Geotechnical Performance of Obsidian for Stabilization of Clayey Soils

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Abstract
The clayey soil consisting of fine grains and containing clay mineral are known as expansive and problematic soils. They cause various stability problems due to their sensitive to water. To overcome the problems arising from the ground, soil stabilization is a widely applied method. In this experimental study, obsidian was used as an additive material to stabilize a clayey soil. The obsidian is a naturally occurring volcanic glass form of an igneous rock. After grinding, different percentages of obsidian were added to the clayey soil. The mixtures of obsidian and clayey soil were prepared by blending manually. The samples obtained by compaction process were subjected to the laboratory tests and analyses. According to the experimental results, the obsidian is an effective material to improve the geotechnical properties of clayey soil. The addition of obsidian decreased the liquid limit, plastic limit and plasticity index values and increased the maximum dry unit weight and unconfined compressive strength values. Maximum improvement was obtained with the addition of 10% obsidian content and at the 28 days curing time. The results showed that environmentally friendly natural obsidian is suitable for use as an alternative additive for applications of clayey soil stabilization.

Keywords: Clayey soil, Obsidian, Soil stabilization, Mechanical property, Compressive strength

1. Introduction

The soil environment is referred to as three-phase system due to its solid particles, liquid and gas content. It generally has low strength due to its structure consisting of grains of different sizes (Hejazi et al., 2012; Nath et al., 2017; Davari et al., 2021). Since its characteristic properties are largely dependent on environmental conditions, soil has a significant potential for distress due to the loss of soil strength in rainy seasons and shrinkage in summer. The soil containing clay mineral is considered as problematic soil because it swells and shrinkages when exposed to varying moisture content (Kalkan and Bayraktutan, 2008; Viswanadham et al., 2009; Phanikumar and Muthukumar, 2014; Kalkan et al., 2019; Soundara and Selvakumar, 2019; Kalkan et al., 2020; Kumar and Kumar, 2020). All structures are built on the ground, and it is known that the best ground for construction should be chosen and problematic grounds should be avoided. However, it is sometimes required to choose problematic soil areas such as expansive soils for construction due to rapid urbanization and development. In such cases, it is necessary to give the desired properties to expansive soils (Soundara and Selvakumar, 2019; Alazigha et al., 2018; Darikandeh, 2018; Julina and Thyagaraj, 2018; Kumar et al., 2018; Phanikumar and Nagaraju, 2018).

Soil stabilization method is applied to the problematic soils to improve soil performance. For this purpose, the binder is added to soil, the granulometry of soil is changed, the density of soil is increased and etc. The lime and cement are traditionally and commonly used as binder material in geotechnical engineering applications (Curtis et al., 2009; Horpibulsuk et al., 2012; Kalkan, 2012; Bshara et al., 2014; Raftari et al., 2014; Neramitkornburi et al., 2015; Yoobanpot et al., 2017; Rashid et al., 2018; Mat Said et al., 2019; Saldanha et al., 2021). Nowadays, there is a growing trend on the exploration of alternative non-traditional materials as additive for use in the geotechnical field. There are some investigations carried out using new approaches, which can be replace traditional binders (Consoli et al., 2011; Blanck et al., 2013; Latifi et al., 2016; Hassan et al., 2017; Latifi et al., 2018; Rashid et al., 2018; Tabarsa et al., 2018; Dehghan et al., 2019; Hassan et al., 2019; Kalkan, 2020; Hosseinpour et al., 2021; Saldanha et al., 2021; Kalkan et al., 2022).

The physical, mechanical and chemical methods are used in soil stabilization applications. In the clayey soil (CS), many important studies have been performed to develop a sustainable method to increase the strength to the desired level and keep the swelling behavior under control (Celik and Nalbantoglu, 2013; Behnood, 2018; Mirzababaei et al., 2018; Silveira et al., 2018; Talluri et al., 2020; Tiwari et al., 2021; Yarbaşı et al., 2023). This method uses additives such as natural, fabricated and waste material. The chemical stabilization method, applied to improve the geotechnical properties of CS, uses natural, fabricated and waste material as additive material (Nalbantoglu and Tuncer, 2001; Horpibulsuk et al., 2004; Al-Rawas et al., 2005; Seco et al., 2011; Khemissa and Mahamedi, 2014; Tran et al., 2014; Abbey et al., 2017; Eyo et al., 2017; Eyo et al., 2020; Abbey et al., 2021; Orlandi et al., 2024).

