Journal of Advanced Engineering Trends
ISSN : 2682 - 2091

Vol.42, No.2. July2023

http://jaet.journals.ekb.eg

Characterization of polyurethane foam conditioned sand

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ABSTRACT

In construction projects, determining the type and properties of materials is a significant aspect. Not all soil has the potential to support the structure above it. If the building is constructed on weak ground, it is at risk and susceptible to collapsing due to differential caused by the soil's poor shear strength and high compressibility. Therefore, changing soil properties to increase its engineering performance is highly required. In this research, experiments were carried out to improve the strength of sand utilizing polyurethane-resin (P.U.) as additive material conducted in this research. This research aims to investigate the effects of adding polyurethane-resin for soil shear strength, settlement, deformation modulus, and unconfined compressive strength. In this study, three types of sand were injected with Polyurethane. A plate loading test was conducted before and after polyurethane injection. The settlement, ultimate bearing capacity, and deformation modulus were determined based on the results of the plate loading test. Cylindrical samples were extracted from the injected sand mass, tested by the unconfined compressive strength test, and determined deformation modulus. For assessing the effect of polyurethane mixing ratio on shear strength parameters and unconfined compressive strength, samples with different polyurethane mixing ratios 0.5, 1, 2, and 4% by weight were prepared and tested utilizing the unconfined compressive strength and direct shear box.

Keywords: *Sand conditioning; polyurethane foam; shear strength parameters; unconfined compressive strength, settlement, deformation modulus.*

1. INTRODUCTION

Soil conditioning is defined as an artificial change in the properties of soil to improve its performance when subject to different loads[1]. Soil conditioning improves soil parameters such as shear strength and density while decreasing compressibility[2]. Several conventional methods used for soil conditioning are classified according to the material used for the conditioning process. Cement, lime, fly ash, and Blast Furnace Slags[3]. Chemical stabilization and other polymers are used in soil conditioning[4]. Fiber is the most common conditioning material that can be used to stabilize soft, expansive soils [5]. Waste cotton clothes coated with Bitumen are also used for soil stabilization[6].

Soil conditioning by injection technology is costly compared to other techniques, but it might be considered the best solution and the most effective method for existing buildings and structures[7]. Furthermore, soil injection using an expandable polyurethane is one of the most efficient modern techniques[8]. It is suitable for all soil types because it hardens quickly, is easy to inject, is the light weight of the resin, and is not affected by ground water[9]. Polyurethane resin is lightweight material; the stress-strain curve of different polyurethane samples with different densities demonstrate that increasing the density of Polyurethane increases the failure stress and modulus of elasticity while decreasing the yield strain [1, 10].

The technology was first used in (1996) by (Carlo Canteri), the founder of Uretek company in Italy[11]. This technique involves drilling a hole in the soil or foundation with a diameter ranging from 12 to 30 mm, with a steel pipe inserted into the hole, and the polyurethane components are mixed in a hydraulic pump and pumped into the steel pipe to the soil under high pressure [11-16]. Polyurethane foam (P.U.) is a polymer composed of organic units joined by carbamate compounds. It is formed by reacting tri- or

Revised:16 January, 2022, Accepted:17 February , 2022

diisocyanate with polyol [17-23]. Polyols are polymers in their nature and contain on average two or more hydroxyl groups per molecule, and come from vegetable oil, such as soybean[24, 25], castor[26, 27], palm oils[28, 29], sunflower[30, 31] and rapeseed oil (R.O.)[32-34]. The isocyanates used in the manufacturer of Polyurethane contain two or more isocyanate groups on each molecule[35-37]. The polyurethane components mixing ratio is 1:1[38, 39]. Polyurethane foam reduces settlement, lift, and improves soil bearing capacity under existing buildings and structures[9]. It strengthens soils of the roadbed of transport construction by reducing the thickness of the additional layer, preventing frost heave of the subgrade, and providing a stable water-heating regime of the subgrade [40]. In contrast, P.U. is used for improving shear strength parameters due to its outstanding properties, such as flexural strength, mechanical properties, well-sealed, and excellent abrasion resistance[41]. P.E.R.M.A.N.A., Y.M [42] conducted an experimental study on the effect of Polyurethane on volcanic sand shear strength by preparing samples with different polyurethane ratios (2%,4%, 6%, and 8 %), using direct shear test, and results were compared after (0 and 7 days). The author found that Polyurethane increases volcanic sand shear strength after 7 days by 14.91% compared to original shear strength, the strength of 0 day curing time is less than the original soil without additive material.

According to Keene, A.K et al.[43], the flexural test results for Polyurethane mechanical properties he used in his study demonstrate that Polyurethane treated ballast prevents water seepage and can withstand high loads. Compressive strength test results indicate that Polyurethane conditioned ballast has a longer life cycle than natural ballast. Sidek, N., et al. [2] conducted laboratory tests to study the mechanical properties of polyurethane-modified sand using unconfined compressive strength. Different samples were tested, and the results showed that strength of sand modified with Polyurethane is more than natural sand. Fakhar, A. and A. Asmaniza [44] conducted a laboratory tests to investigate the spread of polyurethane foam in soil voids under highways and concrete floor by injecting Polyurethane. The injected soil samples were extracted by core and laboratory investigation revealed that Polyurethane filled soil voids and swelling index was reduced. Golpazir, I., et al.[45] studied the dynamic behavior of polyurethane-sand mixture in geotechnical structures like bridge abutment, retaining walls and driven pipes, and dynamic lateral earth pressure effect. Different samples of Polyurethane- sand mixture were tested using the dynamic triaxial test, and the results showed that Polyurethane improve shear modulus of conditioned sand. The effect of increasing polyurethane ratio on shear resistance, and Polyurethane is an alternative solution to reduce dynamic lateral earth pressure. Kumar, A., et al.[46] carried out experimental work on the effect of Polyurethane on cotton soil, and test results revealed that Polyurethane increases unconfined compressive strength and California bearing ratio (C.B.R.). It filled all cotton soil voids and reduced settlement under existing structures foundations. According to Jais, I.B.M., et al.[47] using an oedometer test, polyurethane increase the compressibility factors of peat soil void ratio, compression index and swelling index.

2. Material properties

2.1. soil

In this study, three types of sandy soil were injected with polyurethane foam in the field, Brtobate-Maghagha, Village 8- El-Minia, and Mallawi-western desert road, soil properties, and soil classification according to M.I.T. is depicted in Table.1. Effective diameters can be calculated using the grain size distribution of each soil shown in Figure 1 classified with (M.I.T) system, as well as the coefficient of permeability.

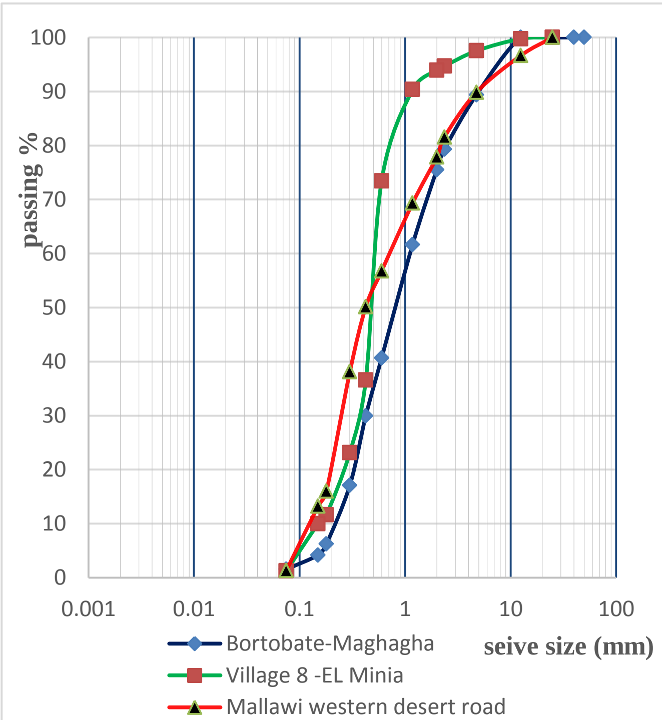

Figure 1. Grain size distribution of soils.

Table 1. Soil properties.

