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EFFECTS OF WILDFIRES ON SOIL IDENTIFICATION AND MECHANICAL PROPERTIES*

EFEITOS DOS INCÊNDIOS NAS PROPRIEDADES DE IDENTIFICAÇÃO E MECÂNICAS DE SOLOS

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ABSTRACT

Wildfire-induced instabilities, such as those observed following the October 2017 wildfires in Oliveira do Hospital (Portugal), are well documented and have been studied in recent decades. Laboratory and field research has identified various soil changes that explain some of these phenomena. However, only a limited number of studies approach the issue from a geotechnical perspective. This research investigates potential soil changes in slopes affected by wildfires where mass movements have occurred, aiming to better understand how microscale soil alterations influence key physical, mechanical, and hydrological properties. Analysing natural and burned samples with a muffle furnace to simulate wildfire effects reveals that changes in grain size cause increased shear strength and hydraulic conductivity in burned soils. These findings emphasise the need to account for local vegetation and soil coverage when evaluating slope stability after wildfires.

Keywords: Post-wildfire geotechnical characterisation, laboratory testing, physical properties, shear strength, hydraulic conductivity.

RESUMO

As instabilidades induzidas por incêndios florestais, como as que se seguiram aos incêndios florestais de outubro de 2017 em Oliveira do Hospital (Portugal), estão bem documentadas e têm sido estudadas ao longo das últimas décadas. Estudos laboratoriais e *in situ* identificaram várias alterações no solo que explicam alguns destes fenómenos. No entanto, apenas alguns estudos abordam uma perspetiva geotécnica. O presente estudo analisa as potenciais alterações no solo em taludes afetados por incêndios florestais onde ocorreram deslizamentos, com o objetivo de compreender melhor como as alterações microscópicas no solo influenciam propriedades físicas, mecânicas e hidrológicas fundamentais. A análise de amostras naturais e queimadas numa mufla para simular os efeitos dos incêndios florestais revela que as alterações na granulometria causam um aumento da resistência ao corte e da permeabilidade nos solos queimados. Estas conclusões realçam a necessidade de considerar a vegetação local e a cobertura do solo ao avaliar a estabilidade das taludes após incêndios florestais.

Palavras-chave: Caracterização geotécnica pós-incêndio, ensaios laboratoriais, índices físicos, resistência ao corte, permeabilidade.

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Introduction

Each year, Portugal loses about 100,000 hectares of forest to wildfires (Pereira *et al.*, 2006), mainly during July 1 to September 30 (Charlie phase). Increased vegetation from rural abandonment (Lourenço *et al.*, 2012), wildfire-prone species like pine and eucalyptus (Prats *et al.*, 2014), and poor planning are key causes. The north-central region, including Serra do Açor, where the case study is located, and Serra da Estrela, has experienced significant losses since 1975, especially during wildfires in 1987, 1991, 2005, 2017, and 2022. Heavy rains following wildfires have caused flooding (1998, 2006) (Pereira and Lourenço, 2006) and slope instability in the north-central region of Portugal in 1993, 2005, 2018, 2019, and 2022 (Lourenço, 1995; Melo and Zêzere, 2017; Araújo Santos *et al.*, 2020).

The connection between forest wildfires and subsequent slope instability is extensively documented (Esteves *et al.*, 2012). These authors argue that wildfires eliminate vegetation cover and change soil hydrological response. The loss of vegetation cover leads to increased surface runoff and erosion (Malvar *et al.*, 2016). Although these adverse effects exist, they typically do not lead to geotechnical instability. In Portugal, documented landslides and other instabilities are linked to heavy rainfall events (Zêzere *et al.*, 2015).

