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Effect of Wet and Dry Conditions on Strength of Silty Sand Soils Stabilized with Epoxy Resin Polymer

Seyed Abolhassan Naeini and Masoud Ghorbanalizadeh
Department of Civil Engineering, Imam Khomeini International University,
P.O. Box 288, Ghazvin, Postal Code 34149-16818, Iran

Abstract: This study reports on a laboratory experiment conducted to evaluate the stabilization of a silty-sand (SM) material with epoxy resin and effect of wet and dry conditions on strength of stabilized silty sand. The additive mixture was composed of a 1:0.15 of epoxy resin to polyamide hardener. Specimens were prepared by adding different amount of epoxy resin polymer emulsion (3, 4 and 5%) to silty sand with (0, 10, 20, 30, 35, 45 and 60%) silt content at dry density of 17 kN m^{-3}. The unconfined compressive strength of specimens determined with uniaxial test and compared to each other under the same mixing, compaction and curing condition to derivation the effect of polymer emulsion on silty sand. All specimens submerged in water for 24, 96 and 168 h and then taken out from the water and their unconfined compressive strength were recorded. The results of this study indicated that the addition of epoxy resin improves significantly the compressive strength and modulus of elasticity of samples under dry condition. This improvement depends on the content of polymer and silt. However, polymer significantly enhanced the strength of the samples after 7 days of submerging in water but strength of wet samples is less than the dry samples.

Key words: Mechanical properties, epoxy resin, modulus of elasticity, submerge, curing time, silty sand

INTRODUCTION

The alteration of soil property to improve its engineering performance is known as soil stabilization (Lambe and Whitman, 1979). The main soil properties of concern in soil stabilization are mechanical properties, permeability, volume stability and durability. Construction of buildings and other civil engineering structures on weak or soft soil is highly risky because such soil is susceptible to differential settlements due to its poor shear strength and high compressibility. Improvement of certain desired properties like bearing capacity, shear strength (c and Ø) and permeability characteristics of soil can be undertaken by a variety of ground improvement techniques such as the use of prefabricated vertical drains or soil stabilization. We have two type of stabilization; Traditional and Non-traditional stabilization. Traditional stabilization methods include the application of various combinations of lime, cement, fly ash and bituminous materials. These traditional stabilization techniques often require lengthy cure times and relatively large quantities of additives for significant strength improvement. Some operations such as military operations often cannot be delayed to permit sufficient curing of stabilized materials or afford to allocate significant shipping volume for construction materials. Non-traditional stabilization additives have become increasingly available for commercial and military applications. In recent years, polymer modified mortars and polymer modified grouts are widely used in buildings, because they overcome some disadvantages such as delayed hardening, low tensile strength, large drying shrinkage and low chemical resistance.

A review of the literature indicates that there has been a large quantity of research completed regarding the application of traditional stabilization additives such as lime, cement and fly ash. However, there is little independent research about the use of nontraditional stabilization additives. Some of researches about nontraditional stabilization are presented in following:

Gopal *et al.* (1983) performed comparative studies to stabilize dune sand using Urea-Formaldehyde (UF) and its copolymers. In this research papers studying many non-traditional stabilizers were studied. Ajayi-Majebi *et al.* (1991) managed an experiment planned to determine the effects of stabilizing clay-silt soils with the combination of an epoxy resin (bisphenol

Corresponding Author: Seyed Abolhassan Naeini, Department of Civil Engineering, Imam Khomeini International University, P.O. Box 288, Ghazvin, Postal Code 34149-16818, Iran
Tel: 0098 912 6813 425 Fax: 0098 281 3780 073

A/epichlorohydrin) and a polyamide hardener. The additive mixture was composed of a 1:1 ratio of epoxy resin to polyamide hardener. They concluded that admixing up to 4 percent stabilizer into a clay-silt material produced large increases in the load-bearing capacity of the material in terms of its unsoaked California Bearing Ratio (CBR). Palmer *et al.* (1995) have presented that lignin, a natural polymer, introduces better improvement for ground modification compared to non-organic stabilizers. The polymeric materials used for soil stabilization may be either natural or synthetic. Natural polymers, for example, liquid asphalts, have been used for stabilization and surfacing of low-volume roads (Mamlouk and Zaniewski, 1999).

