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Determination of shear strength parameters of compacted high plasticity clay soils based on different laboratory tests

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Shear box test
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ABSTRACT

In civil engineering projects, soils are compacted to improve their engineering behavior and properties. Compacted soils are widely used in dams, embankments and road infrastructure. Compacted fine-grained soils, especially clay-containing soils, are frequently used as barriers to water and pollutant movement in landfills. Shear strength parameters of compacted high plasticity clay soils depend on many variables such as consistency limits, dry density, and degree of saturation. In this study, 20 high plasticity clay soil samples were used and geotechnical identification tests were performed on each of them. Direct shear box and unconfined compression tests were carried out to determine the shear strength parameters of the samples prepared by compression in their compaction characteristics. As a result of this study, the relationships between the geotechnical properties of soil samples and both the effective shear strength parameters and total shear stress parameters were evaluated.

1. INTRODUCTION

Compaction is one of the most important processes applied to improve soils during the construction of structures. The purpose of compaction is to improve the engineering properties of the soil mass. It is desired that the embankments used in the construction of structures such as highways, airports and embankment dams should be placed more firmly. This is achieved by reducing the air volume in the soil. Densification of soil by compaction depends on two factors, water content and compaction energy. The construction of earthen structures involves the use of compacted soils. In geotechnical problems such as bearing capacity, lateral soil pressure and slope stability, the shear strength parameters of compacted soils are primarily important. The shear strength parameters of compacted structural fills are usually measured using laboratory compacted samples. Wheeler and Sivakumar (1995) and Kong and Tan (2000) have studied the shear strength of unsaturated compacted soils.

Laboratory test methods have been developed to simulate the correct field conditions under the controlled conditions of the laboratory, and its main purpose is to accurately represent the mechanical behavior of the samples in the laboratory when exposed to the loads in the field (Yaghoubi et al. 2018). In order to understand the soil behavior after compaction in the field, it is necessary to determine the physical and engineering properties of the soil. Engineering tests to be carried out on samples prepared by compression in the laboratory environment on this basis provide important information on the behavior of fine-grained soils (Çalık and Sadağlı 2014). The performance of the compaction performed in the field is determined by comparing the compaction characteristics determined in the laboratory. Because laboratory compaction experiments are laborious and take a long time, many researchers have conducted research to determine the compaction characteristics depending on the physical properties of the soil. Çokça et al. (2004) examined the relationship between the strength parameters of the clayey sample and the water content in their laboratory study. As a result of this study, it has been shown that the cohesion value of the sample increases as it approaches the optimum water content, the cohesion value decreases at water contents above the optimum water content, and the internal friction angle decreases with increasing water content. Vondráčková et al. (2016) examined the parameters affecting cohesion in fine-grained soils. In this study, they stated that the saturation degree plays an important role on cohesion. Both Akgün et al. (2017) and Gençdal et al. (2018) evaluated the effect of increased water content on

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strength. When evaluated in general, they stated that the soil strength decreased with increasing water content.

There are many experimental methods in the laboratory environment to examine the strength behavior of high plasticity clay soil to be used as a filling material under different loading conditions.

Ghosh (2012) conducted a series of veyn tests in the laboratory to examine the effect of water content on the shear strength of compacted clay soils. According to the results of the veyn test, it was determined that the increase in the water content caused a decrease in the undrained shear strength. VandenBerge et al. (2014) carried out consolidated undrained (CU) triaxial compressive tests on the soil they compacted with standard compaction in order to determine the undrained shear strength of the soil.

In this study, unconfined compression strength (UCS) and direct shear box (DSB) tests were conducted to determine the shear strength behavior of the specimens prepared by compression, and the relationships between the obtained strength parameters were investigated.

2. MATERIAL AND METHOD

2.1. Material

Soil samples excavated from the filling areas made in the same region but in very different locations were used. In order to determine the geotechnical properties of 20 different samples used in the experimental study, necessary classification experiments were carried out in the laboratory. In order to determine the compaction characteristics (optimum water content, OWC, and maximum dry density, MDD), the Standard Proctor test was carried out. Statistical evaluation of the geotechnical properties of the samples is given in Table 1. Fig. 1 shows the compaction curves of the samples, Fig. 2 shows the locations of the samples on the plasticity card, and Fig. 3 shows the distribution of the grain size in the samples.

