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Effect of clay mineral types on the strength and microstructure properties of soft clay soils stabilized by epoxy resin

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Abstract. Soft clay soils due to their various geotechnical problems, stabilized with different additives. Traditional additives such as cement and lime will not able to increase the soil strength properties significantly. So, it seems necessary to use new additives for increasing strength parameters of soft clay soils significantly. Among the new additives, epoxy resins have excellent physical and mechanical properties, low shrinkage, excellent resistance to chemicals and corrosive materials, etc. So, in this research, epoxy resin used for stabilization of soft clay soils. For comprehensive study, three clay soil samples with different PI and various clay mineral types were studied. A series of uniaxial tests, SEM and XRD analysis conducted on the samples. The results show that using epoxy resin increases the strength parameters such as UCS, elastic modulus and material toughness about 100 to 500 times which the increase was dependent on the type of clay minerals type in the soil. Also, In addition to water conservation, the best efficiency in the weakest and most sensitive soils is the prominent results of stabilization by epoxy resin which can be used in different climatic zones, especially in hot and dry and equatorial climate which will be faced with water scarcity.

Keywords: epoxy resin; clay mineral; UCS; elastic modulus; SEM; XRD

1. Introduction

Soft clay soil is one of the problematic soils that covered considerable part of earth and generally stabilized in order to improve their behavioral and strength properties (Sasanian 2011, Ouhadi *et al.* 2014, Vichan and Rachan 2013, Modarres and Nosoudy 2015, Yi *et al*. 2016, Sukpunya and Jotisankasa 2016). These types of soils have various geotechnical problems such as low strength, excessive settlements, high plasticity, swelling, dispersivity, erodibility, high compressibility and sensitivity to environmental conditions properties (Huat 1994, Ouhadi *et al.* 2014, Ahmed 2015). Considering high price of land in addition to economic issues, design and construction of different civil structures on such soils is undeniable (Yilmaz and Civelekoglu 2009, Dash and Bora 2013). Deep mixing method (DMM) is one of the methods that used to improve the soft clay soils problems. In this method binders such as cement, lime, fly ash, gypsum and other additives have been mixed with the soil in order to form stone columns of a hardened material which can improve the classification properties and strength parameters of problematic soils (Porbaha 1998, 2002, Sukontasukkul and Jamsawang 2012, Voottipruex and Jamsawang 2014, Anagnostopoulos 2015). Cement mixing techniques is becoming widely established for stabilizing soft soils (Kasama *et al.* 2012, Yang *et al.* 2013). Despite the positive points mentioned about the DMM, traditional additives are incapable of increasing the strength and ductility properties of stabilized soft clay soils significantly (Kamruzzaman *et al.* 2000, Horpibiulsuk *et al.* 2011, Petchgate *et al.* 2003, 2004, Saride *et al.* 2013, Tabbaa 2003, Impe and Flores 2006, Pakbaz and Alipour 2012, Khemissa and Mahamedi 2014, Anagnostopoulos 2015). Considering the large amount of cement used in the geotechnical and geo-environmental projects, it is necessary to use new materials in order to improve the behavioral properties of cement-stabilized clay soils significantly. In recent years using of non-traditional chemical solutions, such as resins and co-polymer emulsions, has been suggested by some researchers (Anagnostopoulos *et al.* 2003, Al-Khanbashi and Abdalla 2006, Estabragh *et al.* 2011). Considerable research has been performed about the impact of epoxy resin on the civil materials behavior such as cement concrete, granular soil and fine-grained soils (Ajayi *et al.* 1991, Anagnostopoulos and Hadjispyrou 2004, Anagnostopoulos and Papaliangas 2012, Anagnostopoulos 2015, Ferdous *et al.* 2016, Sadowski *et al.* 2016, Al-Bayati 2017, Benmokranea *et al*. 2017, McSwiggan and Fam 2017), but the influence of epoxy resins on the behavior of clay soils haven’t been extensively investigated. However, there are a few number of studies conducted about the effect of epoxy resins on clay soils behavior. Clay soils behavior strongly depends on the type of clay mineral types included (Ouhadi 1997, 2003a, b, 2003, 2006). Moreover, in spite of significant effect of the type and percentage of clay minerals on clay soils behavior and stabilized clay soils, there is not any comprehensive study about the effect of clay minerals type on the properties of epoxy-resin-stabilized clay soils. Clay mineral type and pore fluid

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properties affect the double layer properties. Consequently, it affects the polymerization reactions between cation in clay double layer and components of epoxy resin structure. Therefore, efficiency of improvement results of clay soils containing various clay mineral types will be different. Therefore, epoxy resin and cement additives used to improve stabilized clay soils with different clay minerals in this research. A series of experiments were carried out on the clay soil samples with different clay minerals. Clay soil samples that tested experimentally were kaolinite, calcium bentonite and sodium bentonite. Different quantities of cement such as 0%, 5%, 10%, 20% and 30% by total dry mass were added to clay soil samples and soil samples remolded with constant energy. Epoxy resins exist in different viscosity and generally used in combination with curing or hardening materials. Some of the significant advantages of epoxy resins are; achievement of excellent physical and mechanical properties, treated at various temperatures range from room temperature to the temperature of 175℃, preventing form the monomers escape during curing, low shrinkage during curing, excellent resistance to chemicals and corrosive materials and solvents materials and good adhesion to fillers and fibers. When these two components (epoxy resin and hardener) are mixed, a chemical reaction begins that initiates the hardening of the epoxy. The epoxy molecule itself reacts again and again, growing in size, in a process called polymerization (Anagnostopoulos 2015). The soil samples tested after 7 and 28 days of curing. In this way, 500 samples which stabilized with cement and epoxy resin have been tested and some results of experiments presented in this research. The research results indicate that clay mineral types of soils have a significant effect on the efficiency of soil improvement. That is, uniaxial strength of sodium bentonite stabilized samples increased about 200 to 500 times while it reaches to more than 50 MPa in some other samples in addition to significant increase in ductility. In continuance, X-ray diffraction analysis (XRD) and scanning electron microscope (SEM) conducted in order to study the microstructural reactions.

