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SHEAR STRENGTH PARAMETERS AND DEFORMABILITY PROPERTIES OF SILICATE-BASED RESIN ADDED SAND-TYPE SOIL SPECIMENS

*Eren KÖMÜRLÜ[1]

[1]Giresun University, Faculty of Engineering, Department of Civil Engineering, Giresun

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ABSTRACT

In this study, the shear strength, uniaxial compressive strength (UCS) values and deformability properties of silicate-based polymer resin added silty sand type soil specimens were examined through a series of experimental studies. Although the UCS and shear strength values increased, minor decreases in the internal friction angle values were measured as the resin ratio increased. It was determined that the main reason for the improvement in strength values due to the increase in resin content is the increase in cohesion values. It was found that the UCS values calculated according to the cohesion and internal friction angle parameters of the Mohr & Coulomb failure criterion (UCSc) were 2.6-3.0 times lower than the values obtained from the direct UCS experiment. According to this finding, it was concluded that the Mohr & Coulomb failure criterion is not properly usable to represent the mechanical behaviors of resin added sands. As another outcome, the ratio between UCS/UCSc slightly decreased with an increase in the resin amount. In other words, it has been determined that the Mohr&Coulomb failure criterion gives a bit more inaccurate results for the specimens with low binder contents. With the increase in the resin content ratio, significant increases were obtained in both elastic modulus and ductility properties of the samples. It has been evaluated that the silicate-based polymer resin binder is advantageous to provide significant increases in the toughness and energy absorption capacity of soils.

Keywords: Resin stabilized sands, Soil improvement, Silicate based resins, Shear box test, Compressive strengths of binder added sands.

SİLİKAT ESASLI REÇİNE KATKILI KUM TİPİ ZEMİN ÖRNEKLERİNİN KESME MUKAVEMETİ PARAMETRELERİ VE DEFORMABİLİTE ÖZELLİKLERİ

ÖZ

Bu çalışmada farklı oranlarda silikat bazlı polimer reçine eklenmiş siltli kum türü bir zeminin makaslama dayanımı, tek eksenli sıkışma dayanımı (UCS) değerleri ve deformabilite özellikleri bir dizi deneysel çalışma ile incelenmiştir. Reçine oranı arttıkça UCS ve makaslama dayanımı degerleri artmasına rağmen içsel sürtünme açısının azaldığı belirlenmiştir. Reçine içeriği artışına bağlı dayanım değerini iyileştiren ana etkenin kohezyon artışı olduğu tespit edilmiştir. Kohezyon ve içsel sürtünme açısı değerleri ile Mohr&Coulomb yenilme ölçütüne gore hesaplanan UCS (UCSc) değerlerinin direk UCS deneyinden elde edilen değerlerden 2.6-3.0 kat düşük olduğu belirlenmiştir. Bu bulguya göre, Mohr&Coulomb yenilme ölçütünün reçineli kumları iyi temsil edemediği sonucuna varılmıştır. UCS/UCSc arasındaki arasındaki oranın reçine oranı artışı ile biraz azaldığı bulunmuştur. Bir diğer ifade ile bağlayıcı içeriği düşük olan numunelerde Mohr&Coulomb yenilme ölçütünün daha hatalı sonuçlar verdiği belirlenmiştir. Reçine oranının artışı ile numunelerin hem elastisite modülü hem de süneklik özelliklerinde anlamlı artışlar görülmüştür. Silikat bazlı polimer reçine bağlayıcının önemli bir avantajı olarak zeminlerin tokluk ve enerji emme kapasitesi özelliklerinde önemli artışlar sağlayabildiği değerlendirilmiştir.

Anahtar kelimeler: Reçine katkılı kumlar, Zemin iyileştirme, Silikat esaslı reçine, Zemin makaslama kutusu deneyi, Bağlayıcılı zeminlerin sıkışma dayanımları.

***Corresponding Author/ Sorumlu Yazar:** ekomurlu@giresun.edu.tr

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1. Introduction

Polymer materials can be divided into two main groups as thermosets and thermoplastics. Thermosets are generally purchased before their polymerization in the liquid form. One or more components of thermoset polymers in the liquid form are mixed, chemically react with each other and solidify as a consequence of the polymerization reactions. Thermoset polymers are used in various geotechnical applications of spraying membranes, grouting in anchorage holes, ground improvement injections, soil mixing and etc. [1-4].

Resin additives used for ground improvement works are thermoset type chemical products used in geotechnical engineering. There are different commercial soil injection polymer material types such as silicate, polyurethane, acrylic, epoxy based ones. It is possible to find resin products with a wide range of viscosity and curing time properties depending on the purpose. It is important to choose a resin with an appropriate liquid phase time and viscosity properties depending on the details of the application. The liquid phase time, which is a few seconds in spray membrane applications, can be several minutes for resins used in ground injection applications [5-7].