Puppala and Hanchanloet (1999) have demonstrated the evaluation of a new chemical (SA-44/LS-40) treatment method on strength and resilient properties of a cohesive soil. Santoni *et al.* (2005) found that polymers have the best potential to increase strength of silty-sand soils under wet and dry conditions. They reported that the examined polymers maintained good strength potential in both dry and wet conditions. Al-Khanbashi and El-Gamal (2003) conducted an experiment to determine the effects of stabilizing sand soils with the combination of a waterborne polymer emulsion system. The system was found to increase the mechanical properties, modulus of elasticity and reduce the hydraulic conductivity of sand by incorporating small percentages of polymer.

Notwithstanding the good results polymers give in soil stabilization, their use - and non-traditional stabilizers in general - is considered limited due to the lack of adequate studies and publications (Scholen, 1995; Rauch *et al.*, 2002, 2003; Petry and Little, 2002; Al-Khanbashi and Abdalla, 2006; Yssaad and Belkhodja, 2007; Zhi *et al.*, 2008; Yudianti and Iadrarti, 2008). Furthermore, most of the available research is focused on clay and, to a lesser extent, on silty sand soils. The objective of this study was to investigate the effect of wet and dry conditions on loose silty sand soils stabilized with epoxy resin polymer.

MATERIALS AND METHODS

Materials: A commercial product of Epoxy Resin (bisphenol A) and a polyamide hardener was used in this research. A multi component resin grout that usually provides very high, tensile, compression and bond strengths. The additive mixture was composed of a 1:0.15 of epoxy resin to polyamide hardener, respectively. Some important properties of the epoxy resin used in this study are given in Table 1. Seven silty sand soils with different percents of silt content (0, 10, 20, 30, 35, 45 and 60 wt.% (% by dry weight)) were used in this research. The sand and silty used in this study was obtained from Caspian mine in the Alamot region of the Iran. The sand was characterized by grain sizes ranging from 0.075 to 4.75 mm and with a specific gravity of 2.68. The silt was characterized by grain sizes ranging from 0.075 to 0.002 mm and with a specific gravity of 2.67. The sand and silt was classified based on the Unified Soil Classification System (ASTM, 2000) as well graded sand (SW) and low plasticity silt (ML), respectively. The grain size distributions of soils are shown in Fig. 1.

Table 1: Physicochemical properties of epoxy resin emulsion

Name	Epoxy resin
Density (kN m^{-3})	22
Solvability in water	Insoluble in water
Chemical type	C_3H_5O [$C_{18}H_{19}$O3]n $C_{18}H_{19}O_3$
Elastic modules (GPa)	20
Boiling point (°C)	>200°C

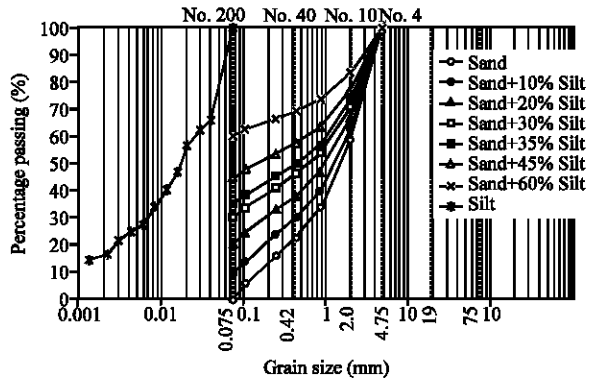

Fig. 1: Grain size distribution curves

Specimen preparation: Because of using polymer which is insoluble in water, in all experiments, soils were owned dried for 24 h to eliminated soil's water, then specified amount of polymer added to the dry silty sand and specimens were prepared by mixing the polymer with silty sand in the loose dry density of 17 kN m^{-3}. The soil/polymer mixture was processed into dough using a mechanical kneader. The uniformly mixed dough was subsequently placed into a steel mold measuring 89 mm in height and 38 mm in diameter. Finally, the molded specimens were left to cure, at room's temperature. Specimens containing 3, 4, 5 wt.% (% by dry weight) polymer and 0, 10, 20, 30, 35, 45 and 60 wt.% (% by dry weight) silt were prepared using this method. Other sets of samples prepared using the same method and submerged in water for 24, 96 and 168 h.

