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Research Article

Effect of Epoxy Resin Mixtures on the Physical and Mechanical Properties of Sand

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Abstract: The use of new materials for soil strengthening is crucial for geotechnical engineering, especially in foundation construction. The main objective of this study was to investigate the potential use of two-component water-soluble epoxy resin to improve the physical and mechanical properties of medium sand, because the efficacy of these resins on soil strengthening has not yet been properly investigated. The experiments were conducted using resins with different epoxy resin-to-water ratios. The results of this study indicate that the epoxy resins improve the physical and mechanical properties of the sand significantly and if successfully grouted into a formation, the resins could provide a suitable solution for the stabilization of the foundation material. In separate experiments, electro osmotic treatment of sand/resin mixtures was conducted with the aim of identifying the effectiveness of electro kinetic method on the early strength development of sand/resin mixtures. From the results it was observed that the electroosmotically treated specimens appeared to have much greater strength enhancement than the one of the untreated specimens.

Keywords: Chemical grouting, electro osmosis, epoxy resin

INTRODUCTION

Grouting is a common technical method with numerous applications (Cambefort, 1977). For example, it is used for stabilizing and strengthening the foundation soil, especially in the case of coastal engineering structures, for reducing the ingress of water to underground facilities, or leakage through a dam site.

Cement suspensions and chemical solutions are the two main types of materials that are utilized for grouting purposes. Cement suspensions have been used successfully in granular soils with large voids or in fractured rock with wide crack openings, because they penetrate easily into soil pores, propagate large distances under low pressure, completely fill the voids, maintain the required properties in the hardened state and are inexpensive (Widmann, 1996). According to the previous experience, micro fine cement is expected to flow sufficiently through soils with coefficient of permeability (k) greater than 10^{-5} m/s. As a result, the use of chemical grouts is restricted to soils with very small void size or rock mass with narrow joints, where cement suspensions cannot be inject able or their penetration is very limited.

Various materials are used for chemical grouting depending on the purpose of grouting and the properties of ground. The most common are calcium chloride in combination with sodium silicate (joosten method), sodium silicate with form amide as a reactant to form silica gel, acrylate, lignin, urethane and resin grouts (Al-Khanbashi and Abdalla, 2006). In particular, epoxy resins are one of the principal resins used for grouting. They generally consist of two components. The epoxy component (A-component) is mixed with an amine component (B-component) to obtain the epoxy resin. The final product is characterized by a high strength under compression and tension, a strong bond, high durability, high resistance to acids, alkalies and organic chemicals and low shrinkage when cured. In addition, some epoxies may be diluted with water up to twice their volume to provide a low cost product, but their strength consequently decreases. This reduction of strength is proportional to the amount of water added to the epoxy resin. Although, numerous studies have been conducted concerning the application of epoxy compounds for structural repair or in fractured concrete (Issa and Debs, 2007), there is limited published data (Ajayi-Majebi *et al*., 1991; Anagnostopoulos *et al*., 2011) on the efficacy of epoxy resin grouts, especially low-cost water-soluble epoxy resin grouts, for soil or rock strengthening. Additionally, Anagnostopoulos *et al*. (2011) from mechanical tests on medium sand, mixed with different epoxy resin grouts, demonstrated the retarding action of water on the early strength development of resin/sand mixtures at all Epoxy Resin-to-Water (ER/W) ratios. Consequently, it is worth checking if the application of electro osmosis (Ou *et al*., 2009; Abdullah and Al-Abadi, 2010; Liaki *et al*., 2010)

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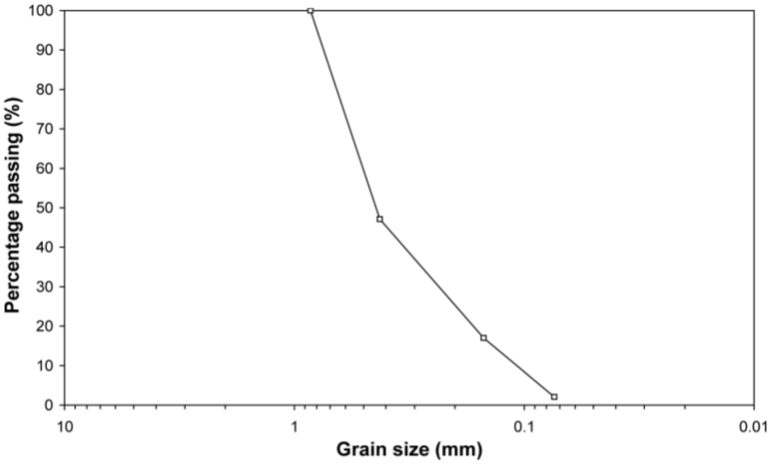


Fig. 1: Particle size distribution of the tested sand

can be beneficial in dewatering and improving the development of strength of resin/sand mixtures, since no information is available on the implementation of this method with such purpose.

The specific objectives of this comprehensive laboratory project are as follows:

- To supplement the available data from the literature on the effect of two-component water-soluble epoxy resin grouts, with different resin to water ratios, on the physical and mechanical properties of medium sand
- To investigate the influence of electro osmotic processing on the acceleration of strength development of sand/resin mixtures

MATERIALS USED

Commercially available CEN, a standard medium siliceous natural sand that conforms to standard CEN EN 196-1 (2005) was used. It was clean with a round shape and generally isometric particles. The grains ranged from 0.074 to 0.85 mm in size. The particle size distribution of the used sand is shown in Fig. 1. It has a coefficient of uniformity C_u of 4.64 and it is classified as poorly graded sand based on the USCS classification. The physical properties of the sand with a relative density (D_r) of 50% are the following: dry unit weight (γ_d) of 15.8 KN/m^3, porosity (n) of 41.6% and permeability coefficient (k) of $4\cdot10^{-4}$ m/s. The friction angle φ is 32.3° and was determined from direct shear tests conforming to ASTM D 3080 (2005).

The epoxy resin used is a commercial product with the trading name EPOXY PRIMER-W and it is distributed by ISOMAT SA, Greece. It is water soluble and composed of two components, A and B. The mixture ratio by weight of the two components A (epoxy resin) and B (hardener) is A: B = 2.5:1. According to the manufacturer, the epoxy resin, without any addition of water, attains its final strength after 7 days. The compressive strength reaches the maximum value of 70 MPa and the flexural and adhesive strengths are in excess of 35 and 3 MPa, respectively.

The viscosity of epoxy resin emulsions, especially when mixed with large amounts of water, is slightly higher than that of water. This low viscosity of epoxy resin emulsions in combination with the small size (25 - 100 nm) of the dispersed resin particles in the water enable their use for grouting purposes, even in especially fine sands.