Thermoset polymer resins can be injected into the soil in place or can be mixed with soils to prepare a filling material mix. Polymer materials are preferred considering their mechanical properties and their high chemical resistances which make them advantageous in terms of their service lifetimes. Another important reason for using polymer materials is their high energy absorption capacities. Engineering polymers that provide good mechanical properties are preferred because of their strength values as well as their high energy absorption capacities [8-10].

High energy absorption capacity polymers supply an advantage of improvement under both static and dynamic load conditions by providing soil reinforcement. As some polymer resins can polymerize in contact with water, novel resin types can supply another important advantage in the watery regions against conventional materials [11,12]. Resins are also usable to improve the liquefaction resistance of soils [13-15]. Due to their different advantages, the use of soil improvement resin chemicals in geotechnical engineering is becoming more widespread every day.

In this study, the shear strength properties of silicate-based resin added sand samples were investigated. The influences of using different ratios of resin additives were investigated. In addition to the strength values, the effect of using different ratios of resin additives on the deformability properties of the improved soil mixes was also investigated. In addition to the shear strength tests, uniaxial compressive strength values were also performed. Using the cohesion (c) and internal friction angle (ϕ) values obtained from the shear box test, UCS values were calculated in accordance with the famous Mohr & Coulomb (MC) failure criterion relation given in Equation 1. The UCS values calculated using the MC failure criterion (UCS_c) were compared with the uniaxial compressive strength test results. In this way, the usability of the famous MC failure criterion was aimed to be examined for resin-added soil mixes.

2. Materials and Methods

Soil specimens of this study were taken from Giresun city of the Black Sea Region of Turkiye. To use in the experimental study, soil specimens were firstly sieved before tests to prepare all the particles for passing the 8 mm sieve. To classify the soil specimens with particles under 8 mm, size distribution analyses were carried out using 4.00 mm, 2.00 mm, 1.00 mm, 0.50 mm, 0.25 mm, 0.125 mm and 0.074 mm sieves (Figure 1). The particle size distribution of soil specimens is given in Table 1. The soil specimen was evaluated to respectively have the coefficient of uniformity (C_u) and the coefficient of curvature (C_c) values of 8.8 and 0.4. As the soil has no a C_c value between 1 and 3, it was assessed to be a poorly-graded soil [16].

To classify the soil with 7% content of particles passing the No. 200 sieve (0.074 mm), liquid and plastic limits (Atterberg limits) were determined. The Casagrande test was carried out for determination of the liquid limit value (Figure 2). The methodology stated in the ASTM D4318-10 coded standard was followed in the Casagrande test [17]. The liquid limit was determined as the water content of soil specimens for closing the groove due to the impact of 25 blows of the Casagrande cup. The soil specimen passing under the No. 40 (0.425 mm) sieve was used in the Casagrande test. The water content was

*Corresponding Author/ Sorumlu Yazar: ekomurlu@giresun.edu.tr

calculated as the ratio of mass of water to mass of dry soil. To make dry soil, specimens were heated in the 105 °C stove for a day. The plastic limit test is performed by rolling soil rods on the standard glass plate. As stated in the ASTM D4318-10 coded test standard, the plastic limit was determined as the water content of soil rods which just crumbles when they are carefully and gently rolled to a diameter of 3 mm. Liquid and plastic limits of the soil were determined as 39% and 27%, respectively. According to the unified soil classification system (USCS), the soil sample can be classified as SP-SM (Poorly-graded sand with silt).