2. Material and method

2.1 Material and experiments

The kaolinite soil identified as super zenous kaolinite (kaolinite-z) from north western-Iran (Tabriz). The calcium bentonite soil (named as c-bentonite) gathered from south eastern-Iran (Kerman). The sodium bentonite sample (named as s-bentonite) was provided by “Iran Barit Company”. According to the extensive use of cement type II, used it to soil stabilization. Some chemical properties of cement determined in Table 1. In Table 2, some geotechnical properties of soil samples were determined according to ASTM, 1994. The XRD analysis and SEM photos were conducted on the soil samples for microstructure analyses. The SEM analysis was performed through SEM Jeol-Jsm 840A.The SEM performed by SEM model of TESCAN VEGA//XMU. The XRD analysis was performed based on the method suggested in the study

Table 1 Chemical composition of cement

Product type	Sio_2	Al_2o_3	Fe_2o_3	Cao	Mgo	K_2o	Na_2o	Total alkaline	Free Lime	SO_3	LOI	Insoluble residue
Type II	22.2	5.13	3.90	61.39	1.65	0.81	0.65	0.97	0.82	2.41	1.15	0.43

Table 2 Some geo-environmental and geotechnical properties of clay samples

Geotechnical properties	Kaolinite	C-Bentonite	S-Bentonite
XRD Analysis	Kaolinite, Quartz, Carbonate, Calcite	Montmorillonite, Carbonate, Quartz, Kaolinite	Montmorillonite, Carbonate, Quartz, Kaolinite
pH	8.93	9.36	9.86
Clay (%)	58	67	78
Silt (%)	38	31	22
Sand (%)	4	2	0
Liquid limit (%)	36	99	160
Plastic Limit (%)	20	27	40
Plasticity Index (%)	16	72	120
G_s	2.75	2.79	2.86
Classification	CL	CH	CH

reported by Ouhadi and Yong (2003). Model of X-ray diffraction instrument was Philips PW1730. Epoxy resin consists of two components, epoxy resin and hardener. The first epoxy resin is based on diglycidyl ether of bisphenol that denoted by E and the second aminoamide-based hardener that denoted by H. It's important that the resin portions of the products are considered as non-toxic, but the hardeners could cause skin irritation and sensitivity. So, use of disposable rubber gloves and protective clothing is necessary when working with epoxy compounds in the early hours during polymerization reactions, but epoxy resin is completely safe after hardening.

2.2 Sample preparation and studied parameters

For sample preparation different percentages of cement were mixed with soil in dry condition to obtain homogenous mixture. In cement-stabilized samples, water (equal to epoxy resin percentage) added to dry mixture and mixed about 5 minutes with mixer apparatus and compacted in uniaxial mold. In epoxy resin and cement stabilized samples, water replaced with epoxy resin and optimum epoxy resin content for each soil samples was added to the dry soil-cement mixture. To obtain optimum epoxy resin content, different epoxy resin content used instead of water for soil compaction. Then, the amount of epoxy resin in accordance with the most UCS after 7 and 28 days was adopted as optimum epoxy resin content. The optimum percentage of epoxy resin for kaolinite, c-bentonite, and s-bentonite were 40, 40 and 60 respectively. According to the manufacturer recommendations, epoxy resin and hardener were combined with E/H=2 ratio by electric mixer for 4 minutes until white homogenous sample has been formed. Prepared mixture of epoxy resin and hardener denoted by ER. Then, optimum epoxy resin content for each soil samples were added to the dry soil-cement mixture and the mixture have been mixed for about 6 minutes by the mixer according to ASTM C938-97. Finally, samples were compacted in the uniaxial mold. Cement contents were be 0, 5, 10, 20 and 30 percentage of total dry weight (clay soil and cement). Due to undeniable influence of sample preparation on the soil mechanics experiment results, in order to unification of sample preparation and studying the effect of epoxy resin on the compactibility of stabilized soil, the samples were compacted by constant energy method. The preparation compaction energy equal to standard proctor test energy (0.055 kg.m/cm^3). Uniaxial tests performed by the universal apparatus (model ZWICK 1498) of Shahid Bahonar University of Kerman. The mentioned apparatus in addition to the ability to apply high loading, also capable to record displacement samples of 0.01 millimeter (equal to 0.00014 axial strain). The ability to record small displacement led to an appropriate accuracy for calculation of parameters obtained from uniaxial test such as elastic modulus and materials toughness.

For determination of the soil stabilization efficiency, unconfined compressive strength (UCS) and elastic modulus for different percentages of cement in presence and absence of epoxy used to determine the optimum percentage of stabilizer additive.

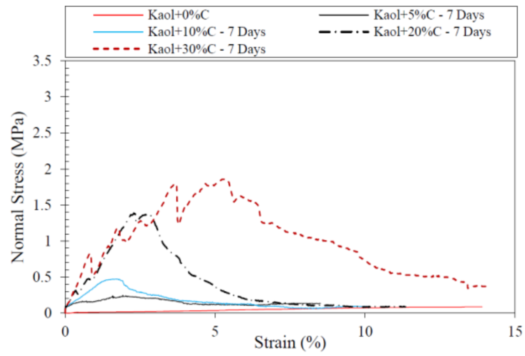
3. Results and discussion

3.1 Uniaxial test results

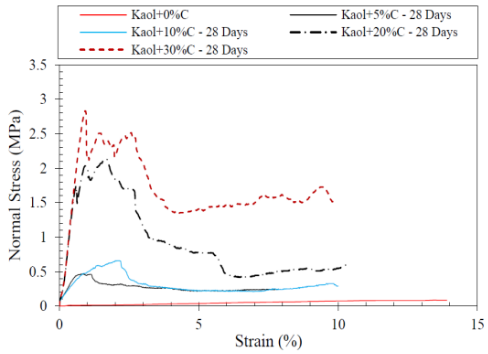
3.1.1 Uniaxial test results of kaolinite clay samples

The stress-strain curves of 7- and 28-day samples are shown in Fig. 1. The stress-strain curves of 7-day and 28-day samples stabilized by cement are shown in Fig. 1(a) and 1(b) respectively and the stress-strain curves of 7- and 28-day samples stabilized by cement and epoxy resin are shown in Fig. 1(c) and 1(d) respectively. In presence of epoxy resin, stabilized samples could sustain more than 60% axial strain without cracking. Increase in cement percentage does not have any effect on ductility of different samples while strength properties decreased. Therefore, it is possible that addition of epoxy resin in cement-stabilized samples prevent completion of pozzolanic reactions. So, in kaolinite clay soil samples the optimum percent of cement is zero. It was also noticeable that no considerable increase in strength parameters of kaolinite (due to the clay mineral types including) indicate that the kaolinite does not have appropriate potential to react with the used epoxy resin.