Curing time: Curing times of 1, 2, 4, 6 and 8 days were used in this research. Two samples for each curing time were prepared in order to provide an indication of reproducibility as well as to provide sufficient data for accurate interpolation of the results. Additional curing times beyond 8 days may be desired in some cases to investigate longer term changes in strength.

Submerge of specimens in water: In this study, each specimen was arranged vertically in a steel mold and submerged in a water tank after the specimen in each steel mold was allowed to be cured under room temperature. Specimens submerged in water for 24, 96 and 168 h and then taken out from the water and tested within 10 min of removal from the soaking reservoir and their unconfined compressive strength were recorded. The dates were evaluated to derivation the effect of water on stabilized samples.

Unconfined Compressive Strength Testing (ASTM, 2002): Unconfined Compressive Strength (UCS) testing was performed on all extracted specimens using a strain rate of approximately one percent per minute. A data acquisition system was used to record the applied load and deformation. Corrections to the cross-sectional area were applied prior to calculating the compressive stress on the specimen. Each specimen was loaded until peak stress was obtained, or until an axial strain of 20% was obtained.

RESULTS

The following section presents the results of laboratory tests performed for silty sand soils that have caused problems during construction or resulted in poor performance in service.

Testing program: For this research, it was desired to evaluate the effectiveness of the stabilizer mixed with soils at the dry and wet conditions. Low to high dosage rates were used for soils at dry condition. The stabilizer dosage rates used for this study are 3, 4 and 5%.

Effect of curing time in soils strength: The results of curing times and polymer contents on unconfined compression strength listed in Table 2 and are shown in Fig. 2-4 for different percentage of polymer. Since, this research did not involve investigation of variations of curing temperature, all samples were cured at room temperature (approximately 20°C).

The unconfined compression strength of stabilized samples increases with curing time. Specimens containing polymer content of 3 wt. % were having curing time of 6 days and specimens containing polymer contents of 4 and 5 wt. %, having curing time of 4 days for sand and 4 days for silty sand. So, by increasing the polymer contents, cross linking between polymer network increased and the strength of soil increased.

The strength of the specimens containing 3% polymer content at two days of curing time achieved 55 to 23% of the final strength for sand and silty sand (45% silt

Table 2: The UCS results of specimens at different curing and submerge periods, with polymer emulsions (Mpa)

Polymer emulsion (%)	Silt content (%)	Curing time (h)					Time of submerge (h)			
		24	48	96	144	192	0	24	96	168
3	0	1.27	1.49	2.21	2.3	-	2.3	0.708	0.98	1.361
	10	0.18	0.26	0.53	0.64	0.65	0.65	0.13	0.171	0.261
	20	0.045	0.062	0.1	0.18	0.19	0.19	0.038	0.084	0.162
	30	0.027	0.031	0.06	0.084	0.087	0.087	0.033	0.0426	0.075
	35	0.015	0.019	0.024	0.045	0.051	0.051	0.031	0.024	0.015
	45	0.008	0.012	0.017	0.035	0.041	0.041	0.024	0.017	0.009
	60	-	-	-	-	-	-	-	-	-
4	0	3.09	3.12	3.19	-	-	3.19	2.25	2.44	2.63
	10	0.91	1.12	1.69	1.7	-	1.7	0.75	0.85	1.12
	20	0.4	0.59	1.15	1.17	-	1.17	0.40	0.52	0.67
	30	0.17	0.33	0.36	0.40	-	0.40	0.21	0.27	0.37
	35	0.05	0.06	0.15	0.21	0.21	0.21	0.15	0.18	0.19
	45	0.04	0.05	0.12	0.19	0.20	0.20	0.15	0.13	0.12
	60	0.041	0.048	0.11	0.16	0.17	0.17	0.09	0.06	0.05
5	0	4.35	4.37	4.4	-	-	4.40	3.30	3.54	4.33
	10	1.43	1.8	2.9	3.1	-	3.10	1.50	2.21	2.49
	20	1.06	1.36	2.2	2.2	-	2.20	0.97	1.16	1.40
	30	0.54	0.75	1.3	1.3	-	1.3	0.66	0.82	0.96
	35	0.37	0.42	0.6	1.1	1.2	1.2	0.66	0.75	0.86
	45	0.26	0.39	0.5	0.6	0.6	0.6	0.34	0.46	0.52
	60	0.15	0.16	0.24	0.29	0.3	0.3	0.09	0.19	0.29