In-situ	Brtotabate Maghagha	Village 8-El-Minia	Mallawi -western desert road
Specific gravity	2.62	2.65	2.71
Water content %	2.0	1.20	0.70
Max. dry density(g/cm^3)	1.96	2.01	2.04
Min. dry density (g/cm^3)	1.51	1.61	1.64
Dry density (g/cm^3)	1.64	1.73	1.81
Max.Void ratio	0.735	0.646	0.65
Min. void ratio	0.34	0.32	0.33
Natural void ratio	0.596	0.532	0.50
Relative density R_D%	35.19	34.96	46.9
Soil description	Medium dense	Loose	Medium dense
Coefficient of permeability cm/sec	0.049	0.0226	0.0168
Angel of internal friction (ϕᴼ)	32.8ᴼ	28ᴼ	33.1ᴼ
D10	0.22	0.15	0.13
D30	0.44	0.36	0.256
D60	0.92	0.54	0.53
Cc	0.961	1.6	0.95
Cu	4.143	3.6	4.08
Soil classification M.I.T.	Gravelly sand trace silt	Sand some gravel trace silt	Gravelly sand trace silt

2.2. Polyurethane foam.

The properties of polyurethane foam used in this study are demonstrated in Table.2

Table 2. Properties of Polyurethane used for sand conditioning.

	polyol	isocyanate
Free density kg/m^3	80.8	
Specific gravity	1.15	1.24
Viscosity at 25ᴼ MPa.s	260	185
Cream time (sec)	50 -60	
Gel time (sec)	95-105	

2. Field tests.

Sand cone test was performed to determine the bulk unit weight of sand, water content, and, therefore, dry unit weight and void ratio. A standard plate loading test (S.P.T.) with a circular plate 300 mm diameter was conducted on each soil before and after polyurethane injection at a loading rate of 50 kpa. The bearing capacity, settlement, and the modulus of deformation are determined from the following formula[48]:

$$E = \frac{\pi . P . \alpha}{2 . S} \left(1 - \upsilon^2\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots....(1)$$

Where: E: Modulus of deformation, P: stress applied on a circular plate, α: radius of plate and υ: Poisson ratio, For sand, the Poisson ratio is taken to be in the range (0.25 -0.4) and S: settlement.

Two points were injected in each site to extract Polyurethane conditioned sand samples, and the other performed a standard plate loading test after injection. The injection setup is depicted in Figure.2. It consists of two tanks with the same volume for two polyurethane components connected from one side to a compressor and has two equal air out-lets with pressure gauge 100 bar and the other side with a pressure hose. In addition, they are connected to a pipe, which is pushed into the ground for injection. A schematic diagram for the injection setup is shown in Figure.3. The polyurethane components ratio in this study is 1: 1; consequently, each tank contains the exact weight of each polyol and isocyanates. They produce polyurethane resin with the same component mix ratio when they are mixed.

Figure 2. Polyurethane injection set up.

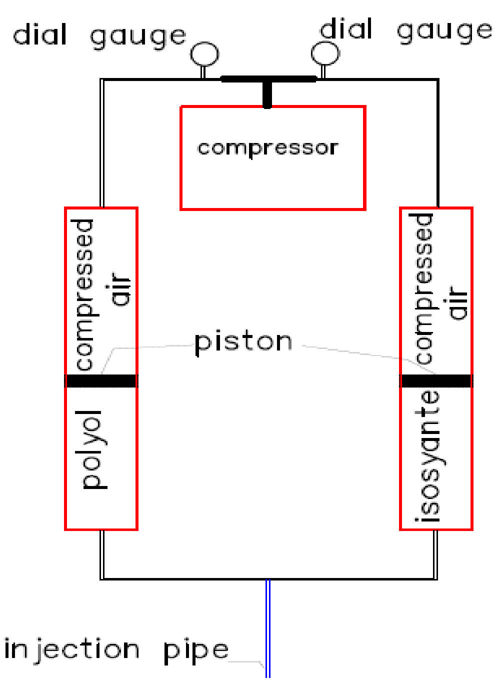

Figure 3. A schematic diagram for the injection set up..

The injection process can be illustrated as follows [9, 16, 49]; in this study, an injection pipe with a diameter of 25 mm is driven into the soil an electric drill to a depth of 1.20 m beneath the ground surface (Figure.4). The pressure tanks were connected to the injection pipe. By turning on the air compressor until the pressure is equalized in both cylinders dial gauges, the valves were opened to pump polyol and isocyanates under high pressure. Polyol and isocyanates are pumped from tanks and meet at the beginning of the injection pipe a 1:1 mixing ratio of Polyurethane. Polyurethane components are mixed in an injection pipe to produce polyurethane resin, and the pressure required to produce polyurethane grout ranges from (103-138) bar [50]. When polyurethane resin is pumped into the sandy soil, it penetrates the voids of sand particles and covers sand particles. When the polyurethane injection process is terminated, the injection pipe is extracted from sand and Polyurethane conditioned sand is left for two days to cure.

Figure 4. Electric drill to drive injection pipe into sand.

After two days, each site underwent a plate loading test to study the effect of polyurethane injection on settlement, bearing capacity, and modulus of deformation. The other point was excavated, and injected polyurethane sand mass was extracted in Figure 5. The average diameter was determined, and the Polyurethane injected sand mass was weighted to determine Polyurethane injection ratio.

Figure 5. Polyurethane injected sand mass from three sites.

4. Laboratory tests on field injected samples.

4.1 Unconfined compressive strength.

4.1.1 Sample preparation.

Sand samples and polyurethane-injected masses from each site were taken to the laboratory, where specific gravity, water content, relative density, direct shear test, and grain size distribution tests were conducted to determine the mechanical properties of natural pure sand; the results are displayed in Table.1.

Each polyurethane conditioned sand mass was brought from each site. Five cylindrical samples 40 mm diameter and 80 mm height are extracted from each mass of each site using a core machine Figure 6. Samples were tested using an unconfined compressive strength test at a low loading rate (Figure.7). The unconfined compressive strength was determined, then stress-strain curves were drawn, and the modulus of elasticity was determined and compared to the modulus of deformation value obtained from the field plate loading test.

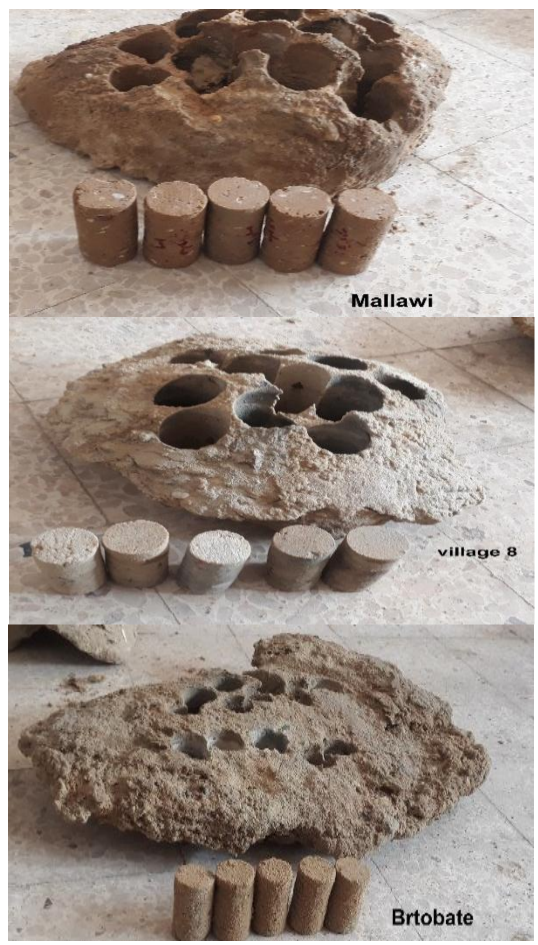

Figure 6. Cylindrical samples extracted from polyurethane conditioned masses.

The laboratory study was carried out on the sand from village 8 – El Minia to determine the optimum polyurethane injection ratio; a laboratory test was carried out on one type of sand with the results demonstrated in Table.1, mixed with various polyurethane ratios 0.5, 1, 2 and 4 % by weight. Unconfined compressive strength, shear strength parameters, and modulus of elasticity were determined to investigate the effect of polyurethane mix ratio on sand mechanical properties. For unconfined compressive strength, a two-part cylindrical mold 50 mm diameter and120 mm length is used to prepare cylindrical sand samples with the same properties as those used in the field. Samples 50 mm diameter and 100 mm height were prepared by mixing sand with various polyurethane foam ratios 0.5, 1, 2, 4%, respectively, by weight, with five samples for each mixing are prepared, and twenty samples for all of the various mixing ratios Figure.7.

Mixed sand with polyurethane well. The mixture is placed in the container in layers, and each layer is compacted so that the mixture dictates the height of the container without increasing or dipping; thus, the density of the sample is equal to the density of the specific soil in nature. The sample's surface is leveled, and the sample is left to solidify. According to the properties of Polyurethane, the polymerization process starts after the end of the cream time (40-50) seconds and reaches most of its hardening within an hour, hence the mold is removed and the sample extracted after 24 hours and left for curing at 25^{o} for two days, then it is tested using an unconfined compressive strength.

