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# Influence of Curing Time and Water Content on Unconfined Compressive Strength of Sand Stabilized Using Epoxy Resin

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Improvement and stabilization of soils are widely used to improve the physical and mechanical properties of sandy soils. Despite the abundance of researchers that have been conducted on this topic to date, most of them have focused on dry soil. The effects of the existing water in the soil and different curing durations (curing environment) have not been investigated. In this study, different percentages of epoxy resin and sand with different level of water content were studied. In this paper, a series of unconfined compressive strength (UCS) tests were conducted on mixtures of sand-resins using different percentages of resins at different water content levels. In addition, these specimens were cured under different moisture conditions, and the effect of moisture on specimens was evaluated over time. The results of this study showed that the addition of epoxy resin to sandy soil significantly increased its UCS which highly depended on epoxy resin percentage, water content and curing time. As the concentration of epoxy resin and the curing time increased, the strength increased; however, epoxy resin was more effective. On the other hand, increasing the water content had a negative effect on their strength of the specimens. According to this study, the epoxy resin could be selected to be appropriate and beneficial as a stabilizer for sandy soil due to its relatively high compressive strength and high resistance to aggressive environment.

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## 1. INTRODUCTION

Soil improvement techniques used to change the characteristics of soil for improving the mechanical properties of soil, and these techniques have been widely used. Soil improvement techniques are growing since they are feasible and economical. Soil improvement (also known as soil stabilization) is the change of properties of the soil to improve its engineering performance [1-3]. The main properties of soil which are of interest to engineers are the strength, the durability, the volume stability, the compressibility and the permeability [4-6].

Soil improvement techniques could be classified in various groups including mechanical, chemical, and physical stabilization [4, 7-9]. In mechanical stabilization, the soil density is increased by the application of mechanical forces such as surface layer compaction. Physical stabilization includes changing the physical conditions of soil by heating or freezing [10]. In chemical stabilization, additives are used such as cementitious, natural soils, industrial by-products or waste materials. Chemical stabilizers can be categorized into two groups as follows: 1) traditional stabilizers such as lime, cement, and fly ash, and 2) nontraditional stabilizers such as resin and enzymes [11]. The traditional stabilization techniques often require long cure time and relatively large quantities of additives. Furthermore, sometimes the common stabilizers are not suitable. For example, the UCS of 4% cemented sand is approximately 0.25 MPa which is relatively low compared to nontraditional stabilization [12].

Time-consuming of curing and considerable transportation volume of stabilization materials are a great issue. Non-traditional stabilizers have become increasingly available especially for commercial or other urgent application [13-15]. In recent years,

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polymer modified mortars, polymer concrete and polymer modified grouts (liquid dispersions that are injected into the soil to improvement its properties) are widely used as construction materials [16, 17]. They have advantages such as high tensile and compressive strength, less curing time and drying shrinkage, high durability and chemical resistance [10, 18-20]. The stabilization techniques depend on the reaction of the soil with additives. Strength, durability, volume stability, and permeability are the four main aspects of soil behavior that can be improved using additives. The use of a particular additive depends on given situation, e.g., circumstances of soil, the structure which is going to be built on the soil, and its environment condition [16].

Polymer material like epoxy resins has been used in civil engineering for repair and rehabilitation of concrete structures and pavement materials [21-23]. Furthermore, the epoxy resin can be used as stabilizer material to improve the mechanical properties of soils. In addition, epoxy resin as stabilizer improves different characteristics of the soil [24-27]. Tingle and Santoni examined the effect of different resins on UCS and tensile strength of cohesive soil [27] and reported that resins could significantly increase the strength of cohesive soil. Rauch et al. conducted a series of experiments to investigate the effects of various nontraditional stabilizers on the treatment of different clay. They concluded that all these stabilizers improve the soil characteristics. However, the growth of them is different which dependent on soil aggregation and resin type [28].

