed on two confinement pressures (27.6 kPa and 55.16 kPa). The results showed that the soil treatment of Enzyme-1 increased the shear strength of soil-1 and soil-2 by 9% and by 23%, respectively. On the other hand, in case of Enzyme-2 treatment, the increases in shear strength for soil-1 and soil-2 were 31% and 23%, respectively. Besides, they also performed resilient modulus tests with different confining and deviator stress. For instance, at 7 psi deviator stress, unlike for Enzyme-1, highly improvement in resilient modulus was noticed for soil-1 with Enzyme-2 whereas the increase in resilient modulus was about 55% for 85%. For Soil-2, at the same deviator stress level the increase of resilient modulus reached to 51 % to 61% with Enzyme-1 and 57% to 137% with Enzyme-2.

The application of enzymatic solution in the field is usually done via five sequential steps: (a) ripping with a grader in order to facilitate moisture adjustment and prevent drainage of the enzymatic solution upon application; (b) the pavement location is treated with dribble bar from a watercart in order to increase the moisture content near the optimum moisture content (OMC); (c) the enzymatic preparation is diluted according to the manufacturer guidelines; (d) the diluted enzymatic solution is sprayed over the pavement material and thoroughly mixed using a stabilizer and finally; (e) shaping of the pavement is done using smooth drum roller several times (Renjith et al., 2017).

The objective of this paper is to investigate the performance of five different soils, with a good wide range of particle distribution, treated with two different enzymes. Soil strength, dry densities and permeability of the improved soil were determined by laboratory investigations.

2. Experimental program

2.1. Soil properties

In order to assess the influence of enzymes on the soil performance, five types of soils are selected to represent a wide range of soils existing in the different sites. Laboratory tests are carried out to determine the engineering properties and strength characteristics of selected soils before and after treatment by enzymes. Table 1 shows different engineering properties of soils used in this study. Figure 1 shows photos for the examined soils and the grain size distribution according to (ASTM D-2487. ASTM D-2487, 1998). Soil_1 and soil_2 are coarse grain materials (sandy soil) and the soils 3, 4 and 5 are fine-grained materials. The soils used were collected from different locations in Beni-Suef city and neighbor cities, Egypt, Figure 1, shows the latitude and longitude locations of the different soils. All soils with and without enzymes were then tested to determine the soil strength after 2 weeks curing period. The Proctor test was carried out to determine the maximum dry density and the OMC of the samples. The enzyme solution was mixed with the soil samples to reach the desired concentration and the optimal moisture content.

2.2. Enzymatic preparations

The enzymatic preparations used in the current study were obtained from commercial distributors. These preparations are natural non-toxic, dark viscous liquids with molasses-like smell. Two preparations were used during this study: Terrazyme denoted by Enzyme-A, purchased from Nature Plus Inc. USA, is composed of ethoxylated alcohols, fermented vegetable extracts and non-ionic surfactants (Khan & Taha, 2015). Permazyme purchased from Pacific Enzymes Inc. USA,

Table 1. Particle size distribution and physical properties of untreated soil

Type of soil	Soil-1 Sand (1)	Soil-2 Sand (2)	Soil-3 Sand & silty clay	Soil-4 Clay (1)	Soil-5 Clay (2)
Gravel (%)	1.77	1.50	—	0.77	—
Sand (%)	84.82	94.85	40.52	18.73	13.80
Silt (%)	8.90	1.00	19.48	40.5	70.17
Clay (%)	4.50	2.50	40.00	39	16.00
c_u	7.00	5.45	53.57	—	50.00
c_c	1.85	1.55	0.07	—	12.50
Specific gravity G_s	2.64	2.7	2.45	2.41	2.71
LL%	—	—	36	38	32
PL%	—	—	25.3	25.2	22.8
PI%	—	—	10.7	12.8	9.2
γ_{dmax} (kN/m^3)	19.2	18.2	17.4	17.6	17.4
O.M.C (%)	9.70	11.6	14.40	17.80	18.50
pH	8	9.9	7.62	7.67	7.8
Soil Classification USCS (ASTM D-2487. ASTM D-2487, 1998)	SW	SP	CL	ML	ML
Ashto Classification	(A—2–4)	(A—1—B)	(A—6)	(A—6)	(A—4)

