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Research Article

Mechanical Properties of An Epoxy Resin and Bentonite-Grouted Sand

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Abstract: The primary objective of the present study was the investigation of the usefulness or not of two-component water-soluble epoxy resin, alone or in combination with different quantities of bentonite, to improve the static and cyclic behavior of medium-fine sand. The effect of these resins on soil strengthening has not been properly investigated yet. The conduction of the experiments took place with the use of resin solutions having varying epoxy resin-to-water ratios. The impact of grouting on the static behavior of grouted sand was evaluated by performing unconfined compression tests on specimens prepared at different curing ages. Stress control mode at level of frequency of 1 Hz with varying load amplitudes was used to investigate the behavior of grouted sand subjected to cyclic type of loading. The study herein shows that the epoxy resins, especially when combined with bentonite, significantly improve the mechanical properties of the sand. In case successful grouting takes place, the foundation material could be stabilized using the resins above.

Keywords: Bentonite, epoxy resin, grouting, strength

INTRODUCTION

Grouting is a technical method widely used in many geotechnical applications to strengthen the soil mass and in many cases to prevent liquefaction by filling the void spaces with stabilizing materials which bind the soil particles together (Nonveiller, 1989). Cement slurries are successfully grouted in coarse soils with a coefficient of permeability greater than 10^{-2} m/s (Cambefort, 1977; Dano *et al*., 2004; Mollamahmutoglu and Yilmaz, 2011). On the other hand, chemical solutions are restricted to fine soils with tiny void size, where cement suspensions cannot be injectable or their penetration is minimal (Perret *et al*., 2000).

Various materials are incorporated in chemical grouting (Widmann, 1996; Porcino *et al*., 2012). The most common are sodium, silicate, acrylamides, lignosulfonates, phenoplasts, aminoplasts and resin grouts. Particularly, one of the principal resins used for grouting is an epoxy resin. Epoxy grouts generally consist of two components. Epoxy components (A-component) are mixed with amine components (B-component) to obtain epoxy resins. The final product is characterized by high strength in compression, tension, bond, durability, high resistance to acids, alkalis and organic chemicals and low shrinkage when cured.

Lots of studies have been conducted having to do with the application of various chemical solutions for the improvement of soil strength (Maher *et al*., 1994; Ata and Vipulanandan, 1999; Vipulanandan and Ata, 2000; Anagnostopoulos, 2005; Anagnostopoulos, 2006; Tsukamoto *et al*., 2006), however only few studies are available on the effect of epoxy resin grouts on soil strengthening (Anagnostopoulos and Hadjispyrou, 2004; Anagnostopoulos and Papaliangas, 2012), whereas there is not any published information on the dynamic properties of epoxy resin grouted soils and their liquefaction resistance.

The primary objective of the current experimental study was the investigation of the mechanical behaviour of epoxy resin grouted sands with grouts proportioned with different resin-to-water ratios and varying amounts of bentonite when subjected under monotonic or dynamic loading.

MATERIALS USED

Epoxy resin is water soluble and is based on the diglycidyl ether of bisphenol-A. An aliphatic amine was employed as a curing agent for the resin. The optimum mixture ratio by weight of epoxy resin (A) and hardener (B) is A:B = 2.5:1. The manufacturer states that the epoxy resin, without the addition of water, attains its final strength after seven days.

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Table 1: Index properties of sand used

USCS classification	SP
D_{60} (mm)	1.51
D_{30} (mm)	1.10
D_{10} (mm)	0.91
Coefficient of uniformity, C_u	1.66
Coefficient of curvature, C_c	0.88
Specific gravity, G_s	2.66
Maximum void ratio, e_{max}	0.71
Minimum dry unit weight, γ_{dmin} (kN/m^3)	1.56
Minimum void ratio, e_{max}	0.58
Maximum dry unit weight, γ_{dmax} (kN/m^3)	1.68

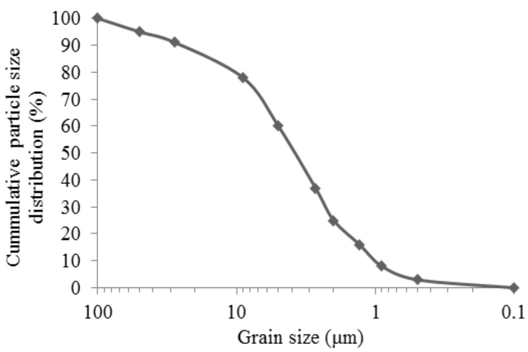


Fig. 1: Particle size distribution of bentonite

Fig. 2: Testing apparatus for grouting experiments

Standard medium-fine siliceous natural sand was collected from natural river deposits. It has a round shape and in general isometric particles. The grains ranged from 0.84 to 2 mm in size and its physical properties are given in Table 1.