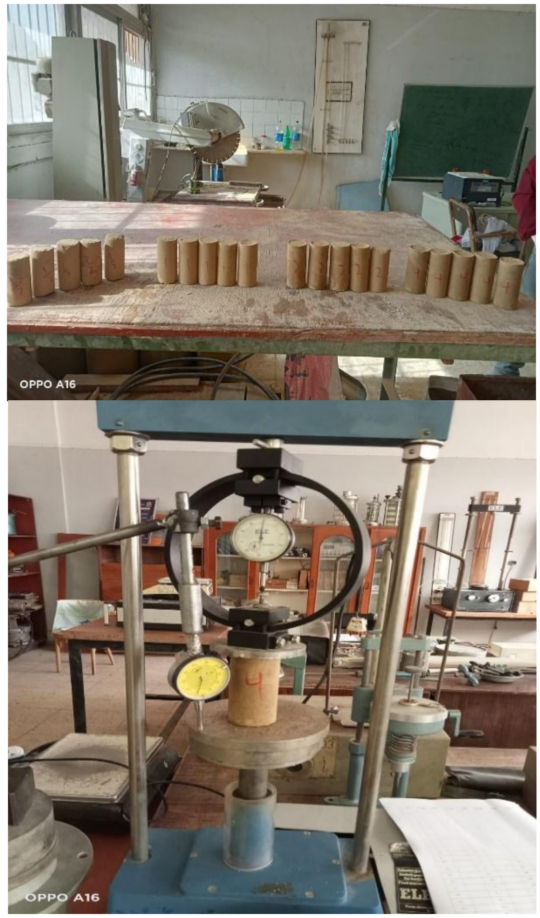

Figure 7. Sand samples with various Polyurethane mixing ratios from village 8 - El Minia site.

4.2 Direct shear test.

4.2.1 Sample preparation

Sand cubes 15 * 15 * 15 cm with the same properties as that on-site mixed with different proportions of polyurethane 0.5, 1, 2, and 4 % by weight. Each mixing ratio yielded three cubes, for a total of twelve cubes for all mixing ratios.

4.2.1 Test procedure

A device similar to the direct shear device was created, but with a larger shearing box with dimensions of 15 * 15 * 15 cm. It also consists of two parts: the lower half is installed in the table, and the upper one is movable, and on is also installed the hydraulic jack for applying load horizontally to the sample and connecting to a proving ring to read load value. Two dial gauges to read vertical and horizontal displacement and a holder with vertical loads fixed on it Figure.8.

Figure 8. Fabricated direct shear device.

For each polyurethane mixing ratio, three cubes were made. Each cube was tested under the influence of a different vertical load; the vertical load remained constant during the test. The first cube was placed in the shearing box with a vertical load equal to half of the over burden pressure. The loading is carried out by the hydraulic jack with a load of 50 kg, and the horizontal and vertical displacement were measured. Then, loading is done with 100 kg, and the reading of horizontal and vertical displacement is taken. This is performed until the sample fails, and upon collapse, the horizontal failure load is determined, and from it the horizontal failure and the vertical stress are calculated

This process is repeated with vertical stress equal to overburden pressure until failure and once more with a vertical load equal to one and a half overburden pressure.

5. Results and discussion

5.1. Field test results

5.1.1 Polyurethane injection ratio.

In this study, specific weight of 2 kg of Polyurethane is injected into each site. After two days of curing time, the Polyurethane injected mass is extracted and weighted; and the polyurethane injection ratio is calculated by the opposite weight of injected Polyurethane to the weight of the injected Polyurethane sand mass, as shown in Table.3.

Table 3. Polyurethane injection ratios.

In-situ	Brtobate - Maghagha	Village 8- el-Minia	Mallawi-western desert road
Ratio % by weight	7.9%	9.3%	10.4%
average diameter of extracted injected mass (cm)	59.5	52.3	48.7

Brtobate – Maghagha sand is characterized by a high void ratio, so when Polyurethane is injected, it spreads more widely and has a greater mass compared to the other two sites, as evidenced by the diameter and thickness of the extracted injected mass, where it appears that the spread more horizontal than vertical. With respect to Village 8 -El Minia, the void ratio is low, consequently Polyurethane spreads less, and the spread is horizontal and vertical. This is demonstrated by the thickness and diameter of the extracted injected mass that are smaller than the diameter of the Bretobe – Maghagha, but thicker. Mallawi western desert road has the lowest void ratio and fine grains; hence, Polyurethane spreads less, and the spread was horizontal and vertical, resulting in a smaller mass than at the

Bretobe – Maghagha and Village 8 -ElMinia sites.

5.1.2 Settlement and bearing capacity

Standard plate loading test (S.P.T.) results for Brtobate – Maghagha site under stress loading of 50 kpa up to 1000 kpa before and after polyurethane injection are shown in Figure.9. Revealed that at the natural case, the settlement increased by elevating the applied stress until it reached 18.41 mm at applied stress 1000 kpa. At the test's beginning, the settlement is 0.25 mm under applied stress 50 kpa. The increase in applied stress is offset by a slight increase in stability up to stress 450 kpa. At stress of 500 kpa, sand fails and the corresponding settlement increases to 5.91mm. Consequently, failure occurs at a stress of 450 kpa, corresponding to settlement 4.49 mm and the maximum bearing capacity is 450 kpa.

When polyurethane was injected, settlement increases with increasing applied stress but with small values than normal conditions. At stress 50 kpa, settlement is 0.19 mm compared to its value of 25 mm in the natural case. Moreover, settlement increases with increased applied stress until reaching 6.57 at applied stress 1000 kpa. That means polyurethane reduces settlement at 1000 kpa by 64.3 %. At stress 450 kpa, the settlement is 2.16 mm in the conditioned case compared to 4.49 mm in the natural case; Hence, at the same stress 450 kpa, settlement reduces by 51.89%. It should be noted that conditioned sand is loaded until stress reaches 1000 kpa and failure does not occur, which proves that conditioned sand does not reach its maximum bearing capacity.

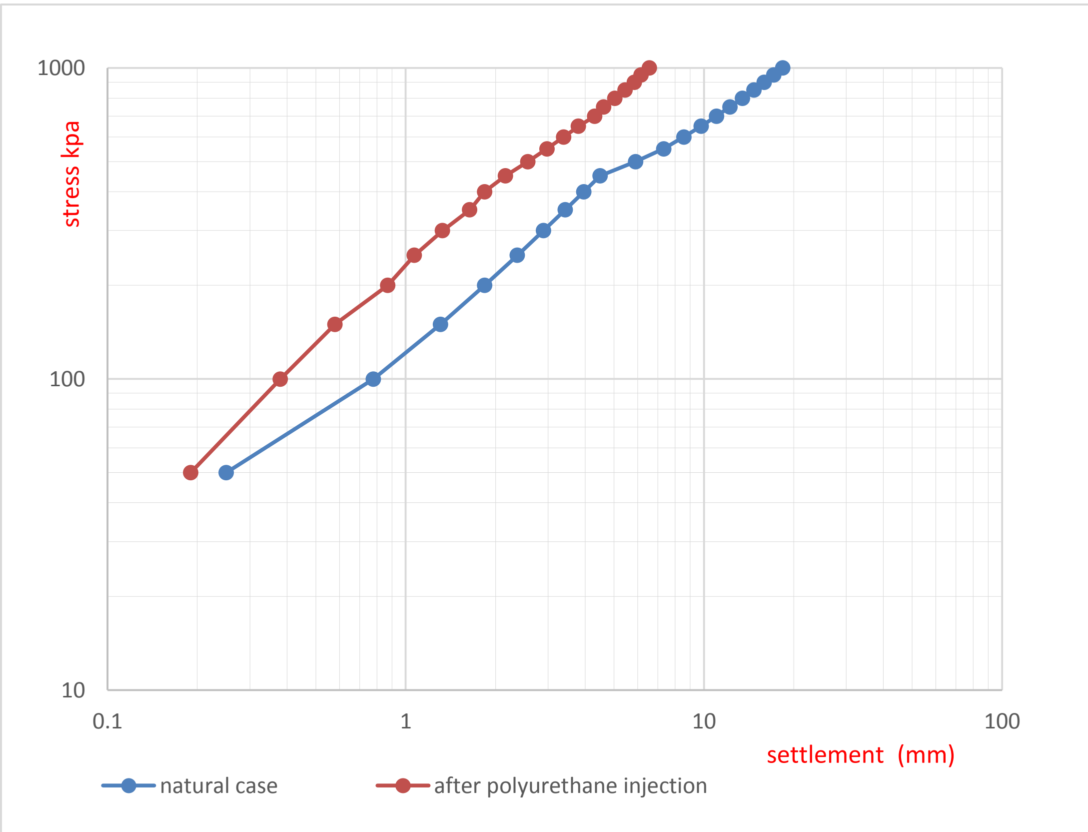

Figure 9. Stress - settlement curve for Brtobate- Maghagha site with PU injection ratio 7.9 %.

Similarly, (S.P.T.) tests were carried out on the other two sites, similar results to that for Brtobate – Maghagha site were obtained. Figures. 10, 11 show that in natural case, the maximum bearing capacity for Village 8 - ElMinia site is 600 kpa corresponds to settlement 2.66 mm and 650 kpa corresponds to settlement 1.89 mm for Mallawi western desert road site.

When polyurethane was injected, conditioned sand of two sites are loaded until stress reaches to 1000 kpa and failure does not occur, which prove that conditioned sand of the two sites does not reach its maximum bearing capacity. At stress 1000 kpa, Settlement reduces by 68.87 % for Village 8 - ElMinia site and 67.68 % for Mallawi western desert road site compared with natural case. At maximum bearing capacity, settlement reduces by 36.84 % for Village 8 – El Minia site and 21.7 % for Mallawi western desert road site compared with natural case.