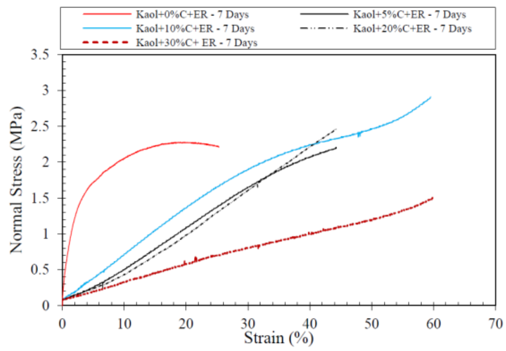
The unconfined compressive strength (UCS) at 20% strain and elastic modulus for different percentage of cement in the presence and absence of epoxy resin are shown in Fig. 2(a) and 2(b), respectively. The UCS of the sample stabilized by 20% cement in 7- and 28-day samples is more than 3 times more than the sample stabilized by 10% cement while by increase the cement percentage to 30%, the UCS of 7- and 28-day samples increased about 30%. Therefore, the optimum cement content in kaolinite without epoxy resin is 20%. In the cement-stabilized samples the growth rate of UCS during pozzolanic reactions except the sample stabilized by 5% cement, is about 65% to 70% in initial days. There is a significant point in the epoxy resin and cement-stabilized samples; by adding epoxy resin



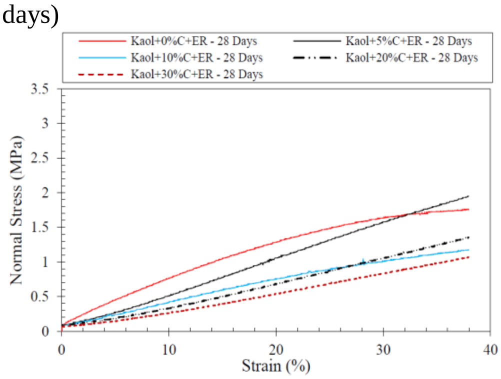
(a) Kaolinite stabilized with cement (7 days)



(b) Kaolinite stabilized with cement (28 days)



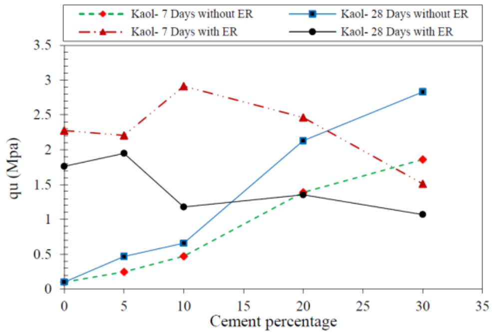
(c) Kaolinite stabilized with cement and epoxy resin (7 days)



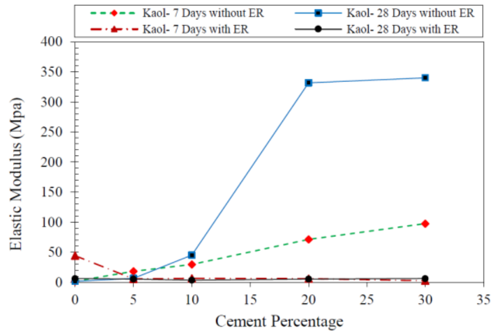
(d) Kaolinite stabilized with cement and epoxy resin (28 days)

Fig. 1 Stress-strain curve of stabilized kaolinite clay samples

to the kaolinite, the strength of 28-day samples decreased in spite of the possibility of epoxy resin polymerization reactions and pozzolanic reactions of cement. In this regard, the UCS of 28-day samples with 0%, 5%, 10%, 20% and

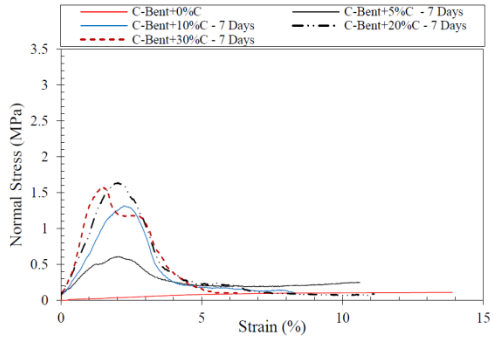


(a) UCS results

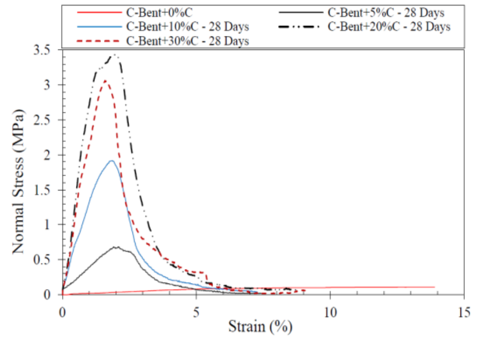


(b) Elastic modulus results

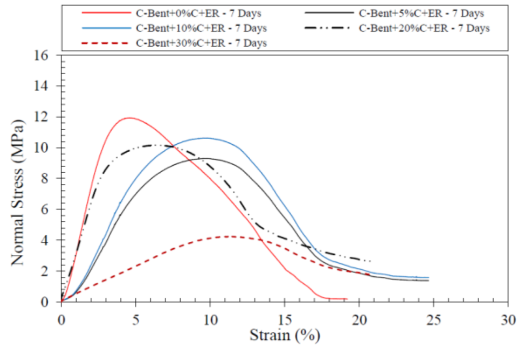
Fig. 2 Variation of UCS and elastic modulus results of the kaolinite clay samples with cement content



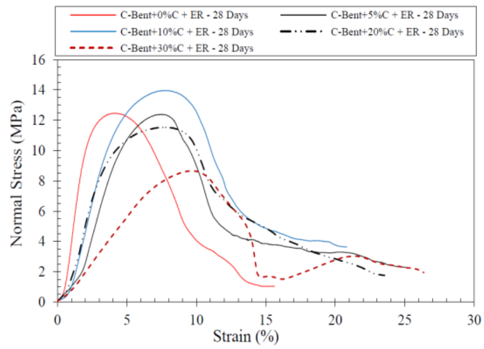
(a) c-bentonite stabilized with cement (7 days)



(b) c-bentonite stabilized with cement (28 days)



(c) c-bentonite stabilized with cement and epoxy resin (7 days)



