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Studying the Effects of Forest Fire on the Consistency Limits of Sandy Soils: A Case Study, Kozağaç, Muğla

Orman Yangının Kumlu Zeminlerin Kıvam Limitleri Üzerindeki Etkisinin Çalışılması: Bir Vaka İncelemesi, Kozağaç, Muğla

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ABSTRACT

The changes in physical, chemical, and mineralogical properties of topsoil after forest fires, and their effect on erosion risk, have been previously studied in different geographical regions and ecosystems. It is well known that the risk of erosion increases after fire due to the loss of shear strength and the changes in hydraulic properties. Consistency limits are strongly related to the shear strength of the soil. Nevertheless, few studies have evaluated the consistency limits of naturally burned soils. In addition, determining the consistency limits of sandy soils can be very challenging due to their low plasticity. The temperatures produced by the forest fire that occurred on the left flank of an irrigation dam in Muğla, Kozağaç village, affected the topsoil. Therefore grain size distribution, soil organic content (SOM), and Atterberg limits of 24 soil specimens collected from the burned and unburned locations were studied. It was found that the grain size distribution of the burned soil did not significantly change, whereas clay content and Atterberg limits increased, and SOM decreased. The methodology followed in this study and the results can serve as a base for future studies of the effect of fire on sandy soils.

Keywords: Atterberg limits, sandy soil, forest fire, clay content, organic matter

ÖZ

Orman yangınlarının ardından toprağın üst katmanında meydana gelen fiziksel, kimyasal ve mineralojik değişimler ve bunların erozyonla ilişkisi bugüne kadar farklı coğrafik bölge ve ekosistemler için çalışılmıştır. Yangın sonrası erozyon riskinin, yangın sonrasında makaslama direnci kaybı ve zeminin hidrolik özelliklerinin değişmesi nedeniyle arttığı bilinmektedir. Kıvam limiti değerleri toprağın makaslama dayanımıyla doğrudan ilişkilidir. Buna karşın, sınırlı sayıdaki çalışmada doğal yollarla yanmış toprakların kıvam limitleri irdelenmiştir. Buna ek olarak, kumlu zeminlerin kıvam limitlerinin belirlenmesi düşük plastisiteye sahip olmaları nedeniyle oldukça güçtür. Muğla'nın Kozağaç mahallesinde bulunan sulama barajının sol sahilindeki yamaçlarda meydana gelen yangında oluşan sıcaklıklar üst toprağı etkilemiştir. Bu nedenle, yanmış ve yanmamış alanlardan toplanan 24 adet örneğin tane boyu dağılımı, organik madde içeriği (SOM) ve kıvam limitleri belirlenmiştir. Yanmış toprağın tane boyu dağılımında anlamlı bir değişiklik olmadığı ancak kil içeriği ve Atterberg limitlerinin arttığı, SOM'nin ise azaldığı belirlenmiştir. Bu çalışmada kullanılan yöntemler ve sonuçlar ileride yangının kumlu topraklar üzerindeki etkisinin araştırılacağı çalışmalar için bir temel olarak kabul edilebilir.

Anahtar Kelimeler: *Atterberg limitleri, kumlu zemin, orman yangını, kil içeriği, organik madde*

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INTRODUCTION

Forest fires are becoming more intense and frequent in Turkey and the world due to human activities and/or extreme climatic conditions. During a forest fire, the topsoil layer is exposed to high temperatures. As a result, soil structure and texture can be destroyed, water-repellent layers can be formed, and accordingly, water infiltration rapidly decreases; all of which will increase the potential risk of erosion (Inbar et al., 1997; Fox et al., 2007; Cerdà & Doerr, 2008; Zavala et al., 2010; Dlapa et al., 2015; Thomaz, 2021). For these reasons, these studies have addressed the aggregate stability, water repellency, and chemical properties of soil after forest fires, which also promote erodibility of the topsoil layer. The relationship between erodibility and the plasticity of soil has been revealed in literature (Khoirullah et al., 2019; Lalitha et al., 2021; Wang et al., 2021). These studies have mainly focused on cohesive soils and their physical and chemical properties after a forest fire or laboratory heat treatment. However, the susceptibility of sandy soils to erosive processes is greater than that of cohesive soils (Mataix-Solera et al., 2011; Deng et al., 2017).

On the other hand, the consistency properties of sandy soils with a fine fraction higher than 5% can have a profound effect on the engineering behavior of the soil. Therefore, using the changes in plasticity of the topsoil layer while estimating the increasing erosion potential after forest fires may give new insight into understanding the effect of consistency data on erosion potential. To date, few studies have dealt with the changes in consistency limits of soils due to forest fires (Vacchiano et al., 2014; Haake, 2020).

The type of vegetation, the bedrock properties on which the residual soil is developed, and the primary or inherent particle size graduation and permeability of the soil layer play a great role in the degree of change in soil due to forest fires. For this reason, the parametric studies revealing the effect of forest fires on the selected soil parameters need to be evaluated separately for different regions of the world. This study, therefore, seeks to find an appropriate methodology to investigate the changes in the consistency of gravel-bearing sandy soil overlying limestones after the fire that occurred in a pine forest in Muğla. The changes in grain size distribution, clay content, and organic content of the soil due to forest fires were also linked to the consistency of burned and unburned soil. Indeed, this study was not specifically designed to evaluate the factors affecting the determination of consistency limits, or the organic and clay content of the soil. Rather, it demonstrated, for the first time, that consistency limits of naturally burned sandy soils significantly change in proportion to the changes in particle size and organic and clay content. The statistical evidence of the differences between burned and unburned variable data was revealed by post-hoc analyses. The relationships between the variations in consistency with the particle size, and organic and clay content were tested by correlation analyses. However, the generalizability of the findings will depend on the similarity of fire intensity and geographical features.