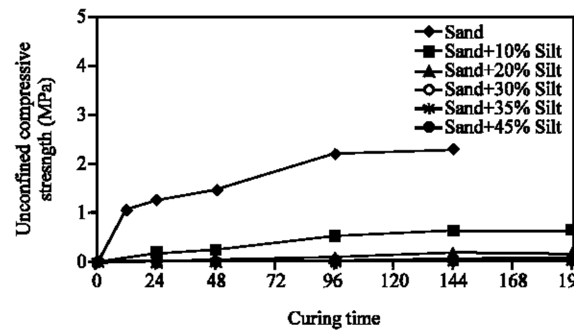

Fig. 2: Effects of curing time on compressive strength of specimens, with 3% polymer

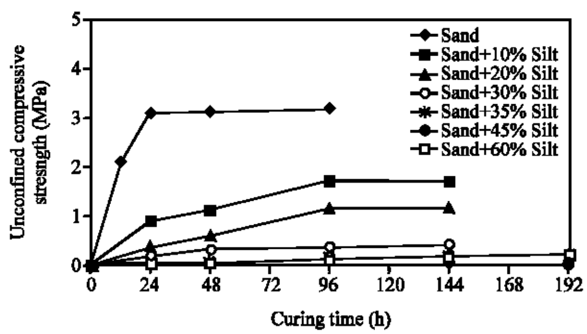

Fig. 3: Effects of curing time on compressive strength of specimens, with 4% polymer

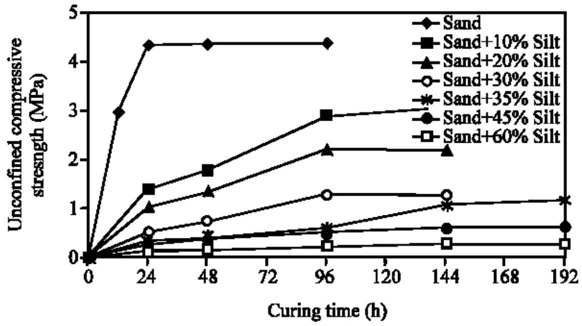

Fig. 4: Effects of curing time on compressive strength of specimens, with 5% polymer

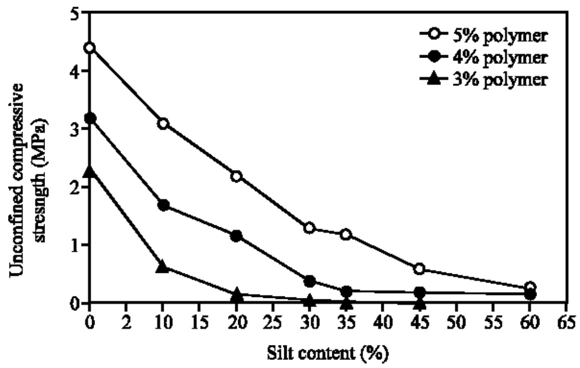

Fig. 5: The unconfined compressive strength, for specimens modified with the different polymer emulsion

content), respectively. For 4% polymer content at 2 days of curing time this rate is 97 to 33%, while for 5% polymer content at two days of curing time it is 99 to 52%. It should be noted that an increase in proprietary cementations stabilizer dosage rate from 3 to 5% will impact the influence of curing time on strength gain.

Effect of silt content in soils strength: The results of unconfined compression strength on stabilized soils with 3, 4 and 5% of polymer are presented in Fig. 5. Stabilized soils with the 3% polymer have lower strength than 4 and 5% polymer. For each specimen, the unconfined compression strength decrease with increment silt content. This means that the soil becomes weakened with an increase in the silt content up to 60%. This phenomenon is explained by the fact that the fine grains of silt positioned around and among the sand grains, the polymer cannot cover all of sample's area.