Bentonite is a Na-activated bentonite from the Greek island of Milos. The bentonite consists mainly of montmorillonite (90%) and minor quartz calcite dolomite and brookite. Figure 1 gives particle size analysis of the bentonite powder. It has a specific surface area of 65.6 m^2/g, cation exchange capacity of 85 meq/100 g (Na-activated), liquid limit w_L of 450 and plastic limit w_P of 45.

EXPERIMENTAL PROCEDURE

Grouts with ER/W ratios of 0.5, 1.0, 1.5 and 2 were used for the injection tests. The proportions of bentonite were 0, 1.5, 2.5 and 5% by weight of water. The experimental set-up for the injection of the sand columns was developed in accordance with the ASTM D 4320, 2009 specification. The set-up consists of a mixing tank with a high speed rotating stirrer, air-operated diaphragm pump, air compressor, pressure regulator and pressure meters, plastic cylindrical moulds and relevant connections (Fig. 2). The internal diameter of the mould was 55 mm and its height was 1500 mm. Prior to specimen preparation, light lubrication was applied to the inner surface of the moulds to eliminate specimen disturbance upon removal from the moulds after the end of injection. For sand columns, the filling process was performed carefully using an air pluviation system to ensure the uniformity of the specimens (Akbulut and Saglamer, 2002; Towhata, 2008). After placing the specimens at the targeted relative density D_r of 50%, the top and bottom end plates of the mould were clamped using tie-rods.

The low plastic viscosity and easy penetration of the epoxy resin grouts into the soil voids allowed for application of a low pressure of approximately 100 kPa during the injection tests. The injection was finished after percolation through the specimen of excess grout equivalent to 120% of the sand pore volume. The grouted specimens were left to cure in the moulds for at least three days to gain adequate strength. Afterwards, they were removed from the moulds and cut into smaller cylindrical specimens with a diameter of 55 mm and length of 110 mm. These specimens were used to study the mechanical response of the grouted sand. The treated samples were then stored at a constant temperature of 25°C until the day of testing. These cylindrical specimens were used for compressive strength and elastic modulus estimations at 3, 7, 30 and 90 days of curing as well as for cyclic triaxial tests at 90 days of curing. All compression tests on grouted specimens were conducted using a strain rate of 0.1%/min. The elastic modulus was determined using the values from the linear segment of the compressive stress-strain curve. Previous research (Anagnostopoulos *et al*., 2014; Anagnostopoulos and Sapidis, 2017) has shown that epoxy resin grouted sands gain most of their final strength after 90 days of curing, after which noticeable improvement is not observed. For this reason, the current experimental program has studied the strength development of grouted specimens at curing ages up to 90 days.

Cyclic triaxial tests were conducted according to the (ASTM D 5311, 2013) specification. Un-grouted and grouted sand specimens were tested under triaxial compression, which means that the cyclic deviatoric stress was always positive with a resultant single amplitude cyclic axial strain. An effective confining pressure of 100 kPa was applied for all cyclic tests. All cyclic and monotonic unconfined compression tests were conducted using an Istron servohydraulic (model 3500 KPX) compression testing machine, equipped with a Linearly Variable Differential Transformer (LVDT) and a load cell linked to a data logging computer used to record the stress-strain values during the test conduction. The cyclic tests were performed under load-control mode at a frequency of 1 cycle/s (1 Hz).

For comparison purposes with the grouted specimens, un-grouted sand specimens were reconstituted with the same D_r of 50% and a back pressure saturated with de-aired water in the triaxial cell. Due to the low hydraulic conductivity of the grouted samples, the pore pressure response during cyclic loading could not be measured. Therefore, during the cyclic tests, the axial strain development and strength loss were used for the quantification of the results of the treated and untreated sand.