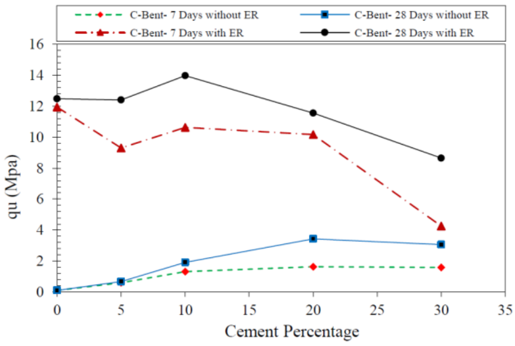
(d) c-bentonite stabilized with cement and epoxy resin (28 days)

Fig. 3 Stress-strain curve of stabilized c-bentonite clay samples

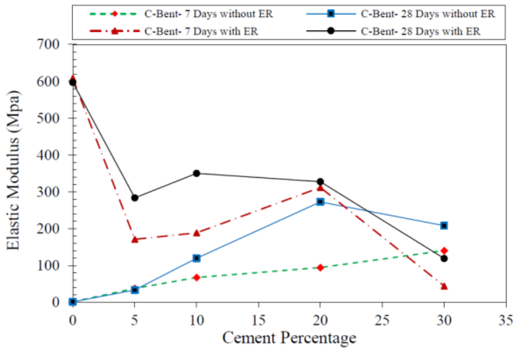
30% cement is 57%, 97%, 56%, 68% and 91% of UCS of 7-day samples respectively. Therefore, it is possible that the pozzolanic reaction of cement has been prevented due to solidification of soil and cement by polymerization reactions of epoxy resin. For cement amount less than 10%, addition of epoxy resin increases UCS of the samples which is in reverse relation with cement percentage. On the other hand, with 0, 5 and 10 cement percent in the presence of epoxy resin the UCS of 7-day samples increases about 22.8, 9 and 6.2 times and the UCS of 28-day samples increases about 17.6, 4.2 and 1.8 times more than cement-stabilized samples respectively. Consequently, it is not recommended to use cement for soil stabilization in kaolinite clay sample in presence of epoxy resin, in other words the optimum percentage of cement will be zero. That means epoxy resin can be appropriate replacement for cement and water. The results of elastic modulus indicate that except the sample containing 0% cement, elastic modulus reduced significantly by adding epoxy resin. In other words, elastic modulus has been reduced significantly by increasing cement percentage in the presence of epoxy resin unlike the cement-stabilized samples. Thus, it can be concluded that pozzolanic reactions of cement have been prevented during the solidification process by the polymerization reaction of epoxy resin as well as the optimum percentage of cement is 0%.

3.1.2 Uniaxial results of c-bentonite clay samples

Results of uniaxial tests conducted on c-bentonite samples are shown in Fig. 3. The stress-strain curves of 7-day and 28-day samples stabilized by cement are shown in Fig. 3(a) and 3(b) respectively and the stress-strain curves of the above-mentioned samples stabilized by both cement and epoxy resin are shown in Fig. 3(c) and 3(d), respectively. In the cement-stabilized samples, failure behavior of samples is brittle in a way the strains associated with UCS are less than 2%. In addition, the strength of samples reduced intensively after peak point suddenly in a way that 30 to 60 times strength reduction observed in



(a) UCS results

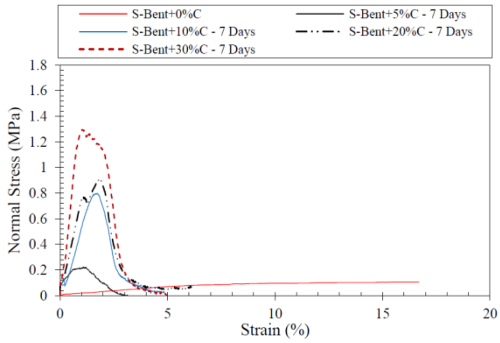


(b) Elastic modulus results

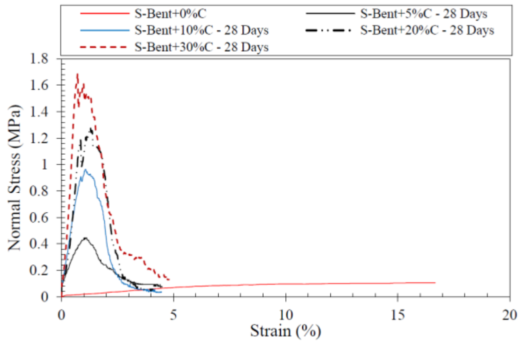
Fig. 4 Variation of UCS and elastic modulus results of the c-bentonite clay samples with cement content

stress-strain curve. By adding epoxy resin for equal cement content, the UCS increased about 3 to 20 times and at 0% cement increased about 120 times in comparison to c-bentonite samples without epoxy resin. Note that, the strains associated with ultimate stress of epoxy resin and cement-stabilized samples increased about 3 to 8 times in comparison to the cement-stabilized samples. Therefore, strength and ductility of the sample increased simultaneously. The important point is that the samples strength (except the sample includes 30% cement) in the range of low strength concrete samples while yield strain in different samples is about 15 to 30 times of the concrete yield strain. Moreover, dry and saturated density of the samples are about 50% and 65% of the bulk density of the fresh concrete respectively. Consequently, c-bentonite clay sample stabilized with epoxy resin and cement is much lighter than normal concrete in addition to higher ductility and appropriate strength.

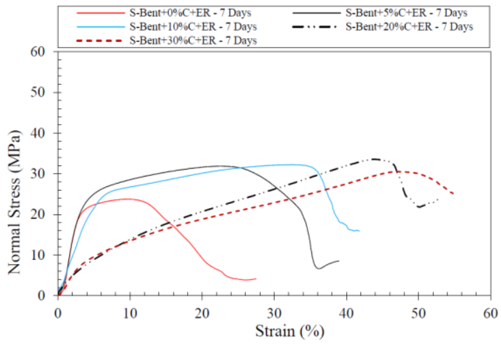
The variations charts of UCS and elastic modulus for cement-stabilized samples with and without epoxy resin are shown in Fig. 4(a) and 4(b) respectively. The UCS of the cement-stabilized samples (except the sample includes 30% cement) is increased by increase in cement percentage. In this regard, with 5%, 10%, 20% and 30% cement, the UCS of 7-day samples is 6.1, 13.2, 16.4 and 15.9 times of the UCS of untreated c-bentonite respectively and it is 6.9, 19.2, 34.2 and 30.6 times of the UCS of untreated c-bentonite respectively for 28-day samples. Therefore, optimum content of cement in the c-bentonite samples without epoxy resin is 20%. By adding epoxy resin to the cement-stabilized samples instead of water, for the same cement content, in 7-day samples for 0%, 5%, 10%, 20% and 30% cement, the UCS is increased 119, 15.3, 8.1, 6.21