Effect of polymer content on soils strength: The variations of the unconfined compressive strength of the

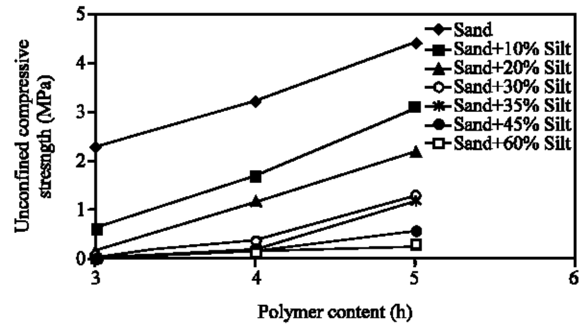

Fig. 6: The unconfined compressive strength, for specimens modified with increment silt content

silty sand/polymer system as a function of polymer concentration for the specimens modified with the different emulsions are shown in Fig. 6; the figure presents result of different soil samples which contain various amount of silt. The unconfined compressive strength increased linearly with a polymer concentration up to 5 wt% for all of the soil used. Comparing the performance of the emulsion in improving the unconfined compressive strength, it could be seen that the unconfined compression strength increases with increment polymer content. This phenomenon is explained by the fact that with increment polymer content, bonding between particles increase, Note that resin epoxy is a cross linked polymer. It could be seen that specimens consist of 5 wt. %, polymer gave the highest value for all specimens and specimens consist of 3 wt. %, polymer gave the lowest values. The unconfined compressive strength value of sand at 3 and 5wt. % polymer content were 2.21 and 4.4 Mpa, respectively, which is 100%, increased.

Effect of wet condition on soils strength: Effects of wet conditions on unconfined compression strength stabilized soils containing 3, 4 and 5% of polymer are presented in Fig. 7-9, respectively and the result of tests listed in Table 2. As discussed earlier, the treated samples were tested using dry and wet test procedures to provide an indication of the material's moisture susceptibility. After an 8-day curing period, placing the specimens in tank of water for 1, 4 and 7 days provided an excellent indicator of the material's durability under wet conditions. As seen, there are two types of results. First, is about specimens that consist of 45 and 60 wt. % silt content at 4% polymer and 35 and 45 wt. % silt content at 3% polymer, the strength properties of these specimens reduced after submerging in water. Second, is about the rest of specimens. The UC strength of these specimens reduced when tested after 1 day of submerging in water. However,

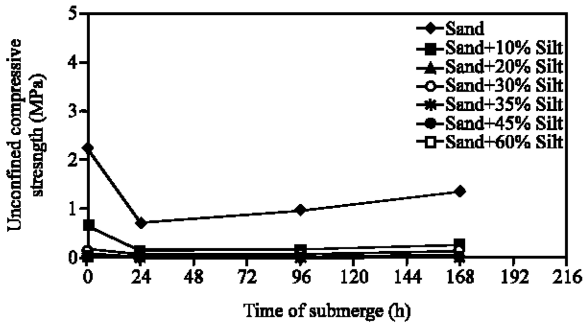

Fig. 7: The submerged unconfined compressive strength, for specimens modified with 3% polymer

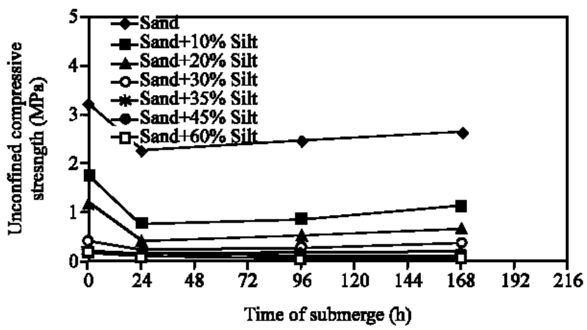

Fig. 8: The submerged unconfined compressive strength, for specimens modified with 4% polymer

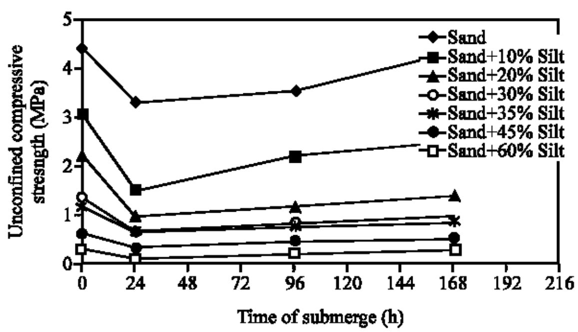

Fig. 9: The submerged unconfined compressive strength, for specimens modified with 5% polymer

after 7 days of submerging, the UC strength of the specimens increased but it was less than the dry condition. The reason of increasing the UC strength of specimens is the role of water as catalyst. When specimens submerged in water, the H^+ ions of water react with three-member epoxies' rings and the epoxies' ring was opened, then the hardener (polyamide) easily can react with resin. So, the strength of specimens increased.