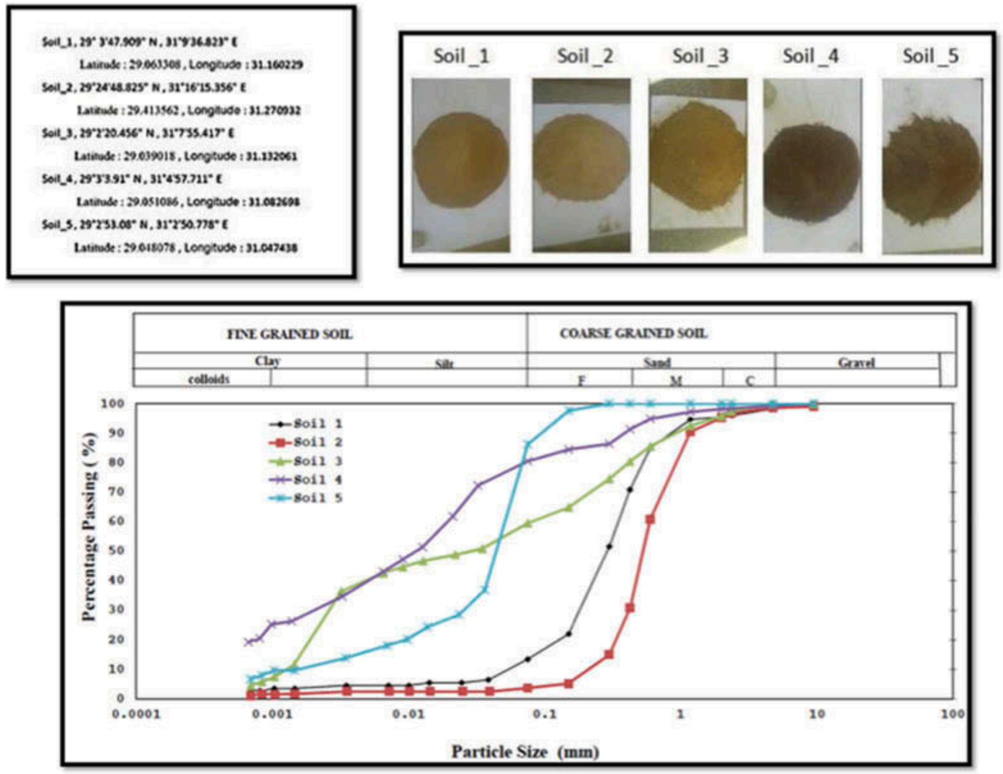


Figure 1. The properties of the soils used in the current study, the upper left panel shows the locations of the soils in terms of the latitude and the longitude values; the upper right panel are photos for the untreated soils samples; the lower panel shows the grain size distribution for the different soils used in the current study.

denoted by Enzyme-B is composed of enzymes, proprietary ingredients and unspecified organic material according to the Manufacturer. For characterization of the two preparations we conducted simple laboratory experiments that showed presence of protein content and non-ionic surfactants in the two preparations.

2.3. X-ray fluorescence

X-ray fluorescence examination of three different soils: clay 1, clay 2 and fine sand were performed. For each soil two samples were examined before and after treatment with Enzyme-B preparation.