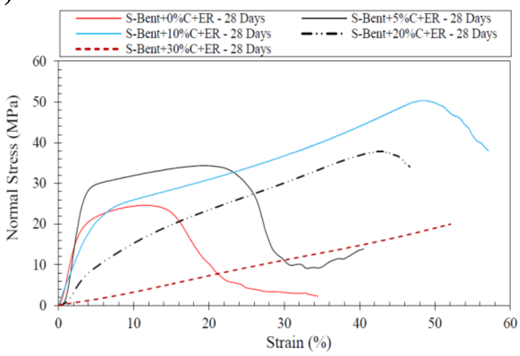
(a) s-bentonite stabilized with cement (7 days)



(b) s-bentonite stabilized with cement (28 days)



(c) s-bentonite stabilized with cement and epoxy resin (7 days)



(d) s-bentonite stabilized with cement and epoxy resin (28 days)

Fig. 5 Stress-strain curve of stabilized s-bentonite clay samples

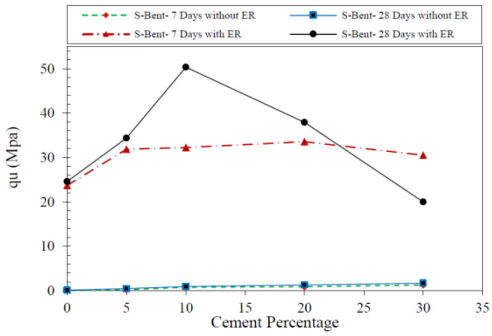
and 2.7 times respectively and it is increased 125, 18.1, 7.3, 3.4 and 2.8 times respectively for 28-day samples. Therefore, epoxy resin increases the UCS of the cement-stabilized samples up to 3 to 20 times and about 120 times in untreated sample. By increasing cement percentage in the epoxy resin-stabilized samples, the ratio of UCS of samples stabilized by epoxy resin and cement to the UCS of samples stabilized just by epoxy resin for 5%, 10%, 20% and 30% cement is 0.78, 0.89, 0.85 and 0.36 respectively at 7 days and 0.99, 1.12, 0.93 and 0.69 at 28 days respectively. Therefore, the optimum content of cement is 10%. Stabilization of the samples just by cement caused to reduce failure strain about 70-80 percent in both 7- and 28-day samples, while by adding epoxy resin to the cement-stabilized samples yield and failure strain and material toughness increased significantly.

Variations of elastic modulus show that for cement percentage less than 20%, stabilizing with epoxy resin increases the elastic modulus. That's, for 0%, 5%, 10%, 20% and 30% cement, by adding epoxy resin to the cement-stabilized samples, the elastic modulus of stabilized samples has been increased 383, 4.46, 2.79, 3.29 and 0.32 times respectively for 7-day samples and 376, 8.35, 2.92, 1.2 and 0.57 times respectively for 28-day samples. The maximum increase in elastic modulus is about 380 times related to the sample stabilized by epoxy resin and 0% cement while reduction in elastic modulus observed only in the sample stabilized with 30% cement in which the elastic modulus reduced about 70% and 40% at 7 and 28 days respectively. Therefore, stabilization with 30% cement is not recommended for c-bentonite. By increasing cement content in the epoxy-resin-stabilized samples, the elastic modulus of samples stabilized by epoxy resin and cement with 5%, 10%, 20% and 30% cement reduced 72%, 69%, 49% and 93% respectively at 7 days and 52%, 41%, 45% and 80% at 28 days respectively. Therefore unlike the cement-stabilized samples, cement reduces elastic modulus about 40-90 percent in the epoxy-resin-cement-stabilized samples.

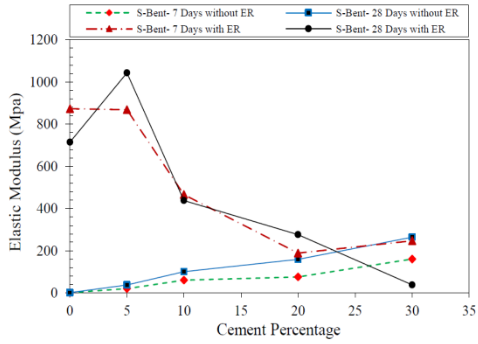
3.1.3 Uniaxial results of s-bentonite clay samples

Results of uniaxial tests conducted on s-bentonite sample are shown in Fig. 5. The stress-strain curves of 7-day and 28-day samples stabilized by cement are shown in Fig. 5(a) and Fig. 5(b) respectively and the stress-strain curves of the epoxy-resin-cement-stabilized samples are shown in Fig. 5(c) and Fig. 5(d) respectively. As shown in Fig. 5(a) and 5(b), failure behavior of sample is brittle which strains associated with maximum strength are less than 2% and normal stress is reduced intensively after pick point suddenly. Also, increase in cement content increases the uniaxial strength. The UCS and the failure strain of the cement-epoxy-resin-stabilized samples have been increased 25 to 230 times and 16 to 60 times respectively in comparison with the cement-stabilized samples, so strength and ductility significantly increased simultaneously. The most important point is that the minimum UCS of samples are more than strength of normal concrete, moreover the strength of some samples is in the range of high-strength concrete while failure strain in different samples is about 30 to 200 times of the concrete failure strain, in addition dry mass density of the samples is about 1 g/cm^3 that about 40% of bulk density of the fresh concrete and wet mass density is about 1.6 g/cm^3 that about 65% of the bulk density of the fresh concrete, therefore stabilized samples with cement and epoxy resin is much lighter than concrete in addition to higher ductility and higher strength.