Modulus of elasticity: Several methods are available for determining (actually estimating) the stress-strain

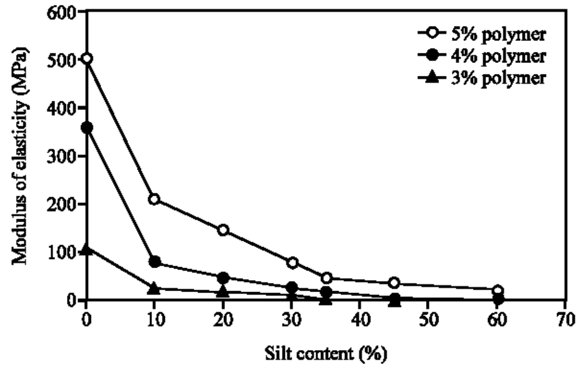

Fig. 10: Variations of the modulus of elasticity, as function of silt content

modulus, one of several methods is unconfined compression test. Unconfined compression tests tend to give conservative values of E_s; i.e., the computed value (usually the initial tangent modulus) is too small, resulting in computed values of ΔH being large compared with any measured value. In this study, the Secant modulus (E_{50}) for strain equivalent 0 and 50% maximum unconfined strength was computed. Secant modulus is the slope of a straight line connecting two separate points of the curve.

Effect of silt content on modulus of elasticity: The variation of the modulus of elasticity of the silty sand/polymer system as a function of silt content for the specimens modified with the different silt contents is shown in Fig. 10. It can be seen that with increasing silt contents, the modulus of elasticity decreased. The rate decreased at higher polymer percentages. This is explained by the fact that the fine grains of the silt positioned around and among the sand grains, the cover polymer areas become less, therefore samples becomes soft and the modulus of elasticity decreased.

Effect of polymer content on modulus of elasticity: The variation of the modulus of elasticity of the silty sand/polymer system as a function of polymer concentration for the specimens modified with the different contents of polymer is shown in Fig. 11. The modulus of elasticity increased linearly with a polymer concentration up to 5 wt. % for the entire polymer contents used. A very important characteristic is the rate of increase of strength and modulus (slope of trend line) for each of the specimens. The rate increased at higher polymer percentages. It is obvious that the slopes of the trend lines for specimens including fine grains had esplanade. Note that with increase of fine grain diminished cross linked of polymer.

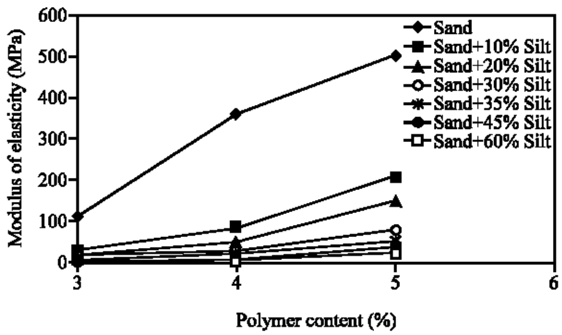

Fig. 11: Variations of the modulus of elasticity as function of polymer contents

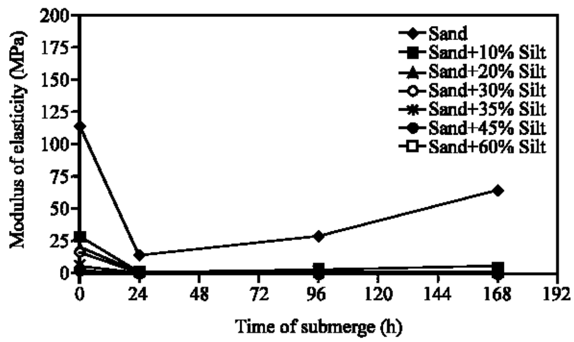

Fig. 12: The submerges modulus of elasticity for specimens modified with 3% polymer