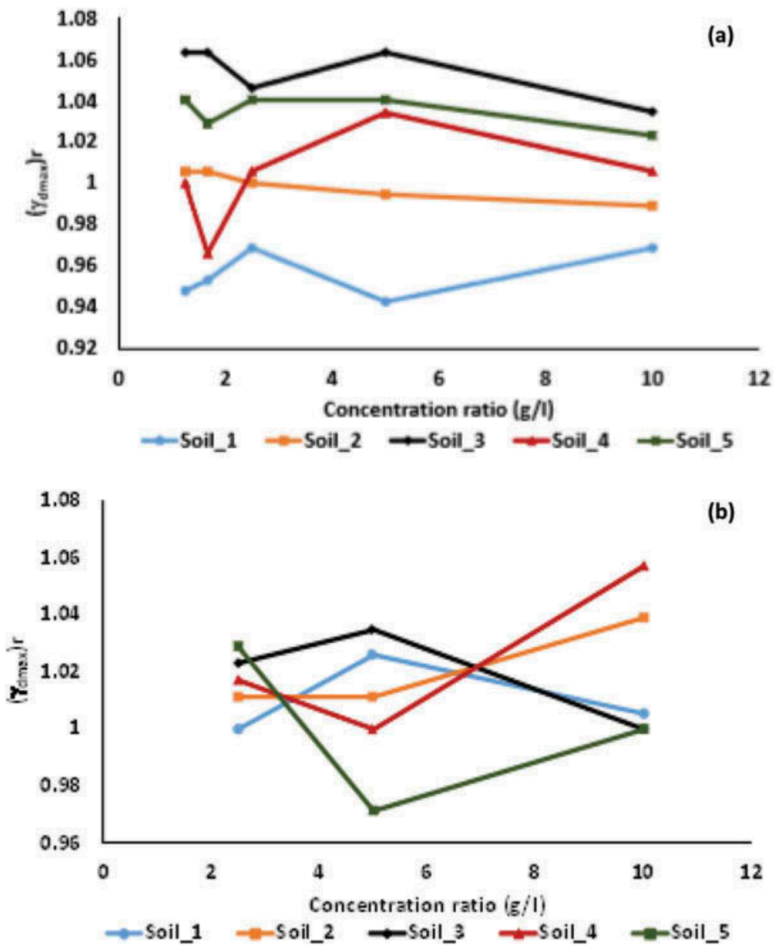
3. Results and discussions

A series of experimental tests were performed on the five selected soils in order to investigate the amount of improvement in dry density, soil permeability and soil strength. The value of improvement is presented here as a dimensionless factor. This factor indicates the ratio of improvement of treated soil to untreated soil.

3.1. Maximum dry unit weight (γ_{dmax})

The modified proctor test was performed on all natural soils and the same procedure was used to identify any improvement in (γ_{dmax}) due to enzymes, the results are concluded in Figure 2. The improvement in (γ_{dmax}) is presented by dimensionless factor $(\gamma_{dmax})_r$ whereas the maximum dry unit weight of stabilized soil is normalized to that observed in case of untreated soil. Figure 2 shows the change in $(\gamma_{dmax})_r$ due to the variation of enzyme concentration. It can be seen that the value of $(\gamma_{dmax})_r$ slightly increase for fine soils by 1 to 6% and the Enzyme-B is more efficient. The best concentration ratio for these soil types is about 0.005. For sandy soil, slightly decrease in $(\gamma_{dmax})_r$ can be observed for the two types of enzymes. Overall, insignificant improvement in dry unit weight for treated soils was observed.

Figure 2. The normalized γdmax values for the different soils before and after treatment with the enzymatic preparations A and B.



3.2. Soil strength

This section presents the result of CBR and unconfined compressive strength (UCS) tests which performed on the treated and untreated soils with. CBR was performed on all soil types and UCS was applied on the all clayey soils at 5 gm/L concentration ratio with Enzyme-B.

3.2.1. California Bearing Ratio (CBR)

The standard test method for CBR test (ASTM D1883–99. ASTM D 1883–99, 2002) is used for evaluate the CBR values of treated and untreated soil. Figures 3 and 4 show the effect of the enzymatic preparations on the soil strength at five different concentration ratios of Enzyme_A and three different concentration ratios for Enzyme_B. The improvement of soil strength is normalized to that of untreated soil and represented by (CBR)r as shown hereinafter.

Figure 3 shows the effect of Enzyme_A through five values of concentration on the (CBR)r. It can be noticed that the fine soil is highly improved by the enzymatic treatment compared to the sandy soil. The results showed that the improvement of CBR values for Soil_3, Soil_4 and Soil_5 are about 2.75, 3.5 and 4.7 times respectively of that observed for untreated soils. These values have been achieved at a concentration of 1.7 g/l for Soil_4 and Soil_5. For Soil_3, the best concentration was found to be 2.5 g/l. On the other hand, for coarse soils (Soil_1, Soil_2), the improvement of the soil strength was moderate and the maximum value of (CBR)r was 1.35 at 2.5 g/l concentration. The same trend was observed for the soils stabilized by Enzyme_B as shown in Figure 4. The soil strength improved especially in soil_3, soil_4 and soil_5 reaching the maximum at enzyme dosage of 2.5 g/l concentration. As observed for Enzyme_A, the improvement of Soil_4 slightly increased

Figure 3. Variation of (CBR)r of enzyme_A treated soil for different dosages.