Each of the reported compressive strength, elastic modulus and cyclic strength values correspond to an average value of at least three specimens, the values of which deviate no more than 5% from the average value of all tested specimens with the same epoxy resin grout.

RESULTS AND DISCUSSION

Injection tests in sand columns showed that epoxy resin grouts, with or without bentonite, can penetrate easily and uniformly into the voids. This resulted in the development of isotropic strength along the distance from the grouting point. Figure 3 depicts some of the above results presenting the compressive strength evolution of grouted sand with grouts having an ER/W ratio of 1 and 2 at a curing age of 90 days in relation to the distance from the injection point. This tendency was observed for all grouted specimens with different ER/W grouts and bentonite content.

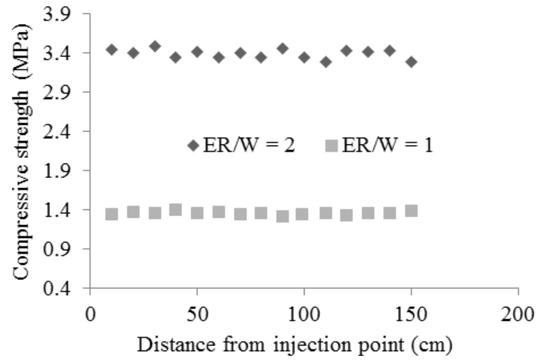
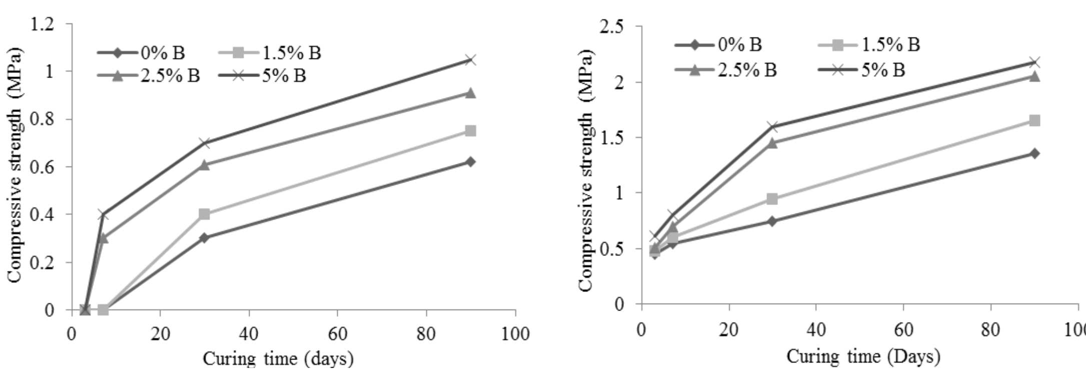
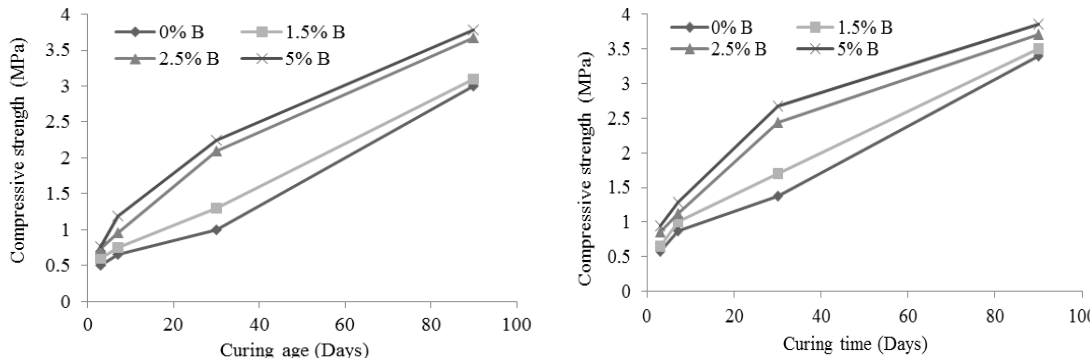


Fig. 3: Compressive strength of grouted specimens with grouts having an ER/W ratio of 1 and 2 in relation to the distance from the injection point