Laboratory procedure: Mixtures were prepared with Epoxy Resin/Water (ER/W) ratios (by weight) of 2, 1.5, 1 and 0.5, respectively. All mixtures were prepared with a high-speed rotating stirrer. An adequate quantity of epoxy resin in the mix ensured that the intergranular voids were completely filled. Mixing was performed by using a three-blade paddle mixer as suggested by the ASTM C 938-80 (1993) specifications. Concerning the preparation of the specimens, the filling and the compaction process were performed carefully to ensure the uniformity and reproducibility of the specimens. The weight of sand/resin mixture required to fill the mould and obtain the required relative density was calculated. This amount of material was poured in cylindrical moulds 5.43 cm in diameter and 11.00 cm high and compacted, so that specimens would be created consistently with a relative density of about 50%. The required density was achieved with a metal rammer weighing 4.5 kg and slightly tapping on the sides of the mould. These cylindrical specimens, with a height to diameter ratio of about 2, were used for compressive and triaxial strength tests after 3, 7, 28, 90 and 180 days, respectively in order to study the development of the strength parameters with time. Free water in the sand/resin mix samples was removed by drying at room temperature. According to manufacturer specifications, the effect of this drying procedure on the polymerization of resin macromolecular chains and, consequently, on strength development or permeability of sand/resin mixes is negligible. The end surfaces of the sand/resin mix samples prepared were cut with a saw to be parallel and smooth to prepare them for the uniaxial or triaxial compression tests. Unconfined compression and triaxial tests were performed under a constant axial strain rate of 1%/min. The compression tests were performed according to ASTM D 4219-02 (2005). The elastic modulus E was determined from the linear part of the compressive stress-strain curve. Splitting tensile tests were conducted following the instructions of ASTM D 3967-95a (2005) on specimens with a thickness to Diameter ratio (t/D) of 2.00/5.43 cm = 0.37.

For the purpose of studying the shear strength parameters of the sand/resin mix (friction angle φ and cohesion c) under triaxial loading, a triaxial testing apparatus (Hoek and Franklin, 1968) was used in a BETA 5 (FORM+TEST PRÜFSYSTEME) 3000 KN compression testing machine to apply the axial load, which incorporates an instrument for measuring the digital load-strain. Triaxial tests were performed under constant confining pressures σ_3 of 1, 2 and 3 MPa, respectively. The same testing machine was used also for all the compression and splitting tensile tests.

Specimens of the same size as the one for the mechanical tests, aged 28 days, were used for the evaluation of water permeability according to ASTM D 5084-03 (2005) and dry unit weight according to ASTM C 29/C 29M-91a (1993). Porosity n was calculated according to the method found in Perret *et al.* (2000). An age of 28 days was chosen for the estimation of the physical parameters. It is considered that beyond this age, the values of physical parameters do not change because the solidification process of the epoxy resin does not influence the density or the volume of the sand/resin mix and the free water has almost completely evaporated.

The method proposed by ASTM D 4320-04 (2005) is a classical laboratory method for the estimation of the physical or the mechanical properties of chemically grouted soils and it has been adopted by many researchers (Anagnostopoulos, 2005, 2006; Dano *et al.*, 2004; Vipulanandan and Ata, 2000; Bolisetti *et al.*, 2009; Akbulut and Saglamer, 2003). This method is important in estimating the strength of a grouted soil with cement grouts, which appears to decrease with increasing distance from the injection point due to the clogging mechanism observed during the injection process. Epoxy resin, in contrast, can penetrate easily and uniformly (the viscosity of the used resin emulsions in this study ranged from 14 to 32 mPa·s), without clogging, into soil voids. This results in the development of isotropic strength along the injection distance (Anagnostopoulos and Hadjispyrou, 2004). Consequently, the authors deemed the method of ASTMD 4320-04 (2005) unnecessary and chose a simpler method for making epoxy resin/sand specimens.

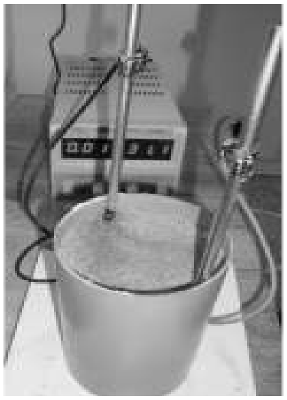


Fig. 2: Experimental set up for electroosmotic treatment of fine sand/resin mixes

The effect of electro osmosis in the dewatering of epoxy resin/sand mixes and consequently in the acceleration of early strength development was studied in the laboratory. All the electro osmotic experiments were carried out in a laboratory environment with the temperature ranging from 20 to 25°C. The details of the experimental set-up are shown in Fig. 2. The experiments were conducted on a cylindrical PVC tube with diameter of 15 cm and height of 30 cm. The plastic tube was chosen because of its high electrical resistance and water impermeability. The different epoxy resin/sand mixes were prepared and placed, in the tube, in three layers. Each layer was subjected to a slight vibration in order to achieve a relative density of 50%. Afterwards, two tubular electrodes to pass the Direct Current (DC) were encapsulated along the sample, apart and diametrical near the tube walls. Both electrodes (anode and cathode) were connected to a DC power supply device. The electrodes were made of graphite with copper coating, having 5 mm diameter. The sample was then subjected to a DC current with a constant voltage gradient of 3 V/cm, as suggested by Abdullah and Al-Abadi (2010), which maintained for a period of 7 days for mixtures with ER/W ratio of 0.5 and 1, a period of 6 days for mixtures with ER/W ratio of 1.5 and a period of 4 days for mixtures with ER/W ratio of 2. All the digital monitoring data (voltage and amperage) were recorded through a data logger system incorporated in the DC device. Samples with thick epoxy mixes were electroosmotically treated for a smaller period than the one of thinner epoxy resin mixes because DC current stopped passes through their mass. This is attributed to the quick formation of a dense polymer matrix which reacts as an electrical insulator. Figure 3 shows the variation of current versus time during electro osmotic treatment of sand at all ER/W ratios. In all cases, the current never remained steady but was decreasing continuously with time from

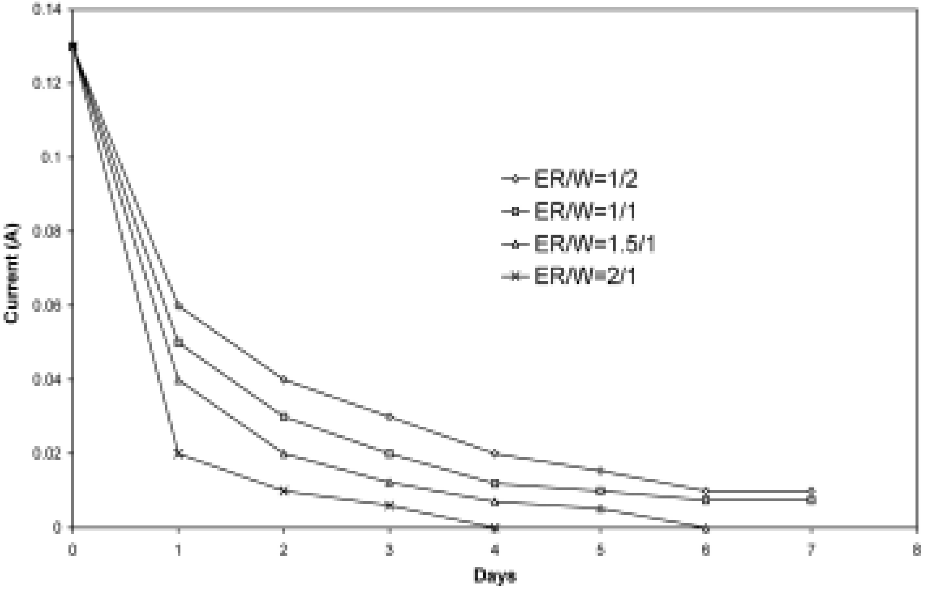


Fig. 3: Variation of current with time during electroosmotic treatment of sand/resin mixes

beginning to end of test. At the end of the processing period, cylindrical specimens with diameter of 5.43 cm and height of 11 cm were extracted from the electroosmotically treated mixtures by using a drilling machine and were tested in compression and splitting tensile strength tests.