Variations of UCS for cement-stabilized samples with



(a) UCS results



(b) Elastic modulus results

Fig. 6 Variation of UCS and elastic modulus results of the s-bentonite clay samples with cement content

and without epoxy resin for different percent of cement are shown in Fig. 6(a). For cement percentage less than 30%, the UCS of the cement-stabilized samples is an increasing function of cement content, but according to growth rate of UCS during pozzolanic reactions the optimum cement content in the s-bentonite without epoxy resin is about 10. In the stabilized samples contain epoxy resin, except the sample with 0% cement with UCS of about 25 MPa, the UCS of all other samples up to 30 MPa that is more than compressive strength of normal concretes. The most strength of 28-day sample is about 53MPa which related to stabilized sample with epoxy resin and 10% cement. Consequently, based on the results of present research, stabilized s-bentonite clay sample with cement and epoxy resin named as clayey concrete. Results of Fig. 6(a) indicate that for 0%, 5%, 10%, 20% and 30% cement, adding epoxy resin instead of water, increases the UCS of 7-day samples 226, 143, 40, 37 and 24 times respectively and 234, 77, 52, 30 and 12 times respectively for 28-day samples. Therefore, epoxy resin increases the UCS of the cement-stabilized samples up to 10 to 230 times. Also, increase in percentage of cement (5, 10, 20 and 30 respectively) in the epoxy-resin-stabilized samples, the ratio of epoxy-resin-cement-stabilized samples to the samples stabilized just by epoxy resin, is 1.34, 1.36, 1.41 and 1.29 respectively in 7-day samples and 1.4, 2.05, 1.54 and 0.81 respectively in 28-day samples. Therefore, in epoxy-resin-cement-stabilized samples the optimum percentage of cement is 10%. That should be noted that stabilization of the samples just by cement caused to reduce failure strain 80-90 percent, while in the presence of epoxy resin in addition to significant increase in UCS, failure strain and material toughness have an outstanding improvement.

The elastic modulus variations are shown in Fig. 6(b).

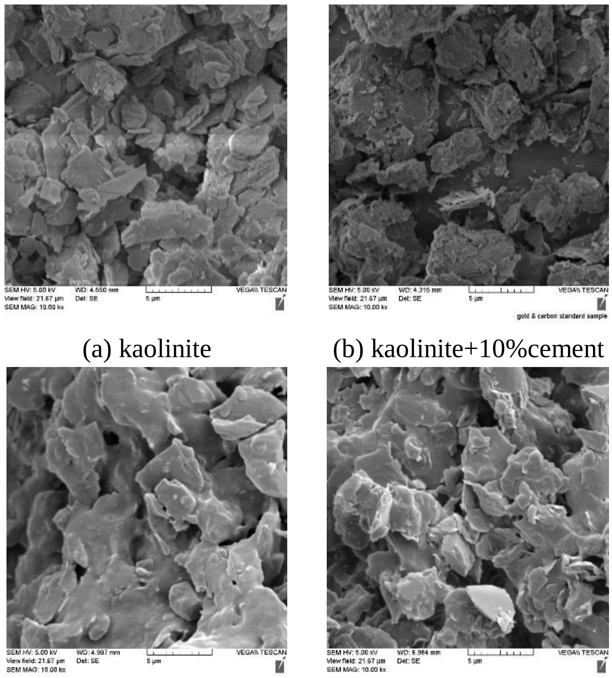
Generally, adding epoxy resin increases elastic modulus of the samples except 28-day sample with 30% cement. That is, adding epoxy resin to the cement-stabilized samples instead of water, the elastic modulus of epoxy-resin-stabilized samples in comparison to the samples without epoxy resin but with equal percentage of cement (0, 5, 10, 20 and 30 respectively) is increased 682, 4.3, 7.7, 2.5 and 1.53 times respectively for 7-day samples and 559, 27.6, 4.3, 1.74 and 0.14 times respectively for 28-day samples. Note that, elastic modulus increased by increasing the cement content in cement-stabilized samples such that increase in cement percentage samples increases elastic modulus about 16 to 210 times in comparison with untreated sample, but increasing in cement content to 5, 10, 20 and 30 percent respectively in the epoxy- resin-stabilized samples lead to the elastic modulus reduced 0%, 47%, 78% and 72% respectively in 7-day samples and in 28-day samples increased 46%, reduced 39%, 61% and 95% respectively. Therefore, except the sample stabilized by 5% cement in which the elastic modulus increased about 50% after 28 days, cement reduces elastic modulus of materials about 40% to 95% in other samples.

3.2 Micro-structural studying

3.2.1 SEM images

The process of interaction between clay soil and additives, which affect the forces between clay flakes and formation of new compound, change the clay soils microstructure and causes formation of new compounds. In this regard, SEM photos and X-ray diffraction analyses have been performed for microstructural studying of the epoxy-resin-cement-stabilized samples. SEM images of kaolinite clay samples are shown in Fig. 7. The untreated sample is shown in Fig. 7(a). Adding 10% cement to the untreated sample, shows marked changes in structure and morphology of cement-stabilized kaolinite in a way that soil structure changed from particle to aggregated structure due to pozzolanic reaction and cementations composition. The SEM image of kaolinite clay sample stabilized by epoxy resin is shown in Fig. 7(c), while epoxy resin caused few changes in kaolinite structure and the soil structure is close to particle structure. Therefore, it can be said that kaolinite clay flakes approximately don’t react completely with epoxy resin and almost epoxy resin is inefficient for stabilization of kaolinite clay sample. This issue is shown in SEM images in which just a gelatinous layer on clay particles made by epoxy resin without any significant changes in the sample structure. However, the positive point in the SEM image is that epoxy resin created a continuous structure through polymerization, which will increase the sample ductility. The SEM image of kaolinite sample stabilized by epoxy resin and 10% cement shows that sample solidification due to polymerization reactions approximately prevents pozzolanic reactions of cement. Therefore, there are not significant changes in the sample structure and just a gelatinous layer created around clay particles that created a significant bond in the sample but the kaolinite structure was not changed significantly.

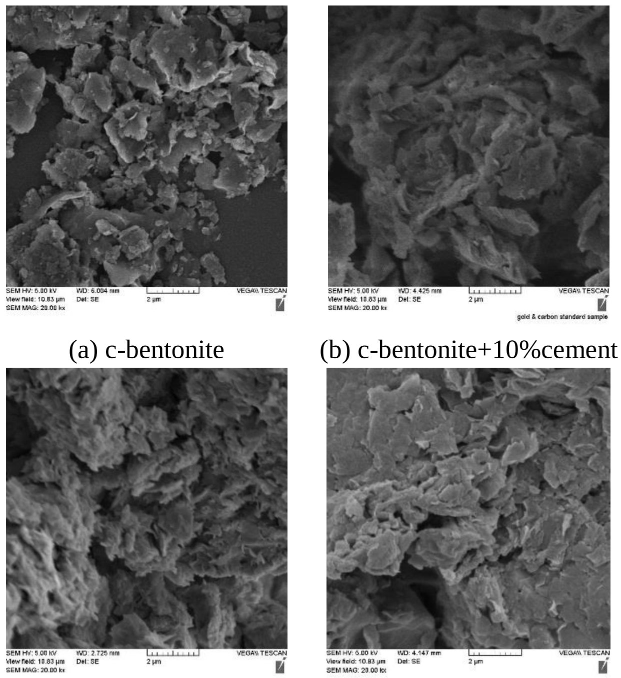
SEM images of c-bentonite samples are shown in Fig. 8.