The conventional additives such as lime, cement, petroleum sulfonate and asphalt are often used as stabilizer to improve the physical-mechanical properties of CS (Kalkan and Akbulut, 2004; Nalbantoğlu, 2004; Federico et al., 2015; Alrubaye et al., 2016; Sadeeq et al., 2016; Sharma and Hymavathi, 2016). However, it is known that the conventional stabilization materials increase greatly the construction cost due to the production costs. Therefore, the investigation of alternative stabilization materials is always up to date. The discovery of a new alternative stabilization material will decrease the high cost of stabilization. Same time, this material will be an alternative to conventional stabilization materials having harmful effects on the environment.

Relatively, the attention to geo-materials has been started to increase significantly due to their abundance and locally available and accessible. There are some important studies conducted by researchers on the use of geo-materials for soil stabilization (Bell and Maud, 1994; Yılmaz and Civelekoğlu, 2009; Agrawal and Gupta, 2011; Bshara et al., 2014; Obeid., 2014; Gurbuz, 2015; Kılıç et al., 2016; Mohanalakshmi et al., 2016; Yılmaz, 2019; Jain et al., 2020; Nikhil et al., 2021).

The obsidian was selected as additive to improve geotechnical properties of CS. Obsidian called volcanic glass is a geo-material. It is a rock formed as a result of the sudden and rapid cooling of volcanic lava as it rises to the surface. It has amorphous structure, geologically hard and brittle and it is very difficult to work and shape for the product but easy to grind for powder production. Its color is black, gray, brown, red and green (Ercan et al., 1989; Chataigner et al., 1998; Bilgin et al., 2012; Doğanay and Altaş, 2013; Nadooshan et al., 2013; Ustabaş and Kaya, 2018; Safaryan et al., 2020).

Powdered obsidian was added to the CS and then compacted in accordance with Standard Proctor procedure to prepare samples of CS-obsidian mixtures. Improving effect of obsidian on CS was investigated by applying laboratory tests and obtained results were presented controversially.

2. Material and Method

2.1. CS

The CS material was taken from the outcrop of sedimentary unit located in Oltu (Erzurum, NE Turkey). This sedimentary unit is over-consolidated and clayey-rock structure. According to the Unified Soil Classification System CS is high plasticity soil (Kalkan, 2003; Kalkan and Bayraktutan, 2008). Its image, granulometry, X-ray diffraction, engineering properties and chemical composition were given in Figs. 1-3 and Tables 1-2, respectively.

2.2. Obsidian

The obsidian material used in the experimental study was obtained from a road excavation at a point on Erzurum-Kars (NE Turkey) highway, near Mescitli Village in Sarikamis District of Kars Province. At this point where the black and brown colors of the obsidian are intense, the obsidian material was taken as mixed in both colors. In order to obtain undeformed obsidian material, 0.5 meters of excavation was made from the surface and clean obsidian material was collected from the inner level. Obsidian material obtained was placed in plastic sample bags and transferred to the laboratory by preserving its natural structure. It was then used in experimental work after drying and grinding. Its image, granulometry, the X-ray diffraction, properties and composition were given in Figs. 1-3 and Tables 1-2, respectively.