The geological and geotechnical responses of burned areas over time rely on various factors organised into two categories based on their relationship to forest wildfires (Robichaud *et al.*, 2010): i) factors unrelated to forest wildfires and ii) wildfire-dependent factors. Independent factors include orography, human activities, and rainfall characteristics, particularly intensity. Dependent factors include wildfire severity, burnt area size, soil vegetation cover, water repellency, soil erodibility, and the time since the wildfire (Robichaud *et al.*, 2010). When studying soil behaviour and post-wildfire response, it is essential to consider three factors: the hydrological response of hydrographic basins, the natural reinforcement of soils from vegetation roots, and changes in soil characteristics. Geotechnical instability cannot be separated from the hydrological conditions of river basins (Zêzere *et al.*, 2015). Following a wildfire, hydrological conditions change, notably due to variations in soil water infiltration regimes and their erodibility (Parise and Cannon, 2012). Increased infiltration stemming from changes in vegetation cover reduces the total suction in the soil, irrespective of its initial saturation, which subsequently lowers effective stresses. Erodibility changes can lead to erosion phenomena that may culminate in debris flows. Furthermore, the development or increase of water repellency in soil is another aspect to consider, particularly in areas affected by intense forest wildfires, since it leads to higher surface runoff. This phenomenon has also been observed in specific types of dead ground cover, such as foliage from eucalyptus trees (Ferreira *et al.*, 2010).

Parise and Cannon (2012) emphasise that a decline in organic matter in the upper soil layers can negatively affect the soil's mechanical response. This degradation is linked to the reduction of microbial activity and roots, both of which enhance the soil's stress response. Changes in vegetation affect several soil response factors relevant to slope stability, including suction, interception, infiltration, surface flow, soil reinforcement, and external loads (Masi *et al.*, 2021). From a geotechnical standpoint, all these factors, except the roots' contribution, are considered when calculating the soil's effective stress state, which is then used to evaluate slope safety against circular failure such as landslides. Roots are also included in the safety assessment. Their contribution resembles apparent soil cohesion (Coppin and Richards, 1990) and is incorporated into the Mohr-Coulomb failure criterion. Apparent soil cohesion varies with factors such as vegetation type and orientation relative to the slip surface (Chok *et al.*, 2015). Depending on the species of plants and the geometry of their roots, the apparent cohesion of roots can range from 1.5 to 94.3 kPa (Wu, 2013; Schmidt *et al.*, 2001). Root depletion occurs in two primary ways: through direct exposure to flames that subject roots to extreme temperatures, particularly within the top 5–10 cm of soil, or through the death of trees or shrubs resulting from injuries related to wildfires, including diseases or pests (Jackson and Roering, 2009). In the first scenario, roots typically die shortly after the wildfire, whereas death may happen much later in the second scenario. The reduction in root resistance reaches its lowest point between 8 to 12 years following tree death, which can contribute to instability issues (Schmidt *et al.*, 2001; Jackson and Roering, 2009).

The burning of organic matter in the upper soil layers can lead to a loss or decline in mechanical behaviour. Wildfires often create more friable soils and, therefore, more susceptible to erosion. This occurs due to the loss of roots and the destruction of microbial activity that enhances soil mechanical properties (Parise and Cannon, 2012). It's also important to note that specific physical properties of soil, such as grain size distribution and plasticity – mainly influenced by organic matter – can change during wildfires. Multiple studies indicate a decrease in clay and silt fractions, resulting in coarser and less cohesive soils more prone to erosion (Parise and Cannon, 2012). These authors also state that the increase in *pH* conditions due to the presence of ashes promotes particle dispersion.

The previous review highlights that soils experience various transformations during wildfires, influencing their behaviour in future climatic or geological events. Recent research has shifted focus beyond just chemical or biological properties (Fernández-García *et al.*, 2019) to include physical characteristics like soil texture (grain size), bulk density (Agbeshie *et al.*, 2022; Hrelja *et al.*, 2020), and hydraulic properties (Ebel and Moody, 2017). However, these studies generally assess each property separately, without providing a comprehensive geotechnical characterisation of soils affected by wildfire. Systematic reviews on how wildfires alter geotechnical responses are scarce and typically focus on mechanical behaviour, considering root system effects (Peduto *et al.*, 2022). Several studies address aggregate stability and erosion processes. However, although these topics are related or dependent, they do not focus on geotechnical parameters such as the angle of shear resistance or cohesion. No research explicitly linking soil particle properties to the geotechnical response after a fire was found in the literature.