(a) kaolinite (b) kaolinite+10%cement

(c) kaolinite+epoxy resin (d) kaolinite+10%cement +epoxy resin

Fig. 7 SEM images of kaolinite stabilized with epoxy resin and cement



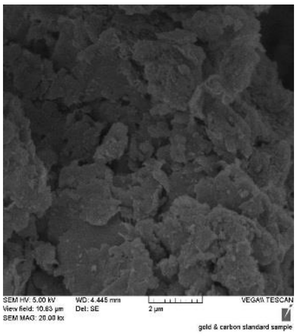
(a) c-bentonite (b) c-bentonite+10%cement

(c) c-bentonite+epoxy resin (d) c-bentonite+10% cement +epoxy resin

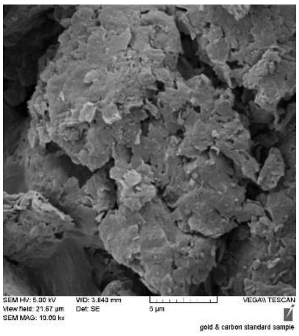
Fig. 8 SEM images of c-bentonite stabilized with epoxy resin and cement

In Fig. 8(b), addition of 10% cement caused the soil structure changed from particle to aggregated structure. Stabilization by epoxy resin caused significant changes in c-bentonite structure in a way that the soil structure changed significantly and particle structure changed completely and replaced with flocculated structure. Therefore, it can be said that epoxy resin is efficient for stabilization of c-bentonite clay sample; As observed in Fig. 8(d), using epoxy resin changes the soil structure and morphology prominently from particle to aggregate structure therefore the stabilization process has been done approximately. The continuous structure created through polymerization will improve the sample ductility, material toughness and critical state parameters of soil.

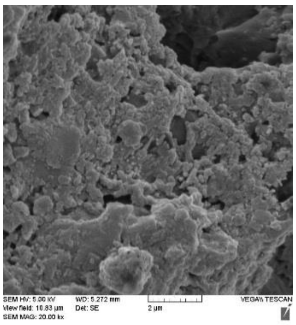
The SEM images of s-bentonite samples are shown in Fig. 9. The un-stabilized sample is shown in Fig. 9(a). Addition of 10% cement caused the soil structure changed from particle to aggregated structure. The SEM image of s-bentonite sample stabilized by epoxy resin shows that epoxy resin caused more significant changes in the s-bentonite structure in a way that the particle structure of clayey flakes was eliminate completely and flocculated structure created and the gelatinous structure formed through the polymerization process. So, as resulted in conclusions of strength parameters of uniaxial tests at section 3.1.3, addition of epoxy resin to the s-bentonite clay sample is the most efficient. Then, effect of cement and its possible pozzolanic reactions on the polymerization reactions is shown in SEM images. Considering the results of SEM images in Fig. 9(d), 10 percent of cement improves stabilization efficiency in the epoxy-resin-cement-stabilized, regarding to the creation of stronger continuous structure. Therefore, the optimum amount of cement is about 5 to 10 percent. Therefore, results of uniaxial and SEM experiments are compatible with each other.



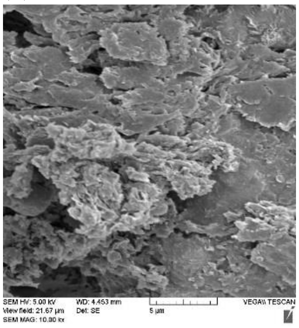
(a) s-bentonite



(b) s-bentonite+10%cement



(c) s-bentonite+epoxy resin



(d) s-bentonite+10% cement +epoxy resin

Fig. 9 SEM images of s-bentonite stabilized with epoxy resin and cement

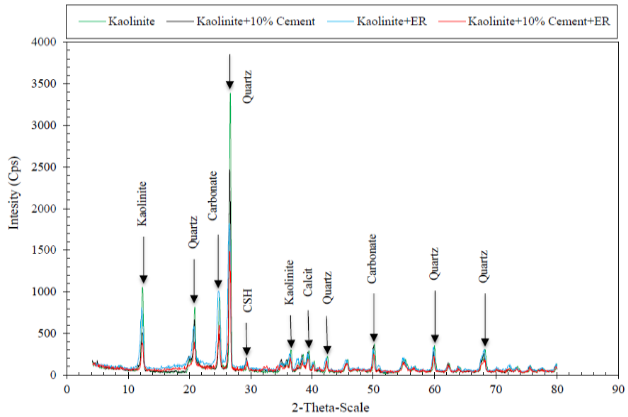


Fig. 10 X-Ray diffraction results of kaolinite stabilized with epoxy resin and cement

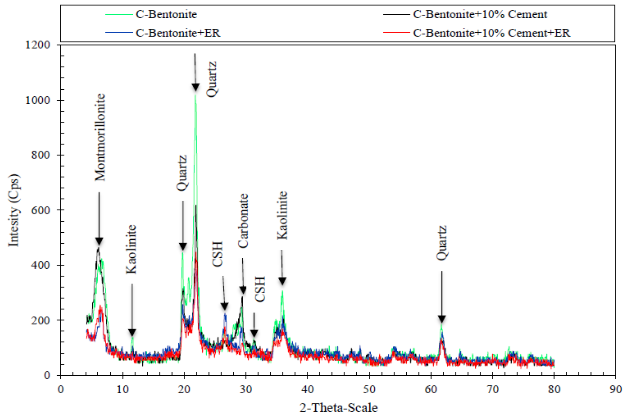


Fig. 11 X-Ray diffraction results of c-bentonite stabilized with epoxy resin and cement