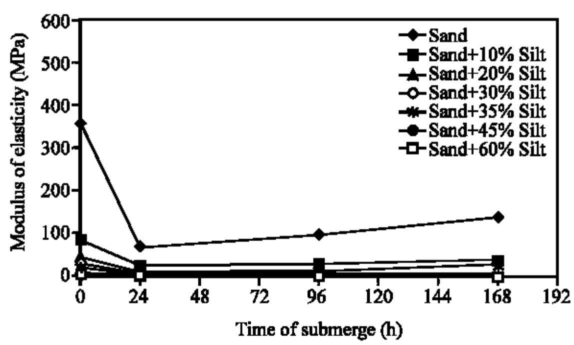

Fig. 13: The submerges modulus of elasticity for specimens modified with 4% polymer

Effect of water on modulus of elasticity: Effects of water on modulus of elasticity of different stabilized soil samples with various amounts of polymers are presented in Fig. 12-14. As seen; the treatment of modulus of elasticity of specimens is similar of their treatment of UC strength. The most modulus of elasticity among specimens belong to specimens consist of 5% polymer at 0% silt content. The least of modulus of elasticity among specimens belong to specimens consist of 3% polymer at 45% silt content. It is obvious that when the polymer content increase, the modulus of elasticity increase but with increase of silt content, the modulus of elasticity decrease.

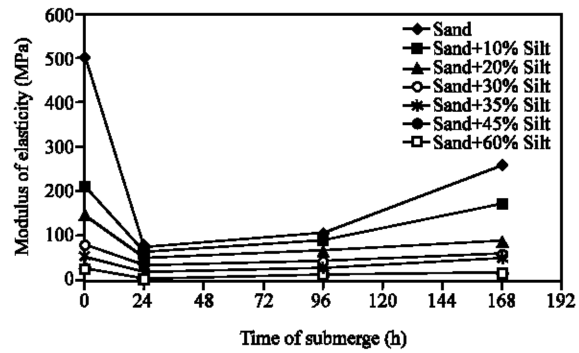

Fig. 14: The submerges modulus of elasticity for specimens modified with 5% polymer

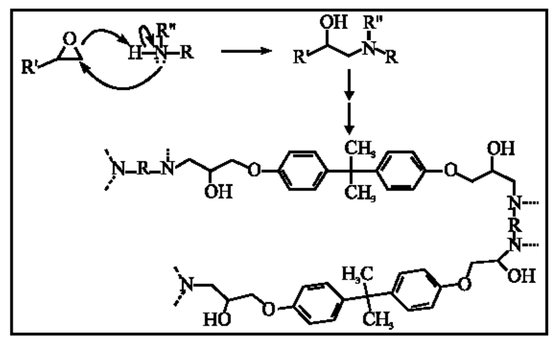

Fig. 15: The reaction between epoxy resin (bisphenol A) and polyamide

Reaction between epoxy resin and polyamide in dry and wet conditions: As discussed earlier, in dry conditions, there isn't any catalyst except polyamide, when the amount of fine particles (silt) increase, the contact between epoxy resin (bisphenol A) and polyamide decrease, then crosslink operations weren't done well, therefore the UC strength specimens don't increase. In wet conditions, the water is as a kind of catalyst, because water has H^+ ions that when the specimens submerged in water, water's H^+ with three-member epoxies' ring react and the epoxies' ring was opened, then the hardener (polyamide) easily can react with resin and crosslink operations were continued. Figure 15 shows the part of epoxy resin and polyamide's crosslink operations.

DISCUSSION

This section presents the comparison of the results of this study with other researchers.