Finally, it is important to emphasise that, due to the expected climate changes in the Mediterranean regions, prolonged periods of severe drought are likely, along with increased storm intensity (Giorgio and Lionello, 2008; Ozturk *et al.*, 2015). The interplay between these two extreme weather events fosters conditions that can lead to more frequent geotechnical instability, especially in the country's harshest regions, like northern central mainland Portugal. This region of Portugal has already been studied following the 2017 wildfires because of the severe water erosion caused by gullies (Martins *et al.*, 2024a). To further understand this phenomenon and other instability events, it is crucial to perform geotechnical assessments in areas significantly impacted by extreme weather, as discussed in this communication, to help societies and their infrastructure adapt and mitigate the potential impacts of climate change. This work aims firstly to evaluate the effects of high temperatures on the intrinsic properties of these soils and compare them to the outcomes published in the literature. Based on previous results and the tests on hydraulic conductivity and shear strength, a geotechnical discussion is provided. It includes an innovative analysis of key wildfire-affected soil parameters to assess its overall and expected response to external loads. Although further analysis is needed, the results for the study area could serve as a basis for future geotechnical assessments of wildfire-related hazards.

Materials and methods

Case study

The case study is located in the Montejunto-Estrela mountain range in the district of Coimbra, Portugal (fig. 1a), more specifically, in the municipality of Oliveira do Hospital (fig. 1b). The study area is located in Serra do Açor, between the villages of Penalva de Alva and São Gião. The northern bank of the Alva River, where the case study is located, has already been examined in previous research, specifically by Martins *et al.* (2024a). The reference point for the case study is located 285 m above mean sea level at a latitude of 40° 20‘ 14.27’‘

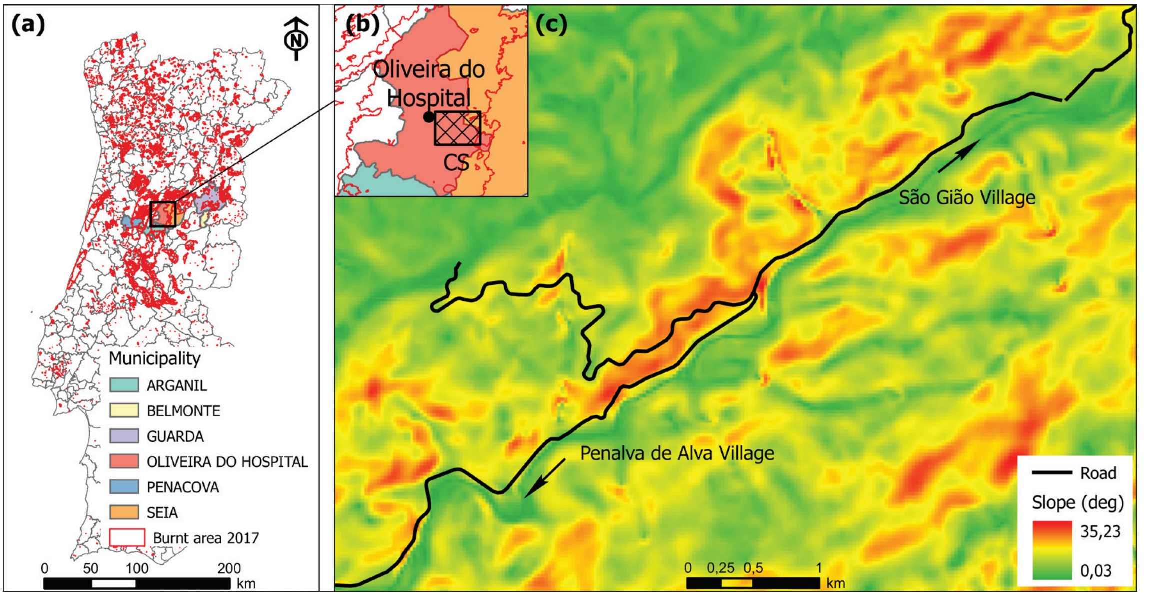

Fig. 1 - Case study location: (a) at national level; (b) at municipal level; (c) detail of the Municipal Road EM 514 and the surrounding slopes.

***Fig.1** - Localização do caso de estudo: (a) a nível nacional; (b) a nível municipal; (c) pormenor da Estrada Municipal EM 514 e taludes envolventes.*

N and a longitude of 7º 49’ 30.44‘’ W. At this location, the slopes face south along the EM 506 municipal road towards the town of Oliveira do Hospital, west along the EM 514 municipal road, west towards Penalva de Alva and east towards São Gião (fig. 1c). The average inclination of the slopes around the EM 514 municipal road is 30º (Araújo Santos *et al.*, 2020) and, geologically, the site is in a geological transition from the primary formations of coarse-grained, porphyritic two-mica granite (Seia granite) to schist formations with occasional intercalations of greywacke stone (part of the Rosmaninhal), with contact metamorphism. Near the study area, soils have been classified as predominantly shallow and stony soils (Umbric leptosol). From a hydrological point of view, the average annual rainfall varies between 900 mm in Penalva de Alva and 1200 mm in São Gião, over 110 to 120 days a year, between October and May (Daveau *et al.*, 1997).