In recent years, more research has been conducted on the mechanical properties of the resin-sand mixture such as strength. Al-khanbashi and Shahib investigated the effect of three water born polymer as a stabilizer for sandy soil. Their results showed an increase of modulus of elasticity and UCS of the examined emulsions by increasing concentration of polymer [11]. Estabragh et al. investigated the effect of resin on engineering properties of the soil-cement mixture. Based on their results, the strength of soil-cement was increased significantly by adding acrylic resin [12]. Naeini and Ghorbanalizadeh performed comparative studies of using epoxy resin to stabilize silty sand. The results indicated that adding epoxy resin to silty sand leads to strength improvement which depends on the content of polymer and silt [19]. In Addition, Anagnostopoulos et al. conducted experiments to evaluate the strength of sand using two-component water-soluble epoxy resin. Their laboratory results indicated that epoxy resin significantly improves the physical and the mechanical properties of sand which depends on time and ratio of epoxy resin and water [29]. Anagnostopoulos investigated the effect of water-soluble epoxy resin and cement on the mechanical properties of silty clay. He reported that adding the desired resin can increase the UCS of silty clay. Additionally, the addition of 20 and 30% cement considerably increase the mechanical properties of all mixes at all ages [30].

Despite the abundance of researchers that have been conducted on this topic to date, most of them have focused on dry soil. The effects of the existing water in the soil and different curing durations (curing environment) have not been investigated. In this study, different percentages of epoxy resin and sand with different level of water content were studied. The objective of this study was to investigate the effect of epoxy resin on the mechanical properties of sand and development of UCS over time through a program of experimental tests. To determine these properties, standard test methods, according to ASTM specifications, were conducted at different curing times. Various conditions were applied to simulate real environmental condition such as humid zone condition or intense rainfall (curing in a chamber) and groundwater table rising (saturation of dry specimens before being tested).

## 2. MATERIALS AND METHODS

**2. 1 Materials** Soil and epoxy resin were the materials used in the specimen's preparation.

**2. 1. 1. Soil** Sandy soil material used in this investigation was collected from Haft-Baq Alavi in Kerman province, Iran [N30.123, E57.164]. The physical properties of the soil are summarized in Tables 1. Figure 1 also shows the grain size distribution of the soil. The soil is classified as poorly graded sand (PS) according to the unified soil classification system (USCS).

**2. 1. 2. Epoxy Resin** In this study, the epoxy mixture consists of two equal parts: one part component A (resin) to one part component "B" (hardener) by weight. The color of the mix is light yellow with a density of 0.1 gr/cm$^3$.

**TABLE 1.** Physical properties of the soil

| Parameter | Description | Values |
|---|---|---|
| Gs | Specific gravity [31] | 2.65 |
| $\omega o_{pt}$ | Optimum moisture content (%) [32] | 11 |
| $\gamma_d$ | Maximum dry density (kN/m$^3$) [33] | 17 |
| Cc | Coefficient of gradation | 0.92 |
| Cu | Coefficient of uniformity | 2 |
| Φ | Angle of internal friction (°) [33] | 34 |
| C | Cohesion (kPa) [34] | 0.018 |

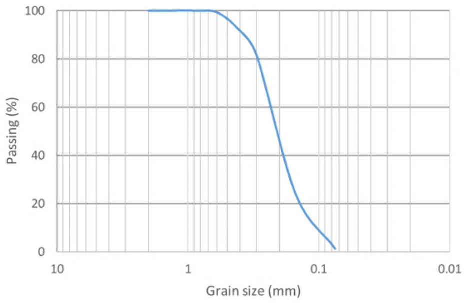



**Figure 1.** Grain size distribution curve

## 3. LABORATORY PROCEDURE

The experimental tests were classified into four groups as follows: 1) dry sand mixed with 2, 4 and 6% of epoxy resin, 2) sand with different water content (2 and 4%) mixed with 2, 4 and 6% of epoxy resin (that were designated as w2 and w4 for specimens stored at room temperature and cw2 and cw4 for specimens covered with a clear film to prevent evaporation), 3) sand with 8, 11 and 14% water content mixed with 4% of epoxy resin and 4) saturated sand with 2, 4 and 6% of epoxy resin that saturation takes place three hours before the tests to allow the water penetrate into specimens. Specimens in group 3 were tested at age 3 and 7 days while the rest of specimens were tested at age 3, 7 and 28 days.