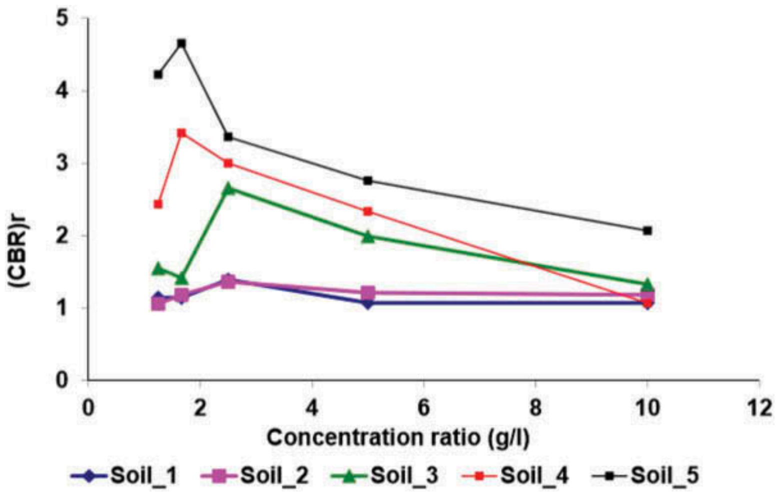
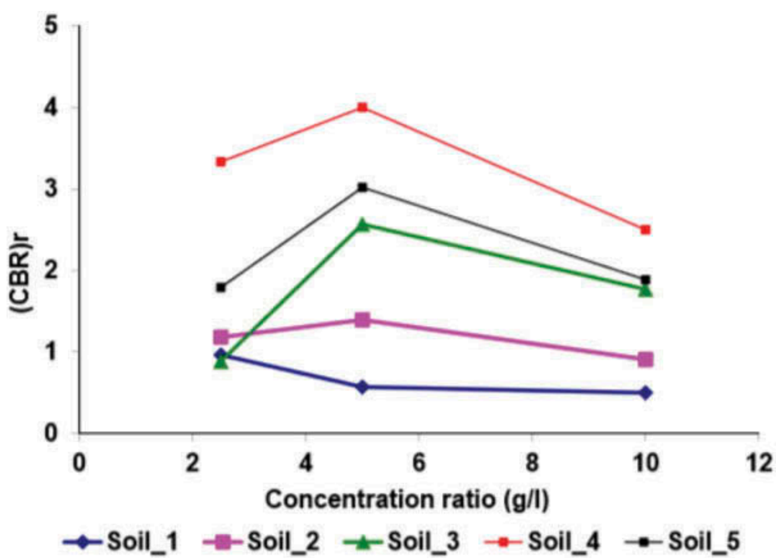


Figure 4. Variation of (CBR)r of enzyme_B treated soil for different dosages.



with the concentration of enzyme. Furthermore, the strength improvement of Soil_5 decreases with enzyme additive increases. In the case of fine soil, it can be seen that the improvement of (CBR)r ranges from 2.5 to 4.5. Venkatasubramanian and Dhinakaran (2011) investigated the improvement in CBR values for three different soils with different dosages. Their results showed that the improvement in CBR values ranged from 12% to 35% through all types of tested soil. In order to investigate the relationship between clay fraction and the value of improvement, Figure 5 is plotted. According the figure, it can be noted that the soil strength improvement increases with the increase of in the clay content. It has been reported by the Manufacturer of the enzymatic preparations that proper percentage of fine particles present in the soil is essential for getting good stabilization results, this allows achieving high compaction and hence improved soil strength characteristics.

3.2.2. Unconfined compressive strength

The standard test method of unconfined compressive strength (ASTM D2166. ASTM, D, 2003) was performed to evaluate the ultimate compressive strength for cohesive soil. All three samples were tested three times on strain control machine in order to determine average values of ultimate compressive strength. Figure 6 shows an example of stress strain relationship predicted from the

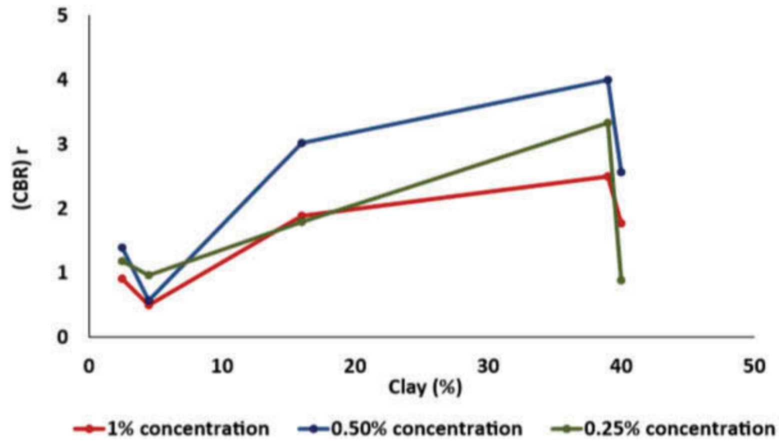


Figure 5. Effect of clay content on the (CBR)r, based on experiments carried out with the enzyme B.