RESULTS AND DISCUSSION

Figure 4 depicts the compressive stress-strain relation of sand/resin specimens with different epoxy resin/water ratios after 7, 28 and 90 days of curing, respectively. The corresponding curves for 180 days of curing are not presented since they are almost identical with the ones for 90 days of curing. Figure 5 shows the development of compressive strength, splitting tensile strength and elastic modulus with increasing curing time. All specimens with different ER/W ratios did not approach any strength value within a time period of 3 days. Mixes with ER/W ratio of 0.5 did not gain any strength even after a curing period of 7 days. Also, it can be observed that beyond 90 days of curing the increase of strength was insignificant at all ER/W ratios. The results reveal the adverse influence of water on the strength development of sand. The strength values, for all ages tested, decrease with increasing water content. The water content had the most pronounced effect on the retardation and reduction of the final strength of the sand/resin mix in the case of grouts with ER/W ratio of 1 and 0.5. The retarding phenomenon may be attributed to the amount of water that is retained by the hydrophilic parts of the epoxy resin, which inhibits to some extent its chemical reaction with the hardener and thus, the development of strength. We attribute the reduction of the final strength, even after the evaporation of water, to the formation of a weaker epoxy resin polymer membrane-sand matrix, because of the high dispersion of chemical substances that occurs in highly diluted epoxy mixes. In the case of epoxy resin mixtures with ER/W ratios of 1 and 0.5, a low strength development was observed at the age of 28 days. However, for ER/W ratios of 1.5 and 2, the strength parameters were multiple times higher. For example, the samples with the thinner ER/W ratio of 0.5 appeared to have mean values for compressive strength, splitting tensile strength and elastic modulus of 0.6, 0.1 and 68.4 MPa, respectively. The same parameters, for the samples with the thicker ER/W ratio of 2, appeared to be 5.23, 0.9 and 420 MPa, respectively.

The strength exhibited an increasing tendency over time, resulting in significantly higher strength values. This tendency was strongly dependent on the ER/W ratio. Nevertheless, samples with thick epoxy mixes (ER/W = 2, 1.5) appeared to have much greater strength enhancement than the samples with thinner epoxy mixes for all curing ages. The lowest final strength values after 180 days of curing were observed for mixes with ER/W ratio of 0.5 and were equal to 1.1 MPa for the compressive strength, 155 MPa for the elastic modulus, 0.21 MPa for the splitting tensile strength. In contrast, mixes with ER/W ratio of 2 resulted in a compressive strength of 8 MPa, elastic modulus of 585 MPa, splitting tensile strength of 1.15 MPa.

Figure 4, which represent the relation between compressive stress and strain, reveals an almost linear initial elastic segment that extends over a large range of strains with a subsequent extended plastic zone that occurs before and after fracture for all ER/W samples and at all ages. All the specimens with the different ER/W ratios did not fail at the end of test but were

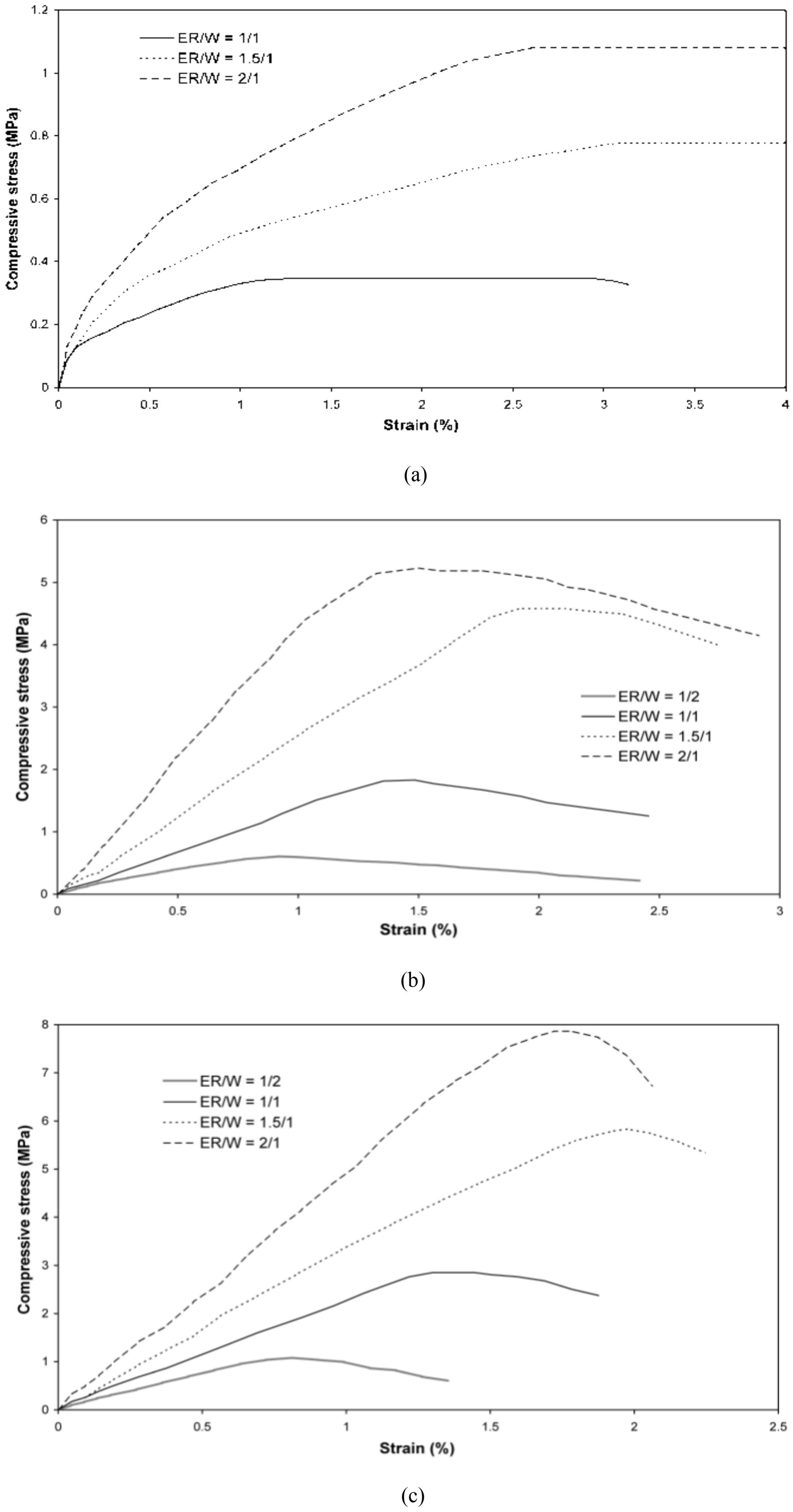
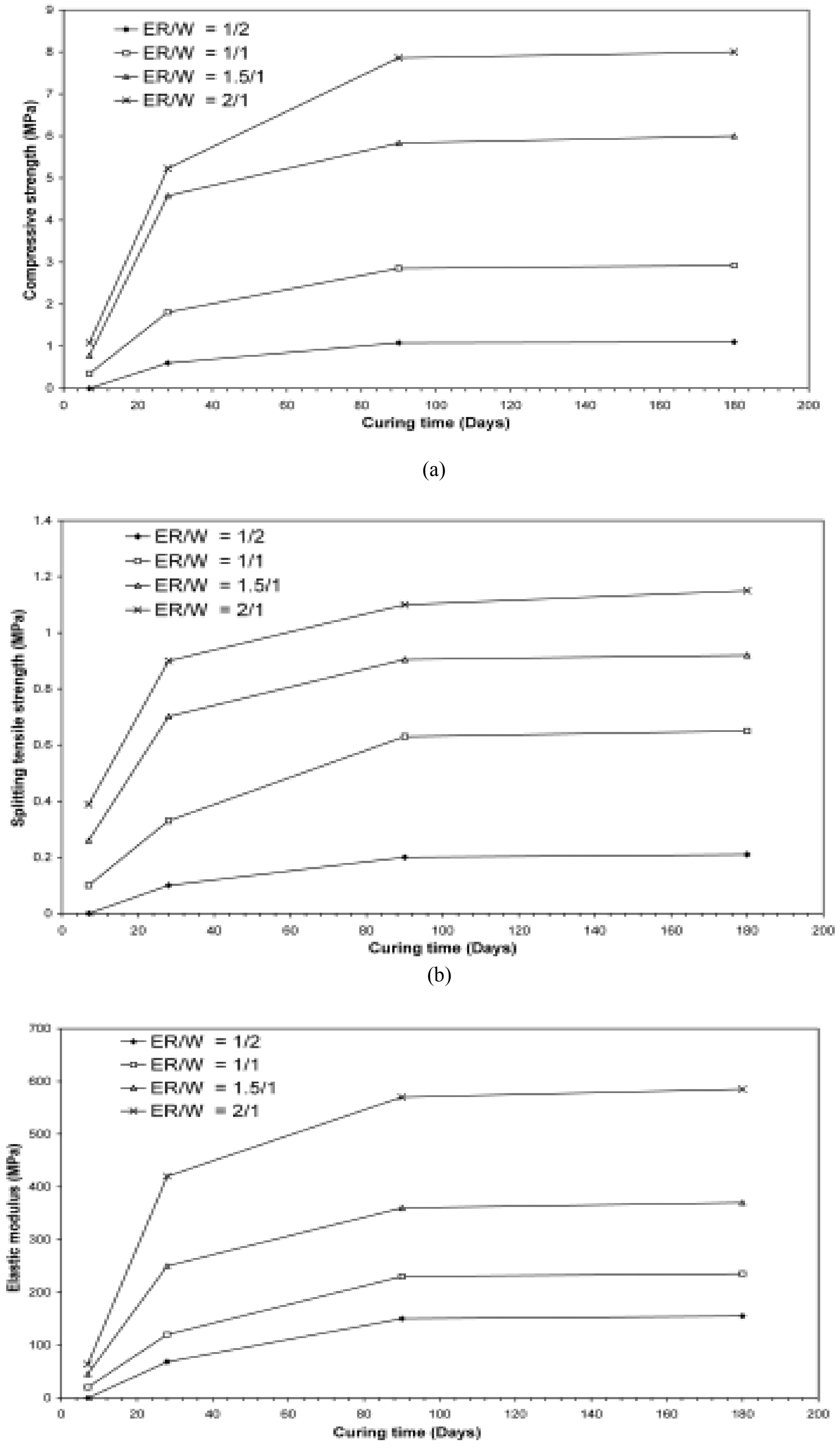