Note that the ratios of epoxy resin to aggregate were 2, 4 and 6% by weight. Sand and resin were weighed with an accuracy of 0.1 gram. A rotating stirrer (three-blade paddle mixer) as suggested by the ASTM C938 specifications was used for mixing [34]. Therefore, the components were mixed using mixing paddle for nearly three minutes until a fully uniform color was obtained [35]. Then, the mixtures were poured into cylindrical molds and then compacted. The dimension of the cylindrical molds was 5 cm in diameter and 10 cm in height. A metal hammer weighing 4.5 kg was used for compaction, and lightly tapping on the sides of the mold. Note that each specimen was filled in thirds with each layer rodded 25 times from a height of 5 mm.

All the specimens had a height to diameter (h/d) ratio of two, since complex stress conditions may occur for lower than this ratio [36]. After the specimens were removed from the molds, the bottom and the top surfaces of the specimens were polished with sandpaper. All specimens were cured at room temperature (approximately 25°C). Figure 2 shows sandy soil stabilized with epoxy resin specimen.

Unconfined compression tests were carried out on the specimens of resin-sand at age 3, 7, and 28 days. The load was continuously applied under a constant axial strain rate of 1 %/min according to ASTM D 4219 [37].

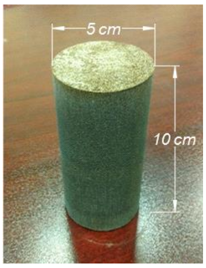



**Figure 2.** Sandy soil stabilized with epoxy resin

## 4. RESULTS AND DISCUSSION

According to the results of the compressive tests as shown in Figure 3, the unconfined compressive strength (UCS) increased by increasing epoxy resin ratio. This figure illustrates the unconfined compressive strength of stabilized dry-sand specimens with 2, 4 and 6 % of epoxy resin. In addition, the increase of UCS over time is most likely a result of a better curing performance. This is because of the adsorption process of epoxy resin. Thus the molecules of polymer can form a bond with soil. Their confinement on soil which is through adsorption of epoxy resin molecules. This adsorption can occur on both internal and external surfaces that cause more cohesion of soil and an increase in unconfined compressive strength of specimens.

To quantitatively evaluate the effect of polymer content and curing time on the unconfined compressive strength of the studied soil, a regression analysis was applied to obtain the following relationships among UCS and time (t) values for soils with 2, 4 and 6% of epoxy resin, respectively:

$$UCS(MPa) = 2.122 + 0.0693 \cdot t\,(days),\quad R^2=0.8665 \tag{1}$$

$$UCS(MPa) = 6.805 + 0.1733 \cdot t\,(days),\quad R^2=0.8665 \tag{2}$$

$$UCS(MPa) = 10.428 + 0.2162 \cdot t\,(days),\quad R^2=0.759 \tag{3}$$

Figure 4 illustrates the UCS of stabilized sand specimens with 2, 4 and 6% epoxy resin with 2% and 4% of water content.

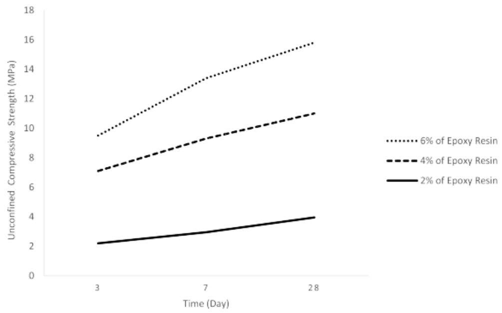



**Figure 3.** The unconfined compressive strength of stabilized dry-sand specimens with 2, 4 and 6% of epoxy resin

In addition, Figure 5 illustrates the unconfined compressive strength of stabilized covered-sand specimens with 2, 4 and 6% epoxy resin with 2% and 4% of water content. As can be seen in Figures 4 (a)-(b) and 5 (a)-(b), the UCS of sand increased by increasing of epoxy resin and UCS increased over time. However, the growth of UCS at the same periods of time and the same amount of epoxy resin were different. The UCS of specimens with lower rates of water content was higher than that of high rates of water content. On the other hand, the UCS of specimens cured in a chamber was lower than that of cured at room temperature.