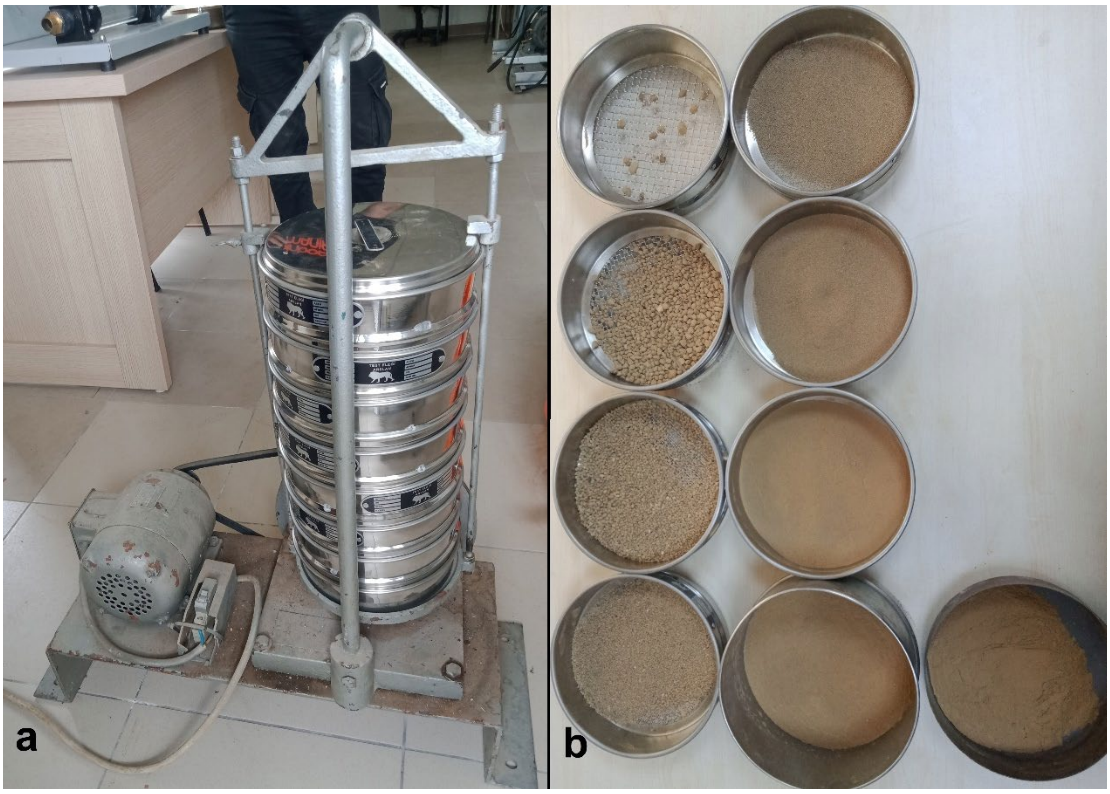

Figure 1. Some photos from the sieve analyses (a and b)

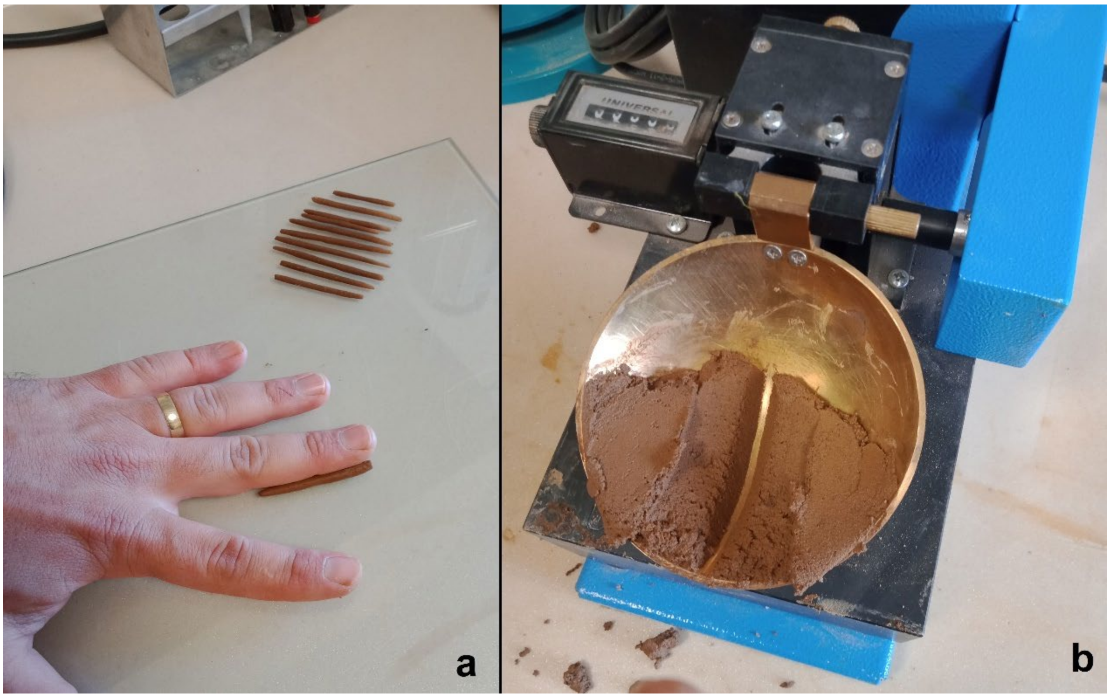

Figure 2. The plastic limit (a) and liquid limit (b) tests

***Corresponding Author/ Sorumlu Yazar:** ekomurlu@giresun.edu.tr

In this study, INSILEX TS brand non-expandable two-component silicate-based resin was used. This product is a Turkish product used in ground improvement processes and is a product of the FMY Kimya company. Some technical specifications of the product are given in Tables 2 and 3 [18]. Curing is supplied by mixing the liquid phase components of the product in the ratio of 1:1 by mass. In other words, the ratio of both components to the total resin amount is 50%.