Figure 4 and 5 present the compressive strength and elastic modulus evolution of the grouted sand in accordance with the curing time. In particular, the experimental results revealed the adverse influence of water on the strength development of epoxy resin matrix, resulting in low early or final strengths of the grouted samples. For example, after seven days of curing, no strength development was obtained for grouted specimens with an ER/W ratio of 0.5, whereas the samples grouted with ER/W ratio of 2 appeared to have mean values of compressive strength and elastic modulus of 3.4 and 380 MPa, respectively. However, as time passed, the strength was increasing, resulting in noticeably greater strength values. This tendency was mainly dependent on the ER/W ratio. Specimens grouted with thick epoxy mixes (ER/W = 2, 1.5) appeared to have a much higher strength increase compared to the samples with thinner epoxy mixes. This phenomenon appeared for all curing ages. Previous studies reported similar findings being consistent with the results above. (Anagnostopoulos and Papaliangas, 2012; Anagnostopoulos *et al*., 2014; Anagnostopoulos *et al*., 2016).

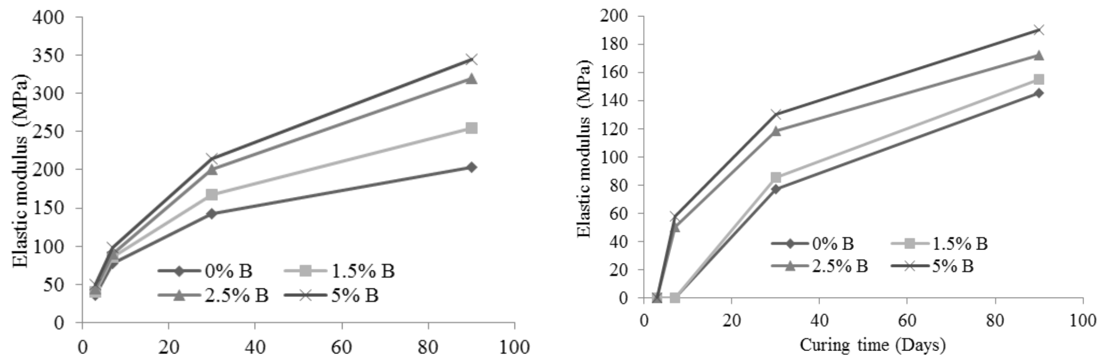


(a) (b)

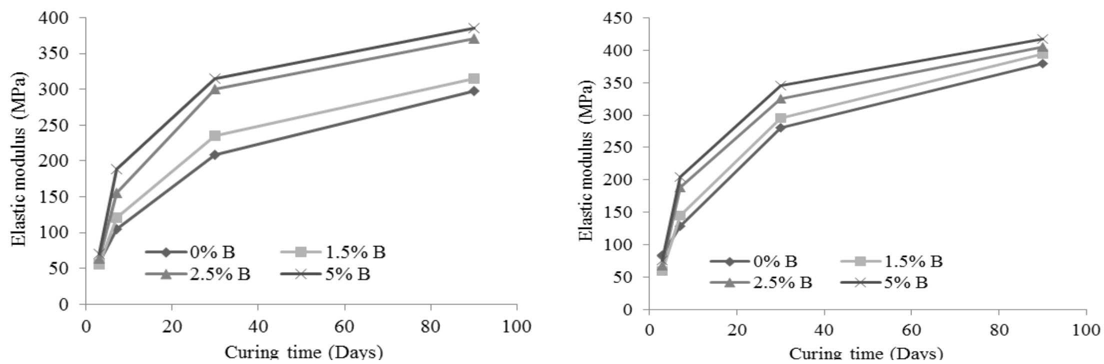


(c) (d)

Fig. 4: Development of the compressive strength of grouted sand with ER/W ratios of: (a) 0.5, (b) 1, (c) 1.5 and (d) 2 and different amounts of bentonite



(a) (b)



(c) (d)

Fig. 5: Development of the elastic modulus of grouted sand with ER/W ratios of: (a) 0.5, (b) 1, (c) 1.5 and (d) 2 and different amounts of bentonite

To diminish the harmful effect of water on the strength of treated samples, Na-bentonite was used as a material that, by absorbing a large quantity of water, would promote the reactions between the epoxy resin and hardener, resulting to a rise of the grout strength. Indeed, the addition of bentonite significantly increased the early and final strengths of all grouted specimens with different ER/W ratios. Figure 4 and 5 reveal that the strength of grouted specimens increases with the increase of the bentonite content. Strength enhancement was more pronounced in the case that bentonite was added in grouts with high water contents. For example, in the case of grouts with ER/W ratio of 0.5 and 2 containing 5% bentonite, the compressive strength increased by 133% and 95%, respectively, in relation to the grouts without bentonite content, both at the age of 30 days. After 90 days of curing, the increment appeared to be 69% and 13% when compared again with the strength of grouts without bentonite content.