The equations and the corresponding correlation coefficients R2 obtained from the regression analysis are as follows:

(a) 2% of water content:

$$UCS(MPa) = 0.1545 + 0.0378.\ t\ (days),\quad R2=0.9785 \qquad (4)$$

$$UCS(MPa) = 2.9379 + 0.0602.\ t\ (days),\quad R^2=0.9743 \qquad (5)$$

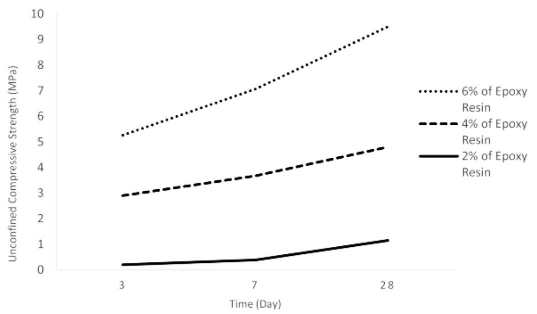
$$UCS(MPa) = 5.1882 + 0.1615\ .t\ (days),\quad R^2=0.9212 \qquad (6)$$

(b) 4% of water content:

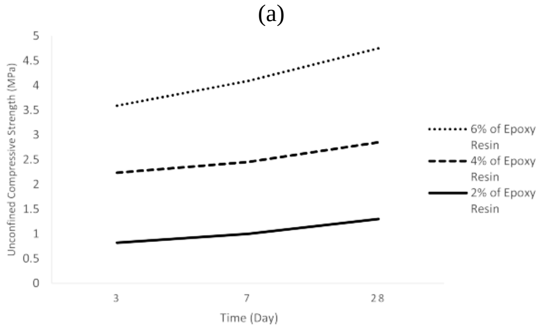
$$UCS(MPa) = 0.8161 + 0.025\ .\ t\ (days),\quad R^2=0.9172 \qquad (7)$$

$$UCS(MPa) = 2.1956 + 0.0602\ .\ t\ (days),\quad R^2=0.9477 \qquad (8)$$

$$UCS(MPa) = 3.5994 + 0.0474\ \ .t\ (days),\quad R^2=0.9427 \qquad (9)$$

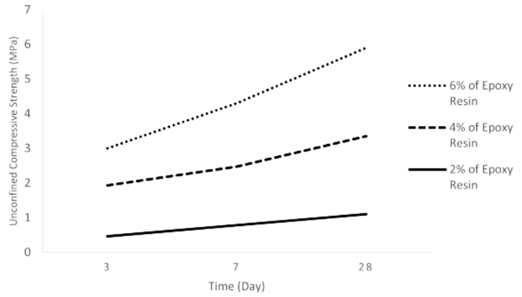



(a)

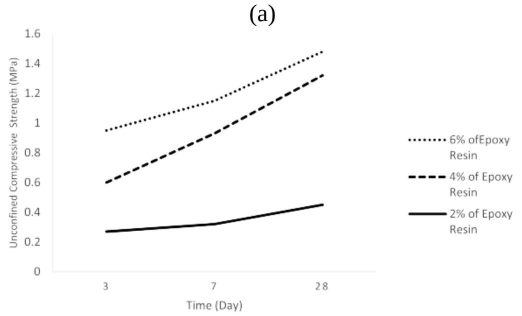



(b)

**Figure 4.** The unconfined compressive strength of stabilized sand specimens with 2, 4 and 6% epoxy resin and (a) 2% of water content (w2); (b) 4% of water content(w4).