Table 1. Particle size distribution of soil the specimen

Sieve aperture (mm)	Passing percentage (%)
8	100
4	92
2	78
1	66
0.5	56
0.25	42
0.125	25
0.075	7

Table 2. Some technical properties of Insilex brand resin components

Component properties	Insilex A component	Insilex B component
Density at 25 °C (kg/m^3)	1.470 ± 40	1.130 ± 40
Viscosity at 25 °C (MPa·sn)	260 ± 40	140 ± 40
Flash point (°C)	-	>200
Mix ratio	1	1
Color	Colorless	Brown

Table 3. Reaction and mechanical properties of the Insilex brand resin (-: no data)

Parameters	25 °C	40 °C
Liquid phase time (sec)	135-150	110-120
Swelling factor	1	1
Maximum temperature due to the reaction (°C)	87	-
Uniaxial compressive strength (MPa)	35	-
Typical adhesive strength (MPa)	4-5	-
Time to fully complete polymerization reactions (day)	1	-

After the sand samples were taken from the field, they were kept in air in the laboratory for a month. It should be noted herein that the particle surfaces were not wet or moist. The contents of the mixes were sensitively weighed using an electronic scale. After the soil and resin components were added into a basin, specimens were mixed by hand for 150 seconds. It should be noted herein that specimens were mixed within the liquid phase time before the gelation. When the gelation starts, the viscosity slowly increases because of the initation of polymerization reactions. Specimens were soft, easily shapable and not solidified as the gelation stage starts. Therefore, the molding process was properly carried out in the early gelation. Because of the liquid phase time limitations of the resin additive, UCS and shear box test specimens were separately mixed and molded (Figures 3 and 4). The specimens tested within this study are shown in Figure 5. Four UCS specimens were molded for the each specimen type. In total, 16 UCS test specimens were prepared. UCS test specimens were filled into the molds in three layers and compacted with 20 mallet strokes after each layers. The up-side surfaces were flattened by mallet drops when the specimens were in the plastic molds. Additionally, roughness of the surfaces of the specimens was gently removed by using a snap blade knife to make a smooth contact with the loading platen. Mixing, casting, molding and remolding procedures are totally the same for all the specimens tested within this study. The diameter of the cylindrical specimen molds was 50 mm and the ratio of length to diameter of the specimens was 2 in this study. According to the ASTM D 2166 coded standard for the unconfined compressive strength (UCS) tests of soil specimens, length to diameter ratio can vary from 2 to 2.5. According to the relevant standard, specimens must have a minimum diameter of 30 mm. Additionally, the biggest soil particle size must be smaller than one sixth of the specimen diameter [19]. The statements of the relevant standard were met since all particles of the soil used in this study passed under the sieve opening of 8 mm.

*Corresponding Author/ Sorumlu Yazar: ekomurlu@giresun.edu.tr

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Specimens were remolded after a day of curing time. Before the UCS test, specimens were cured in air at the room temperature for a total of one week. A sensitive electric motor press with the loading capacity of 50 kN was used to measure the UCS values. In the UCS test, a loading rate was chosen to be 0.5 mm/min according to the ASTM D 2166 coded standard which states to use a strain rate from 0.5% to 2%/min [19]. Secant modulus is one of several methods used to calculate the modulus of elasticity. Calculating the secant modulus involves using two points on a stress-strain curve to calculate the slope of the stress/strain. When using this method, the first point is always zero and the second is a non-zero value. Secant elastic modulus values for 25%, 50% and 75% of the UCS level were calculated to investigate deformability properties under various stress levels. In addition, strain behaviours of the specimens cracked after reaching the UCS level were investigated. Loading was stopped automatically as the maximum load level decreased by 35%. To investigate the ductility properties of the specimens, plastic strain values after the maximum stress level were taken into account.

In addition to the UCS values, shear strength values of specimens were also determined carrying out the shear box test under the unconsolidated and undrained case. The shear box test was performed in accordance with the procedure stated in the ASTM D3080-04 coded American standard [20]. Square shaped specimens with 60 mm x 60 mm x 25 mm sizes were used in the shear box test. For each of the resin contents, the shear strength values were determined under 5 different normal stresses. In total, 20 shear strength test specimens were used for four different resin amounts of 8%, 12%, 16% and 20%. Specimens used in this study are shown in Figure 5. The shear strength test specimens were filled into the molds and compacted by using the standard tamper equipment. The same tamper was used and the same procedure was applied in the compaction process of all shear test specimens. After the resin started to cure and harden, specimens were removed from the mold by pushing them with the standard test tamper on the same day they were molded (Figure 3). The specimens removed from the mold were cured for a week before the test, as in the UCS test. Since the resin completed the polymerization reactions within one day and reached the maximum strength, it was not necessary to test the samples for a cure period longer than one week [18].