Table 2: Cyclic testing results for epoxy resin grouted sand specimens

Sample	CSR	Cycles to 1% strain	Cycles to 2% strain	Cycles to strength loss	Cycles to failure
Untreated sand	0.4	1	3	5	6
	0.6	1	1	2	3
ER/W = 0.5	9.6	1	2	10	15
	7.4	3	8	78	89
	6.8	15	36	95	120
	5.2	45	154	700	750
	4.7	79	300	1230	1330
	4.4	100	400	2700	3010
	3.7	355	1708	5500	6000
	3.3	772	4192	9200	10180
	3.1	1125	6476	16800	18000
ER/W = 1	14.3	1	10	13	15
	13.8	3	28	33	39
	12.9	4	40	124	129
	12.0	4	63	207	217
	10.6	5	107	310	370
	9.3	23	173	736	785
	8.5	150	560	1236	1329
	7.9	479	1240	2650	3000
	7.5	1040	2614	3800	4100
	7	2100	3870	7200	7800
	6.4	5500	11370	11800	13000
	6.0	7500	14900	16100	17723
ER/W = 1.5	18	1	3	15	15
	17.3	1	4	21	22
	16.5	1	6	64	68
	15.4	15	60	146	231
	14.0	75	355	600	614
	13.5	100	550	844	874
	13.2	130	750	1180	1233
	12.1	400	1400	2850	3000
	11.5	900	2800	4400	4646
	11.0	1800	6000	8200	8980
	10.8	4000	8000	12000	13000
	10.4	9500	15000	16800	18000
ER/W = 2	24.8	1	3	15	15
	23.6	1	4	23	25
	22.1	3	7	45	50
	20.7	9	30	94	100
	19.0	15	75	235	250
	17.8	45	200	480	500
	17.1	95	450	720	750
	16.7	120	600	960	1000
	15.6	380	1200	1900	2000
	14.3	1200	3200	4850	5000
	13.7	4500	8000	9600	10000
	13.2	10000	16500	17500	18000

The behaviour of grouted sand under cyclic loading on specimens cured for 90 days was examined since, at later stages, a noticeable difference in cyclic resistance was not expected, as evidenced from the performance of monotonic loading tests. The cyclic behaviour of all specimens was evaluated at different CSRs. The CSR is defined as follows: CSR = $(\sigma_1-\sigma_3)\ /2\sigma'_3$. Un-treated sand specimens were tested at a CSR of 0.4 and 0.6, while the treated specimens were tested at CSR values up to 24.8. To evaluate the success of the epoxy resin grouting, the number of loading cycles required to cause 1 and 2% axial strain and the total number of cycles (N_f) that grouted or un-grouted specimens sustained before failure occurred were recorded for the different CSRs and are summarized in Table 2 and 3. Moreover, Table 2 and 3 present the number of cycles (N_L), which is referred to as the number of cycles to strength loss. Beyond this value, specimens ceased to sustain the maximum pre-set stress value and gradually lost stiffness and strength as cyclic loading continued; a fact that clearly indicates the initiation of failure (Vipulanandan and Ata, 2000). Un-grouted specimens sustained some cycles before the onset of liquefaction. Once liquefaction was triggered, large strains occurred rapidly and the specimens collapsed almost instantly. On the contrary, grouted specimens exhibited much more cyclic resistance. When loaded at the same CSR values, grouted specimens did not liquefy but remained intact, even after 10,000 cycles, when the test was stopped. Failure of the treated samples was observed at significantly higher CSRs and after tens or hundreds of loading cycles. In particular, Table 2 shows the mechanical response of grouted specimens containing only epoxy resin for different CSRs. It should be noted that specimens were not saturated or back-pressured. The increase in cyclic resistance was strongly