Study Area

The study area is located on a ridge neighboring an irrigation dam to the south, in Kozağaç, Muğla on the 1/25000 scale N20-b4 map (Figure 1).

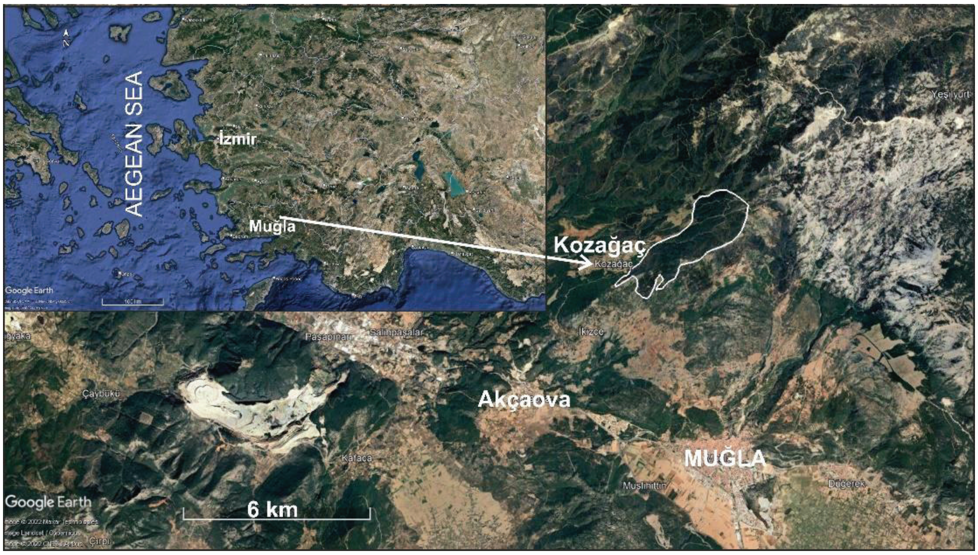

Figure 1. Location map of the study area.
Şekil 1. Çalışma alanının yer bulduru haritası.

The lowest and highest elevations are 967m and 1235m, respectively. The highest slope angle is 33°. The forest fire that occurred in August 2021 caused flame heights of 3-5m along the black pine (Pinus nigra L.) and red pine (Pinus brutia Ten.) overstory (General Directorate of Forestry, 2022). The hot and dry winds with a speed of 27km/h provided favorable conditions for the fire to spread and increase in intensity. The annual mean temperature and precipitation in the Muğla city center are 15.2°C and 120.91mm, respectively (TSMS, 2022). The bedrock is Jura-Createcaous aged, grey-colored fractured limestone (Göktaş, 1998; Gürer et al., 2013; Gül, 2015). The area is referred to as having moderate chemical weathering, according to the classification proposed by Peltier (1950) based on the annual temperature and precipitation. The highly fractured and karstic limestone is overlaid by calcareous regosols (FAO, 2015). The regosols that developed over the soluble rocks such as limestone, constitute weakly-consolidated sand-sized grains, and therefore have slight wettability. These soils are known to be poor in organic content, which does not allow for aggregation.

MATERIALS AND METHODS

Soil Sampling and Field Observations

The burned and unburned pairs of soil sampling locations on the edges of the fire perimeter were selected from the south-facing slopes with similar elevations (Figure 2). During a forest fire, temperatures reach a maximum at the surface (0 cm) and decrease progressively with depth (DeBano et al., 1979; Campbell et al., 1995; Robichaud and Hungerford, 2000). Accordingly, the effect of burning on soil properties becomes indistinct below 2 or 3cm, principally for low or moderate-intensity fires. For this reason, the soil specimens were extracted from the top 3cm of topsoil within a 30cm x 30cm area. Overall, 2-3kg of soil was gathered from each location. The top 3cm of topsoil contains relatively higher organic content and facilitates discrimination between burned and unburned samples. The area is a tended forest stand. Field observations on the destruction of vegetation, the degree of charring, and the thickness of ash development have been carried out for additional evidence of the intensity of the fire.

Sieve Analysis and Soil Classification

Sieve analyses were performed following ASTM D6913/D6913M-17 (2021) standards to obtain the grain size distribution of the soil samples. Prior to sieve analyses, the collected soil samples were dried at 65°C in the oven for 24 hours, contrary to the recommended temperature in the standard. The 65°C drying temperature was selected to maintain the organic content, not to alter the calcite and clay minerals, principally for unburned samples. Afterward, No.40, No.10, No.4, and No.200 sieves depending on the grain size observations were used to perform mechanical sieving with a sieve shaker. The percentage of gravel (>4.75mm) and sand size (< 4.75mm) particles, as well as the percentage of fines (< 0.075 mm), were determined. In conjunction with the Atterberg limit tests, the soil samples were classified according to the USCS classification (ASTM D2487-17e1, 2017).

Sedimentation Analyses

Twenty-four samples having a particle size smaller than 75 microns were used for the sedimentation analysis based on Stokes' law. Glass columns with a diameter of 63 mm were used in this test. 2gr of sodium hexametaphosphate were added to each column filled with distilled water, to separate clay and silt particles. The soil suspension was mixed and was allowed to stand for 22 hours and 10 minutes. Afterward, the suspended clay-sized material was removed with a vacuum-operated siphon. This procedure was repeated until the suspension became clear and purified of clay particles. Afterward, the settled silt-size particles were dried in an oven at 65°C and weighed. Equations 1 and 2 were used to calculate the clay fractions in the total soil weight.