When the identification test results are evaluated statistically, it is seen that the liquid limit (LL) values of 20 samples vary between 52% and 72% and the average value is 60%. Plasticity index (PI) values also vary between 25% and 39%, with an average value of 31.1%. Soil samples are fine-grained, and the fine-grain ratio is between 71.4% and 96.2%. The locations of 20 samples used in this study on the Casagrande Plasticity Card are shown in Fig. 2. As can be seen from this figure, all of the samples used in the experimental study are in the high plasticity clay (CH) class in the Unified Soil Classification System.

2.2. Method

Unconfined compression strength (UCS) and direct shear box (DSB) tests were carried out on the samples. During the engineering tests, ASTM D2166-00 and ASTM D3080/D3080M-11 standards were followed for the unconfined compression test and the shear box test, respectively.

Table 1. The statistical data of the geotechnical properties of the soil samples

Property	Num.	Value			
		Min.	Max.	Mean	Std. Deviation
Grain size					
<0.002 mm (%)	20	33.1	64.5	49.6	9.5
<0.075 mm (%)	20	71.4	96.2	89.1	6.6
<4.75 mm (%)	20	84.6	100.0	97.9	4.1
Atterberg limits					
LL (%)	20	52.0	72.0	60.0	5.3
PL (%)	20	25.0	36.0	28.9	2.6
PI (%)	20	25.0	39.0	31.1	3.9
Gs	20	2.73	2.81	2.77	0.002
Std. Proctor					
-MDD (Mg/m^3)	20	1.421	1.616	1.537	0.046
- OWC (%)	20	21.6	29.4	24.4	2.0
-S (%)	20	78.6	89.8	83.9	3.5