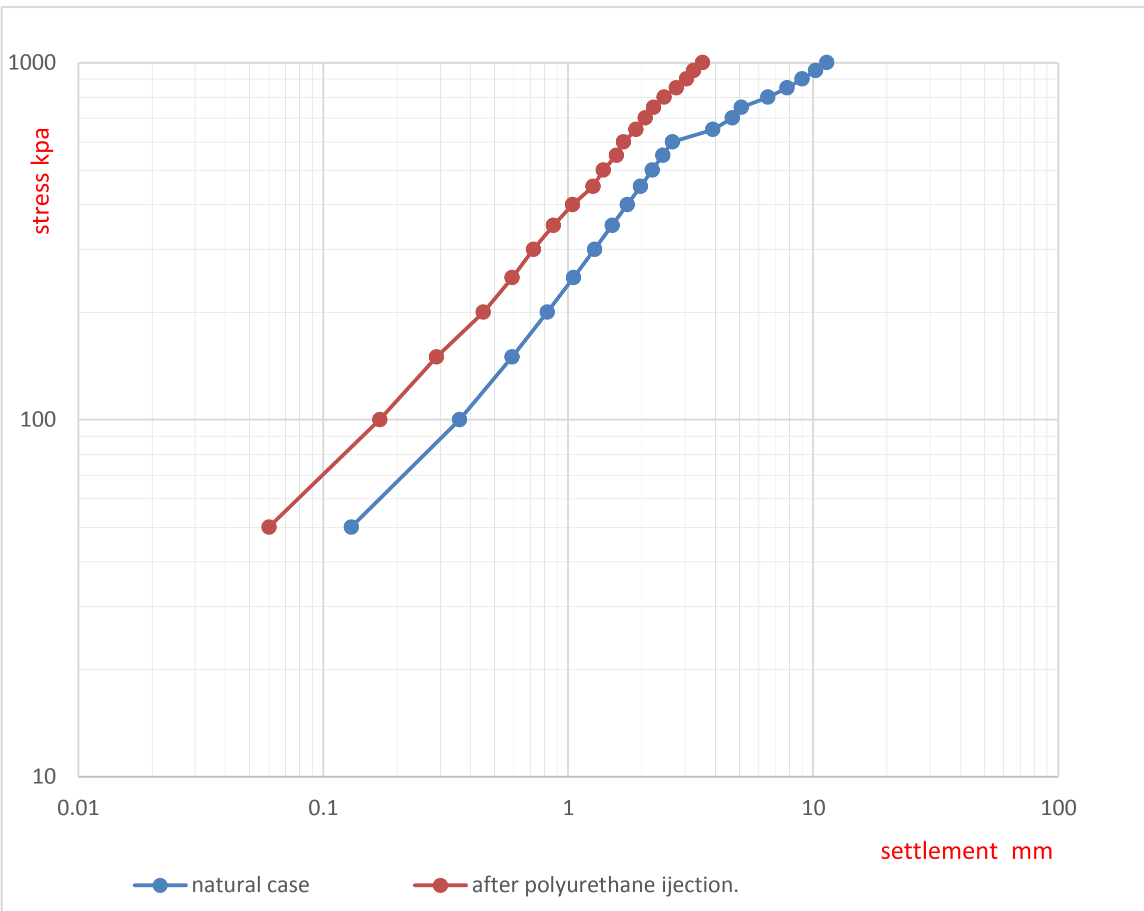

Figure 10. Stress - settlement curve for Village 8 - El Minia. site with PU injection ratio 9.3 %.

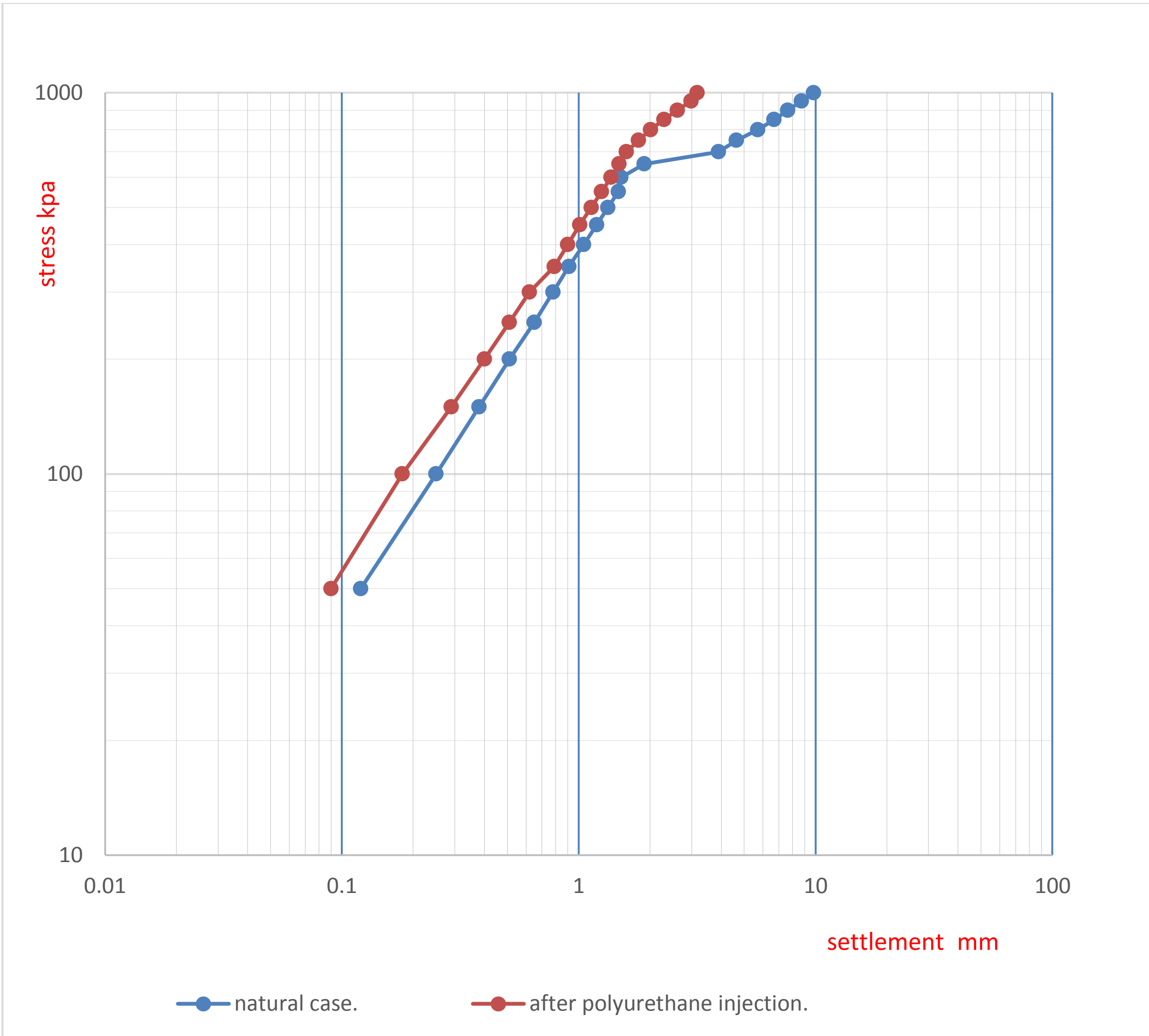

Figure 11. Stress - settlement curve for Mallawi western desert road site with PU injection ratio 10.4 %.

5.1.3 Modulus of deformation and unconfined compressive strength for extracted samples.

Unconfined compressive strength and modulus of deformation at failure of extracted samples for each site is given in Table. 4. For Brtobate – Maghagha, the average value for five samples is 1923.58 kpa with average strain at failure of 5.31 % For Village 8 – El Minia, the average unconfined compressive value for five samples is 3980.48 kpa with an average strain at failure 6.47 %, For Mallawi western desert road, the average unconfined compressive value for five samples is 4044.43 kpa with an average strain at failure of 4.27 %. Figures. 12, 13, 14 show the stress- strain curves for samples extracted from different study sites.