Shear force and stress values were read instantly with the horizontal load cell on the electric motor shear box test equipment and recorded by its software. Peak internal friction angle and cohesion values were calculated depending on the maximum stress values at the failure. Uniaxial compressive strength values were calculated depending on the cohesion (c) and internal friction angle (ϕ) values according to the Mohr&Coulomb failure criterion as seen in the well-known Equation 1 [21]. The UCS values calculated according to Equation 1 (UCS_c) and the strength values obtained from the direct uniaxial compressive strength test (UCS) were compared to investigate whether the Mohr & Coulomb failure criterion is usable and representable for the mechanical properties of the specimens. Some photos from the shear box test and the UCS test are given in Figures 6 and 7.

$$UCS_c = 2c(\cos\phi)/(1-\sin\phi) = 2c\tan(45+\phi/2) \tag{1}$$

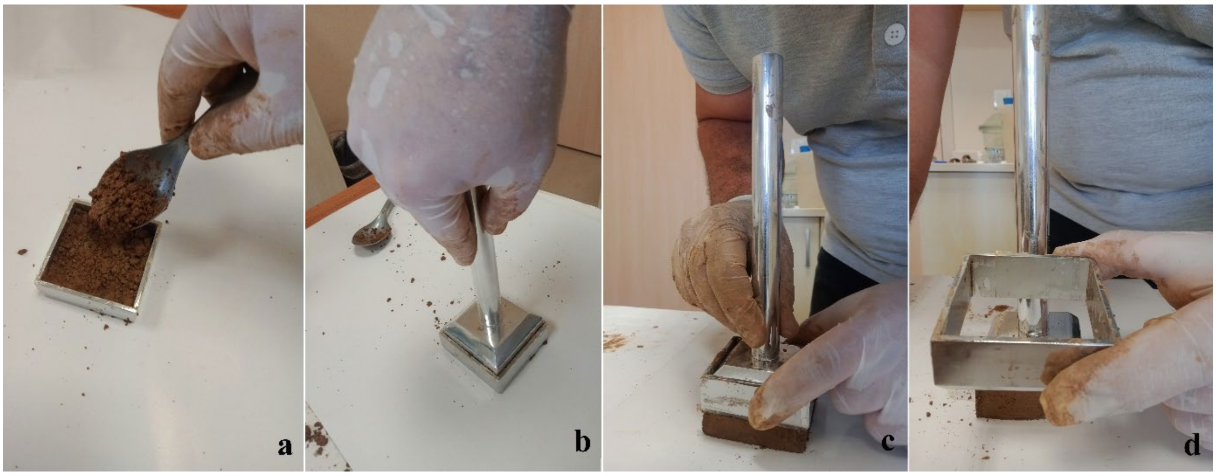

Figure 3. Shear strength specimen molding: a) soil filling into the mold, b) compaction, c and d) removing the mold