Fig. 4: Typical stress-strain curves of sand/resin mixes with different ER/W ratios (a) 7 days, (b) 28 days, (c) 90 days



(a)

(b)

(c)

Fig. 5: (a) Compressive strength, (b) splitting tensile strength, (c) elastic modulus development of sand/resin mixes

Table 1: Values of major principal stress taken from triaxial tests on treated sand specimens with different ER/W ratios

	Major principal stress σ_1 (MPa)															
	ER/W = 1/2 curing time (days)				ER/W = 1/1 curing time (days)				ER/W = 1.5/1 curing time (days)				ER/W = 2/1 curing time (days)			
σ_3 (MPa)	7	28	90	180	7	28	90	180	7	28	90	180	7	28	90	180
1	-	4.2	5.1	5.0	2.4	5.4	6.2	6.3	3.0	7.6	9.5	9.7	3.4	8.9	12.5	12.7
2	-	6.3	6.9	6.8	4.5	6.9	8.3	8.4	5.3	10.7	12.3	12.1	5.5	11.3	14.6	14.9
3	-	7.6	8.7	8.7	6.1	9.4	10.3	10.4	6.9	12.3	14.4	14.6	7.3	13.7	16.7	17.0

Table 2: Values of elastic modulus taken from triaxial tests on treated sand specimens with different ER/W ratios

	Elastic modulus (MPa)															
	ER/W = 1/2 curing time (days)				ER/W = 1/1 curing time (days)				ER/W = 1.5/1 curing time (days)				ER/W = 2/1 curing time (days)			
σ_3 (MPa)	7	28	90	180	7	28	90	180	7	28	90	180	7	28	90	180
1	-	333	360	375	87.5	429	590	602	105	535	716	725	132	655	1,080	1,092
2	-	375	422	430	101	487	742	749	123	625	772	788	170	822	1,350	1,365
3	-	425	460	466	125	569	966	978	141	912	1,330	1,342	226	1,200	1,511	1,528

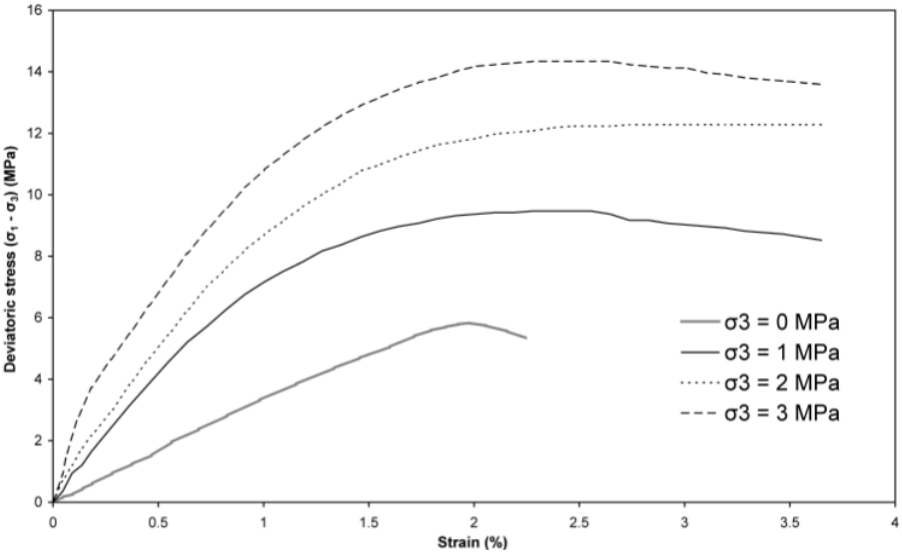


Fig. 6: Typical deviatoric stress-strain curves of sand/resin mixes with ER/W ratio of 1.5 cured for 180 days

continuously deformed, up to a strain of at least 2.5 to 4%, at which point the test was stopped. This is an indication of the strong adhesion between the formed polymer film and sand grains. It also demonstrates the domination of the elastoplastic behavior of the epoxy resin on the mechanical response of the whole mixture.

Table 1 and 2 present the values of major principal stress at failure and the values of elastic modulus taken from triaxial tests on sand/resin mix specimens. Also, typical trends in the deviatoric stress (σ_1-σ_3) -strain obtained from triaxial tests on specimens with ER/W ratio of 1.5 cured for 180 days are shown in Fig. 6. These results reveal the beneficial effect that epoxy resins have on the strength and stiffness of the sand. As expected, the peak strength and initial stiffness strongly increased with an increase in the ER content and confining pressure. For example, the application of a 3 MPa confining pressure on specimens with an ER/W ratio of 2 that were cured for 180 days caused a deviator peak value increment of about 146% compared to the unconfined test. Generally, the degree of post-peak strength loss tends to decrease with increasing confining pressure and ER/W ratio resulting in relatively constant peak strength. The strain at which the peak stress was achieved generally increased with increasing confining pressure and ER/W ratio, although some scatter was observed. The effect of the confining pressure and ER content on the enhancement of $(\sigma_1\text{-}\sigma_3)_{max}$ stress is seen in Table 1.