Table 4. The unconfined compressive strength and modulus of deformation results of extracted samples from injected polyurethane masses for different sites.

sample	Brtobate- Maghagha			Village 8- El Mania			Mallawi – western desert road		
	q_{max} kpa	Strain at failure %	Modulus of deformation at failure Mpa	q_{max} kpa	Strain at failure %	Modulus of deformation at failure Mpa	q_{max} kpa	Strain at failure	Modulus of deformation at failure Mpa
1	1849.3	3.88	47.66	3728.44	6.125	60.87	4093	4.425	92.50
2	1812.05	5.2	34.85	3803.01	5.625	67.60	4101.28	4.487	91.40
3	2046.92	6.23	32.85	3933.51	6.67	58.97	3985.7	4.075	97.81
4	1964.89	5.54	35.47	4231.78	7.12	59.43	4049	4.31	93.94
5	1994.78	5.73	34.81	4205.668	6.8	61.80	3993.16	4.07	98.11

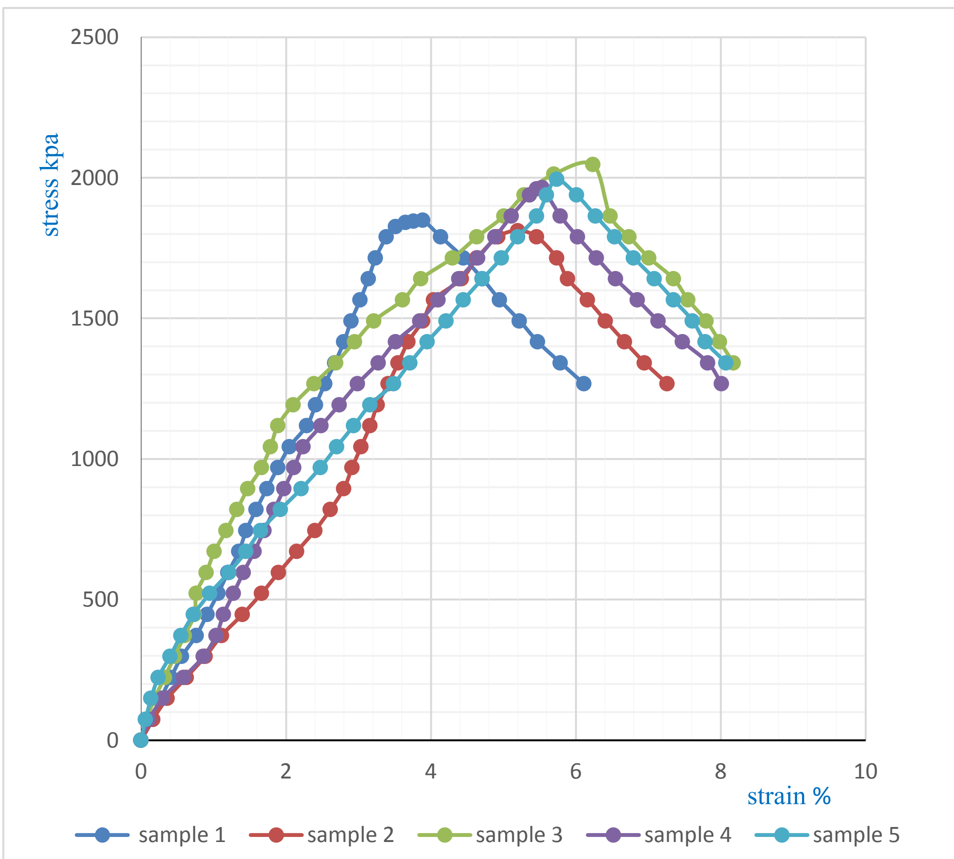

Figure 12. Stress- strain curve of Brtobate - Maghagha samples with PU injection ratio 7.9%.

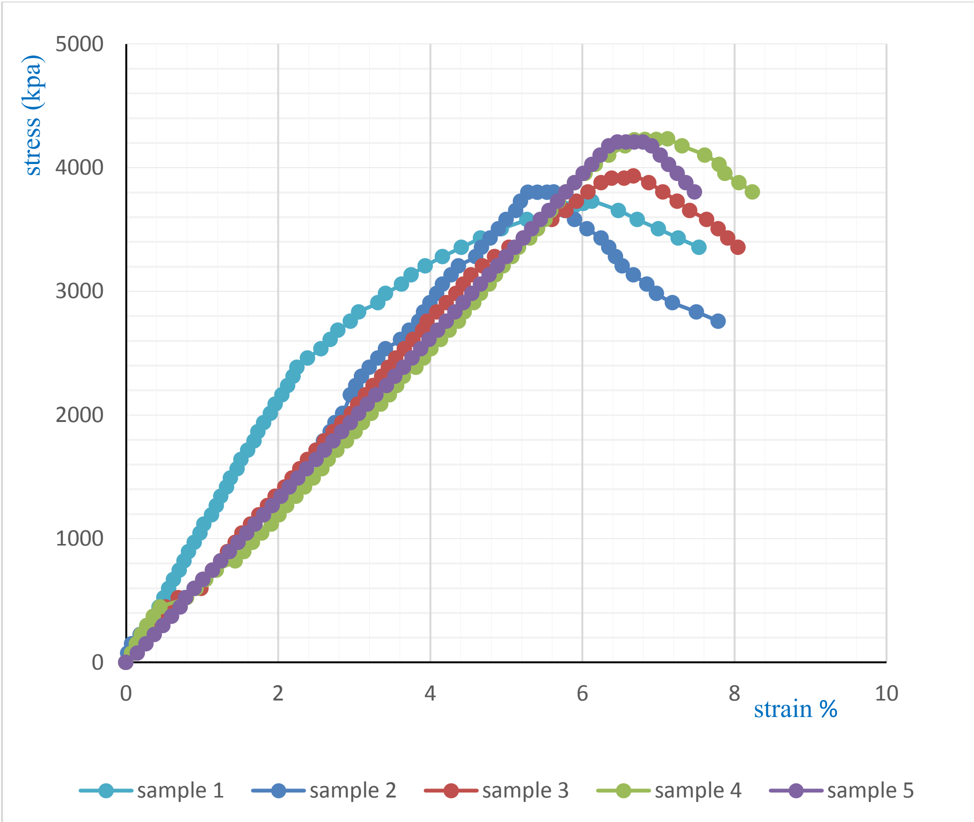

Figure 13. Stress strain curve of Village 8 - El Minia samples with PU injection ratio 9.3%..

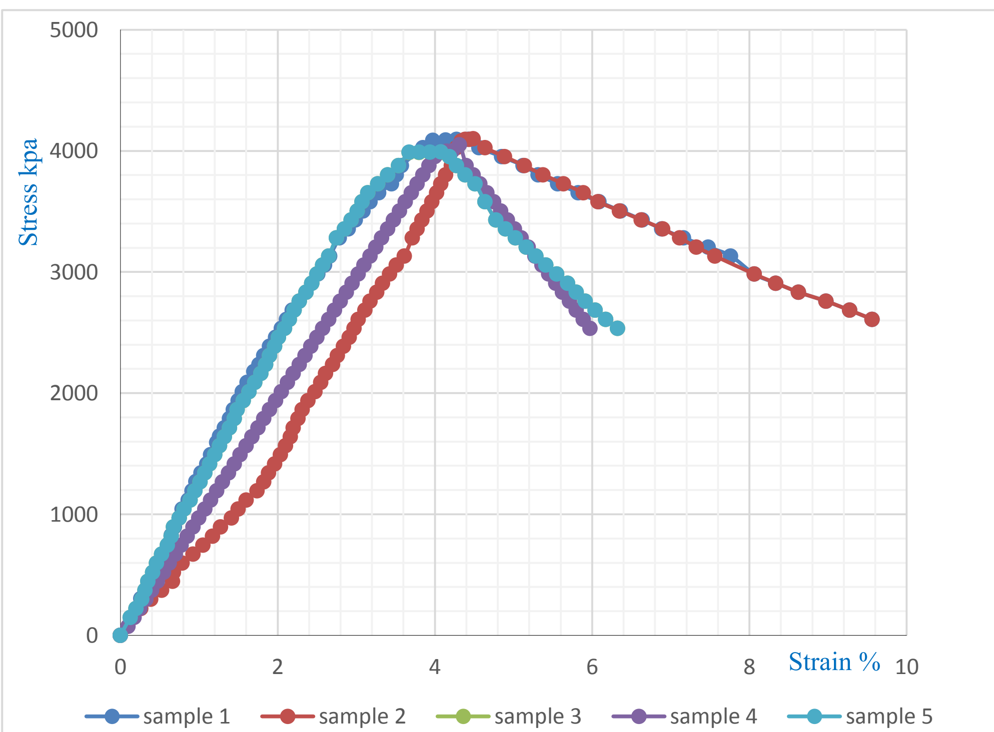

Figure 14. Stress strain curve of Mallawi - western desert road samples with PU injection ratio 10.4%.

5.1.4 Modulus of deformation from plate loading test.

In the field, the modulus of deformation is calculated at maximum bearing capacity of each soil before and after polyurethane injection from equation.1. At laboratory modulus of deformation is determined based on the unconfined compressive strength test and compared to the modulus of deformation after polyurethane injection; Table. 5 shows values of modulus of deformation and modulus of elasticity for different sites.

5.2. Laboratory tests results on conditioned samples.

5.2.1Modulus of deformation and Unconfined compressive strength.

Laboratory study results of sand samples from Village 8 – El Minia with different polyurethane mix ratios (P.U.) to determine the polyurethane injection ratio that gives required compression strength and shear strength parameters. Unconfined compressive strength, strain and modulus of deformation at failure are given in Table.6.

Table 5. Modulus of deformation from unconfined compressive strength vs field plate loading test at ultimate bearing capacity.