Table 3: Cyclic testing results for bentonite-epoxy resin grouted sand specimens

Sample	CSR	Cycles to 1% strain	Cycles to 2% strain	Cycles to strength loss	Cycles to failure
ER/W = 1 and 5% B	9.8	6	7	8	8
	8.6	14	19	16	19
	7.8	16	40	48	51
	7.3	20	100	114	118
	7.0	22	170	230	233
	6.7	25	375	390	394
	6.5	205	740	745	750
	6.2	1250	1508	1505	1508
	6.1	1750	2000	2188	2192
ER/W = 1.5 and 9.5% B	16.9	1	6	6	6
	14.0	1	8	12	12
	13.0	1	14	23	24
	12.3	1	21	40	42
	11.2	1	35	129	134
	10.8	6	133	144	149
	10.0	35	315	351	357
	8.8	50	667	793	800
	8.1	65	1412	2385	2392
	7.1	120	6283	9490	9500
	6.8	152	7879	10792	10800
	6.7	210	8900	11570	11578
ER/W = 1.5 and 5% B	18.3	1	6	6	6
	17.4	1	9	14	14
	16.3	1	12	21	21
	14.8	2	60	57	62
	13.5	3	110	147	151
	13.1	9	179	180	184
	12.4	11	420	582	588
	12.2	20	660	781	786
	12.0	24	700	901	907
	11.8	26	850	1192	1197
	11.6	30	1020	1292	1300
ER/W = 2 and 2.5% B	18.3	1	2	5	5
	17.5	1	2	6	6
	14.1	1	3	19	20
	12.4	1	3	37	41
	11.8	1	20	46	50
	9.5	1	48	97	102
	8.1	23	187	202	208
	7.9	85	285	302	308
	7.1	100	685	860	867
	6.7	110	900	1506	1513
	6.4	125	1250	2770	2775
ER/W = 2 and 5% B	18.3	1	6	7	7
	17.5	1	8	32	35
	16.5	1	49	71	76
	15.4	1	70	89	93
	13.7	10	205	263	267
	12.9	12	340	706	711
	12.3	25	913	1437	1443
	11.7	33	1100	1611	1620

correlated with the ER/W ratio. It is worth noting that specimens did not rapidly collapse when they ceased to sustain the maximum pre-set value but were continuously deforming for several cycles until failure occurred. However, when the grouted specimens were saturated and back-pressured during repetitive triaxial loading, in order to study the mechanical response under pore water pressure conditions, their cyclic resistance appeared to be negligible for all ER/W ratios. These results could be attributed to the weakening or damage of polymeric network, because of the disruption of the hydrogen bonds among polymer segments or the hydrolysis of linkages, such as the ether linkage, by water molecules (Powers, 2009).

Addition of 1.5% bentonite did not improve the dynamic response for all ER/W ratios. However, the addition of higher amounts of bentonite (2.5% and 5%) led to a remarkable increase of cyclic resistance (Table 3). An exception is the case of grouting with grouts having ER/W ratio of 0.5 (proportioned with 2.5% and 5% bentonite) and ER/W of 1 (proportioned with 2.5%), at which the cyclic resistance remained insignificant.

Inspection of values presented in Table 3 reveals that when the specimen ceases to sustain the maximum stress, failure occurs almost instantly or after a few cycles. This observation is interesting because it is in opposition to the results obtained from grouted

Table 4: Values of regression coefficients

Compressive strength (MPa)											
a	b	c	d	e	f	g	h	i	j	k	l
-0.11	0.13	1.37	10.9	0.81	1	--1.72	0.23	-0.76	0.77	7.66	0.98
Elastic modulus (MPa)											
-287	1	0.95	-3.45	0.03	1.35	34.5	0.87	0.97	0.04	1.65	1.28
Compressive strength (MPa)											
m	n	o	p	q	r	s	t	u	v	R2	
-1.3	1.1	0	0.63	1.17	0.81	10.69	-1.3	2.17	0.54	0.97	
Elastic modulus (MPa)											
33.5	12.5	11.5	-	-	-	-	-	-	-	0.98	

specimens containing only epoxy resin. Obviously, there is a physico-chemical reaction between bentonite and epoxy resin polymeric membrane which determines the mechanical response of the whole composite.