(a)




(b)

**Figure 5.** The unconfined compressive strength of stabilized covered-sand specimens with 2, 4 and 6% epoxy resin and (a) 2% of water content (cw2); (b) 4% of water content (cw4)

The results of unconfined compressive tests for specimens with a different water content of 8, 11 and 14% mixed with 4% of epoxy resin are shown in Figure 6. The existence of high water content in these specimens causes low strength; therefore, the other percentages of epoxy resin at different periods were not tested. Note that the water particles saturate the surface area of aggregates, and these particles prevent to form a strong bond between the epoxy resin and aggregate particles. The results show that the growth of UCS with an increase of epoxy resin and time. Also, the UCS of specimens with high water content was low, and it reveals the adverse effect of water on the strength development of sand at all ages. The existence of high water content prevents proper curing; therefore, the difference of the UCS at the age of 3 and 7 days was not as high as dry treated sand specimens.

In the case of 8, 11 and 14% water content, a low strength development was observed at the age of 3 and 7 days. However, for specimens with 2 and 4% water content, the strength parameters were significantly higher than that of with 8, 11 and 14% water content. For example, the UCS of the specimens with the 2% water content (cw2 with 4% epoxy resin) was 3.35 MPa; however, for the specimens with 14%, water content appeared to be 0.09 MPa.

Uniaxial compressive tests results for saturated specimens are shown in Figure 7. The results demonstrate that the UCS increased with increasing epoxy resin content and curing time. The slope of UCS curves of specimens was varied with different epoxy resin percentages. This difference in slope could be attributed to the existence of relatively high pores in the surface of the specimens with relatively low epoxy resin ratios. In other words, the UCS of specimens with high epoxy resin content were less affected by saturation. According to Figure 7, unconfined compressive strength of stabilized saturated-sand specimens more than semi-saturated-sand specimens. While unconfined compressive strength of stabilized saturated-sand specimens less than dry-sand specimens.

## 5. COMPARISON OF RESULTS

Figure 8 (a)-(c) depicts the UCS of dry mixtures and mixtures with 4% water content and 2, 4 and 6% epoxy resin at the age of 3, 7, and 28 days. Based on results, the UCS of all specimens grew with increasing epoxy resin and curing time. These results reveal the importance of curing times and also the adverse the influence of water content on UCS. The UCS of specimens with low water content was higher than that of high water content. As aforementioned, the difference can be attributed to the existence of water content which prevents epoxy resin to have a strong bind with sand aggregates.

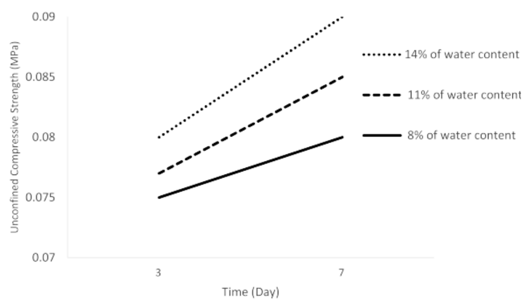



**Figure 6.** The unconfined compressive strength of stabilized sand specimens with 8, 11 and 14% of water content mixed with 4% of epoxy resin

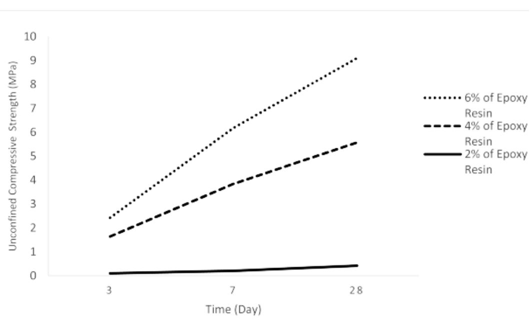
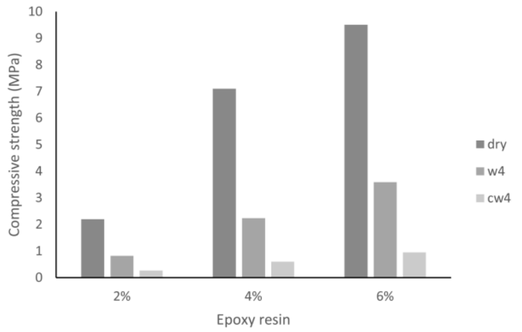