A significant extension of the plastic zone for all grouted samples with the different ER/W ratios is observed. Undoubtedly, one of the main advantages of the epoxy resin mix is the strain hardening behavior induced even at large deformations. This behavior suggests potential application of the epoxy resin grouting in shallow foundations, embankments overlying soft soil deposits and other earthworks that may suffer excessive deformations. Generally, no strain localization with inclined shear bands occurred and the failure was associated with a fairly uniform, strong expansion of the specimen for high ER/W ratios. However, strain localization with inclined shear bands did occur for low ER/W ratios.

The shear strength parameters (friction angle φ and cohesion c) of sand/resin mixes with different ER/W ratios were determined by plotting the modified failure envelope in p-q diagrams. The failure envelopes for all cases appeared to be linear with correlation coefficients R^2 ranging from 0.98 to 0.99. Table 3 illustrates the values of φ and c over time for the different ER/W ratios. It is observed that φ reduced for all ER/W ratios, at all ages and varied between 15.5° to 29.9° with significant scatter. The reduction of φ can be attributed to the polymer coverage of particle surfaces which reduced the friction. Strong evidence supporting the above hypothesis is the considerable higher values of φ for the mixes with ER/W ratio of 1, 1.5 and 2 at 7 days of curing; a time at which the cross linked formation of polymer film coatings is still very limited, as it is revealed from the low strength of the specimens. However, the values obtained for c confirmed the considerable influence of the ER/W ratio and curing time. By increasing the ER/W ratio and curing time, the value of c substantially increased, to a maximum value of 3.6 MPa, which was observed for an ER/W ratio of 2 with a curing time of 180 days.

The failure envelopes of mixes with the different ER/W ratios that were cured for 180 days are plotted in comparison with the failure envelope of untreated sand and presented in Fig. 7. The intersection of the two lines (dotted one corresponds to the failure envelope of untreated sand) shows the value of critical vertical stress after which epoxy resin is no longer effective in improving the sand strength. Table 4 summarizes the values of critical normal stress (direct shear conditions) and the values of critical confining pressure (triaxial conditions) of sand/resin mixes with different ER/W ratios that were cured for 180 days.

The critical normal stress σ_n and the critical confining pressure σ_3 were calculated as follows:

$$\sigma_n = \frac{c_{mix}}{\tan\varphi_{sand} - \tan\varphi_{mix}} \tag{1}$$

$$\sigma_3 = \sigma_n \cdot \sin(2\cdot\theta) - \tau_n \cdot (1 + \cos(2\cdot\theta)) \tag{2}$$

where,

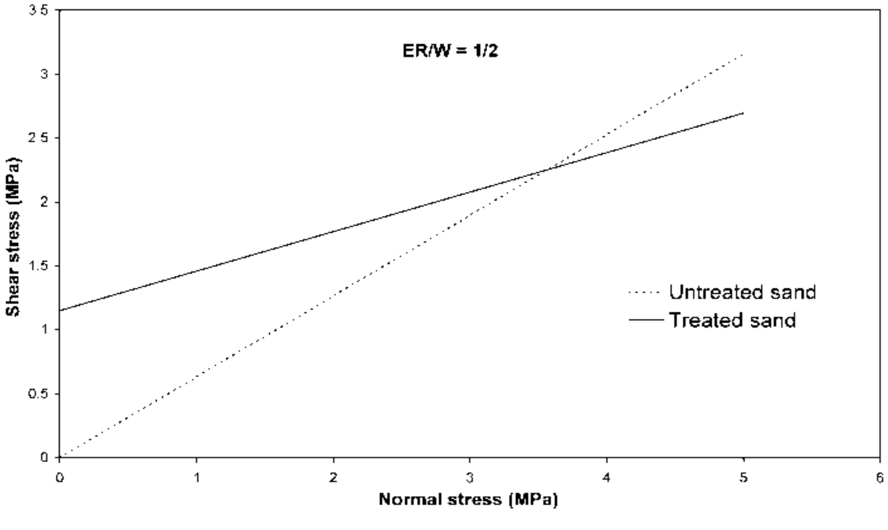
c_{mix} = The cohesion of sand/resin mix
φ_{sand} = The friction angle of sand
φ_{mix} = The friction angle of sand/resin mix
θ = $45 + \varphi_{mix}/2$
τ_n = $\sigma_n \cdot \tan\varphi_{sand}$

As a result, the epoxy resin mixes could be applied in ground improvement applications because the values of σ_n and σ_3, beyond which the use of epoxy resin grouting is detrimental to the soil strength, are especially high.

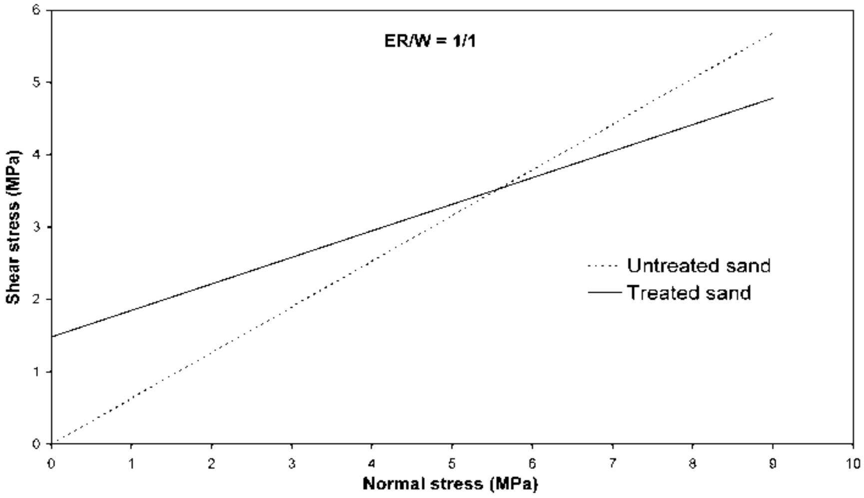
The physical parameters of the sand/resin mixes are included in Table 5. Similar to the mechanical properties, the improvement of the physical properties is dependent directly on the ER/W ratio. In the case of thick mixes, the permeability test results confirm the formation of a dense polymer film-sand matrix in which

Table 3: Shear strength parameters of treated sand specimens

	Friction angle φ (degrees) curing time (days)				Cohesion c (MPa) curing time (days)			
ER/W	7	28	90	180	7	28	90	180
1/2	-	15.50	17.10	17.20	-	0.98	1.18	1.15
1/1	27.30	20.03	20.16	20.20	0.20	1.10	1.45	1.48
1.5/1	29.72	23.99	24.90	24.70	0.32	1.78	2.28	2.32
2/1	29.90	24.20	21.20	21.40	0.40	2.10	3.54	3.60



(a)