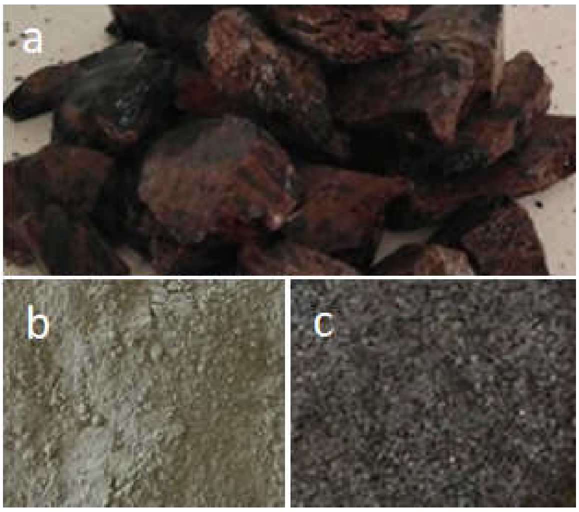

Fig. 1. a) Natural obsidian, b) ground CS and c) ground obsidian

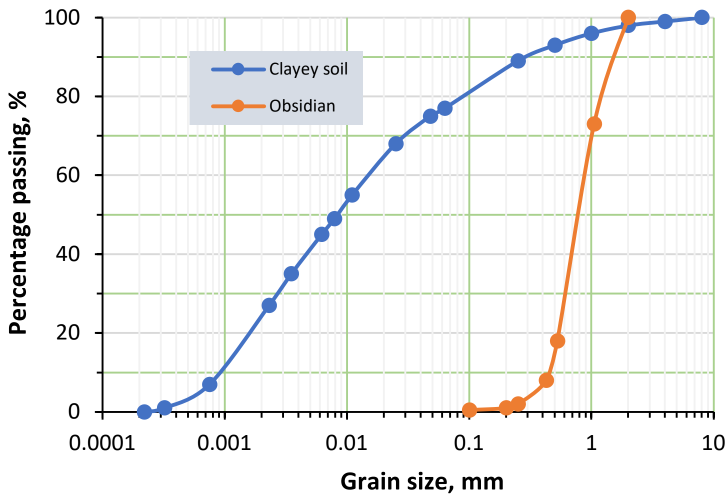

Fig. 2. Grain size distribution of CS and obsidian (Kartal, 2021)

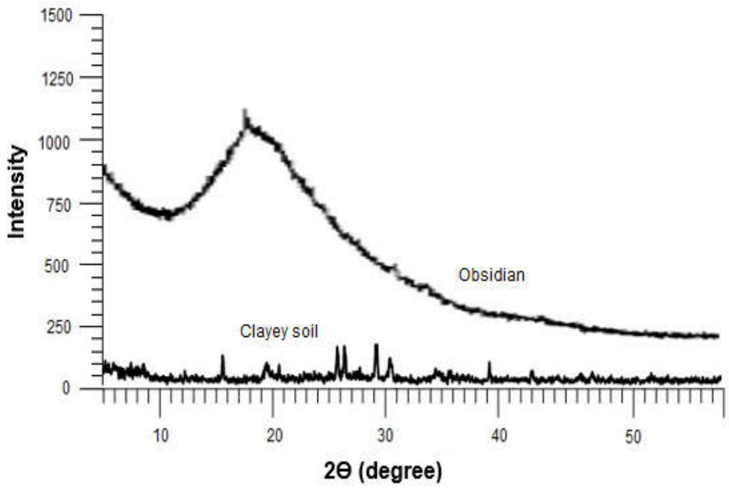

Fig. 3. XRD pattern of CS and obsidian (Kartal, 2021)

Table 1. Engineering properties of CS and obsidian (Aghamalyan et al., 2019; Kartal, 2021)

Property	Value	
	CS	Obsidian
Density (g/cm^3)	2.63	2.348
Liquid limit (%)	72	-
Plastic limit (%)	35	-
Plasticity index (%)	37	-
Specific surface area (m^2/g)	243.6	-
Unified Soil Classification (USCS)	CH	-
Clay mineral	Montmorillonite	-
Non-clay mineral	Quartz and calcite	-
Relative index (*n*)	-	1.4863
Glass transition temperature (°C)	-	750
Linear expansion coefficient (°C)	-	5.32×10^{-6}
Softening point ((°C)	-	810

Table 2. Chemical composition of CS and obsidian (Kartal, 2021)