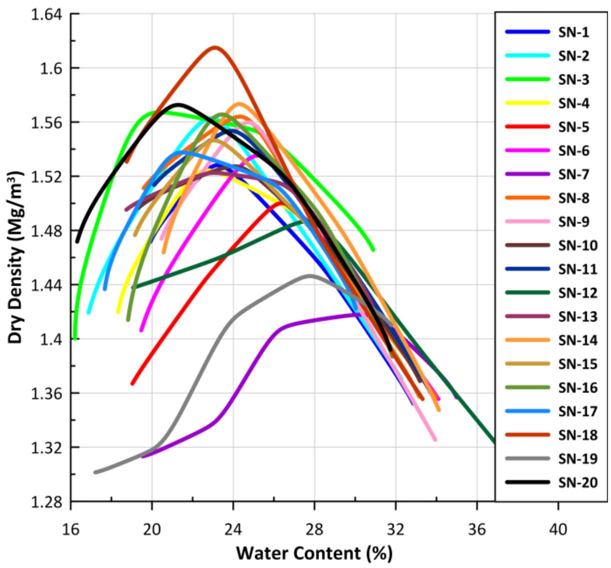


Figure 1. Compaction curves of the samples

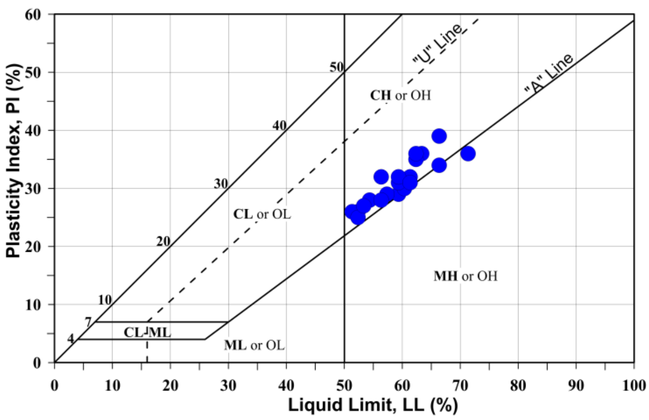


Figure 2. Location of the samples on the Casagrande Plasticity Card

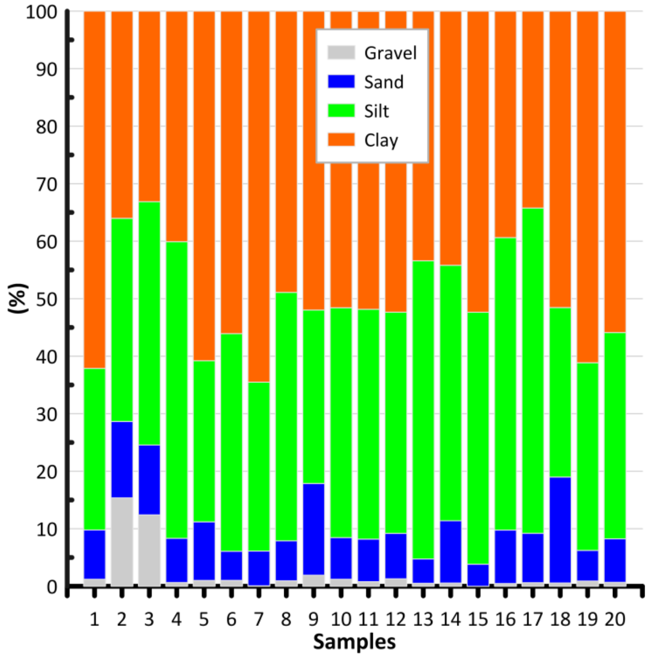


Figure 3. Grain size distributions of the soil samples

2.2.1. Preparation of samples

The disturbed samples were ground with a plastic-headed hammer and passed through a 4.75 mm mesh sieve. The amount of water needed to be added to bring it to the optimum water content was calculated and after adding the necessary water to the samples, they were packed in an air and watertight manner and waited for 24 hours to ensure a homogeneous distribution of the water in it. For the samples brought to the optimum water content, it was calculated how much sample should be compressed considering the dry density and mold volume. After the samples were compressed, they were wrapped in cling film in order to distribute the water in them homogeneously and kept in the desiccator for 24 hours.

All experiments within the scope of this study were carried out in the laboratory of Eskişehir Osmangazi University.

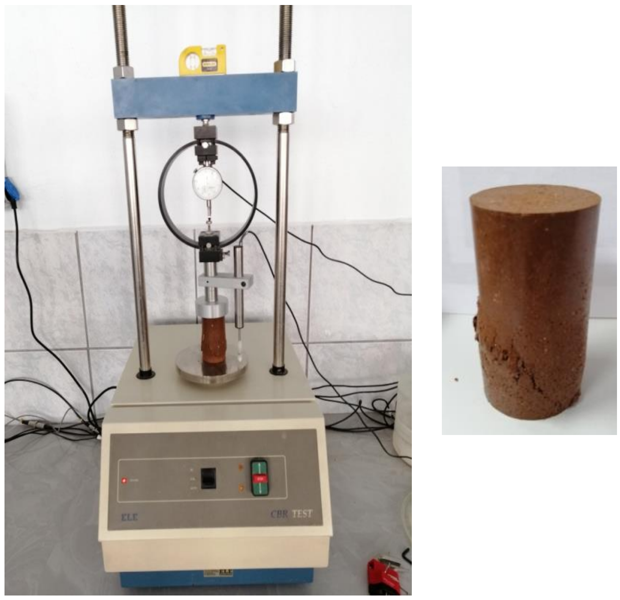
2.2.2. Unconfined compression strength test

UCS test is a widely used test because it gives very quick results. Although this test is performed in two ways as stress-controlled and deformation-controlled, the deformation-controlled method is commonly preferred. Since the drainage conditions of the sample were not controlled during the test, it is assumed that the undrained shear strength of the soil is obtained by rapid loading. In the test, the ratio of the sample length to the diameter is taken as 2, so that the loading head does not prevent the failure planes formed in the sample. UCS tests were performed on the samples prepared by compression in steel cylinders with a diameter of 50 mm and a height of 100 mm. In the experiment carried out under deformation control, the loading speed was chosen as 1 mm/min. The stress-strain relations of the samples were obtained and the unconfined compressive strength value at the time of collapse was obtained. Fig. 4 shows the unconfined pressure test equipment and shows the failure plane of the specimen after the test.

2.2.3. Direct shear test

The parameters found by the DSB test method are considered to be drained. For this reason, the cutting speed in the shear box should be selected at a speed that will not allow the formation of pore water pressure in the sample. Therefore, while the shear rate is high due to the high permeability of coarse-grained soils, the shear rate is quite slow in fine-grained soils due to low permeability.