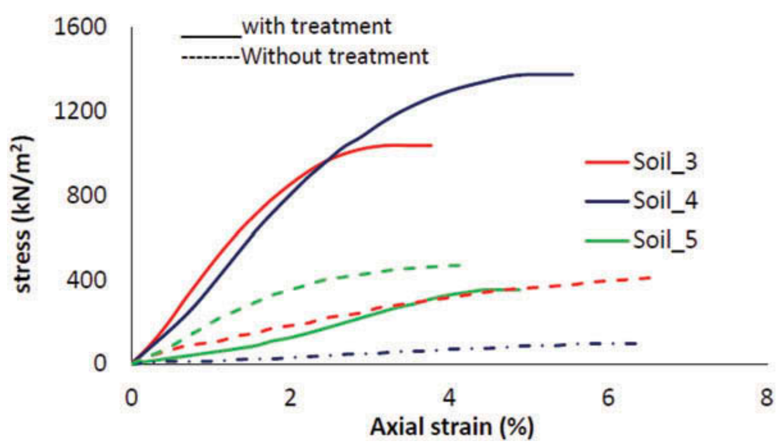


Figure 6. Unconfined compression test results for untreated and treated soils using enzyme-B.

test; it shows a comparison between the treated and the untreated soil samples. It is clear that significant enhancement in the soil strength for the cohesive soils. This attributed to that the enzyme provide some additional shear strength to soil whereas, the ultimate strength for stabilized soil increased by about 2.2, 3.3 and 3.6 times of ultimate strength that observed for untreated soils for Soil_3, Soil_4 and Soil_5 respectively. These results are in a good agreement with the results obtained from the CBR test at the same conditions. Peng et al. (2011) reported a similar trend in their results.

3.3. Soil permeability

In addition to enhance the geotechnical engineering parameters such as shear strength and stiffness, the sub-base soil must be designed to exhibit reasonable level of permeability. Undrained water in soil layers that supporting the layer of pavement can freeze and expand that will create internal pressures in pavement structures and hence long term deformation. The performance in permeability of soil due to enzymatic stabilization is illustrated in Table 2. In order to investigate the enhancement in soil permeability, both constant and falling head permeability tests were performed for four soils, either untreated or treated using Enzyme-B at concentration ratio of 1.67 gm/l according to (ASTM D2434–68. ASTM, D, 2006). It can be noticed from Table 3, that the enzymatic stabilization resulted in significant decrease in soil permeability of all tested soils. Since the treated soil became tighter materials due to the enzymatic treatment, hence the soil configuration reduces the migration of water through the voids between particles. The coefficient of permeability of treated soil ranged from 0.4 to 0.16 times of the untreated soil. Figure 7 shows the relation between clay content and permeability ratio Kr where kr is the ratio between

Table 2. Coefficient of permeability, k (cm/s) for untreated and treated soil

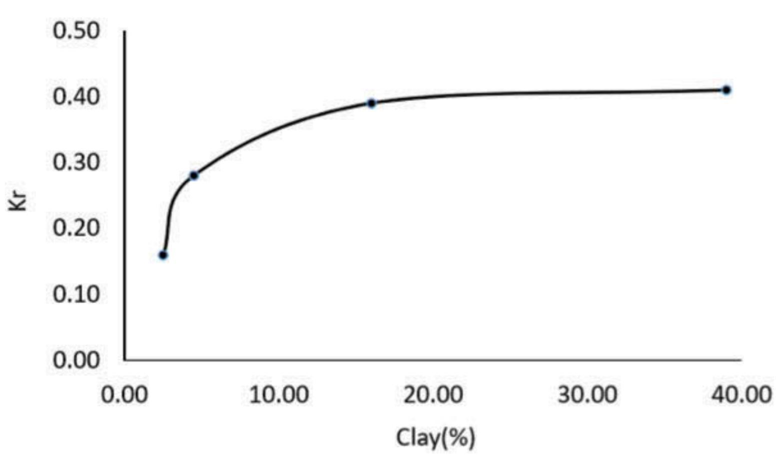
Soil type	Treated soil	Untreated soil	Improvement ratio	Test type
Soil_1	1.13E-3	2.87E-3	0.4	Constant head
Soil_2	1E-3	2.45E-3	0.41	Constant head
Soil_3	5.15E-8	3.3E-7	0.16	Falling head
Soil_5	1.8E-7	6.54E-7	0.28	Falling head