Compound	CS	Obsidian
Al2O3	13.94	12,98
CaO3	23.49	-
CaO	11.03	0.36
Fe2O3	6.23	1.85
MgO	3.48	-
SO3	0.13	-
SiO2	41.62	77.33
Na2O	-	4.49
K2O	-	2.89
TiO2	-	0.10
Heat loss	0.08	0.30

2.3. Preparation of mixtures and samples

Before the mixtures of CS and obsidian were prepared, the CS and the obsidian were dried at 60 °C (ASTM D4318). The required amounts of CS and obsidian were weighted and were blended. The obsidian was selected in percentage of 2,5%, 5%, 7,5%, 10%, 12,5% and 15% by the total weight of material mass. All mixtures were manually blended by adding the water in the optimum amount. The combinations of clayey soil, obsidian and water were thoroughly kneaded by hand to obtain a homogeneous structure. Then, they were kept in the desiccator at room temperature for 2 h to achieve constant moisture content (Sundary et al., 2022). All mixtures were compacted by Standard Proctor apparatus (ASTM D 698-78).

2.4. Laboratory tests

The compaction, consistency limits and unconfined compression tests have been made to study the geotechnical performance of stabilized CS by using obsidian. In compaction test carried out in accordance with the ASTMD 698. This test was performed to obtain values of compaction parameters. The consistency limits tests and unconfined compression tests have been made in accordance with ASTM D 4318 and ASTMD 2166, respectively.

2.5. Microstructural Analyses

In literature, it is emphasized that the Scanning Electron Microscopy (SEM), Fourier Transform Infrared Spectroscopy (FTIR) and Energy-Dispersive X-ray (EDX) is very useful in soil treatment studies. These analysis methods are performed for in-depth analysis of soil material. By using these methods, it is possible to substantiate characteristics of specimen (Osinubi et al., 2015; Al-Swaidani et al., 2016; Sani et al., 2018; Hassan et al., 2019; Baldovino et al., 2021; Ekpo et al., 2021; Etim et al., 2021; Chompoorat et al., 2022). The FTIR, SEM and EDX analyses were performed in Ataturk University, Erzurum, NE Turkey. In analyses, VERTEX 70v FTIR Spectrometer and Zeiss Sigma 300 Scanning Electron Microscopy were used for FITIR and SEM/EDX analyses, respectively.

3. Results and Discussion

3.1. Effect of obsidian on compaction parameters

Effect of obsidian on compaction parameters was illustrated in Fig. 4. As seen in the figure, with the addition of obsidian to the CS, values of compaction parameters changed. Maximum dry unit weight (MDUW) increased and optimum water content (OMC) decreased with increasing obsidian ratios in mixtures of CS-obsidian. Obsidian has been effective up to its ratios of 10% on MDUW values and at more than ratios of 10%, the effect of obsidian decrease. As can be seen in the Fig. 4, the MDUW amount increases from 1,26 kN/m^3 to 1,34 kN/m^3 when the quartzite content increases from 0% to 15%. The increase in MDUW was attributed to the addition of course and denser particles of additive material to the CS. Also, obsidian acted also as a filler material when it added to the CS samples (Cai et al., 2006; Al-Mukhtar et al., 2012; Saygili, 2015). The increase in MDUW is an indicator to improved CS properties (Al-Swaidani et al., 2016). In literature, there is a similar trend was observed by using natural pozzolanas (Hossain et al., 2007; Harichane et al., 2011; Al-Swaidani et al., 2016; Yin et al., 2022) and increase is probably a result of the higher specific gravity.