The test was carried out under 3 different normal stresses, at a speed of 0.05 mm/min. After the sample was placed, the arm to which the normal stress would be transferred was placed on the sample. Distilled water was filled into the chamber and consolidation was initiated under the corresponding normal stress. After the sample had consolidated, shearing was performed at a speed of 0.05 mm/min. After the cutting process was carried out, the wet weight of the sample removed from the cutting box apparatus was taken and its dry weight was determined after it was kept in the oven for 24 hours. The experimental setup, the prepared sample and the post-test sample are shown in Fig. 5.



(a) (b)

Figure 4. (a)Unconfined compressive strength equipment, (b) Image of the sample after the test

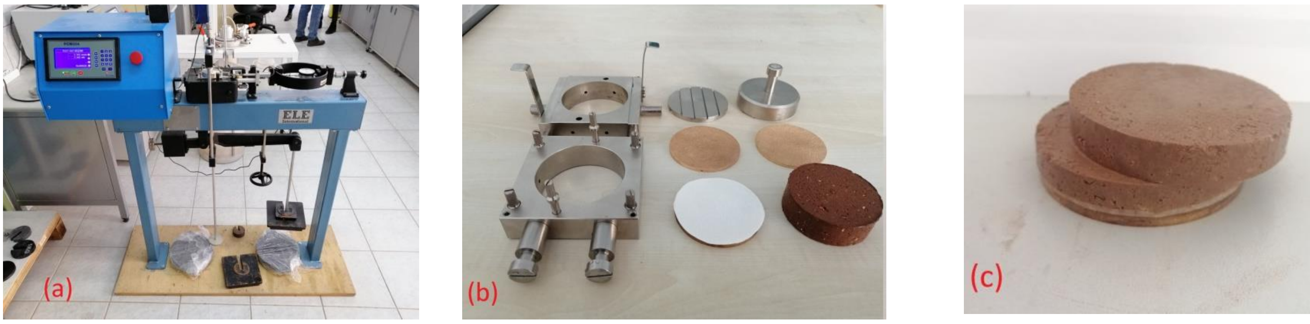


Figure 5. (a) Shear box assembly. (b) Compacted specimen, porous stones and cutting box apparatus. (c) Visual of the sample after the test

3. RESULTS AND DISCUSSION

The strength values at the time of failure (q_{un}) and axial deformation values were determined from the coordinates of the peak point in the stress-strain curves obtained as a result of the UCS experiments. In Figure 6, the stress-strain relations obtained as a result of the UCS test performed on samples 1 and 2 are presented as an example. Table 2 presents the q_{un} results for all samples. It was observed that the compressive strength of the samples was between 107 kPa and 250 kPa and the average value was 173 kPa. The axial strain values at the time of failure were also between 1.41% and 3.48%.

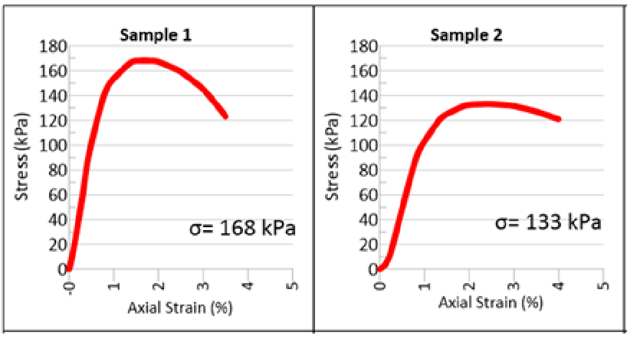


Figure 6. Stress-strain relations obtained as a result of unconfined compressive strength test for samples 1 and 2

Shear stress deformation curves obtained from DSB experiments were obtained for three different normal stresses. As an example, the curves obtained for samples 1 and 2 are presented in Fig. 7. As seen in Fig. 7, larger shear stress values were achieved with increasing normal stress values. Peak shear strengths were found from the peak of the curves. Residual shear strength values were also determined as the value at which the stress remained constant with increasing deformation. With the reduction of the grain size in clays, the specific surface increases, thus causing a decrease in residual strength.

Fig. 8 shows both the peak and residual strength envelopes for samples 1 and 2 as an example.

The shear strength parameters obtained from the engineering tests carried out within the scope of this study are presented in Table 2.