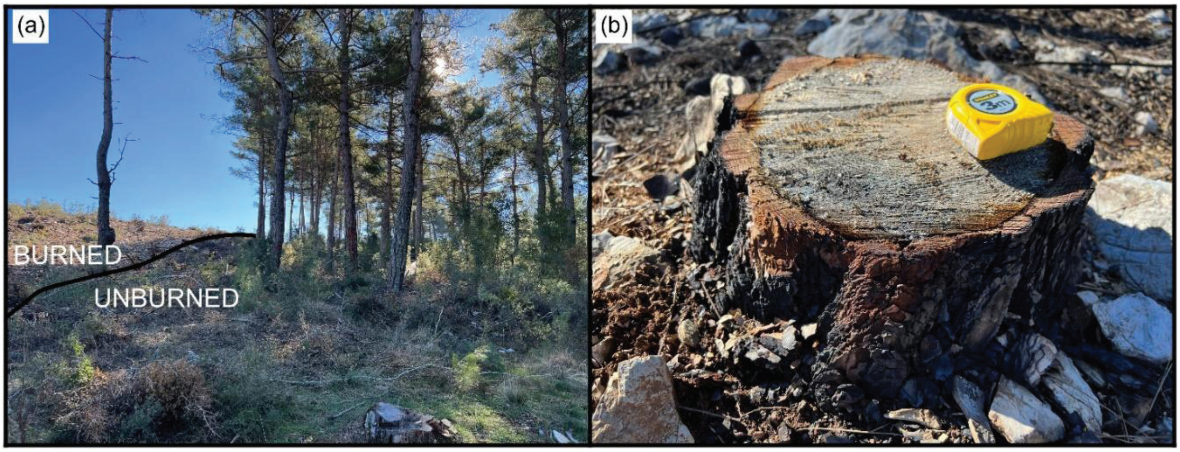

Figure 2. Sampling locations from (a) adjacent burned and unburned areas; (b) near burned tree roots.

Şekil 2. (a) Birbirine komşu olan yanmış ve yanmamış alanlardan; (b) yanmış ağaç köklerinin yakınından örnekleme lokasyonları.

Clay in fines fraction (Cf, %) =

$$\frac{Initial\ weight - dried\ weight\ after\ siphoning}{Initial\ weight}\ x\ 100 \quad (1)$$

Clay in total weight (C, %) =

$$\frac{Cf\ (\%)\ x\ Fines\ in\ sieve\ analysis\ (\%)}{100} \quad (2)$$

Loss on Ignition

Loss on ignition (LOI) values, typically determined at 1000°C, represent the amount of organic and inorganic carbon in soil. On the other hand, there have been several attempts to estimate soil organic content (SOM) between temperatures of 200 and 550°C with the loss on ignition method (Schulte et al., 1996; Konare et al., 2010; Salehi et al., 2011; Hoogsteen et al., 2015; Chase, 2022). However, the temperature, duration, sample size, and pre-treatment temperature of soil samples are of great importance in gathering accurate data from LOI. Therefore, a temperature of 350°C, which was also recommended by Salehi et al. (2011), seems to be optimal, as it burns the most organic carbon, destroys less inorganic carbon, and causes less clay or calcite structural water loss. In addition, a sample mass of 20g was used to minimize the variation in LOI values, as suggested earlier by Hoogsteen et al. (2015). The samples were oven dried at 65°C and weighed before they were combusted at 350°C in a Protherm Laboratory Furnace for 3 hours. After combustion, the samples were cooled in a desiccator and weighed again. Finally, the percentage SOM was estimated by Equation 3.

$$SOM\ (\%) = \frac{soil\ weight\ after\ combustion - initial\ oven\ dried\ soil\ weight}{initial\ oven\ dried\ soil\ weight}\ x\ 100 \quad (3)$$

Atterberg Limits Test

The term consistency refers to the degree of cohesion of the soil particles and to the resistance against forces that deform or rupture the soil aggregate (Terzaghi et al., 1996). This property is typically attributed to clayey soils. However, non-cohesive soils, which have a considerable amount of fines (5%-50%), should also be investigated in terms of the behavior of their fines fraction.

Atterberg limit tests were performed to determine the liquid limit (LL) and plastic limit (PL) of the soil samples. The LL determination of clayey soils with the Casagrande test was declared to have more sources of error in the operation than the fall-cone method because their principles are different (Dipova, 2011; Haig, 2012). On the other hand, sandy soils have a lower amount of clay in their composition, and the material passing the 0.425mm sieve that is used in the experiment includes more fine sand. The percentage of the sand and silt portion of the soil significantly affects the LL and PL values (Gündüz & Dağdeviren, 2009; Wagner, 2013). As a result, samples are sometimes recorded by the Casagrande test as non-plastic. However, non-plasticity cannot be detected by the fall-cone method (Orhan et al., 2005). For these reasons, the liquid limit of the sandy soils was determined by the Casagrande test device and AASHTO T 89 (2022) Method B was followed. Method B was chosen because it allows the determination of the liquid limit of a greater number of soil samples in relatively less time than the standard method. The soil samples that passed the 0.425mm sieve were prepared for the test. Approximately 50g of the dry sample were hydrated using distilled water and profoundly stirred and chopped with a spatula until a uniform mass of a stiff consistency was achieved. After that, the soil sample was placed in the Casagrande cup and divided into two halves by the AASHTO grooving tool. It is necessary to note here that the AASHTO grooving tool is easier to use in low-plasticity soils such as sandy soils. A blow number between 22 and 28 was assured to obtain closure of the two halves of the soil paste in the Casagrande cup at least 13mm. Finally, the soil remaining in the Casagrande cup was transferred to the mixing dish without adding any additional water and the test was repeated to ensure that the closure again occurred within the ±2 blows of the initial test. Finally, a slice of 20gr of soil sample perpendicular to the direction of closure was extracted from the Casagrande cup to obtain water content. The water content obtained from the Casagrande test to determine the liquid limit was later corrected for the number of blows (N), as shown in Equation 4.LL (%) =