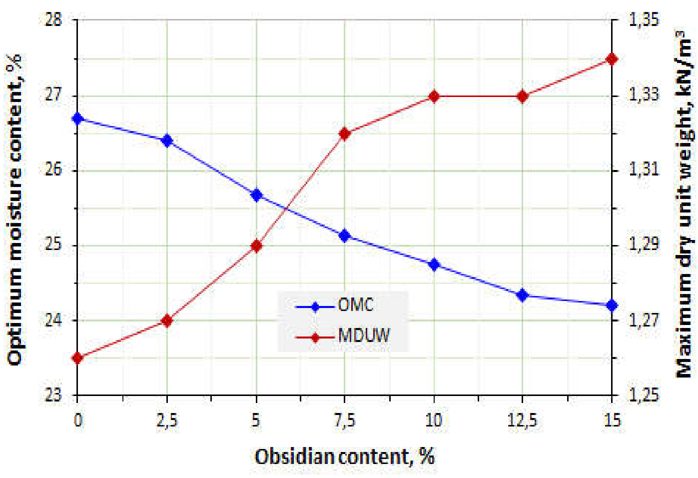

Fig. 4. The variation of compaction parameters with the addition of obsidian

The OMC value decreases with the increase of obsidian content. By adding obsidian as stabilizer, the OMC decreases as shown in Fig. 5. The OMC decreases from 26,70% to 24,20% when increasing material content from 0% to 15%. Harichane et al. (2011) observed that the natural pozzolans decrease in OMC values of cohesive soils due to apparently results from the lower affinity of natural pozzolan for water. The obsidian as a natural pozzolanic material has larger grains that of CS. With the addition of obsidian, which has coarser grains than clayey soil, the surface area of the clayey soil-obsidian mixtures decreased. Mixtures having less surface area needed less water. Hossain et al. (2007), Harichane et al. (2011), Al-Swaidani et al. (2016) and Yin et al (2022) presented similar results.

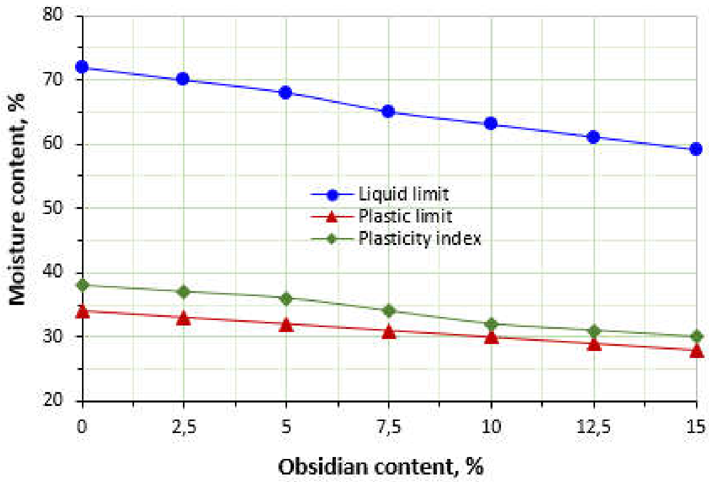

Fig. 5. The variation of consistency limit values with the addition of obsidian

3.2. Effect of obsidian on consistency limits

Effects of obsidian on consistency limits of the stabilized CS are illustrated in Fig. 5. Results of experimental studies showed that with the obsidian addition, consistency limits have a downward trend. Obsidian decreases the values of consistency limits. This is attributed to non-plastic properties of obsidian material added to the CS that varies with the additive amount (Bell, 1993; Nweke and Okogbue, 2017; Okagbue and Ochulor, 2007; Kalkan et al., 2022). Obsidian as a non-plastic material (Go et al., 2010) replaced CS (Kalkan, 2003). Consistency limit values decreased due to low water absorption non-cohesive and low active character (Shah et al., 2020). With the addition of obsidian to the CS, the soil group of CS was changed (Fig. 6). The change took place from high to low plasticity group due to increasing amounts of obsidian.