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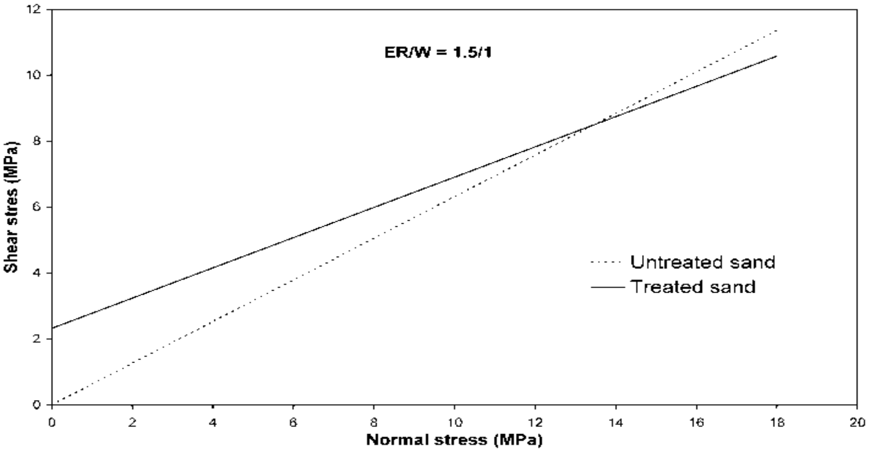

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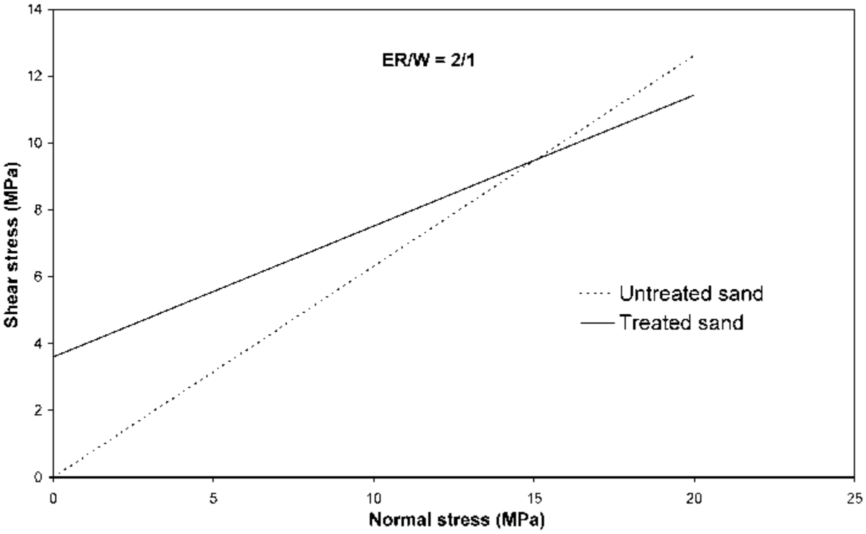


(d)

Fig. 7: Failure envelopes of untreated and treated sand with ER/W ratio of (a) 0.5, (b) 1, (c) 1.5, (d) 2

Table 4: Critical confining and normal stress values of sand specimens treated with different ER/W ratios, cured at 180 days

ER/W ratio	Confining pressure (MPa)	Normal stress (MPa)
1/2	1.81	3.56
1/1	2.94	5.60
1.5/1	7.24	13.40
2/1	7.90	14.93

Table 5: Physical properties of treated sand specimens with different ER/W ratios

	ER/W ratio			
Properties	1/2	1/1	1.5/1	2/1
Dry unit weight (KN/m^3)	1.63	1.67	1.71	1.74
Porosity (%)	27.80	23.20	20.10	16.10
Coefficient of permeability (m/s)	3.15×10^{-5}	7.84×10^{-6}	1.63×10^{-6}	8.2×10^{-7}

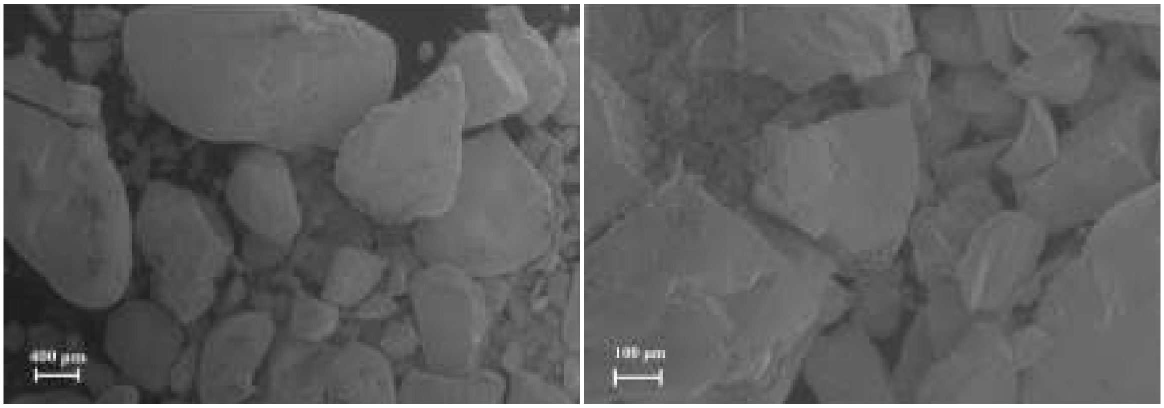
a large number of pores are filled or sealed resulting in a significant reduction of the water permeability. The permeability coefficient k decreased almost three orders of magnitude for an ER/W ratio of 2 and about two orders of magnitude for an ER/W ratio of 1.5. Despite the weakening of the polymer membrane-sand matrix in the case of thin mixes, a noticeable decrease of the water permeability was obtained.

The porosity and dry unit weight values confirm the aforementioned observations about the influence of ER/W ratio. There is an adverse impact of water when it exists in high concentrations within the mix composition.

The observed improvement of the physical and mechanical properties of the sand/epoxy mix can be further assessed through scanning electron micrographs. Figure 8 shows micrographs of an untreated sand specimen in which the sand particles appear almost unconnected with large voids around their periphery. In contrast, Fig. 9 shows a micrograph of the view perpendicular to the failure surface of a sand/resin mix specimen with ER/W ratio of 2. The micrographs reveal that a large number of voids are filled with polymer particles that act as adhesive ties to the sand grains to form a dense impermeable high strength structure and impart a significant cohesion factor. Furthermore, the inter-particle contacts seem to be reduced due to the disturbance of the particle assembly and the coating of their surface with the epoxy resin polymeric membrane which can explain the appreciable reduction of the friction angle.

Figure 10 shows the values of compressive strength, splitting tensile strength and elastic modulus of mixed fine sand specimens with different ER/W ratios at 7 and 28 days of curing in comparison with the strength values of electroosmotically treated specimens. It can be seen that the development of strength parameters of mixes treated by electroosmosis was much higher than the one obtained for untreated mixes at the age of 7 days. Especially, in the case of mixtures with ER/W ratio of 0.5, strengths of the electroosmotically treated specimens appeared to be a little higher even than the ones of untreated specimens for a curing time of 28 days. Generally, as the ER/W ratio increases the duration of electro osmotic process and its effectiveness in the enhancement of mechanical parameters of mixtures decrease. For example, electro osmotic treatment on specimens with an ER/W ratio of 0.5 caused a compressive strength, splitting tensile strength and elastic modulus value increment of 15, 10 and 40%, respectively, compared to the strength values of untreated material for curing time of 28 days. In contrast, treated mixes with ER/W ratio of 2 exhibited compressive strength, splitting tensile strength and elastic modulus values of 53, 63 and 62%, respectively, the corresponding ones of untreated mixes for a curing time of 28 days.