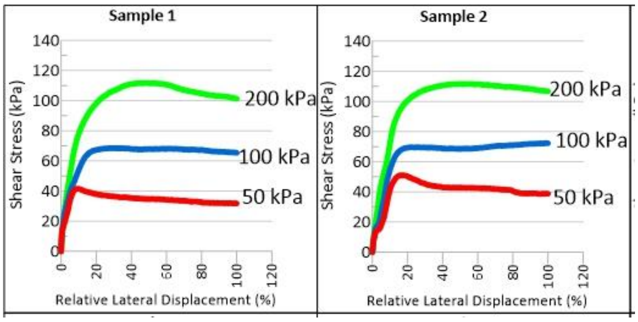


Figure 7. Stress-strain relations obtained as a result of direct shear box test for samples 1 and 2

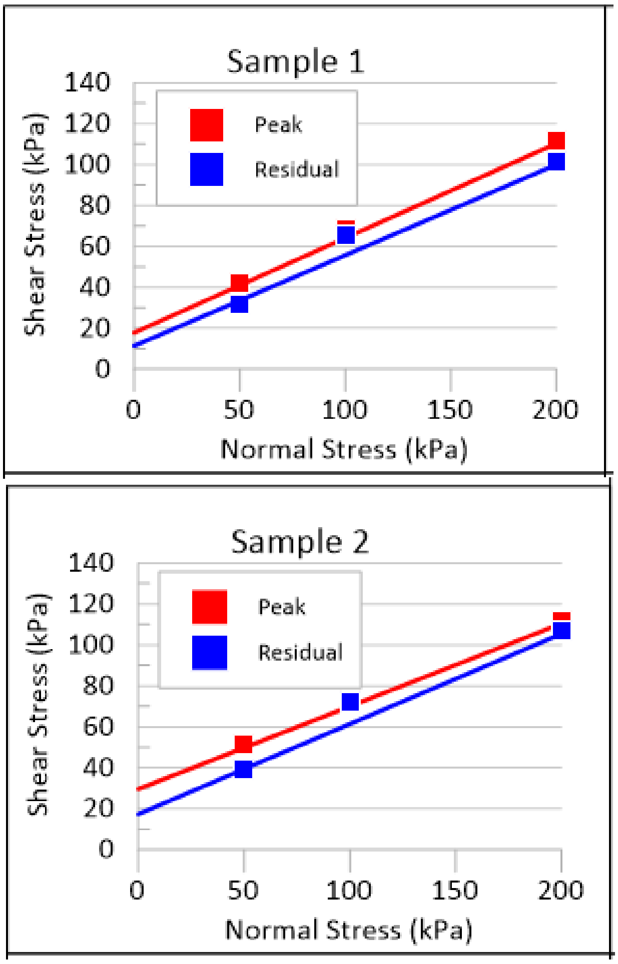


Figure 8. Failure envelopes for samples 1 and 2

The peak effective cohesion (c'_{peak}) and internal friction angle ($Ø'_{peak}$) values of the samples were in the range of 15.7-43.1 kPa and 15.7-27.3°, respectively. Residual effective cohesion (c'_{rez}) and internal friction angle ($Ø'_{rez}$) values, which are the residual strength parameters, also varied in the range of 4.5-17.7 kPa and 14.2-28.6°, respectively. The results showed that the residual cohesion strength values reached at large deformation levels were much lower than the peak strength values, especially when evaluated in terms of cohesion resistance, which is important on the strength of clay soils. Considering the cohesion and friction components, which are defined as shear strength parameters according to the Mohr Coulomb failure criterion, since the intergranular bonds are completely removed as a result of large deformations, when the permanent state is reached, even in high plasticity clays, there is no cohesion effect or takes very low values. Therefore, it has been shown by many researchers that the permanent shear strength is only due to intergranular friction (Skempton 1964; Mesri and Shahien 2003).

When a general statistical evaluation was made, no significant relations could be reached between the consistency limits and strength parameters. Although there was a tendency to decrease in strength with the increase of the consistency limits, a significant scattering was observed in the data. It can be said that the main factor controlling the shear strength is the mineralogical structure of the soil grains. Although all samples are classified as high plasticity clay, the variability of the clay mineral types they contain may be a factor in this situation.

The obtained relationships are presented in Figures 9, 10 and 11. As seen in Fig. 9, it has been determined that optimum water content (w_{opt}) has a negative correlation and maximum dry density ($ϱ_{dmax}$) value has a positive correlation on q_{un}. In Fig. 10, the effect of w_{opt} and degree of saturation (S) on the peak shear strength parameters obtained from the shear box test results is shown. There was a negative correlation between the w_{opt} and the effective peak internal friction angle, while a positive correlation was observed between the S and the effective peak cohesion values.