$$(\%) = Water\ content\ (\%)\ x\ \left(\frac{N}{25}\right)^{0.121} \quad (4)$$

On the other hand, the plastic limit of the soil was determined according to the ASTM D4318-17e1 (2018) standard. The wet samples were rolled by palm on a glass plate with adequate pressure to produce a soil thread of 3mm diameter throughout its length. Fissures developed right before the thread reached a diameter of 3.0mm, representing the plastic limit for the soil sample. The average of three tests performed on the same sample was assumed to be the plastic limit. Following this, the plasticity index (PI= LL-PL) was calculated.

Texture classification

According to the USDA (2017), soil texture can be defined by considering the fractions of sand, silt, and clay in the soil. Some researchers have argued that this classification lacks adequate representation of the engineering properties of soils (Das & Sobhan, 2017) because the plasticity of the soil, which is a well-known classifier of soils in terms of engineering behavior, is not considered in the USDA classification. Until now, the ratio of PI to LL proposed by Moreno-Maroto & Alonso-Azcàrate (2018) was termed the clay factor (CF) by Moreno-Maroto & Alonso-Azcàrate (2022). They used CF with the sand fraction of the soil on the XY chart to classify the texture of soils more precisely. In this study, both the USDA and Moreno-Maroto & Alonso-Azcarate classifications were utilized to classify the textures of unburned and burned samples before comparing.

Statistical Analyses

Statistical analyses involve tests of normality, correlation, and comparison. The data set consists of 12 burned and 12 unburned samples and both data analyses were performed separately for burned and unburned samples. Since the sample size (n) is 12, initially, the distribution of the dataset, whether it is normally distributed or not, was determined by the Shapiro–Wilk normality test. If the dataset is not normally distributed and/or the sample size is less than 30 ($n < 30$), non-parametric correlation and post-hoc tests are recommended because non-parametric tests are less sensitive to the outliers in the dataset, as they consider the median values, not the mean values. Nevertheless, they are less robust than parametric statistical analyses. That is why, even though the sample size is less than 30 in this study, normality tests were carried out to ensure that non-parametric tests are obligatory. As all the data sets obey normal distribution terms (mod=mean=median), parametric correlation and comparison tests were applied to the dataset. In this context, paired samples t-tests were carried out to compare each paired group (unburned-burned) and quantify the difference and the significance between them. Subsequently, the statistical differences between burned and unburned liquid limit (LL), plastic limit (PL), plasticity index (PI) values, fines (F), sand (S), clay (C), and soil organic content (SOM) were revealed. Following this, Pearson correlation analyses were carried out to investigate the strength and significance of the relationships between dependent and independent variables. The dependent variables were the percentage changes in LL (ΔLL), PL (ΔPL), and PI (ΔPI). The independent variables were the percentage changes in the sand (ΔS), fines (ΔF), clay(ΔC), and soil organic content (ΔSOM). The percentage changes due to forest fire were calculated as in Equation 5.

$$\Delta\ (\%) = \frac{Burned\ data - Unburned\ data}{Unburned\ data}\ x\ 100 \qquad (5)$$

RESULTS AND DISCUSSION

Changes in Soil Properties After the Forest Fire

The study area is not wide and one geological unit is exposed; furthermore, the fire intensity was observed to be uniformly distributed. Thus, the test data is not largely scattered. Since the Shapiro-Wilk tests yielded p>0.05, indicating the datasets are normally distributed, the parametric statistical analyses were employed on the datasets.

The sandy soils showed a variety of behaviors under rolling for plastic limit; for example, some of them were split into small aggregations of particles in lengths of approximately 10mm, principally from the ends of the soil thread. The others required relatively more pressure to deform the thread, and they almost reached the plastic limit. These experimental observations indicated a low plasticity soil that confirmed the PI values presented in Table 1 and Table 2.

Table 1. Laboratory test results of unburned (UL) samples.
Çizelge 1. Yanmamış (UL) örneklerin laboratuvar deney sonuçları.

SAMPLE	LL (%)	PL (%)	PI (%)	G (%)	S (%)	F (%)	C (%)	CF	SOM (%)	USCS	MA
UL-1	37.1	27.0	10.1	17.6	72.5	9.90	4.2	0.272	5.040	SM	SL
UL-2	37.3	27.4	9.9	18.2	71.7	10.1	4.9	0.265	4.902	SM	SL
UL-3	38.4	26.9	11.5	16.9	69.5	13.6	5.3	0.299	5.102	SM	SL
UL-4	39.9	31.2	8.7	19.6	66.3	14.1	5.9	0.218	2.027	SW-SM	SL
UL-5	38.5	31.8	6.7	18.3	68.3	13.4	5.5	0.174	2.014	SW-SM	SL
UL-6	39.8	28.9	10.9	16.4	69.1	14.5	6.1	0.274	3.456	SM	SL
UL-7	37.1	26.9	10.2	19.4	68.2	12.4	4.3	0.275	4.985	SM	SL
UL-8	37.5	26.1	11.4	17.1	72.2	10.7	5.1	0.304	4.832	SM	SL
UL-9	39.1	28.0	11.1	18.2	68.7	13.1	6.2	0.284	3.856	SM	SL
UL-10	38.6	26.8	11.8	16.8	69.3	13.9	5.8	0.306	5.025	SM	SL
UL-11	40.1	30.5	9.6	20.1	65.4	14.5	6.4	0.239	3.023	SW-SM	SL
UL-12	42.6	31.3	11.3	19.6	64.5	15.9	6.6	0.265	4.125	SW-SM	SL

G: Gravel, F: Fines, S: Sand, C: Clay, CF: Clay Factor, SOM: Soil Organic Matter, USCS: Unified Soil Classification System, MA: Texture classification of Moreno-Maroto & Alonso-Azcarate (2018), SL: Sandy Loam

Table 2. Laboratory test results of burned (BL) samples.