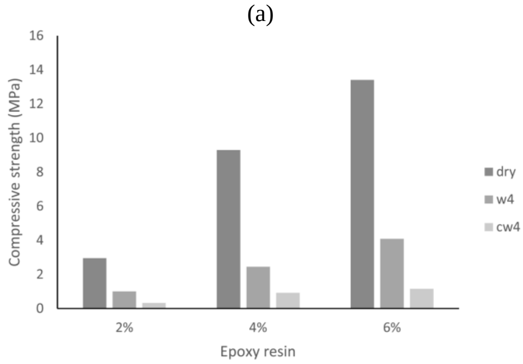

**Figure 7.** The unconfined compressive strength of stabilized saturated-sand specimens with 2, 4 and 6% of epoxy resin

Furthermore, it can be seen that all the specimens stored in the chamber (no evaporation) had lower UCS than others since evaporation almost prevented in the chamber. Therefore, incomplete curing occurred.

Figure 9 (a)-(c) presents the UCS of dry and saturated specimens with different amount of epoxy resin at the age of 3, 7, and 28 days. The results reveal the adverse influence of saturation on the strength of specimens using different percentages of epoxy resin. The strength values for all curing times decreased after saturation. The UCS for the specimens with 4% epoxy resin after 7 days was 9.3 MPa and for the saturated specimens with the same amount of epoxy resin was 3.84 MPa. However, these strength values for resin mixed specimens, even saturated, were significantly higher than that of specimens stabilized traditionally.




(a)

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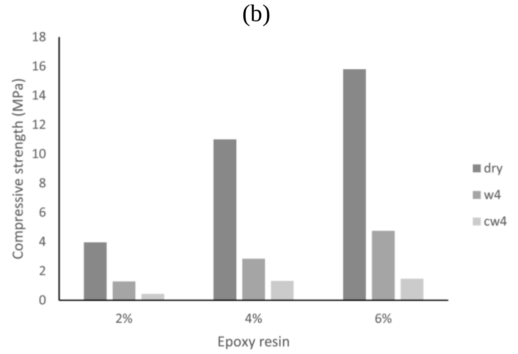
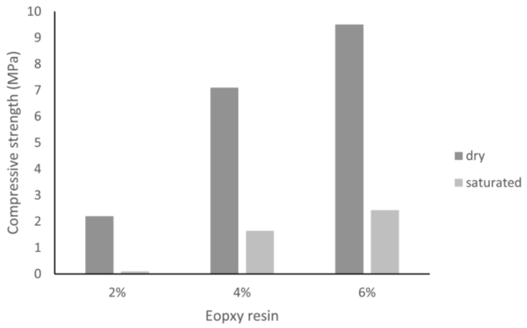


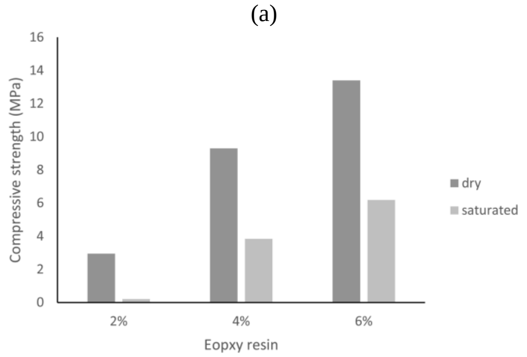

(c)

**Figure 8.** The unconfined compressive strength of stabilized sand (for dry, w4 and cw4 specimens) after (a) 3 days; (b) 7 days; and (c) 28 days

Table 2 presents the ratio of UCS of dry to saturated specimens at the age of 3, 7, and 28 days. These ratios showed a decreasing tendency over time. This tendency was highly dependent on the amount of epoxy resin and curing time. By epoxy resin increasing, the ratio of UCS of all specimens and ages reduced and this reduction in strength could be attributed to the existence of less pore in the surface of the specimens. Therefore, less water could penetrate into the specimens to influence the strength of specimens. Curing time was also an important factor for strength ratio improvement. The bonds between the epoxy resin and soil aggregates became strong over time; therefore, UCS increased. Nevertheless, unconfined compressive strength of all specimens decreased after saturation.