In-situ	Ultimate bearing capacity at natural case from plate loading test (kpa)	Field Modulus of deformation at ultimate bearing capacity		Laboratory Modulus of deformation at ultimate bearing capacity Mpa
		Natural case Mpa	After polyurethane conditioning Mpa	
Brtobate – Maghagha	450	21.498	44.67	45.83
Village 8 – El Minia	600	48.36	76.58	80.79
Mallawi western desert road	650	73.74	94.17	101.23

Table 6. The average unconfined compressive strength, strain and modulus of deformation at failure of conditioned samples with various polyurethane mix ratios of Village 8 -El Minia site.

P.U. %	q_{max} kpa	Strain % at failure	Modulus of deformation at failure Mpa
0	----	---	31
0.5	248.08	0.65	39.41
1	489.49	0.91	55.1
2	1196.10	1.65	73.47
4	2520.98	2.65	95.39

Figure.15, 16, 17,18. demonstrate the stress strain curve for samples with various PU mix ratios. Increase in polyurethane mix ratio increase unconfined compressive strength and increase modulus of deformation as shown in Figure.20.

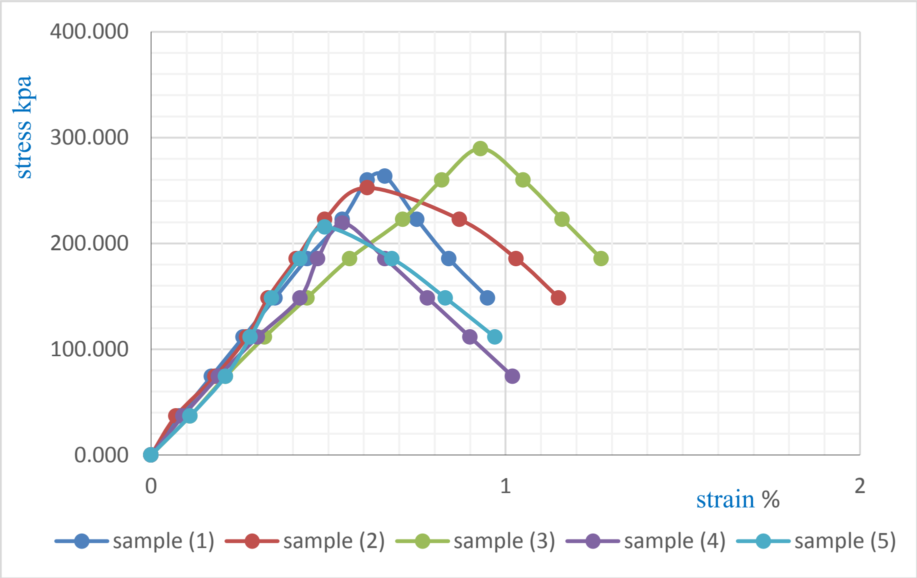

Figure 15. The unconfined compressive strength- strain results of Village 8 -El Minia samples with a P.U. mix ratio of 0.5 %.

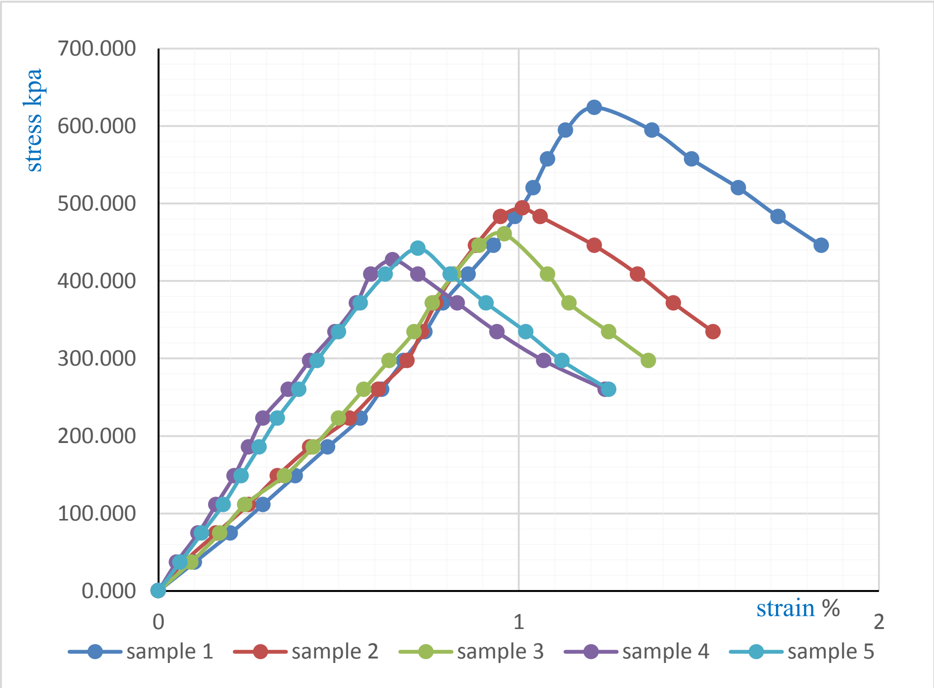

Figure 16. The unconfined compressive strength- strain results of Village 8 -El Minia samples with a P.U. mix ratio of 1.0 %.

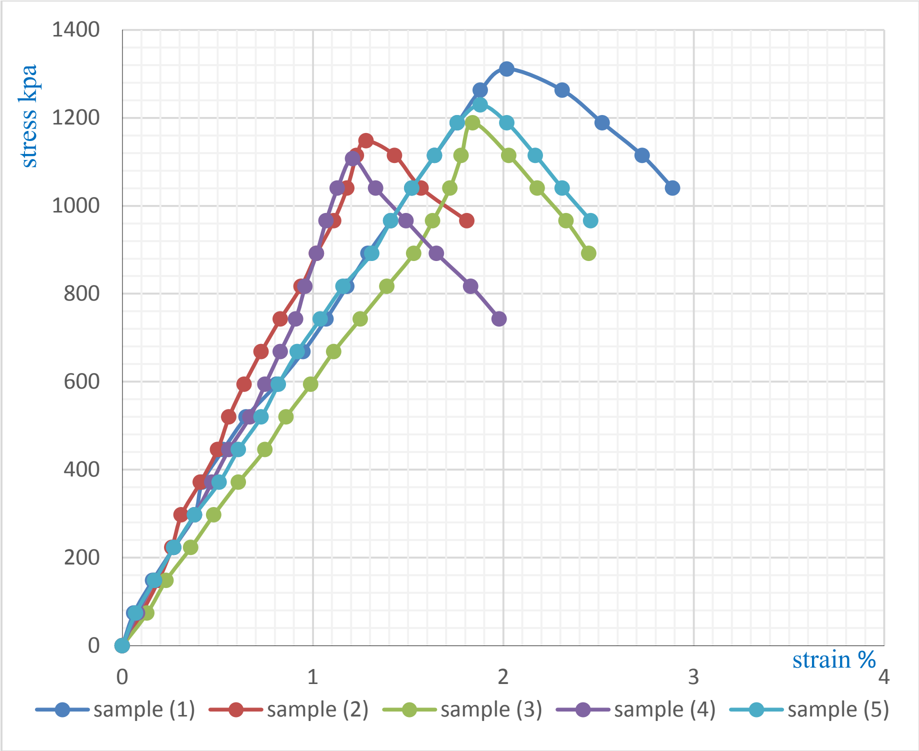

Figure 17.The unconfined compressive strength- strain results of Village 8 -El Minia samples with a P.U. mix ratio of 2.0 %.

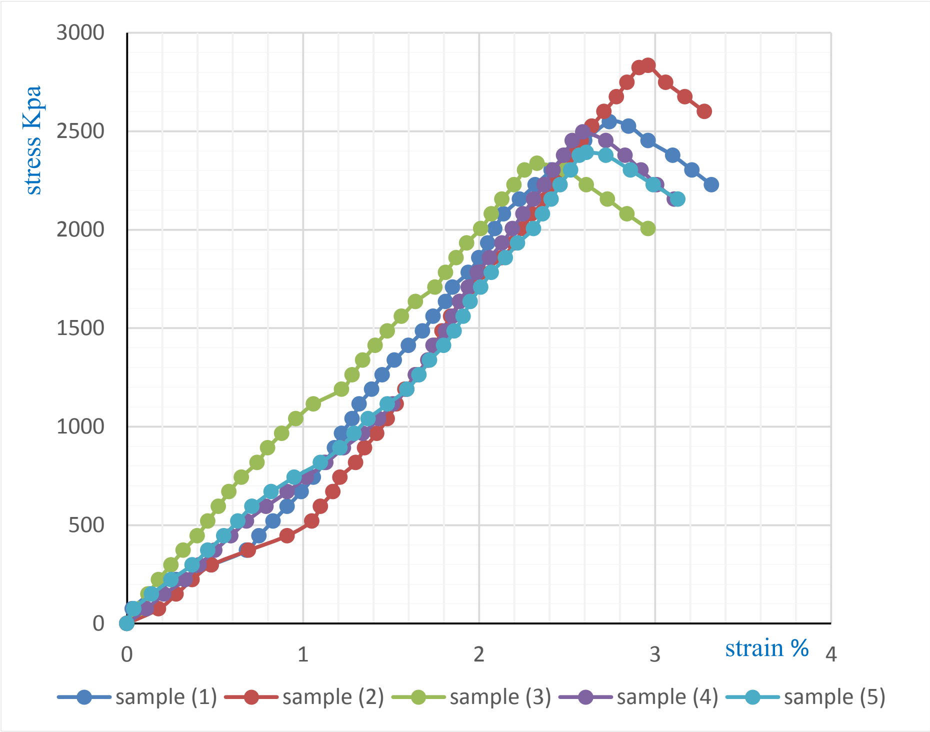

Figure 18. The unconfined compressive strength- strain results of Village 8 -El Minia samples with a P.U. mix ratio of 4.0 %