Vvedenskaya *et al.* (1971) used copolymers of acrylate (GA), methylene bisacrylamide (MBAM) and ethylene dimethacrylamide (EDMA) to stabilize sands, silts and clays. The additive formula consisted of a 24:1 ratio of vinyl monomer to diene. They reported an increase in UC strength of 2.45-2.94 MPa for a 5% additive mixture in sand in less than 10 days, while in this study sand consist of 5% epoxy resin earn UC strength of 4.35 MPa in less than 24 h. Oldham *et al.* (1977) reported that a polymer resin provided the greatest increase in UC strength for the sand materials, the result of this study verify this matter. Ajayi-Majebi *et al.* (1991), reported that admixing up to 4 percent stabilizer composed of a 1:1 ratio of epoxy resin to polyamide hardener into a clay-silt material produced large increases in the strength as low as 3 hours, while with specimens consist of more silt contents and a 1:0.15 ratio of epoxy resin to polyamide hardener, we reached the final strength at 2 days. Santoni *et al.* (2005) used nine nontraditional stabilizers, including lignosulfonates, polymers, silicates and tree resins, to accelerate strength improvement of silty sand (SM). All samples were mixed with selected products and tested under both wet and dry conditions after 1- and 7-day cures. The results indicate increased UCS of samples stabilized with Silicate 1 and Polymer 3 compared with both the untreated control series and the traditional stabilization alternatives. The UCS following the 7-day cure provided the maximum UCS of the samples evaluated in both wet and dry conditions. Almost, the same results were found by this study for wet and dry conditions after 1- and 7- day cures. AL-Khanbashi and Abdalla (2006) used waterborne polymer emulsion systems for structural modification of sandy soils. The first emulsion used was a styrene-acrylic, copolymer emulsion; the second and third were vinyl-acrylic, copolymer-based emulsions. At 5 wt. %, the unconfined compressive strength values were 6.5, 10.2 and 8.1 MPa for emulsion-1, emulsion-2 and emulsion-3, respectively. The molded specimens were left to dry (in the case of emulsion-1 and emulsion-3) or cure (in the case of the cross linking polymer, emulsion-2), for a period of 1 week, while sand consist of 5% epoxy resin (this study) reached UC strength of 4.35 MPa in less than 24 h. Newman and Rushing (2007) performed Laboratory evaluations of several commercially available materials to provide comparisons of these materials for stabilization of silty sand. The laboratory investigation evaluated Portland cement (Type I and Type III), acrylic polymers, polypropylene fibers and various combinations of these materials for stabilizing soil. Short term (1 day) and long term (28 day) curing were both used to determine performance. The section stabilized with fibers and type III Portland cement was determined to be most resistant to permanent deformation with the traffic. After 28 days of cure time, the results indicated that the UCS of specimens consist of 6% Type III cement was equal to 10.3 MPa and specimens consist of 3% Type III cement + 5.8% Polymer was 11 MPa. But the UCS of silty sand soils stabilized with 5 wt. % epoxy resin obtained from this study is 0.6~3.1 MPa, that is less than Type III cement and acrylic polymer. The variation of the unconfined compressive strength and the modulus of elasticity of the sand/polymer system as a function of polymer concentration for the specimens modified with the different emulsions are discussed by Al-Khanbashi and Abdalla (2006). They reported that the UCS and the modulus of elasticity increased linearly with a polymer concentration up to 2 wt. % for all of the three polymers used. The rate of increase diminished at higher polymer percentages. The same trend was observed for unconfined compressive strength and the modulus of elasticity in this study.

CONCLUSIONS

This study was undertaken to investigate the influence of polymer percentage, curing time, dry and wet conditions on the unconfined compression strength and modulus of elasticity of stabilized silty sandy soils. The results of the study are presented in fallowing conclusions:

- The strength of sand will decrease with increment of silt contents up to about 35% and above 35% silt content, the strength of the soil almost becomes constant. This phenomenon is explained by the fact that the fine grains of silt positioned around and among the sand grains, the polymer cannot cover all of sample's area
- The unconfined compression strength of specimens will increase with increment of polymer contents, this phenomenon is explained by the fact that with increment of polymer, the polymer can cover all of sample's area and increase cross links. However, the strength of silty sand is less than the clean sand
- For specimens submerging in water there are two types of results. First, is about specimens that consist of 45 and 60 wt. % silt content at 4% polymer and 35 and 45 wt. % silt content at 3% polymer, the strength properties of these specimens reduced after submerging in water. Second, is about the rest of specimens. The UC strength of these specimens reduced when tested after 1 day of submerging in water. However, after 7 days of submerging, the UC strength of the specimens increased but it was less than the dry condition. The reason of increasing the UC strength of specimens is the role of water as

catalyst. When specimens submerged in water, the H^+ ions of water react with three-member epoxies' rings and the epoxies' ring was opened, then the hardener (polyamide) easily can react with resin. So, the strength of specimens increased

- The treatment of modulus of elasticity of specimens is similar of their treatment of the unconfined compression strength
- The most UC strength and modulus of elasticity among specimens belong to specimens consist of 5% polymer at 0% silt content
- The increase in mechanical properties of the stabilized silty sand specimens with polymer is attributed to the increased inter-particle friction associated with the deposited epoxy resin film and to the inter-particle ties. It should be noted the fact that epoxy resin is a cross linked polymer, thus leading to better overall mechanical properties

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