Çizelge 2. Yanmış (BL) örneklerin laboratuvar deney sonuçları.

SAMPLE	LL (%)	PL (%)	PI (%)	G (%)	S (%)	F (%)	C (%)	CF	SOM (%)	USCS	MA
BL-1	42.3	30.7	11.6	17.7	72.3	10.0	4.4	0.274	3.123	SM	SL
BL-2	45.6	33.3	12.3	20.1	69.5	10.4	5.3	0.270	2.426	SM	SL
BL-3	47.8	33.2	14.6	18.7	67.3	14.0	5.9	0.305	2.245	SM	SL
BL-4	49.9	38.8	11.1	20.1	65.3	14.6	6.5	0.222	0.890	SW-SM	SL
BL-5	46.9	38.6	8.3	18.2	68.2	13.6	5.8	0.177	1.230	SW-SM	SL
BL-6	45.9	33.3	12.6	16.9	68.5	14.6	6.3	0.275	2.856	SM	SL
BL-7	43.8	31.7	12.1	19.4	68.1	12.5	4.5	0.276	3.540	SM	SL
BL-8	44.6	31.0	13.6	17.2	72.0	10.8	5.3	0.305	3.358	SM	SL
BL-9	48.9	34.8	14.1	20.6	65.9	13.5	6.8	0.288	2.023	SM	SL
BL-10	46.6	32.1	14.5	16.9	69.0	14.1	6.1	0.311	2.896	SM	SL
BL-11	49.9	37.7	12.2	20.5	64.5	15.0	7.1	0.244	1.056	SM	SL
BL-12	49.8	36.5	13.3	20.2	63.8	16.0	7.0	0.267	3.125	SW-SM	SL

G: Gravel, F: Fines, S: Sand, C: Clay, CF: Clay Factor, SOM: Soil Organic Matter, USCS: Unified Soil Classification System, MA: Texture classification of Moreno-Maroto & Alonso-Azcarate (2018), SL: Sandy Loam

It is also inferred from Table 1 and Table 2 that LL and PL values represent moderate plasticity silt, while the low PI value indicates a considerable amount of fine sand in the tested soil sample, similar to what was determined by Stanchi et al. (2013). A low PI means that soil consistency will change significantly even with a small change in water content, which is an unfavorable engineering property (Mitchell & Soga, 2005; Wagner, 2013). However, the higher the soil plasticity, the more erodible it is, as previously stated by several researchers (e.g. Khoirullah et al., 2019; Ngezahayo et al., 2019). However, much uncertainty still exists about the relationship between the erosion rate and plasticity index for sandy soils. Data from Table 2 can be compared with the data in Table 1, which shows that the LL, PL, and PI increased for burned samples. This finding is consistent with the results from Haake (2020) but contradicts the results of Vacchiano et al. (2014). However, the plasticity classification either changed to moderate plasticity (BL- 1, 2, 4, 7, and 11) or remained the same (BL-3, 5, 6, 8, 9, 10, and 12) after the forest fire. On the other hand, as the soils have low clay content and relatively higher silt and sand-sized grains, a typical tendency to aggregation after the fire was not observed, which resulted in a slight increase in clay content due to heating.

It is also inferred from the comparison between Tables 1 and 2 that the USCS grain size classification was only changed for the UL-11 sample due to the forest fire. On the other hand, the texture classification on the texture plasticity classification chart by Moreno-Maroto & Alonso-Azcarate (2018) is sandy loam (Figure 3b). This means that the texture classification of the burned and unburned soil samples did not change. Both were classified as sandy loam. Nevertheless, Figure 3a shows that texture classification of the studied soil samples by USDA (2017) failed because the gravel content in the whole sample is up to 20.1%, classifying it as sand on the texture triangle. This finding supports the argument that a considerable amount of gravel content makes the USDA classification unfavorable for coarse-grained soil types.

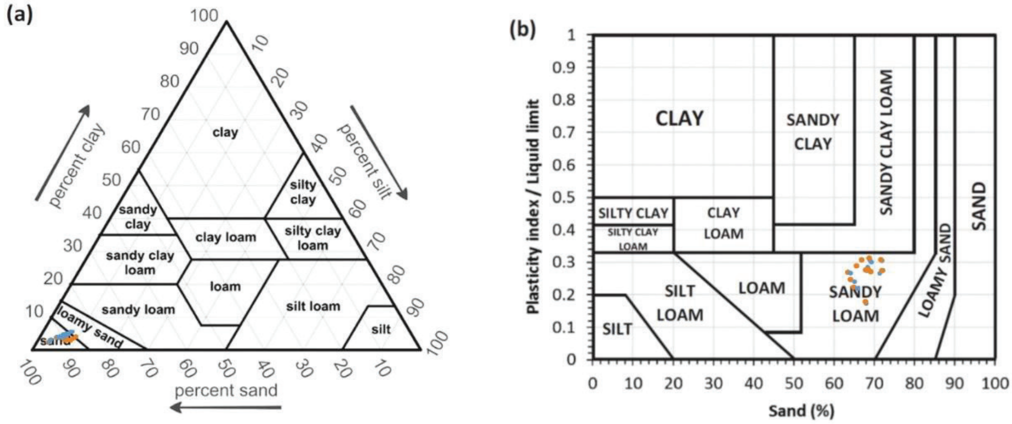

Figure 3. The texture classification of the burned and unburned specimens on **(a)** texture triangle (USDA, 2017); **(b)** texture plasticity classification chart by Moreno-Maroto and Alonso-Azcarate (2018).