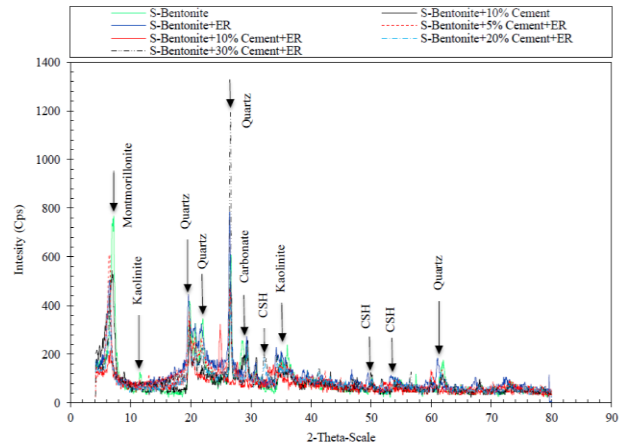


Fig. 12 X-Ray diffraction results of s-bentonite stabilized with epoxy resin and cement

3.2.2 X-Ray diffraction analysis

The results of X-ray diffraction experiments on kaolinite sample with and without additives are shown in Fig. 10. The main minerals of kaolinite clay sample are kaolinite, carbonate, calcite and quartz. Addition of 10% cement results in main peak intensity of kaolinite (d_{100}=7.2 A°) with 1055 Cps, quartz (d_{100}=3.35 A° and d_{100}=4.25 A°) with 818 and 3386 Cps respectively, and carbonate (d_{100}=3.57 A°) with 933 Cps reduced about 52%, 19%, 27% and 48%

respectively. The above-mentioned peak intensities are reduced about 26%, 29% and 46% and increased 8% respectively by adding only epoxy resin. Then, these peak intensities are reduced 64%, 52%, 56% and 36% for stabilizing by 10% of cement and epoxy resin. Moreover, the peak intensity associated with C-S-H nanostructure (d_{100}=3.57 A°) reaches 176 Cps by adding 10% cement which is 29% increase in peak intensity and it reaches 164 Cps by adding 10% cement and epoxy resin which is 21% increase in peak intensity. Therefore, according to reduction of the main peak intensities, cement and epoxy resins are able to stabilize the kaolinite clay samples. However, according to reduction of C-S-H nanostructure peak intensity in the cement-stabilized sample with the epoxy resins in compared with cement-stabilized sample, it can be concluded that the solidification process due to epoxy resin polymerization reaction prevents the completion of cement pozzolanic reaction. It should be noted that polymerization reaction occurs in initial hours while more time needed for completion of pozzolanic reaction. Thus, pozzolanic reaction cannot be completed due to high resistance of hardened structure of epoxy resin.

The results of X-ray diffraction analyses of stabilized and un-stabilized c-bentonite clay samples are shown in Fig. 11. The main minerals of the c-bentonite sample are montmorillonite, quartz, carbonate and kaolinite. By adding 10% cement the main peak intensity of montmorillonite (d_{100}=14 A°), quartz (d_{100}=4.06 A°), carbonate (d_{100}=3.04 A°) and kaolinite (d_{100}=2.5 A°) increased 10%, reduced 39%, increased 26% and increased 33% respectively. The above-mentioned peak intensities reduced about 44%, 62%, 22% and 30% respectively by adding just epoxy resin. In continuance, these peak intensities reduced 40%, 56%, 48% and 45% for stabilizing by 10% cement and epoxy resin. Therefore, considering reduction of main peaks intensity, it can be said that 10% cement performed weaker in comparison to epoxy resin and both cement and epoxy resin. According to significant reduction of main peaks intensity of all minerals in the c-bentonite stabilized just by epoxy resin and by both cement and epoxy resin, it can be said that epoxy resin play significant role in stabilization of c-bentonite. In addition, it can be concluded from the XRD analyses that epoxy resin itself alone reduces peak intensity of montmorillonite and quartz minerals 4% and 6% respectively more than presence of cement and epoxy resin simultaneously which shows appropriate efficiency of epoxy resin to interact with these two minerals and consequently these results led to successful stabilization. However, addition of cement reduces the peak intensity of carbonate and kaolinite about 2 and 1.5 times in comparison to the epoxy resin-stabilized sample which means that cement helps epoxy resin to perform better.

The results of XRD test of s-bentonite samples are shown in Fig.12. The main peak intensity of carbonate (d100=3.04 A°), montmorillonite (d100= 14 A°), quartz (d100=4.3 A°), quartz (d100=3.34 A°) and kaolinite (d100=2.5 A°) are reduced about 28%, 19%, 18%, increased about 1% and reduced about 39% respectively, by adding 10% cement. The above-mentioned peak intensities decrease about 33%, increased about 7%, 29%, 7% and decreased about 14% respectively by adding just epoxy resin. Then, these peak intensities reduced 72, 41, 83, 59 and 55 percent respectively for stabilizing by 5% cement and epoxy resin; reduced 20, 11, 13, 31 and 38 percent respectively for stabilizing by 10% of cement and epoxy resin; reduced 60, 39, 35, 8 and 34 percent respectively for stabilizing by 20% of cement and epoxy resin; reduced 49, 39, increased 96, reduced 9 and 30 percent respectively for stabilizing by 30% of cement and epoxy resin. Consequently, considering the dissolution rate of main peaks of s-bentonite clay sample, it can be said that 5% to 10% cement will be the appropriate content.

4. Conclusions

The most important results that concluded in this research are: 1. The efficiency of stabilization by cement and epoxy resin is a function of type and percentage of clay minerals existing in clay soils. 2. In kaolinite clay samples, the ductility improved significantly in comparison to UCS while these two both improved significantly in c-bentonite and s-bentonite in which s-bentonite performed better significantly. 3. By adding epoxy resin, the UCS ratio of s-bentonite to the UCS of kaolinite and c-bentonite samples are about 10-43 and 2-7 respectively, also the elastic modulus ratio of s-bentonite to the elastic modulus of kaolinite samples are about 20-200 and to the elastic modulus of c-bentonite for cement percentage less than and equal to 10% is about 1.2to 5.1 and for greater than 10% is about 0.32 to 0.84, while mostly in the absence of epoxy resin strength parameters of kaolinite and c-bentonite are better than strength parameters of s-bentonite. 4. The UCS of s-bentonite increased about 200 to 500 times by stabilization with cement and epoxy resin and reached to 1 to 2 times of the UCS of normal concrete. 5. The best efficiency in the weakest and most sensitive soils is the important and prominent results of stabilization by epoxy resin. 6. Epoxy resin can be suitable substitution for cement and water in different climatic zones, especially in hot and dry and equatorial climate which will be faced with water scarcity. 7. Stabilization by epoxy resin in problematic soils such as erodible and dispersive soils, expansive soils and soft clay soils which have the significant percentage of montmorillonite mineral group is strongly recommended.

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