5.2.2 Shear strength parameters

Table.7 shows shear strength parameters of conditioned sand with different P.U. % mix ratios obtained from direct shear test. It is noted that increasing the polyurethane mixing ratio PU% increases cohesion but has slightly effect on the internal angle of friction as shown in Figure.19

5.2.3 Optimum polyurethane injection ratio.

From laboratory tests, It is possible to obtain the optimum polyurethane injection ratio, That achieves the required strength and deformation modulus of sand from Figure.20, which can be expressed by the following two equations:

$$q_{max} = 29.3(PU\%)^2 + 515.16\ PU\ \%$$

$$E_{def} = -2637.7(PU\%)^2 + 27056(PU\%) + 29501$$

Where: qmax :unconfined compressive strength of sand (kpa), Edef: deformation modulus of sand (kpa) and PU%:polyurethane injection ratio.

Table 7. The shear strength parameters of Village 8 - El Minia samples were conditioned with different PU% mix ratios.

Polyurethane ratio %	Shear strength parameters Angle of internal friction φ^0	Cohesion C Kpa
0	28.1^0	-----
0.5	28.49^0	90.68
1	28.49^0	199.68
2	28.48^0	472.18
4	28.34^0	1060.80

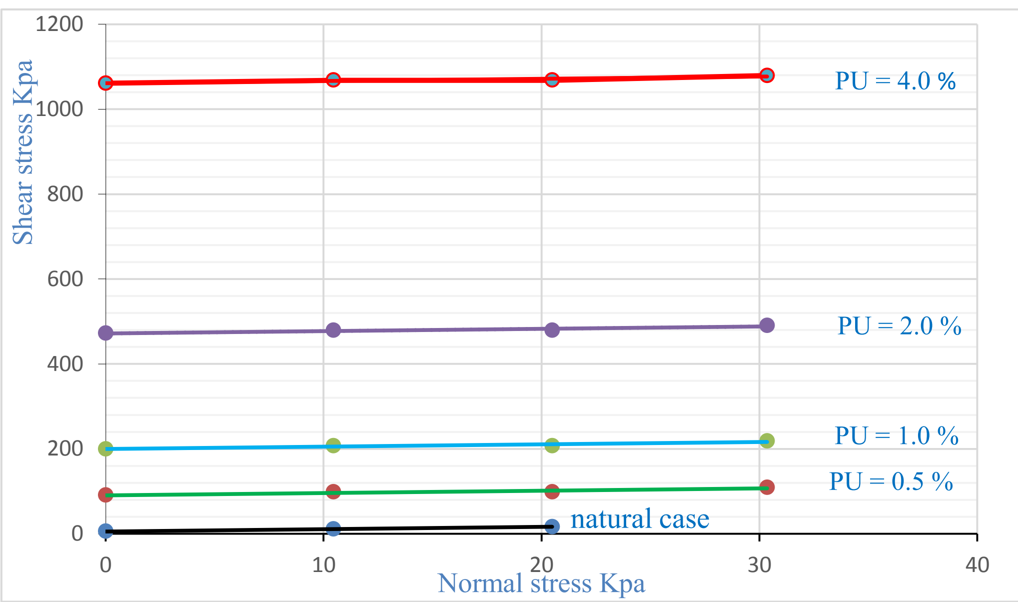

Figure 19. Shear strength parameters of Village 8 - El Minia conditioned samples with different PU% mix ratios.

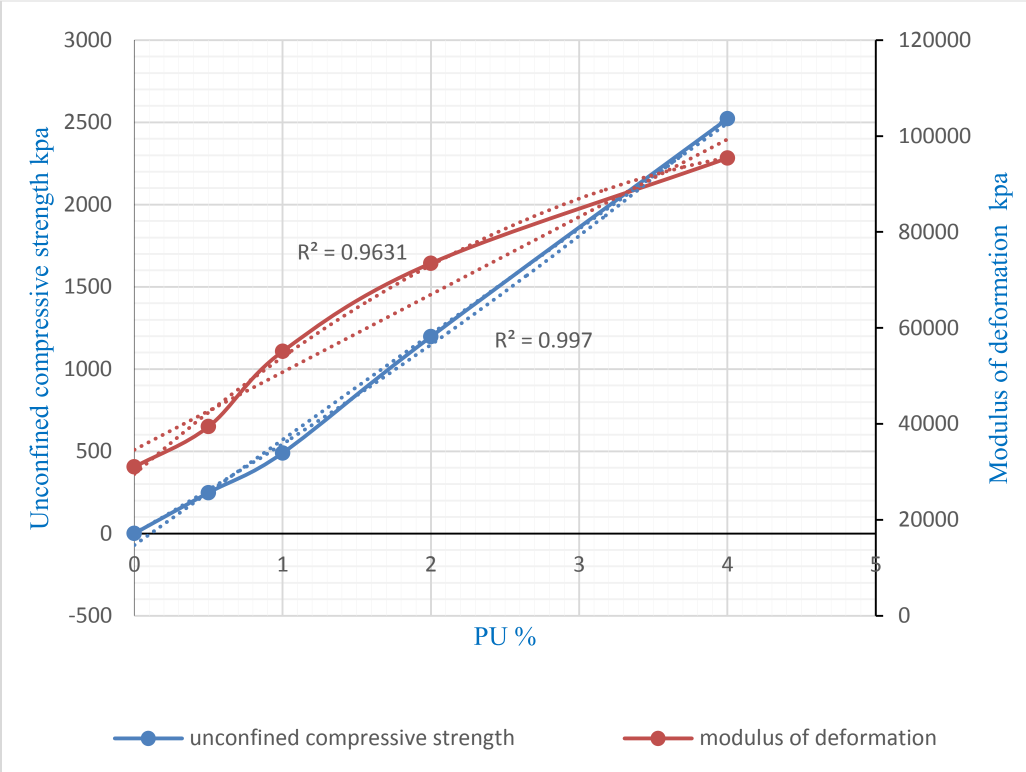

Figure 20. Unconfined compressive strength and modulus of deformation for Village 8 - El Minia conditioned samples with different PU % mix ratios.

6. CONCLUSION

From polyurethane foam field injection:

1. The lower voids in the soil, the higher pressure is required to inject Polyurethane, and the larger the voids in the soil, the Polyurethane is distributed horizontally. It is detected by the average diameter of each mass of the three locations.

2. Polyurethane reduces settlement; whenever the void ratio is high, the Polyurethane fills and expands inside, and consequently, the decrease in the settlement is high and requires a low injection ratio. At the ultimate bearing capacity, Brtobat – Maghagha site settlement reduces by 51.89%, Village 8 – El Minia settlement reduces by 36.84 %, and Mallawi western desert road by 21.7 % compared to the natural case.

3. Polyurethane increases the deformation modulus. From the plate loading test before and after polyurethane injection at ultimate bearing capacity, 51.84% for Brtobate – Maghagha site, by 58.33% for Village 8 – El Minia and by 27.7 % for Mallawi western desert road as compared to the natural case.

4. For three sites after polyurethane injection, the ultimate bearing capacity increases up to 1000 kpa compared to its value in the natural case. Nevertheless, the unconfined compressive strength showed that Polyurethane significantly improved the soil strength with deformation modulus, whose value is close to the value obtained at the site.

According to laboratory tests, by preparing samples with different polyurethane mix ratios:

1. Polyurethane increases cohesion from 90.68 kpa at a polyurethane mix ratio of 0.5% to 1060.80 at a polyurethane mix ratio 4.0 % with a slight increase in the angle of internal friction.
2. The increase in polyurethane foam mix ratio increases unconfined compressive strength from 248.08 kpa at a polyurethane mix ratio of 0.5% to 2520.98 kpa at a polyurethane mix ratio 4.0 with increasing the modulus of deformation at failure from 39.41 Mpa polyurethane mix ratio 0.5% to 95.39 Mpa polyurethane mix ratio 4.0 %.