Şekil 3. Yanmış ve yanmamış numunelerin (a) doku üçgeni (USDA, 2017); (b) Moreno-Maroto & Alonso-Azcarate (2018) tarafından önerilen doku-plastisite sınıflama kartı üzerindeki doku sınıflaması.

The relationships between the physical and consistency properties of unburned and burned samples were illustrated earlier in Figure 4 before the paired sample t-tests. The 1:1 line, which represents the equality between the parameters, was also drawn on the scatter plot graphs.

The paired samples t-tests were used to compare the burned and unburned soil properties and the results are presented in Table 3. The mean differences between groups, the standard deviation of the differences as well as the t and p-values of the statistical analyses, are presented in Table 3. The t-value is a measure of the size of the difference relative to the variation in the dataset. Thus, as the t-value increases, it refers to a greater difference between the variables. On the other hand, if the p-value is lower than the confidence level (95% confidence level: 0.05 or 99% confidence level: 0.01), it means that there is a statistically significant difference between compared variables. However, it should be noted here that with a very low mean paired difference (low t-value), care must be taken. For example, even though the p-value is lower than 0.05 for the comparison of burned and unburned samples, F and C may not provide clear evidence for the difference between them (FB-FU; C_B-C_U).

Table 3. The paired samples t-test results.

Çizelge 3. Eşleştirilmiş örneklem t-testi sonuçları.

Paired samples	Paired Differences Mean	Standard deviation	t-value	p-value**
LL_B-LL_U*	8	1.57	17.598	0.000
PL_B-PL_U	5.74	1.21	16.385	0.000
PI_B-PI_U	2.26	0.53	14.668	0.000
F_B-F_U	0.25	0.162	5.334	0.000
S_B-S_U	-0.94	0.94	-3.469	0.005
C_B-C_U	0.39	0.19	7.213	0.000
SOM_B-SOM_U	-1.63	0.69	-8.251	0.000

** LL_B: LL of burned samples; LL_U: LL of unburned samples; ** 95%confidence level*

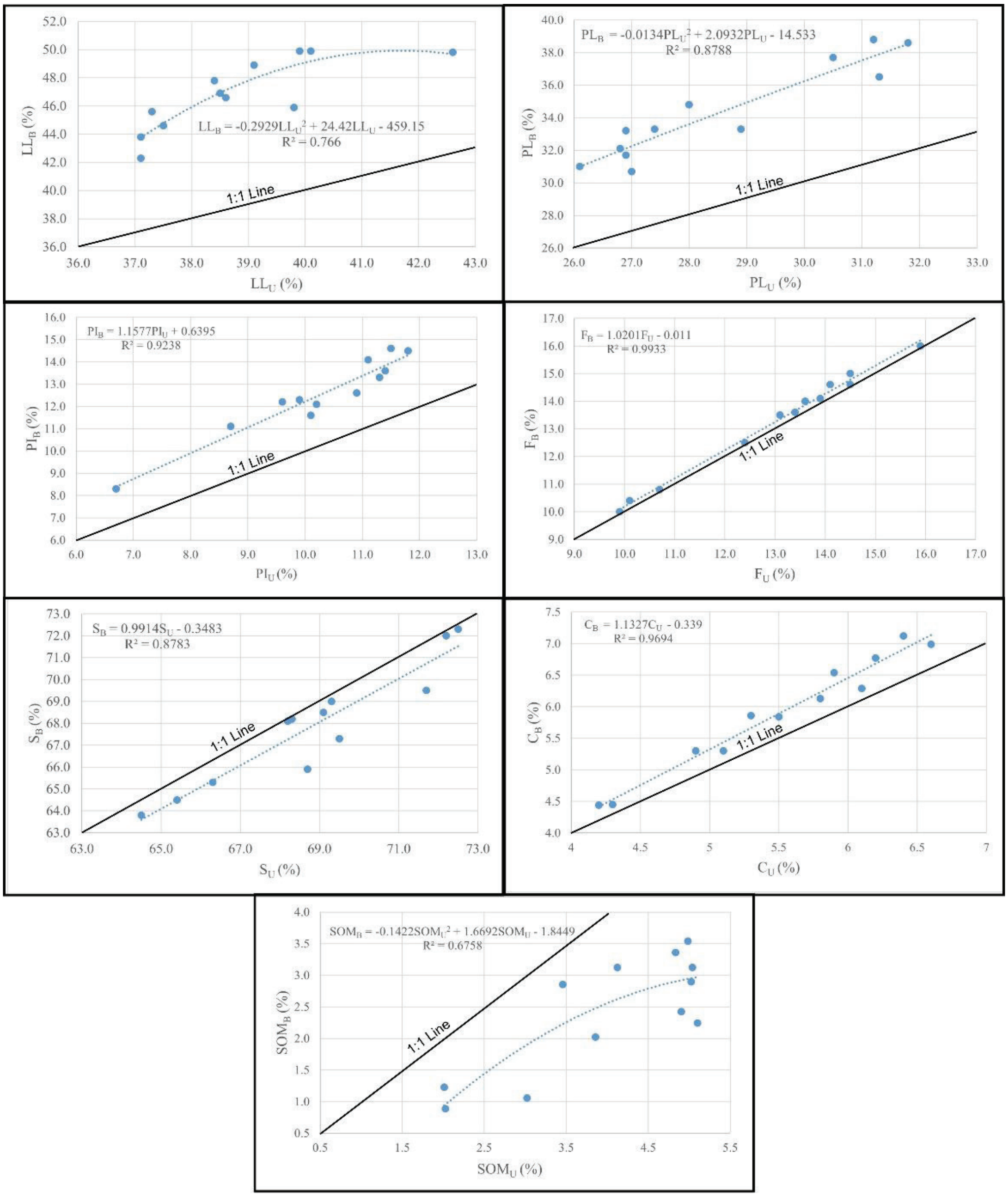

Figure 4. The scatter plot graphs of the physical and consistency parameters of unburned and burned samples.