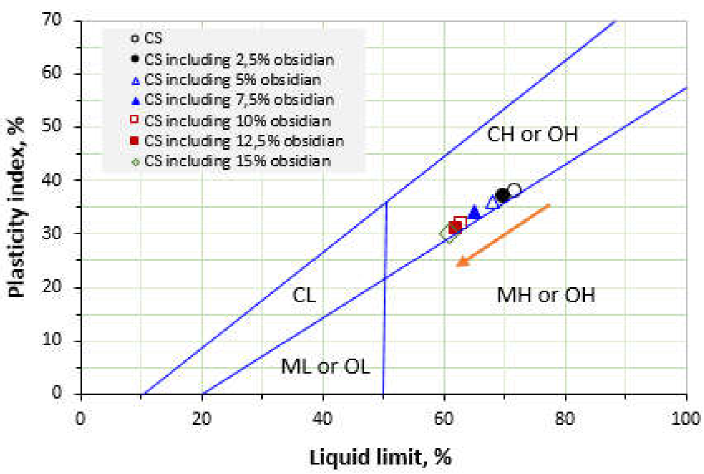

Fig. 6. Plasticity chart for natural CS and obsidian stabilized CS

3.3. Effect of obsidian on the UCS

The UCS values of prepared samples were determined by unconfined compressive test apparatus (Fig. 7). Also, the effects of obsidian on the UCS over time were illustrated in Fig. 8. The results show that with the addition of obsidian the UCS increased. It is clearly visible that although the UCS increases significantly with obsidian content up to 10%, the UCS is insignificantly affected with more obsidian content. It can be stated that 10% obsidian content is an optimal ratio.

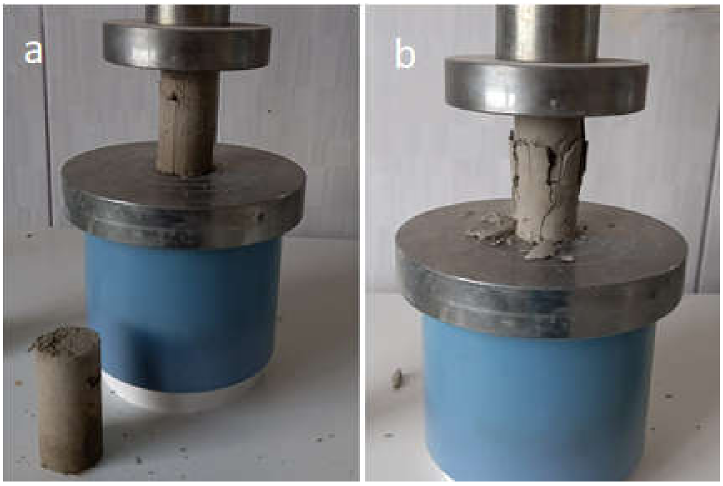

Fig. 7. The unconfined compression test for; (a) stabilized CS (10% obsidian) and (b) stabilized (10% obsidian) and cured CS (28 days)

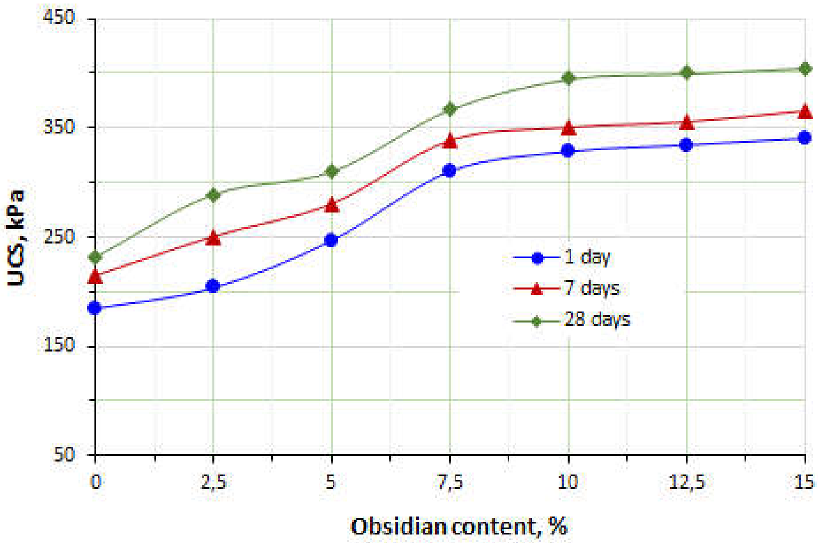

Fig. 8. The effect of obsidian on the UCS values of stabilized CS depending on curing period

The increase in the UCS values is due to the increased maximum dry unit weight and internal friction angle values due to addition of obsidian (Kalkan and Akbulut, 2004; Kalkan et al., 2022). According to the literature, the addition of additives changes the composition, mineralogy and particle size distribution of clayey soils (Gillot, 1968; Ola, 1978; Kalkan and Akbulut, 2004). Also, increase in UCS is attributed to chemical reaction between additive and CS particles.