(a)

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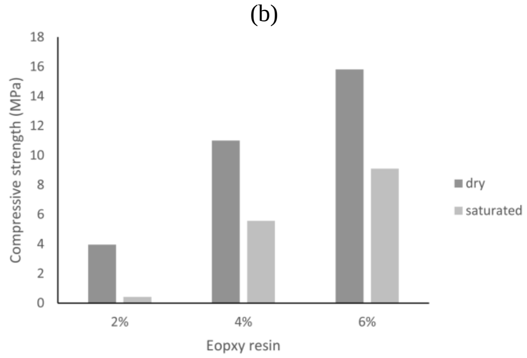


(c)

**Figure 9.** Unconfined Compressive Strength of dry and saturated specimens after (a) 3 days; (b) 7 days; and (c) 28 days

For example, the ratio of the strength of dry to saturated specimens with 4% epoxy resin at the age of 7 and 28 days were 2.4 and 2.0, respectively and for 6% epoxy resin after 7 days rose to 2.0.

In addition, the epoxy resin can be used mainly for stabilizing the soil due to its excellent material performance. Epoxy resin forms excellent bonds to soil particles. Note that chemical resistance of epoxy resin is excellent compared to regular Portland Cement. Therefore, the epoxy resin could be a good material as a stabilizer, especially in aggressive environments. Tables 3-9 presents the results of stabilized sandy-soil considering all the conditions and parameters.

**TABLE 2.** Ratio of UCS of dry specimens on UCS of saturated specimens

| | **Ratio of UCS of dry specimens on UCS of saturated specimens** | | |
|---|---|---|---|
| Epoxy resin | 3 days | 7 days | 28 days |
| 2% | 22 | 14.7 | 9.4 |
| 4% | 4.3 | 2.4 | 2 |
| 6% | 3.9 | 2.2 | 1.8 |

**TABLE 3.** UCS of dry sand with different epoxy resin ratios

| | dry sand (Figure 3) | | |
|---|---|---|---|
| Epoxy resin | 3 days | 7 days | 28 days |
| 2% | 2.2 | 2.95 | 3.95 |
| 4% | 7.1 | 9.3 | 11 |
| 6% | 9.5 | 13.4 | 15.8 |

**TABLE 4.** The UCS of Threated sand with 4% Water

| | Uncovered threated (figure 4b) | | |
|---|---|---|---|
| Epoxy resin | 3 days | 7 days | 28 days |
| 2% | 0.82 | 1 | 1.3 |
| 4% | 2.23 | 2.45 | 2.85 |
| 6% | 3.59 | 4.09 | 4.75 |

**TABLE 5.** The UCS of Threated sand with 2% Water

| | Uncovered threated (figure 4a) | | |
|---|---|---|---|
| Epoxy resin | 3 days | 7 days | 28 days |
| 2% | 0.2 | 0.39 | 1.15 |
| 4% | 2.9 | 3.67 | 4.8 |
| 6% | 5.26 | 7.06 | 9.5 |

**TABLE 6.** The UCS of Covered threated sand with 4% Water

| | Covered threated (figure 5b) | | |
|---|---|---|---|
| Epoxy resin | 3 days | 7 days | 28 days |
| 2% | 0.27 | 0.32 | 0.45 |
| 4% | 0.6 | 0.93 | 1.32 |
| 6% | 0.95 | 1.15 | 1.48 |

**TABLE 7.** The UCS of Covered threated sand with 2% Water

| | Covered threated (figure 5a) | | |
|---|---|---|---|
| Epoxy resin | 3 days | 7 days | 28 days |
| 2% | 0.46 | 0.78 | 1.11 |
| 4% | 1.93 | 2.47 | 3.35 |
| 6% | 3 | 4.3 | 5.9 |