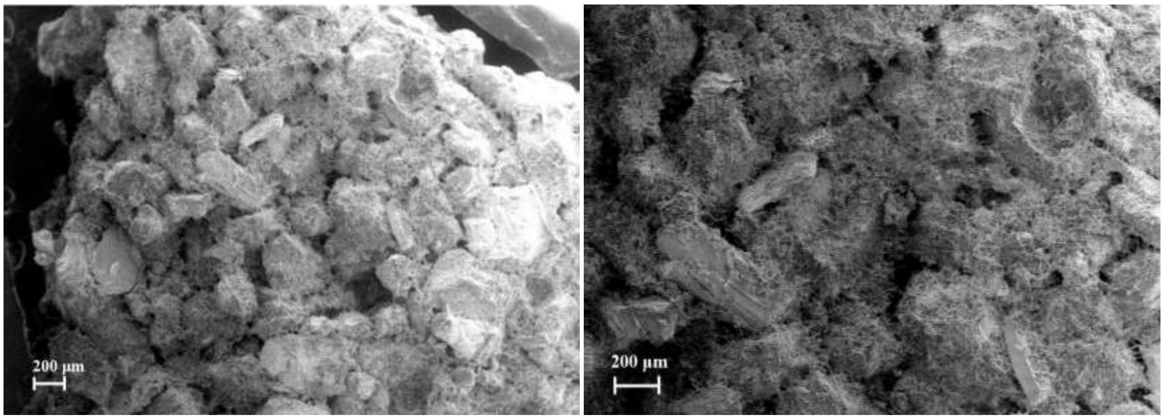
It was observed for all sand/resin mixes that after the end of electro osmotic process the whole mass of the specimen had dried out except of a small one in the vicinity of the anode which was still wet and weaken as a result of the large water quantity still remained. This result is interesting because it is in opposition to the results obtained by Ou *et al*. (2009), Liaki *et al*. (2010), Alshawabkeh and Sheahan (2003), Huweg *et al*. (2010) and Kaniraj and Yee (2011) which support the



(a)

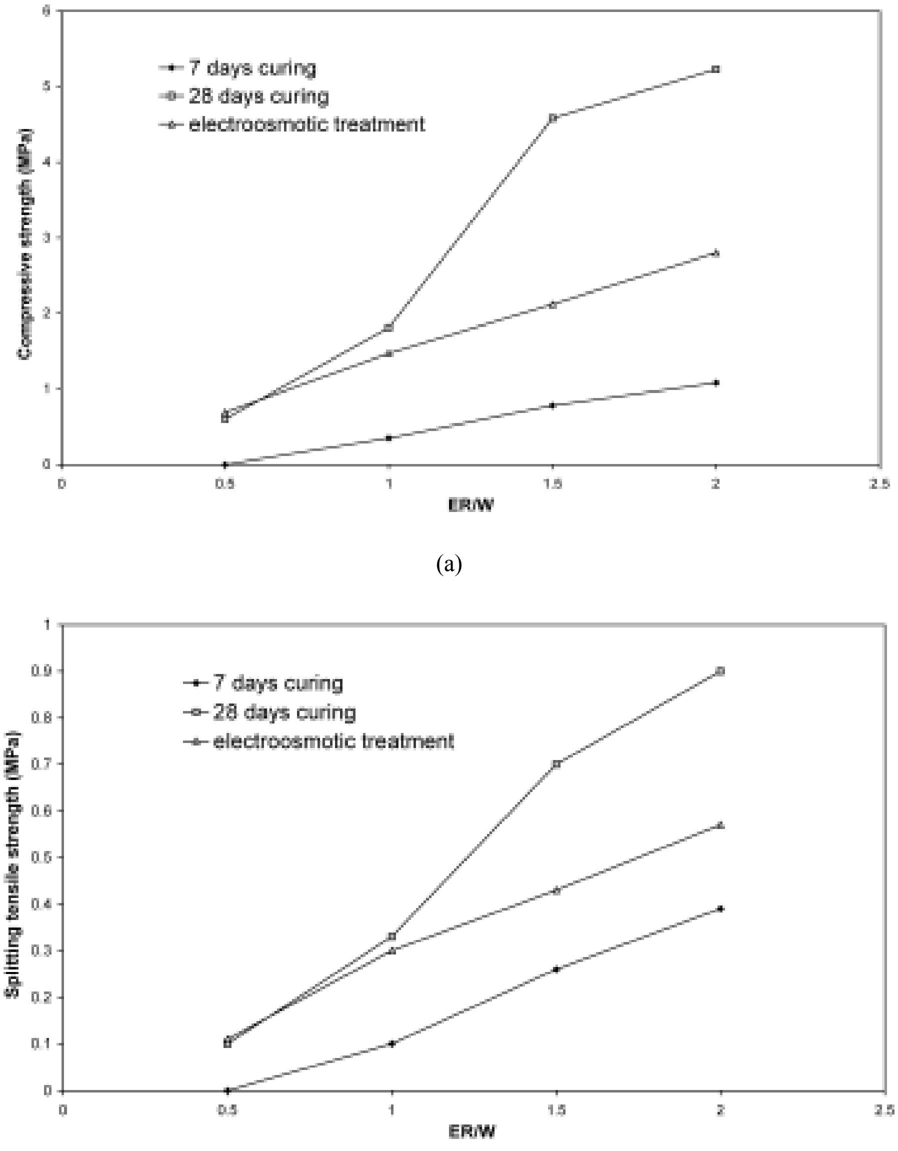
(b)

Fig. 8: A scanning electron micrograph of untreated sand with magnification of (a) 50 times and (b) 200 times



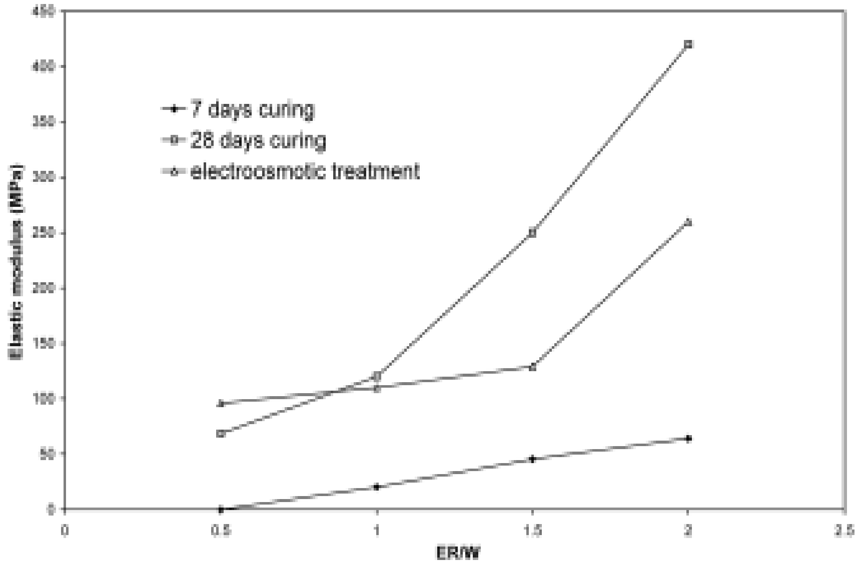
(a) (b)

Fig. 9: A scanning electron micrograph of treated sand with magnification of (a) 70 times and (b) 110 times



(a)

(b)



(c)

Fig. 10: Variation of (a) compressive strength, (b) splitting tensile strength, (c) elastic modulus of electroosmotically treated sand/resin mixes in comparison with the ones of untreated cured for 7 and 28 days

conclusion that the application of DC in a clay soil or even in a coarser sandy soil generates a relatively steady flow towards the cathode but the improvement decreases with the increase of the distance from the anode. This phenomenon is attributed to the migration of positive ions towards the cathode (electro migration). Positive ions do exist in a thin electric layer, close to the soil particle surface, that allows charge neutralization of the negatively charged clay particles. When the electric field is applied to the soil, the cations move from the particle surface towards the cathode. This movement determines a force on the fluid and therefore a flow in the same direction. Electro migration shortens significantly the treatment time. In contrast, the electro osmotic experiments of this study showed that no electro migration occurred (flow from anode to cathode) due to the low concentration of cations in the surface of sand particles and their possible entrapment by the macromolecular chains of epoxy resin coated to the surface of grains. Obviously, the reverse flow (from cathode to anode) is stemming totally from electrolysis reactions in the immediate vicinity of electrodes causing a subsequent transportation of hydroxides from anode to cathode, a fact that explains the wet condition of sand near the anode after the end of electro osmotic process.