Table 2. Strength parameters obtained from UCS and DSB test results

SN	q_{un} (kPa)	c'_{peak} (kPa)	$Ø'_{peak}$ (°)	c'_{rez} (kPa)	$Ø'_{rez}$ (°)
1	168	17.88	24.8	11.42	23.88
2	133	29.59	22.0	17.34	23.78
3	236	26.13	25.3	12.43	25.47
4	189	17.06	24.7	6.57	23.94
5	123	26.63	20.1	14.74	19.45
6	171	43.12	15.7	17.67	18.36
7	107	25.36	20.5	16.30	19.29
8	160	30.19	21.1	13.76	22.84
9	133	27.83	25.5	9.68	28.62
10	148	19.92	25.4	9.39	26.33
11	170	24.87	23.3	7.79	25.53
12	139	32.99	17.7	14.85	16.71
13	193	33.53	21.3	13.90	23.97
14	199	40.19	22.0	16.61	23.74
15	235	27.92	23.5	11.41	23.41
16	194	32.91	21.5	14.86	22.74
17	210	18.34	23.0	6.53	23.71
18	166	29.19	19.6	9.97	21.31
19	134	15.72	15.9	7.36	14.15
20	250	17.76	27.3	4.46	28.26

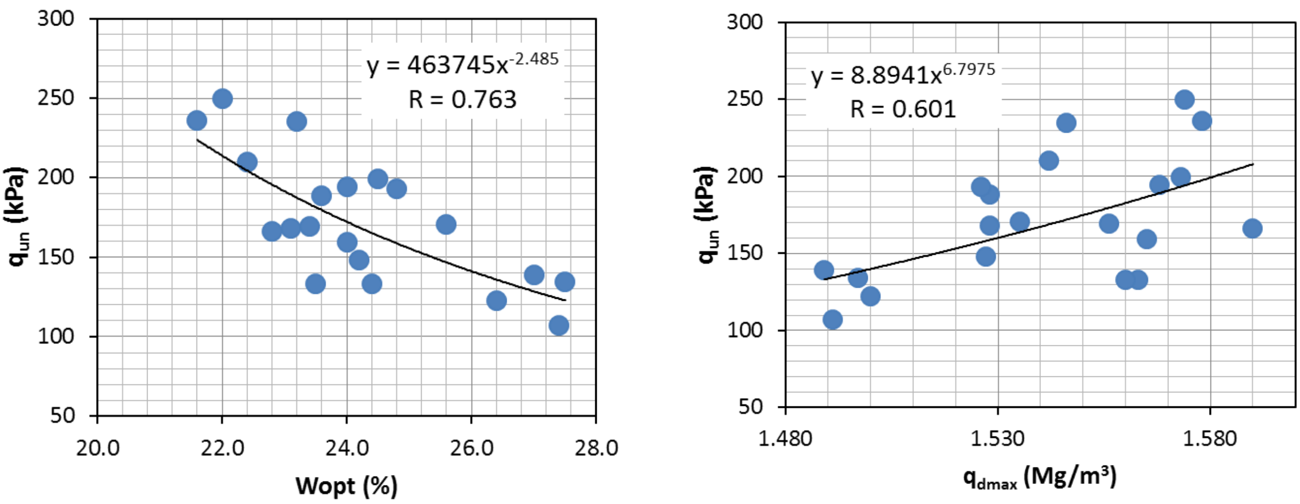


Figure 9. Relationships between unconfined compressive strength and compaction characteristics