On the basis of the experimental results and using the SPSS v17.0 statistics program, non-linear regression analysis was performed to correlate the compressive strength and elastic modulus of the epoxy resin-bentonite grouted sand to the descriptor variables, including ER/W ratio, bentonite content and curing age. The models that provide the best correlation concerning the mechanical parameters have the following form:

Compressive Strength (CS):

$$CS = a + v[b + (ER/W)^c][d + (CT)^e][g + (B)^f] + n[i + (ER/W)^h][k + (CT)^j][m + (B)^l] + p[o + (ER/W)^q][s + (CT)^r][u + t(B)] \quad (1)$$

Elastic modulus (EM):

$$EM = a + o[b + (ER/W)^c]\,[d + (CT)^e][g + (B)^f] + n[i + (ER/W)^h]\,[k + (CT)^j]\,[m + (B)^l] \quad (2)$$

where,

a-v = Coefficients obtained from the regression analysis
B = The percentage of bentonite content
CT = The curing time measured in days

The different values of the regression coefficients and the corresponding correlation coefficients R^2, for each mechanical parameter, calculated from the regression analysis are given in Table 4. The above relations for the mechanical properties of the grouted specimens at any age, ER/W ratio and bentonite content were found to fit the experimental data satisfactorily, as shown in Fig. 6 and 7. These figures illustrate a plot of the measured parameter values versus the predicted values resulted from the regression analysis. The straight line in the figures represents the line of perfect equality, where the values being compared are equal. As can be seen from Fig. 6 and 7, the scattering is minimal.

Also, regression analysis resulted to a simplified model that relates the number of cycles until failure (N_f) to the CSR level. This model follows the power law.

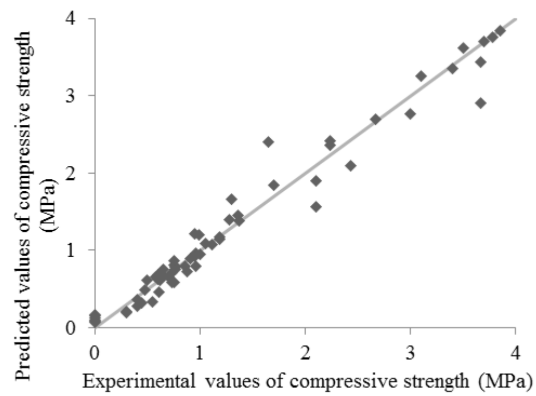


Fig. 6: Cross plot of experimental values of compressive strength against predicted values from the regression Eq. (1)

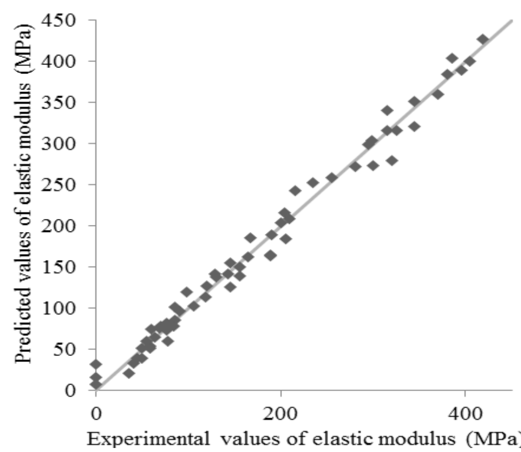


Fig. 7: Cross plot of experimental values of elastic modulus against predicted values from the regression Eq. (2)

$$CSR = a\, N_f^{\,b} \quad (3)$$

where a and b are coefficients obtained from the regression analysis. Figure 8 to 11 depict the different values of the regression coefficients and R^2 for all grouted specimens with different ER/W ratios and bentonite content.