Table 3. Multi-element analysis of different soils before and after treatment with enzyme B solution using X-ray fluorescence (XRF)

Sample	Untreated Soil-2 (Sand 2)	Treated Soil-2 (sand 2)	Untreated Soil-3 (Sandy & silty clay)	Treated Soil-3 (Sandy & silty clay)	Untreated Soil-4 (clay 1)	Treated Soil-4 (clay 1)
SiO_2	65.2	71.9	35.3	40.2	47.2	48.6
Al_2O_3	2.51	1.99	12.6	13.4	13.4	14.7
Fe_2O_3	1.09	0.99	6.14	6.29	9.73	9.77
CaO	17.9	12	11.6	11.9	7.83	7.71
MgO	0.73	0.67	2.28	2.4	3.28	3.56
SO_3	3.26	3.1	11.1	7.09	0.8	0.9
Na_2O	0.63	0.47	1.27	1.47	1.1	0.9
K_2O	0.46	0.53	0.89	0.73	0.94	0.93
TiO_2	0.2	0.24	0.7	0.72	1.93	1.8
P_2O_5	0.08	0.07	0.08	0.07	0.2	0.24
Cr_2O_3	-	-	0.05	0.05	0.09	0.04
MnO	-	-	-	-	0.23	0.14
Cl^-	0.65	0.42	1.2	1.01	0.28	0.12
PdO	-	-	-	2.11	-	-
L.O.I	7.03	7.39	16.5	12.3	12.7	10.4
Total	99.79	99.81	99.71	99.73	99.71	99.81

Oxide content is according to ASTM C114–00
L.O.I: loss on ignition is according to ASTM C114–15

Figure 7. Effect of clay content on the coefficient of permeability ratio (Kr) based on results obtained by enzyme B.



coefficients of permeability of treated soils and the untreated ones. As seen in the results, the value of Kr of the treated soils increases as the clay content increases. The treatment with Enzyme-B is more efficient for fine soils and the amount of improvement increases with the increase of clay content as shown in Figure 5.

3.4. X-ray fluorescence analysis

The use of XRF method allows soil speciation and multi-element analysis. Soil speciation refers to the identification and quantification of the trace elements found in the soil. Table 3 shows the results obtained, SiO_2 recorded values for the treated and untreated samples respectively were as follow: soil-2, 65.2% and 71.9%; soil-3, 35.3% and 40.2%; soil-4, 47.2% and 48.6%. These results indicated increase in the silica content of the treated samples. The results are for soils treated with Enzyme-B preparation. This indicates the probability that Enzyme-B preparation contain silica-based additive either in organic or in inorganic form to aid in stabilization process. In literature nano-silica and silica fumes have been described as effective soil stabilizer (Bahmani, Huat, Asadi, & Farzadnia, 2014). In case of soil-2, the CaO value was higher in the untreated sample compare to the treated sample, this is probably due to local micro-environment variations in the soil type, this is verified by the CaO results obtained for the other types of the soils, soil-3 and soil-4 which showed no variation in the CaO content. The LOI—loss on ignition—values were almost similar before and after treatment, which indicates there, was no much change in the organic material remained in the treated samples compared to the untreated samples.