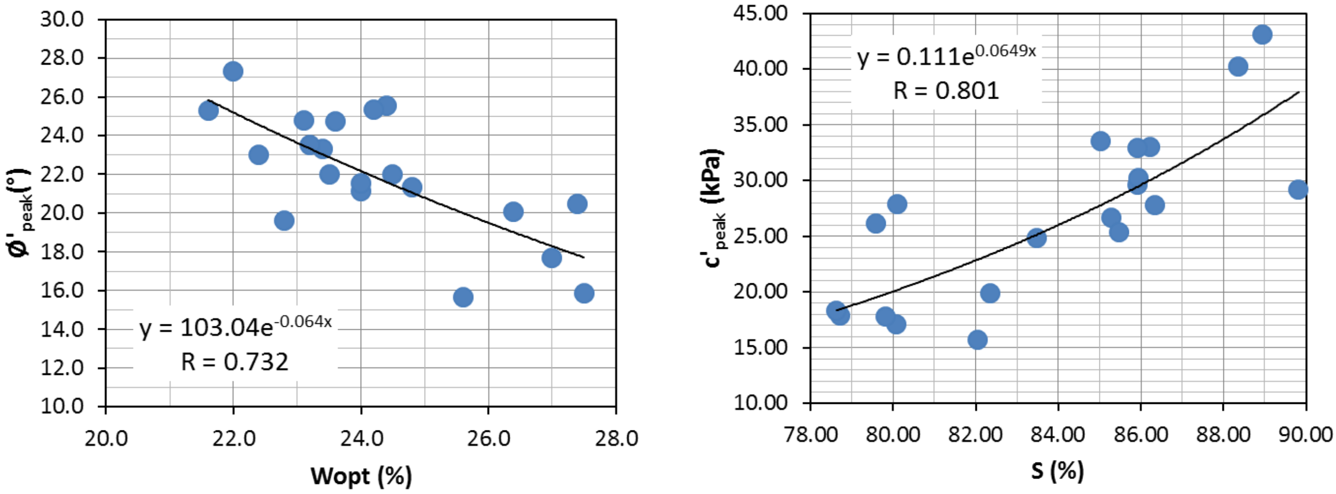


Figure 10. Relationships between effective peak strength parameters and, w_{opt} and S

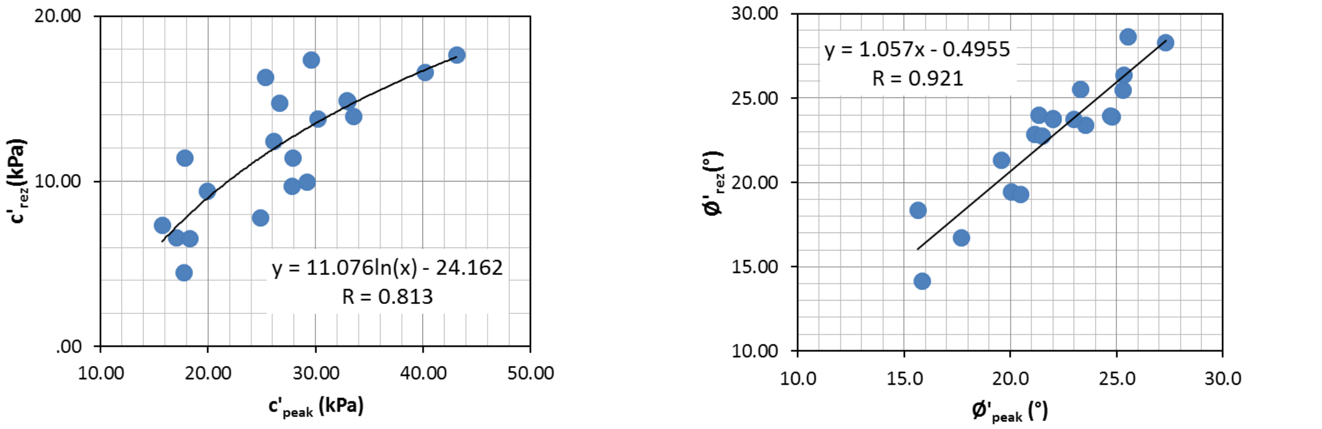


Figure 11. Relationships between effective peak and residual strength parameters

In Figure 11, the relationships between the peak and residual strength parameters found as a result of the shear box test are presented. It has been determined that the relations between the peak and residual strength parameters are at a very significant level. It has been seen that by using these relations, it is possible to approximate the strength parameters on the basis of effective and total stress.

4. CONCLUSION

In this study, shear strength parameters of compressed high plasticity clay soils were determined on the basis of both effective stress and total stress. The relationships between the geotechnical properties of the soil samples and the strength parameters were investigated. It has been observed that compaction characteristics are more important than other physical properties of soil samples on unconfined compressive strength. Although the geotechnical properties of the soil samples are quite close to each other, differences were determined between the strength parameters. For this reason, it should be noted that it will be necessary to evaluate the chemical and mineralogical properties of the samples in future studies.

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Author contributions

Burak Yılmaz: Investigation, Experimental, Writing. **Murat Türköz:** Conceptualization, Design, Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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