Increase in UCS value of CS with increased curing time (Fig. 8). This is due to the effect of the cementing gel produced after the pozzolanic reactions occurring for a certain time period (Thompson, 1968; Okagbue and Onyeobi, 1999). As a result, the mechanical resistance increases with curing time (Okyay and Dias, 2010). Ustabas and Kaya (2018) emphasized from experimental research result that the obsidian high pozzolanic activity index value. The obsidian mainly composed of silica SiO_2 and other major oxide is alumina (Al_2O_3) shows a strong indication of very good pozzolanicity (El Turkey, 1992; Mohmmed, 2004).

3.4. FTIR analysis

Fig. 9 shows FTIR spectra of natural CS sample and stabilized CS with 10% obsidian sample. In this figure, the interval of 3500 to 4000 cm^{-1} indicate clay. Also, the intervals of 1200 to 3000 cm^{-1} and 500 to 1200 cm^{-1} point out minerals and organic matters, respectively (Nweke and Okogbue, 2017; Tiwari et al., 2020). Broadband of 3614.2 cm-1 displays vibratory band belong to H-O-H adsorbed in clay mineral. The vibrations of band from 1600 to 1400 cm-1 form the area defined as track field of clay mineral and it can be explained by the Si-O and Si-O-Al stretching. The vibrations band of between 813 and 1242 cm^{-1} demonstrate Si-O-Si and Si-O stretching's in clay mineral. Si-O-Al and Si-O-Mg founding in sample can be attributed to the Si-O-Fe band vibrations (Zawrah et al., 2018; Miraki et al., 2022).

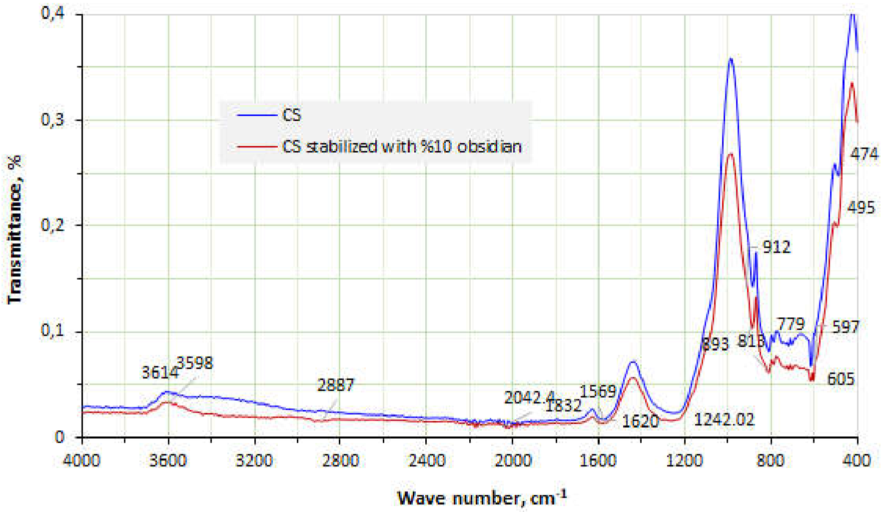

Fig. 9. FTIR spectra of CS and CS stabilized with 10% obsidian

It can be stated that interaction has occurred, and the bond peaks have changed relatively, but structurally the structure of the clay mineral has not deteriorated. In addition, there is no peak in the clayey soil at the specified points, but there is a peak in the clayey soil containing obsidian. It can be expressed that the peak in 972 cm^{-1} may an indicator for the abundance of clay mineral. The FTIR analysis of the obsidian doped clay structure is shown in red (Fig. 9). Peaks of obsidian are located around 2042, ~1832 and ~1620 cm^{-1}. As a result of the bonding between the clay structure and obsidian, it was determined that the bond vibrations in the clay structure caused some shifting, but did not cause much change.