3.5. Notes on the enzymatic-based stabilization of soils

Enzymatic preparations commercially available in the market are labeled as safe preparations derived from natural sources, however, the exact chemical composition is not revealed for commercial reasons. It has been described in literature that the enzymatic preparations are acting on the surface properties of the soils rather than typical chemical changes and formation of new compounds as illustrated in case of other soil stabilizers (Rauch et al., 2002). For example, calcium-dependent soil stabilizers stabilize soil particles via formation of hydration products such as calcium-silicate-hydrates (C-S-H), calcium-aluminate-hydrates (C-A-H) and calcium-aluminum-silicate-hydrates (C-A-S-H). One of the theories that explain the enzymatic-based soil stabilization is the activity on the surface charges of the soil particles. Most clayey soils have a molecular structure with a net negative charge. In order to maintain the electrical neutrality, the edges and surfaces of clay particles attracts cations (positively charged). These cations are called "exchangeable cations" because in most cases cations of one type may be exchanged with cations of another type. When the cation charge in the clay structure is weak, the polarized water molecules are attracted by the remaining negative charge as well as the spaces of the clays structure is filled with ionized water. Enzymatic preparation are probably provides strong and soluble cations that can exchange with the weaker clay cations to eject the water from the clay structure. The loss of moisture leads to strengthening of the particle arrangement of the clay and also in a reduction of the particle size and plasticity in a soil as well as higher density and permanent structural change (Rauch et al., 2002). Furthermore, enzyme stabilizer improves the bonding that allows soil materials particles to become closer to each other and more densely compacted. The penetration of the enzymatic preparation active ingredients is aided by the wetting agents—the surfactants—found in the enzymatic preparations.

4. Conclusion

In this experimental study, the effect of Bio-enzymatic stabilization on the performance of five different type of soil is investigated. The selected soils represent a good wide range of particle size treated with two different enzyme types. The improvement of soil compressive strength, compaction characteristic and permeability is determined by laboratory investigations and the following conclusions can be drawn:

Enzymatic stabilization introduced a significant improvement in unconfined compressive strength and California bearing ratio. It can be noted that the fine soil is highly improved by enzyme additive when it compared by the sandy soil. For fine soil, the improvement in ratio ranges from 2.75 to 4.5 times those values observed for non-treated soil and the best concentration ratio is found to be 0.25%. Also, significant enhancement of soil permeability is achieved due to Bio-enzymatic stabilization and whereas, the coefficient of permeability of treated soil ranges from 0.4 to 0.16 times that observed for untreated soil. Furthermore, the improvement in soil strength and soil permeability increases with the increase of clay content in soil.The results showed little improvement in maximum dry density for fine soil and insignificant increase for coarse soil.

Although the enzymatic stabilization resulted a good improvement in soil strength accompanied by an enhancement in its permeability, but at the same time we emphasize that the laboratory results must be verified under real conditions in the construction site. Typical enzymatic activity that involves creation of new chemical bonds between soil particles or between soil particles and water cannot be claimed unless supported by robust experimental techniques

Acknowledgments
Initiatives and National Campaigns, Academy of Scientific Research and Technology (ASRT), 101 Kasr El-Ainy St. Cairo, 11516, Egypt, is acknowledged for funding the project titled "Low Cost Technology for Roads Construction" Contract No. 24/201, in collaboration with Beni-Suef University, PI, Dr. Yasser Gaber.

Funding
This work was supported by the Academy of Scientific Research and Technology, Egypt [24/2014].

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Competing interests
The Authors declares no conflicting of interest

Citation information
Cite this article as: Experimental evaluation of strength characteristics of different Egyptian soils using enzymatic stabilizers, Abdullah AbouKhadra, Ahmed F. Zidan & Yasser Gaber, *Cogent Engineering* (2018), 5: 1517577.

References

ASTM D-1557–03. ASTM, C. (2003). *1557–03.". Standard test method for tensile strength and young's modulus of fibers,"*. Chicago: ASTM International.

ASTM D1883–99. ASTM D 1883–99. (2002). *Standard test method for CBR (California bearing ratio) of laboratory-compacted soils* (pp. 1–8). West Conshohocken, PA: Annual Book of ASTM Standards, American Society for Testing and Materials.

ASTM D2166. ASTM, D. (2003). *2166 (2000) Standard test method for unconfined compressive strength of cohesive soil.* (4 (08)). Philadelphia: Annual book of ASTM Standards, American Society for Testing and Materials.

ASTM D2434–68. ASTM, D. (2006). 2434–68,". Test method for permeability of granular soils (Constant-head). *Annual Book of ASTM Standards*, 4, 191–195.

ASTM D-2487. ASTM D-2487. (1998). *Standard classification of soils for engineering purposes (Unified soil classification system)*. West Conshohochen, PA: American Society for testing and materials.