Şekil 4. Yanmış ve yanmamış örneklerin fiziksel ve kıvam özelliklerinin dağılım grafikleri.

As Table 3 shows, there is a significant difference between the paired groups of LL, PL, PI, F, SOM, and C, except for S, considering the t and p values together. In other words, the consistency limits, clay, and soil organic content showed statistically significant ($p< 0.05$) differences for the burned and unburned samples, while the sand fraction in burned and unburned samples are very similar (Figure 4, Table 3).

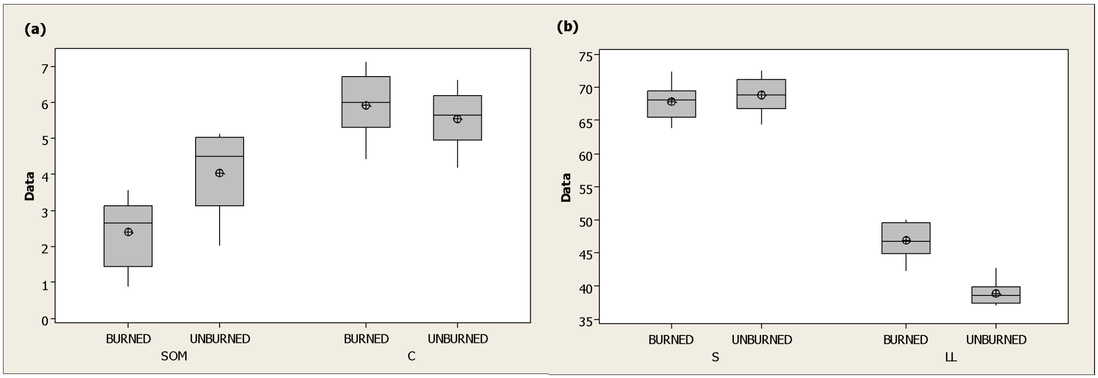

Figure 5. Boxplots showing the variations in **(a)** soil organic matter (SOM) and clay content (C); **(b)** the sand percentage (S) and liquid limit (LL) of unburned and burned samples.

Şekil 5. Yanmamış ve yanmış örneklerideki (a) Toprak organik madde (SOM) ve kil içeriği (C); (b) Kum yüzdesi (S) ve likit limit (LL) değişimlerini göstern kutu grafikleri.

The sand fraction in burned soils decreased by an average of 1.37%, and the paired sample t-test yielded a p-value of 0.005, both of which indicated an insignificant change. On the other hand, the fines fraction increased by an average of 1.91%, and accordingly, the clay content within the fines increased relatively by an average of 7%. Consequently, LL increased by 20.6 % on average, whereas the PI increased by 22.1% (Figure 5).

SOM in the topsoil decreased due to forest fires (17.36-65.07%). This decrease in SOM has been linked to moderate fire intensity or a heat treatment between 200°C and 400°C in the literature (Fernández et al., 1997; Badía & Martí, 2003; Agbeshi et al., 2022). In contrast to these studies, a slight increase in SOM has also been reported in low-intensity fires (Certini, 2005; Varela et al., 2010a). The findings of this study are consistent with the studies which found a significant decrease in SOM. Likewise, there are contradictory results for grain size because the low, moderate, and high-intensity burning promotes variations. For example, soil aggregation has been observed to decrease at low-intensity fires (Fox et al., 2007; Varela et al., 2010b; Mataix-Solera et al., 2011), whereas contradictory results have been reported for high temperatures up to 500°C (Soto et al., 1991; Badía & Martí, 2003; Kavdir et al., 2005; Jordán et al., 2011). Previously, high-intensity fires have been argued to produce temperatures between 500 and 700°C, with short peaks of 1500°C (Countryman, 1969; Dunn and DeBano, 1977). On the other hand, field observations on the partial destruction of vegetation, the moderate degree of charring, and the 1.5-3cm of ash thickness, pointed out that the sampling points were subjected to low to moderate fire intensity. These observations are consistent with laboratory test results that indicated the changes in the soil parameters examined in this study likely represent a moderate fire intensity. Overall, it can be stated that forest fire has a remarkable effect on consistency limits as well as clay content and organic content.

Factors Affecting the Consistency Limits After the Forest Fire

The results of the correlation analysis are summarized in Table 4. The percentage changes in sand fraction showed a moderate negative correlation with the changes in consistency limits (Table 4). This means that as the sand fraction decreases, consistency limits increase. Apart from the clay content, the fraction of fines (silt + clay) was found to be more strongly correlated with the changes in consistency limits than the other parameters. It is surprising to find that the consistency limits of the burned samples can be evaluated accurately with the variations in fines content.

Even though the clay content increased 7% for burned samples, the average LL, PL, and PI increased by 20.6%, 20.0%, and 22.1%, respectively. This result is consistent with the findings of Vacchiano et al. (2014) that at a lesser degree of burn severity, there is an increasing trend in Atterberg limits. It is understood that the increase in clay content does not solely explain the increase in consistency limits. When the decrease in sand and clay content are considered together, it is apparent that the fine sand fraction in the sample passing the 0.425mm sieve decreased. This finding can explain the increase in PI after the fire.