3.5. SEM analysis

This analysis was performed to observed the effect of obsidian on the microstructural characteristics of stabilized CS samples after 28 days curing. Figs. 10a-b show the microstructural characteristics of unstabilized CS and CS stabilized with obsidian stabilizer. In these figures, the microstructural changes between unstabilized and stabilized CS samples are clearly noticed. While the unstabilized CS sample has more space structure (Fig. 10a), obsidian stabilized- CS sample are without space (Fig. 10b). The decrease in the pores increased value of maximum dry unit weight. Clay particles covered the surface of obsidian particles and structure of the stabilized CS samples become the less pores (Kalkan et al., 2022).

The particles of obsidian in the pore space among the CS grains react to form hydration products (flocculation products) around of CS grains. This causes a significant improvement in the geotechnical properties. The larger aggregates form by bonding of particles and the CS behaves as a coarse-grained strongly bonded particulate material (Okyay and Dias, 2010; Harichane et al., 2011; Kalkan and Yarbaşı, 2013; Kalkan et al., 2020). Due to mainly composed of silica SiO_2 and other major oxide alumina (Al_2O_3), the obsidian has very good pozzolanicity (El Turkey, 1992; Mohmmed, 2004; Ustabaş and Kaya, 2018).

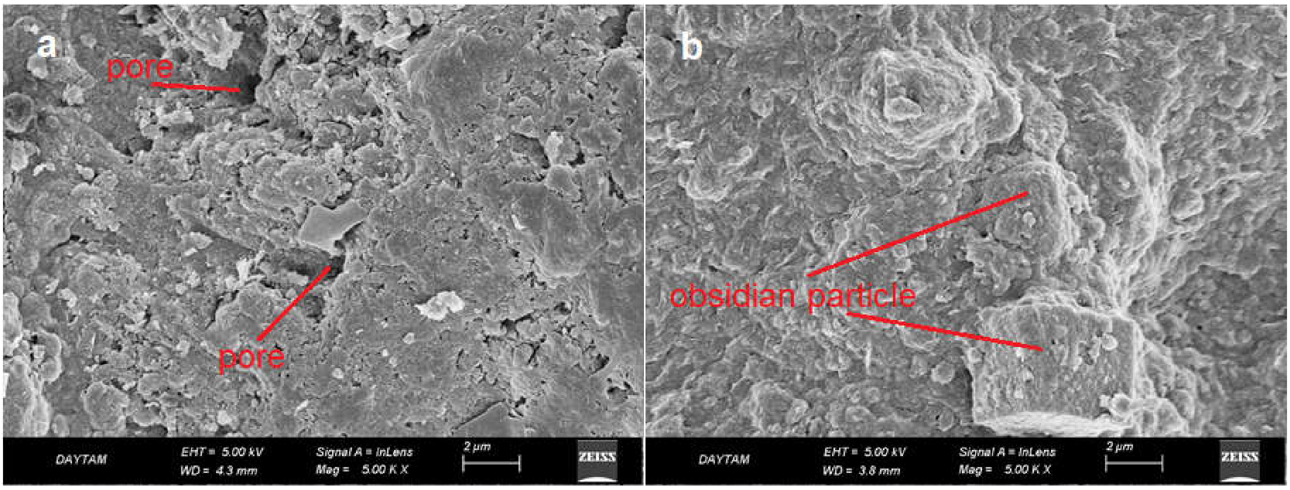

Fig. 10. SEM images: a) CS sample cured 28 days and b) CS stabilized with 10% obsidian cured 28 days

4. Conclusion

The following conclusions were drawn.

- The MDUW increased and the OMC decreased with the addition of obsidian.
- The consistency limits such as the liquid limit, plastic limit and plasticity index values exhibited a decreasing trend.
- The UCS values of obsidian-stabilized CS samples were perceived to rise with the addition of obsidian content. Also, the curing increased the UCS.
- It was observed that the beneficial morphological and physical characteristics are also evident in the obtained mechanical results.
- It was determined that obsidian can be used to improve the geotechnical properties of CS.

Conflict of Interest

The authors have no conflicts of interest to declare relevant to this article's content.

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