Bahmani, S. H., Huat, B. B., Asadi, A., & Farzadnia, N. (2014). Stabilization of residual soil using SiO_2 nanoparticles and cement. *Construction and Building Materials*, *64*, 350–359. doi:10.1016/j.conbuildmat.2014.04.086

Bryson, S., & El Naggar, H. (2013). Evaluation of the efficiency of different ground improvement techniques. In *proceeding of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*. Paris: The French Society for Soil Mechanics and Geotechnical Engineering (CFMS).

Guido, V. A., Chang, D. K., & Sweeney, M. A. (1986). Comparison of geogrid and geotextile reinforced earth slabs. *Canadian Geotechnical Journal*, *23*(4), 435–440. doi:10.1139/t86-073

Hamidi, B., Nikraz, H., & Varaksin, S. (2009). A review on impact oriented ground improvement techniques. *Australian Geomechanics*, 44(2), 17–24.

Katz, L., Rauch, A., Liljestrand, H., Harmon, J., Shaw, K., & Albers, H. (2001). Mechanisms of soil stabilization with liquid ionic stabilizer. *Transportation Research Record: Journal of the Transportation Research Board*, (1757), 50–57. doi:10.3141/1757-06

Khan, T. A., & Taha, M. R. (2015). Effect of three bioenzymes on compaction, consistency limits, and strength characteristics of a sedimentary residual soil. *Advances in Materials Science and Engineering*, *2015*, 1–9. doi:10.1155/2015/798965

Layrea, S. (2003). *Soil stabilization with permazyme 11X* (*MS Thesis*). The University of Nottingham.

Malko, J. A. C., Brazetti, R., Casagrande, M. D. T., & E Silva, B. H. D. A. (2015). Application of enzymes for stabilization of soils in paving. *Key Engineering Materials*, *668*, 150–159. doi:10.4028/www.scientific.net/KEM.668.150

Marasteanu, M. O., Hozalski, R., Clyne, T. R., & Velasquez, R. (2005). Preliminary laboratory investigation of enzyme solutions as a soil stabilizer. Retrieved from https://conservancy.umn.edu/bitstream/handle/11299/991/1/200525.pdf

Peng, H. T., Su, H. T., Zhang, X. P., & Wang, J. (2011). An experimental comparison of compressive strengths of soils stabilized with enzyme and ground quicklime. *Advanced Materials Research*, *280*, 9–12. doi:10.4028/www.scientific.net/AMR.280

Rajoria, V., & Kaur, S. (2014). A review on stabilization of soil using bio-enzyme. *International Journal of Research in Engineering and Technology*, *03*(01), 75–78. doi:10.15623/ijret.2014.0301011

Rauch, A., Harmon, J., Katz, L., & Liljestrand, H. (2002). Measured effects of liquid soil stabilizers on engineering properties of clay. *Transportation Research Record: Journal of the Transportation Research Board*, (1787), 33–41. doi:10.3141/1787-04

Renjith, R., Robert, D., Fuller, A., Setunge, S., O'Donnell, B., & Nucifora, R. (2017). Enzyme based soil stabilization for unpaved road construction. *MATEC Web of Conferences*, (138), 01002. doi:10.1051/matecconf/201713801002

Terzaghi, K., Peck, R. B., & Mesri, G. (1996). *Soil mechanics in engineering practice*. New Jersey, NJ: John Wiley & Sons.

Tingle, J., Newman, J., Larson, S., Weiss, C., & Rushing, J. (2007). Stabilization mechanisms of nontraditional additives. *Transportation Research Record: Journal of the Transportation Research Board*, (1989), 59–67. doi:10.3141/1989-49

Tingle, J., & Santoni, R. (2003). Stabilization of clay soils with nontraditional additives. *Transportation Research Record: Journal of the Transportation Research Board*, (1819), 72–84. doi:10.3141/1819b-10

Velasquez, R., Marasteanu, M. O., & Hozalski, R. (2006). Investigation of the effectiveness and mechanisms of enzyme products for subgrade stabilization. *International Journal of Pavement Engineering*, *7*(3), 213–220. doi:10.1080/10298430600574395

Venkatasubramanian, C., & Dhinakaran, G. (2011). Effect of bio-enzymatic soil stabilization on unconfined compressive strength and California bearing ratio. *Journal of Engineering and Applied Sciences*, *6*(5), 295–298.

Visser, A. (2007). Procedure for evaluating stabilization of road materials with nontraditional stabilizers. *Transportation Research Record: Journal of the Transportation Research Board*, (1989), 21–26. doi:10.3141/1989-44