**TABLE 8.** The UCS of Saturated specimens

| | Saturated (figure 7) | | |
|---|---|---|---|
| Epoxy resin | 3 days | 7 days | 28 days |
| 2% | 0.1 | 0.2 | 0.42 |
| 4% | 1.64 | 3.84 | 5.57 |
| 6% | 2.42 | 6.18 | 9.1 |

**TABLE 9.** The UCS of specimens with high amount of water

| | degrees of saturation (%) with Epoxy resin of 4% in all specimens (figure 6) | | |
|---|---|---|---|
| | 8% | 11% | 14% |
| 3 days | 0.075 | 0.077 | 0.08 |
| 7 days | 0.08 | 0.085 | 0.09 |

## 6. CONCLUSIONS

The study was undertaken to investigate the effect of polymer and water content on unconfined compressive strength of stabilized sand. The following conclusions can be drawn from this study:

- Epoxy resin is effective in stabilizing sand by increasing the unconfined compressive strength. This improvement is a function of the epoxy resin content, time and curing times.
- Curing duration of the sandy soil stabilized with epoxy resin is almost 10 % of that of the regular cement.
- Curing times had a great effect on the UCS. In other words, better curing occurs due to a possibility of water evaporation; therefore, UCS increases.
- The UCS of polymeric sand (whether is dry, wet or saturated) was higher than cemented sand at the same percentage of additives and curing times.
- The UCS of treated dry sand was higher than treated sand with any water content at the same curing times. Furthermore, the UCS was decreased with an increment of water. This phenomenon was explained by the fact that existence of water caused weakening the bond.
- The sandy soil stabilized with epoxy resin has higher compressive strength compared to ordinary Portland cement.
- Saturation of dry sand definitively decreased the strength; however, this decrement depended on epoxy resin the content and the age.
- The UCS of stabilized saturated-sand specimens more than semi-saturated-sand specimens. While unconfined compressive strength of stabilized saturated-sand specimens less than dry-sand specimens.

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# Influence of Curing Time and Water Content on Unconfined Compressive Strength of Sand Stabilized Using Epoxy Resin

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چکیده

بهبود و بهسازی خاک ها به صورت گسترده ای به جهت بهبود مشخصات فیزیکی و مکانیکی خاک استفاده شده است. علارغم وجود تحقیقات بسیار انجام شده در این موضوع، اثرات میزان درصد رطوبت و شرایط مختلف عمل آوری بررسی نشده است. در این تحقیق، مشخصات مکانیکی ماسه تثبیت شده با اپوکسی رزین با در نظر گرفتن زمان گیرش و درجه رطوبت خاک مورد بررسی قرار گرفته است. آزمایش مقاومت فشاری تک محوری روی ماسه با درجات رطوبت متفاوت که با درصدهای مختلف اپوکسی رزین تثبیت شده انجام گردید. به‌علاوه، نمونه‌ها در شرایط محیطی مختلف عمل‌آوری شده‌اند و تأثیر رطوبت محیط بر گیرش در طی زمان ارزیابی شده است. نتایج نشان می‌دهد که افزودن اپوکسی رزین به خاک ماسه‌ای به‌صورت قابل‌ملاحظه‌ای مقاومت فشاری تک‌محوری را افزایش می‌دهد و تابع درصد اپوکسی رزین، رطوبت محیط و زمان گیرش است. هر چه درصد اپوکسی رزین و زمان گیرش افزایش یابد، مقاومت فشاری خاک افزایش می‌یابد. اگرچه درصد رطوبت خاک و گیرش نمونه در محیط‌های بسته تأثیر منفی در افزایش مقاومت دارد. طبق این تحقیق، اپوکسی رزین به دلیل افزایش مقاومت خاک ماسه و همچنین مقاومت در محیط‌های خورنده می‌تواند یک تثبیت‌کننده مناسب باشد.

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