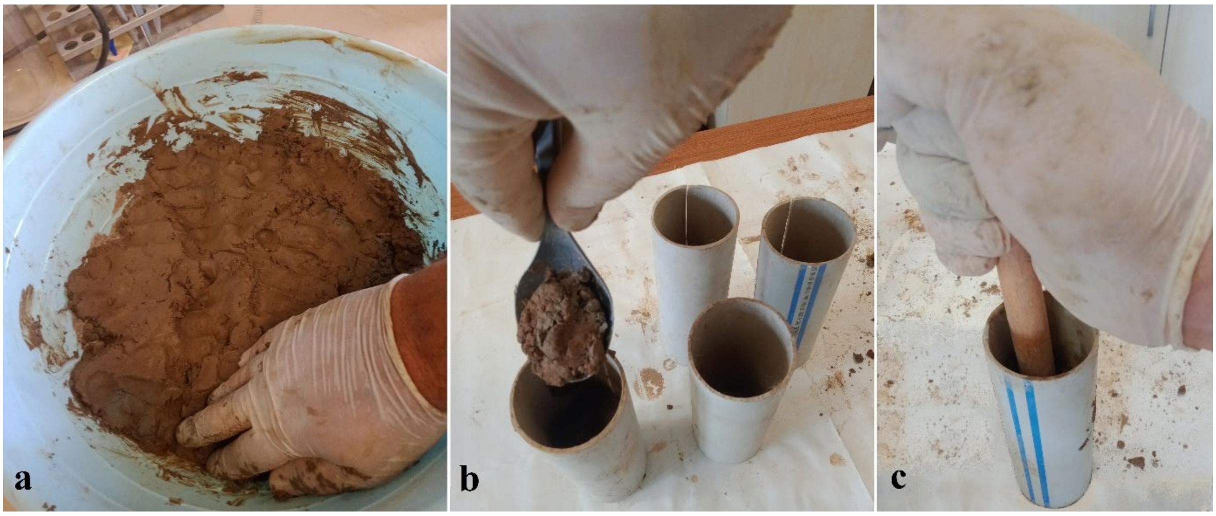

Figure 4. a) specimen mixing, b and c) UCS test specimen molding

Figure 5. UCS and shear strength test specimens used in this study

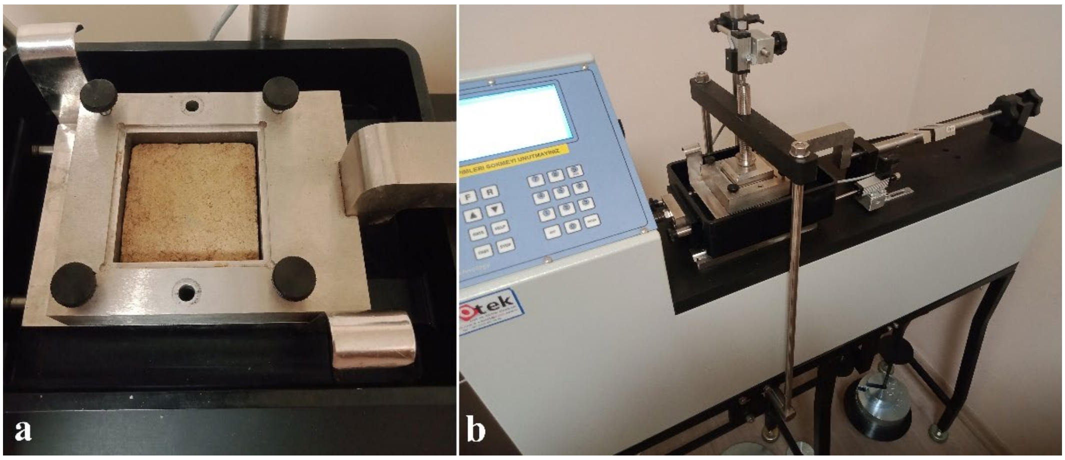

Figure 6. Photos from the shear box test (a and b)

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Figure 7. The UCS test

3. Research Findings

The UCS values and modulus of elasticity values are given in Table 4. According to the results, both UCS and modulus of elasticity values significantly increase with increasing in the resin amount. In Table 4, modulus of elasticity values for various stress levels of 0.25 UCS, 0.50 UCS and 0.75 UCS are respectively given as $E_{sec0.25}$, $E_{sec0.50}$ and $E_{sec0.75}$. As seen from Figure 8 showing the stress strain graphs obtained from the UCS test, the ductility property which can be briefly defined as the plastic deformability of cracked specimens was also found to increase with an increase in the resin amount. The plastic strains from the peak stress to the 35% decrease in the stress level are given in Table 5. The improvement in the ductility property can be seen from the increase in the plastic strain limits.

Shear strength test results are given in Figure 9 and Table 6. The cohesion and internal friction angle parameters were determined for the peak stress case in the shear box test. As seen from the shear box test results, cohesion values increased with an increase in the resin amount, whereas the internal friction angle values decreased due to increases in the resin amount. Therefore, it was assessed that the shear strength values increased as a result of significant increases in the cohesion parameter with increasing resin amount. The relation between UCS_c values calculated in accordance with the c, ϕ from the shear box test and the direct UCS test results is given in Table 6. The UCS/UCS_c ratio was found to decrease with an increase in the resin content. It was assessed that the Mohr&Coulomb failure criterion is not accurately usable for the resin added sand specimens.

Table 4. Mean UCS and modulus of elasticity values of specimens

Specimen type	UCS (kPa)	$E_{sec0.25}$ (MPa)	$E_{sec0.50}$ (MPa)	$E_{sec0.75}$ (MPa)
8% Resin	1047	142	173	189
12% Resin	1530	201	234	246
16% Resin	2154	255	297	305
20% Resin	2693	328	362	349

*Corresponding Author/ Sorumlu Yazar: ekomurlu@giresun.edu.tr

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Table 5. Mean plastic strain values after the peak stress level

Specimen type	Plastic strain
8% Resin	0.0052
12% Resin	0.0091
16% Resin	0.0149
20% Resin	0.0188