CONCLUSION

The experimental results of this study clearly indicate that epoxy resin grout, especially when

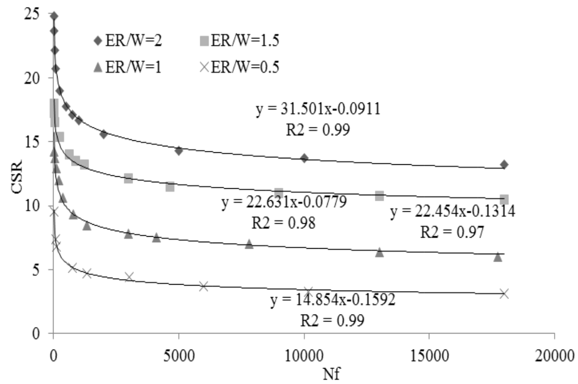


Fig. 8: CSR vs N_f of grouted sand with different ER/W ratios

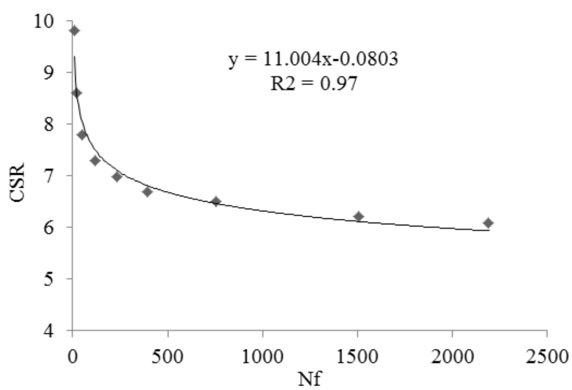


Fig. 9: CSR vs N_f of grouted sand with ER/W ratio of 1 and 5% bentonite content

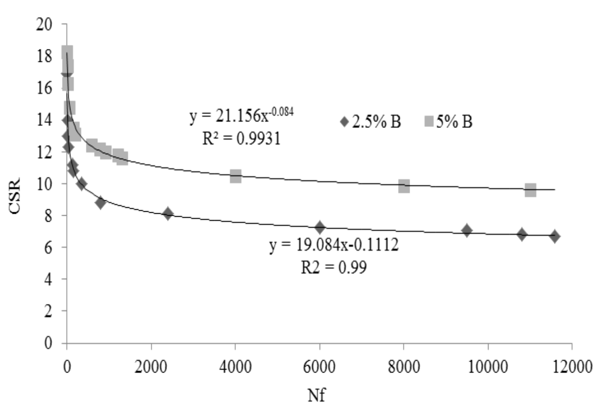


Fig. 10: CSR vs N_f of grouted sand with ER/W ratio of 1.5 and 2.5, 5% bentonite content

combined with bentonite, can provide a suitable solution for the stabilization of a wide range of foundation materials. More specifically, the following conclusions can be noted:

- Epoxy resin grouts, when grouted alone or in combination with bentonite, penetrate uniformly into sand pores, resulting in the development of isotropic strength along a path from the injection point

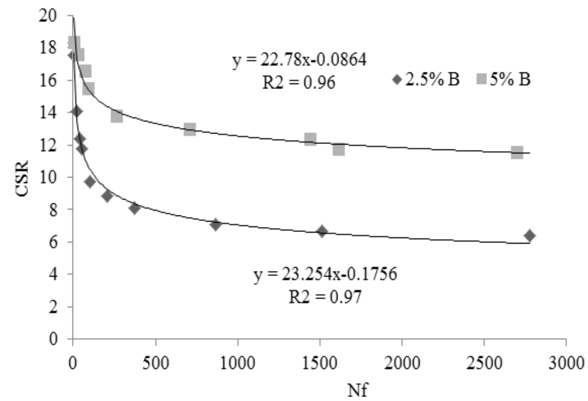


Fig. 11: CSR vs N_f of grouted sand with ER/W ratio of 2 and 2.5, 5% bentonite content

- Compressive strength and elastic modulus development are directly dependent on the ER/W ratio and curing time. The higher the ER/W ratio is, the greater the strength improvement is
- The addition of bentonite contributes considerably to the increase of the mechanical properties of grouted sand for all ER/W ratios at all curing ages. The higher the bentonite content was, the more significant the improvement of the mechanical parameters (compressive strength and elastic modulus) was
- The cyclic resistance of grouted sand is significantly higher than that of un-grouted sand. Cyclic resistance increases as the concentration of epoxy resin in the grouting solution increases
- Under pore water pressure conditions, the cyclic resistance of grouted specimens containing only epoxy resin appeared to be negligible. However, the addition of 2.5 and 5% bentonite increased remarkably the cyclic strength of most of the grouted specimens

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