References

1. Sabri, M.M.S., N.I. Vatin, and K.A.M. Alsaffar, *Soil Injection Technology Using an Expandable Polyurethane Resin: A Review.* Polymers, 2021. **13**(21): p. 3666.
2. Sidek, N., et al. *Strength characteristics of Polyurethane (P.U.) with modified sand*. in *Applied Mechanics and Materials*. 2015. Trans Tech Publ.
3. Makusa, G.P., *Soil stabilization methods and materials in engineering practice: State of the art review.* 2013.
4. Huang, J., et al., *A state-of-the-art review of polymers used in soil stabilization.* Construction and Building Materials, 2021. **305**: p. 124685.
5. Puppala, A., et al., *Fiber and fly ash stabilization methods to treat soft expansive soils*, in *Soft ground technology*. 2001. p. 136-145.
6. Wagare, P., S. Sutar, and S. Virapannanavar, *Soil Stabilization using Waste Cotton Clothes Coated with Bitumen.*
7. Nicholson, P.G., *Soil improvement and ground modification methods*. 2014: Butterworth-Heinemann.
8. Sabri, M.M.S. and K.G. Shashkin, *Subsoil Stabilized by Polyurethane Resin Injection: F.E.M. Calculation.* Construction of Unique Buildings and Structures, 2020. **91**(6): p. 9108-9108.
9. Sabri, M.M., et al., *Soil stabilization and foundation restoration using an expandable polyurethane resin.* Инженерно-строительный журнал, 2018(6): p. 68-80.
10. Saha, M., et al., *Effect of density, microstructure, and strain rate on compression behavior of polymeric foams.* Materials Science and Engineering: A, 2005. **406**(1-2): p. 328-336.
11. Niederbrucker, R., W. Wu, and A. Pasquetto, *Flat Dilatometer Tests for verification of Uretek's Resin-Injektions.* 2015.
12. Buzzi, O., S. Fityus, and S.W. Sloan, *Use of expanding polyurethane resin to remediate expansive soil foundations.* Canadian Geotechnical Journal, 2010. **47**(6): p. 623-634.
13. Sabri, M.M. and K. Shashkin, *Improvement of the soil deformation modulus using an expandable polyurethane resin.* Magazine of Civil Engineering, 2018(7).
14. Sabri, M. and K. Shashkin, *The mechanical properties of the expandable polyurethane resin based on its volumetric expansion nature.* Magazine of Civil Engineering, 2020(6): p. 9811-9811.
15. Popik, M., M. Trout, and R.W. Brown. *Improving soil stiffness beneath pavements using polyurethane injection*. in *Annual Conference of the Transportation Association of Canada*. 2010.
16. Sánchez, F.E., et al., *Underpinning of shallow foundations by expansive*

polyurethane resin injections. Case study: Cardinal Diego de Espinosa Palace in Segovia (Spain). Revista de la Construcción. Journal of Construction, 2017. **16**(3): p. 420-430.
17. Sharmin, E. and F. Zafar, *Polyurethane: an introduction.* Polyurethane, 2012: p. 3-16.
18. Tan, S., et al., *Rigid polyurethane foams from a soybean oil-based polyol.* Polymer, 2011. **52**(13): p. 2840-2846.
19. Sidek, N., et al. *Strength characteristic of Polyurethane with variation of polyol to isocyanate mix ratio: A numerical analysis*. in *2017 IEEE 2nd International Conference on Automatic Control and Intelligent Systems (I2CACIS)*. 2017. IEEE.
20. Adetunji, C.O., et al., *Environmental Impact of Polyurethane Chemistry.* Polyurethane Chemistry: Renewable Polyols and Isocyanates, 2021: p. 393-411.
21. Zafar, F. and E. Sharmin, *Polyurethane*. 2012: BoD–Books on Demand.
22. Thirumal, M., et al., *Mechanical, morphological and thermal properties of rigid polyurethane foam: effect of the fillers.* Cellular Polymers, 2007. **26**(4): p. 245-259.
23. Ivdre, A., et al., *Rigid polyurethane foams with various isocyanate indices based on polyols from rapeseed oil and waste P.E.T.* Polymers, 2020. **12**(4): p. 738.
24. Mizera, K. and J. Ryszkowska, *Polyurethane elastomers from polyols based on soybean oil with a different molar ratio.* Polymer Degradation and Stability, 2016. **132**: p. 21-31.
25. Ji, D., et al., *Polyurethane rigid foams formed from different soy-based polyols by the ring opening of epoxidised soybean oil with methanol, phenol, and cyclohexanol.* Industrial crops and products, 2015. **74**: p. 76-82.
26. Ionescu, M., et al., *Highly functional polyols from castor oil for rigid polyurethanes.* European Polymer Journal, 2016. **84**: p. 736-749.
27. Zhang, M., et al., *study of the mechanical, thermal properties and flame retardancy of rigid polyurethane foams prepared from modified castor-oil-based polyols.* Industrial Crops and Products, 2014. **59**: p. 135-143.
28. Tanaka, R., S. Hirose, and H. Hatakeyama, *Preparation and characterization of polyurethane foams using a palm oil-based polyol.* Bioresource technology, 2008. **99**(9): p. 3810-3816.
29. Ng, W.S., et al., *Preparation and modification of water-blown porous biodegradable polyurethane foams with palm oil-based polyester polyol.* Industrial Crops and Products, 2017. **97**: p. 65-78.
30. Omrani, I., et al., *Synthesis of novel high primary hydroxyl functionality polyol from sunflower oil using thiol-yne reaction and their application in polyurethane coating.* European Polymer Journal, 2016. **82**: p. 220-231.
31. Das, B., et al., *Sunflower oil based biodegradable hyperbranched polyurethane as a thin film material.* Industrial Crops and Products, 2013. **44**: p. 396-404.
32. Zieleniewska, M., et al., *Preparation and characterisation of rigid polyurethane foams using a rapeseed oil-based polyol.* Industrial Crops and Products, 2015. **74**: p. 887-897.
33. Kurańska, M. and A. Prociak, *The influence of rapeseed oil-based polyols on the foaming process of rigid polyurethane foams.* Industrial Crops and Products, 2016. **89**: p. 182-187.
34. Kuraska, M., *The influence of rapeseed oil-based polyols on the foaming process of rigid polyurethane foams.* 2015.
35. Saunders, J. and R. Slocombe, *The chemistry of the organic isocyanates.* Chemical reviews, 1948. **43**(2): p. 203-218.
36. Wenk, K.S. and A. Ehrlich, *Isocyanates.* Dermatitis, 2012. **23**(3): p. 130-131.

37. Brochhagen, F., *Isocyanates*, in *Anthropogenic Compounds*. 1991, Springer. p. 1-95.
38. Sidek, N., et al., *Polyurethane Foams in Soil Stabilization: A Compressibility Effect*, in *InCIEC 2015*. 2016, Springer. p. 369-377.
39. Komurlu, E. and A. Kesimal, *Experimental study of polyurethane foam reinforced soil used as a rock-like material.* Journal of Rock Mechanics and Geotechnical Engineering, 2015. **7**(5): p. 566-572.
40. Polyntsev, E. and A. Kvitko. *Using foam polyurethane sealers for strengthening of soils of a road bed of transport constructions*. in *I.O.P. Conference Series: Materials Science and Engineering*. 2020. I.O.P. Publishing.
41. Hu, X., D. Wang, and W. Cheng, *Effect of dosage of expandable graphite, dimethyl methylphosphonate, triethanolamine, and isocyanate on fluidity, mechanical, and flame retardant properties of polyurethane materials in coal reinforcement.* International Journal of Mining Science and Technology, 2016. **26**(2): p. 345-352.
42. P.E.R.M.A.N.A., Y.M., *SHEAR STRENGTH OF POLYURETHANE-RESIN STABILIZED VOLCANIC SAND*. 2016, U.A.J.Y.
43. Keene, A.K., et al. *Characterization of polyurethane-stabilized ballast*. in *3rd International Conference on New Developments in Soil Mechanics and Geotechnical Engineering, Nicosia, North Cyprus*. 2012.
44. Fakhar, A. and A. Asmaniza. *Road maintenance experience using Polyurethane (P.U.) foam injection system and geocrete soil stabilization as ground rehabilitation*. in *I.O.P. Conference Series: Materials Science and Engineering*. 2016. I.O.P. Publishing.
45. Golpazir, I., et al., *Dynamic properties of Polyurethane foam-sand mixtures using cyclic triaxial tests.* Construction and Building Materials, 2016. **118**: p. 104-115.
46. Kumar, A., et al., *Experimental Investigation on the Effect of Polyurethane Foam on Black Cotton Soil.* Trends in Civil Engineering and Challenges for Sustainability, 2021: p. 421-432.
47. Jais, I.B.M., D.C. Lat, and T.N.D.T. Endut, *Compressiblity of peat soil improved with Polyurethane.* Malaysian Journal of Civil Engineering, 2019. **31**(1).
48. Pantelidis, L., *Determining of the soil strength characteristics through the plate bearing test.* Foundations of civil and environmental engineering, 2008. **11**: p. 55-65.
49. Bodi, J., et al., *Polyurethane grouting technologies.* Polyurethane, 2012: p. 307-337.
50. Mohamed Jais, I.B., *Rapid remediation using polyurethane foam/resin grout in Malaysia.* Geotechnical Research, 2017. **4**(2): p. 107-117.