Based on the aforementioned observations of the electro osmotic experiments, it is concluded that the duration of treatment of sand/resin mixes and the subsequent acceleration of strength development is directly related with the electrolysis of water content.

CONCLUSION

The experimental results showed that the use of water soluble epoxy resin can considerably improve the physical and mechanical properties of sand. In particular, the following conclusions can be drawn:

- The compressive strength, splitting tensile strength and elastic modulus development of the fine sand/resin mix depend directly on the water content of the epoxy resin solution. Mixes with ER/W ratio of 2 and 1.5 resulted in high strength and low permeability. Despite the weakening of the polymer membrane-sand matrix in highly diluted mixes, the 90 and 180 day mechanical properties and permeability appeared to be satisfactorily improved.
- Under triaxial stress conditions, the peak strength and stiffness of all mix specimens with different ER/W ratio increased considerably. The amount of increase depended on the confining pressure and ER/W ratio. A significant extension of the plastic zone was obtained and the difference between the peak strength and ultimate strength was negligible.
- Epoxy resin has a beneficial influence on the shear strength of sand. The cohesion after 180 days of curing varied between 1.15 and 3.6 MPa and increased in proportion to the ER/W ratio, whereas the friction angle reduced significantly. However, the overall shear strength of the sand/resin mix remained much higher than the shear strength of the untreated sand over a large range of stresses.

- Electro-osmotic process can be effectively used to accelerate the development of mechanical properties of mixes at early ages. The quality of electro osmotic improvement is directly related to the ER/W ratio of the mixture.

REFERENCES

Abdullah, W.S. and A.M. Al-Abadi, 2010. Cationic-electrokinetic improvement of an expansive soil. Appl. Clay Sci., 47(3-4): 343-350.

Ajayi-Majebi, A., W.A. Grissom, L.S. Smith and E.E. Jones, 1991. Epoxy-resin-based Chemical Stabilization of a Fine, Poorly Graded Soil System. Transportation Research Record No. 1295, National Research Council, Washington, DC.

Akbulut, S. and A. Saglamer, 2003. Improvement of hydraulic conductivity of soils by grouting. Ground Improv., 7(4): 157-164.

Al-Khanbashi, A. and S.W. Abdalla, 2006. Evaluation of three waterborne polymers as stabilizers for sandy soil. Geotech. Geol. Eng., 24(6): 1603-1625.

Alshawabkeh, A.N. and T.C. Sheahan, 2003. Soft soil stabilization by ionic injection under electric fields. Ground Improv., 7(4): 177-185.

Anagnostopoulos, C.A., 2005. Laboratory study of an injected granular soil with polymer grouts. Tunn. Undergr. Sp. Tech., 20(6): 525-533.

Anagnostopoulos, C.A., 2006. Physical and mechanical properties of injected sand with latex-superplasticized grouts. Geotech. Test. J., 29(6): 490-496.

Anagnostopoulos, C. and S. Hadjispyrou, 2004. Laboratory study of an epoxy resin grouted sand. Ground Improv., 8(1): 39-45.

Anagnostopoulos, C.A., T. Papaliangas, S. Manolopoulou and T. Dimopoulos, 2011. Physical and mechanical properties of chemically grouted sand. Tunn. Undergr. Sp. Tech., 26(6): 718-724.

ASTM C 29/C 29M-91a, 1993. Standard Test Method for Unit Weight and Voids in Aggregate. American Society for Testing and Materials, West Conshohocken.

ASTM C 938-80, 1993. Standard Practice for Proportioning Grout Mixtures for Preplaced-Aggregate Concrete. American Society for Testing and Materials, West Conshohocken.

ASTM D 3080, 2005. Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions. American Society for Testing and Materials, West Conshohocken.

ASTM D 3967-95a, 2005. Standard Test Method for Splitting Tensile Strength of Intact Rock Core Specimens. American Society for Testing and Materials, West Conshohocken.

ASTM D 4219-02, 2005. Standard Test Method for Unconfined Compressive Strength Index of Chemical-grouted Soils. American Society for Testing and Materials, West Conshohocken.

ASTM D 4320-04, 2005. Standard Practice for Laboratory Preparation of Chemically Grouted Soil Specimens for Obtaining Design Strength Parameters. American Society for Testing and Materials, West Conshohocken.

ASTM D 5084-03, 2005. Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter. American Society for Testing and Materials, West Conshohocken.

Bolisetti, T., S. Reitsma and R. Balachandar, 2009. Experimental investigations of colloidal silica grouting in porous media. J. Geotech. Geoenviron., 135(5): 697-700.

Cambefort, H., 1977. The principals and applications of grouting. Q. J. Eng. Geol., 10(2): 57-95.

CEN EN 196-1, 2005. Methods of testing cement-Part 1: Determination of strength. European Standard. European Committee for Standardization, CEN/TC 51, Brussels.

Dano, C., P.Y. Hicker and S. Taillez, 2004. Engineering properties of grouted sand. J. Geotech. Geoenviron., 130(3): 328-338.

Hoek, E. and J.A. Franklin, 1968. A simple triaxial cell for field and laboratory testing of rock. Trans. Inst. Min. Metall., 77: A22-26.

Huweg, A.F.S., F. Kamel and S. Raine, 2010. Investigating the effect of electro-osmosis on sandy soil near saturated conditions. Proceedings of the Southern Region Engineering Conference. Toowoomba, Australia, USQ, SREC2010-T1-2.

Issa, C.A. and P. Debs, 2007. Experimental study of epoxy repairing of cracks in concrete. Constr. Build. Mater., 21(1): 157-163.

Kaniraj, S.R. and J.H.S. Yee, 2011. Electro-osmotic consolidation experiments on an organic soil. Geotech. Geol. Eng., 29(4): 505-518.

Liaki, C., C.D.F. Rogers and D.I. Boardman, 2010. Physico-chemical effects on clay due to electromigration using stainless steel electrodes. J. Appl. Electrochem., 40(6): 1225-1237.

Ou, C.Y., S.C. Chien and Y.G. Wang, 2009. On the enhancement of electroosmotic soil improvement by the injection of saline solutions. Appl. Clay Sc., 44(1-2): 130-136.

Perret, S., K.H. Khayat and G. Ballivy, 2000. The effect of degree of saturation on sand groutability-experimental simulation. Ground Improv., 4(1): 13-22.

Vipulanandan, C. and A. Ata, 2000. Cyclic and damping properties of silicate-grouted sand. J. Geotech. Geoenviron., 126(7): 650-656.

Widmann, R., 1996. International society for rock mechanics-commision on rock grouting. Int. J. Rock Mech. Min., 33(8): 803-847.