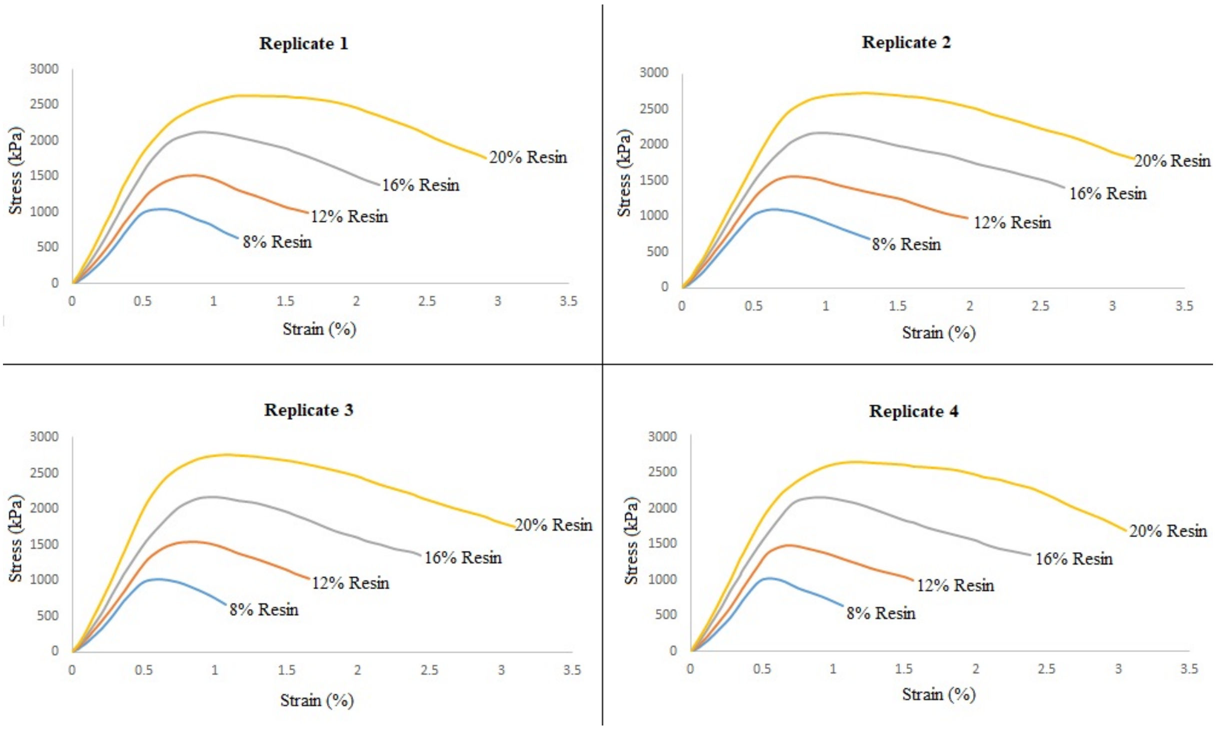

Figure 8. Stress and strain graphs of UCS test specimens

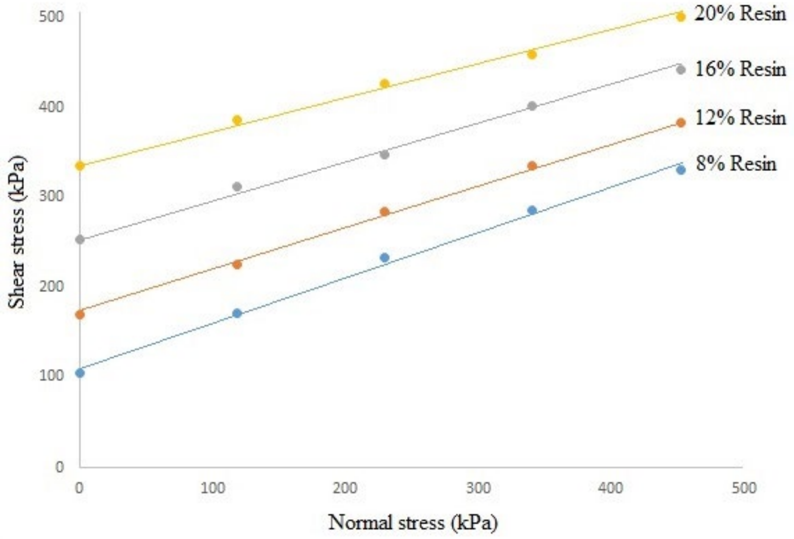

Figure 9. The shear box test results

Table 6. Cohesion, internal friction angle values and relation between UCS and UCS$_c$ values