On the other hand, SOM decreased by maximum 65.07% with an average of 41.3%. A similar finding with a higher degree of organic combustion (90%), signifying temperatures of about 400°C, was found by Zavala et al. (2010). In contrast with this, the combustion of the organic content in samples BL 6, 7, and 12 (17%, 28%, 24%) is less than the rest of the samples. Since the field observations of all sampling points are similar, this finding indicates that the fire may have passed over these locations quickly, thereby not increasing the temperature high enough for greater combustion of organic matter. Another explanation for this could be the overestimation of SOM for these samples (BL 6, 7, and 12) from LOI due to the loss of CO_2 from carbonates and the loss of volatile constituents which may be present in non-clay mineral components, as suggested by Grim (1968). Vacchiano et al. (2014) revealed that at high burn severity, as the combustion of SOM increases, the Atterberg limits decrease. Accordingly, it can be argued that in the study area, the fire-induced heating of the topsoil layer was not enough to cause great SOM combustion and aggregation.

Table 4. Pearson correlation coefficients (R) matrix of the relationships between ΔLL, ΔPL, ΔPI, and changes in the sand (ΔS), fines (ΔF), clay (ΔC), and soil organic content (ΔSOM).

Çizelge 4. ΔLL, ΔPL, ΔPI, ile kum (ΔS), ince taneler (ΔF), clay (ΔC), toprak organik madde (ΔSOM) içeriğindeki değişimler arasındaki Pearson korelasyon katsayısı (R) matrisi.

	Independent variables (Pearson correlation coefficients, R)			
%Dependent variables	ΔS **(%)**	ΔF **(%)**	ΔC **(%)**	ΔSOM **(%)**
ΔLL (%)	-0.632*	0.896**	0.836**	0.833**
ΔPL (%)	-0.622*	0.888**	0.822**	0.815**
ΔPI (%)	-0.618*	0.907**	0.862**	0.864**

***99% confidence level (p < 0.01); *95% confidence level (p < 0.05)*

While the changes in SOM and C are evaluated together, it is seen that the small amount of change in ΔC (%) is strongly related to the decrease in ΔSOM (%) with a high coefficient of determination (R^2= 0.8567) (Figure 6). As a result of correlation analyses, ΔF, ΔSOM, and ΔC could emerge as the predictors of the change in consistency limits after the fire. However, when the results of paired sample t-test and correlation analyses are interpreted together, the changes in SOM after the fire seem to be a major factor affecting the changes in consistency limits. This interpretation is in accordance with the significant positive relationship between aggregation and organic matter found in previous studies (Soto et al., 1991; Varela et al., 2010a). Overall, this leads to an increase in the plasticity of the soil.

CONCLUSIONS

This study investigates the effect of a forest fire that occurred in Kozağaç, Muğla, on the consistency limits of sandy soil in terms of its particle size, organic matter, and clay content. The statistical analyses revealed that the forest fire burned the topsoil and led to disaggregation in the soil structure, which is strongly related to the destruction of organic matter because organic matter is the main agent that promotes aggregation in the soil. Accordingly, the fine sand and clay fractions in the soil increased. It is also necessary to note that particle size distribution, consistency, and organic matter determination techniques all have advantages and drawbacks that control the accuracy of the obtained data. For comparison purposes, it is convenient to use one accepted method for testing, which must remain consistent throughout all the samples tested. Therefore this finding, while preliminary, suggests that the methodology described and followed in this study can be a guide for comparing the burned and unburned specimens in terms of their consistency limits.

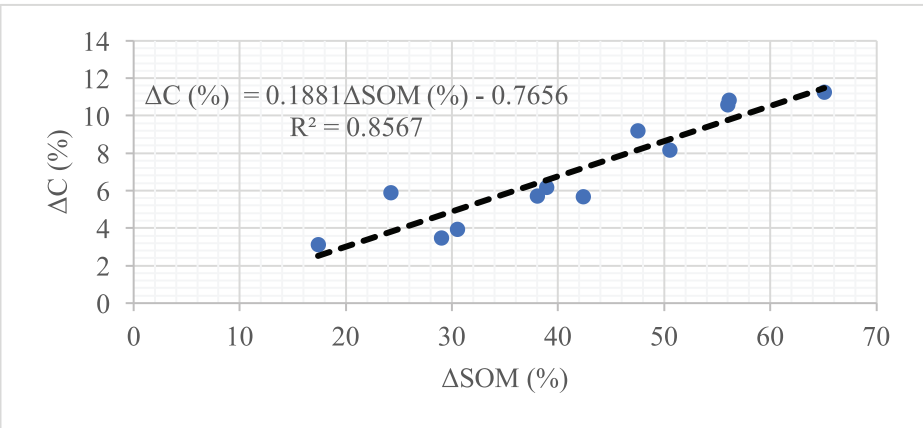

Figure 6. The relationship between the changes in clay and soil organic matter.
Şekil 6. Kil ve toprak organik maddesindeki değişimler arasındaki ilişki.

The degree of changes in the examined parameters also indicated a moderate intensity over the sampling area. This finding confirmed the field observations that the sampling locations in this study involve a very uniformly burned area. Consequently, strong correlations between variables and significant differences in consistency limits and other soil properties were obtained, whereas the texture of the soil did not show any change. However, it should be noted that while studying different fire intensity zones in the same fire-prone area, results may show some discrepancies and thus the findings of this study cannot be extrapolated to all sandy soils. Further studies to enhance the findings of this study may account for the sampling locations from a greater area with a variety of fire intensities.

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