Specimen type	c (kPa)	ϕ (°)	UCS$_c$ (kPa)	UCS/UCS$_c$
8% Resin	106	28	353	2.97
12% Resin	171	26	547	2.80
16% Resin	254	25	798	2.70
20% Resin	337	23	1019	2.64

***Corresponding Author/ Sorumlu Yazar:** ekomurlu@giresun.edu.tr

4. Discussions and Conclusion

According to the findings, shear strength values increased as the resin amount increased. In parallel, strength values are estimated to increase with an increase in binder content [22-25]. The main reason for the increase in strength values as a result of the increase in resin content was determined to be the increase in cohesion value. Significant increases were observed in cohesion values with the increase in resin ratio. As parallel to the outcomes of this study, different researchers reported that the strength improvement of the resin added soil materials is resulted from the significant increases in cohesion values with the increase in resin ratio [26-28]. On the other hand, the increase in resin amount caused a minor decrease in internal friction angle values. As it is known, shear strength values depend on the mechanical parameters of c and ϕ. The uniaxial compressive strength calculated according to the Mohr and Coulomb failure criterion (UCS_c) using the c and ϕ values was lower than the values measured in the direct uniaxial compressive strength (UCS) test. According to the findings, the UCS/UCS_c ratio varied between 2.6 and 3. When other studies in the literature are examined, it is seen that the UCS_c calculated using c and ϕ parameters obtained from the shear box test is lower than the values obtained from the uniaxial compressive strength test [29]. Different studies have been conducted on the subject of the Mohr & Coulomb failure criterion usability for soil mixes by various researchers. According to the outcomes of different researches, the Mohr & Coulomb criterion was found to have some shortcomings to consider its use for soils [30-33].

It is thought that this study will contribute to new researches on the usability of Mohr & Coulomb for resin-reinforced soils. According to the numerical analysis carried out by Komurlu (2019), the standard shear box test gives lower shear strength values of soils than their real strength levels, as there are also tensile stresses at the critical location where crack formation begins in the sample [34]. For this reason, the Mohr&Coulomb criterion should not be seen as the only reason for the incompatibility between UCS_c and UCS.

The price per a tonne of silicate-based resins is approximately 3000 US dollars. Although the strength values notably increase with the increase in the amount of resin, the use of resin with high content may not be economical. According to the study conducted by Komurlu et al. (2024), it was stated that desired strength values can be achieved more economically by using resin and fiber additive together instead of using excessive resin amounts [35]. Polymer-based resins are advantageous compared to traditional binder use because of various reasons like containing no grain particles, selective viscosity and liquid phase time depending on soil properties, high chemical resistance, fast curing and strengthening. Additionally, some soil improvement injection products can polymerize effectively in contact with water. Higher ductility and crack propagation resistance properties than those of conventional binders make the polymer-based resins advantageous in terms of having a higher energy absorption capacity and a better resistance against external forces and factors [36-38].

The ductile material property indicates continuing to bear a load level even if specimens are cracked. Crack propagation resistance improves ductility properties as a result of the increased toughness [39-41]. As the area under the stress strain graph increases, a higher energy absorption capacity is also achieved [42-45]. Therefore, the increase in ductility provides an increase in the energy absorption capacity of the materials. According to the findings, it was found that the resin additive provides a significant advantage in terms of ductility, toughness and energy absorption capacity.

In conclusion, it was observed in this study that resin added soil samples were not well represented by the Mohr & Coulomb failure criterion because of up to three times differences between UCS_c and UCS values. The silicate-based polymer resin binder additive provided significant improvements in both UCS test and shear strength test results of the sand type soil specimens. It was determined that the resin additive increased the elastic modulus values significantly in addition to the strength values. The main reason for the mechanical improvement obtained with the increase in the resin amount was determined as the increase in cohesion. It was observed that the internal friction angle slightly decreased depending on the resin content, while the cohesion values increased significantly with the increase in resin content. As the resin binder content increased from 8% to 20%, the internal friction angle values decreased by 18% and the cohesion value increased by 317%. As a result of increasing in resin additive ratio from 8% to 20%, UCS values increased by 2.6 times and elastic modulus values increased by up to 2.3 times. It was observed that the silicate-based resin provided significant improvements in the ductility properties

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***Corresponding Author/ Sorumlu Yazar:** ekomurlu@giresun.edu.tr

of soil samples. Considering the areas under stress and strain graphs, it was also evaluated that energy absorption capacities of the resin added sand specimens were notably bettered as a result of the increase in the resin amount. In short, it was concluded that silicate-based resin additives are advantageous binder materials that improve strength, deformation modulus, ductility and energy absorption capacity properties. It is thought that it is important for geotechnical engineers to follow the developments in the field of polymer-based synthetic resins, which are contemporary additives used in ground improvement applications.

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