Between October 14 and 16, 2017, forest wildfires consumed 207,938 hectares, including 43,191 hectares in Oliveira do Hospital (ICNF, 2017). This late wildfire outbreak and its impact are linked to the meteorological drought affecting Portugal during that period, which lasted until February 2018 (IPMA, 2018). In 2018 and 2019, significant extreme rainfall events occurred. In March 2018, the study site received 400 to 500 mm of rain, 400% above the average for that location. April saw rainfall exceeding the average by 125%, totalling 150 – 200 mm (IPMA, 2018). Despite a meteorological drought from January to October 2019, the year ended with three consecutive storms, during which the region received 200 to 300 mm of accumulated rainfall over seven days (IPMA, 2019).

Following the various extreme natural events between 2017 and 2019, several phenomena of geotechnical instability were recorded. The emergency plan was activated in the municipality of Oliveira do Hospital after the passage of storm Elsa, during and after which there were 42 occurrences of instability in the municipality, 19 of which were in the study site or its immediate vicinity (Araújo Santos *et al.*, 2020), damaging the EM 514 municipal road. The cost of restoring the affected infrastructure in the municipality totalled 3,000,000 euros, 450,000 of which were in the study area. Finally, it should be noted that before these incidents, there was only one recorded incident in the area, in 2013, a year after wildfires in the region.

Laboratory program

The laboratory program focused on performing tests to identify and characterise the essential geotechnical properties of soils collected from the case study site, specifically along the EM 514 municipal road between Penalva de Alva and São Gião, within Oliveira do Hospital municipality. Visual assessment of the local area identified two distinct soil layers (Alva1 and Alva2). Soil samples were collected from several locations along the road, particularly where landslides had occurred. These events were registered where the slopes present a higher inclination, reaching 35º as depicted in fig. 1c. In each site, up to 5 kg of soil was gathered from the slope surface and stored separately. It should be noted that because soil temperature decreases sharply within the first centimetres (Zuloaga-Aguilar *et al.*, 2016; Chicco *et al.*, 2023), no samples were collected from deeper layers. Depending on the landslide’s extent, multiple samples might have been taken from the same event, totalling approximately 30 kg of each soil type, divided into 8 and 10 samples of Alva1 and Alva2. Once delivered to the Geotechnics and Foundations Laboratory of the Coimbra Institute of Engineering, the materials were prepared according to specification E195-1966 (LNEC, 1966a) for identification tests. Initially, all samples underwent individual grain size analysis. As no significant differences in grain size distribution were detected among them, all the samples were combined into the two main reference soils, Alva 1 and Alva 2, for further analyses. The final appearance of the two soils is depicted in photo 1a and 1b. The soils were designated as Alva1 and Alva2, respectively.

Each soil sample was divided into two identical parts. One half was kept in its natural state, while the other half underwent a two-stage burning process using a muffle furnace to simulate wildfire effects in soils and observe changes in soil response. This method is commonly employed in laboratory experiments, with various contact times ranging from 20 minutes to 18 hours and temperatures from 20 ºC to 1093 ºC, as documented in the literature (Fajković *et al.*, 2022). Firstly, after placing the soil inside the muffle furnace, the temperature is raised from room temperature to 500 ºC. This process takes about an hour. Once this temperature is reached, the second phase of burning the material begins. In this phase, the temperature is increased to 600 ºC and is maintained for thirty minutes. After this period, the equipment is switched off, and the material is allowed to cool to room temperature. The burning temperature was selected based on previous research that examined the effects of wildfires on soil properties. Debano *et al.* (1976) exposed dry and wet sands to 700 ºC during testing water repellency. In a study on thermal changes in soil physico-chemical properties, Araya *et al.* (2016) subjected soil samples to six different temperatures: 150, 250, 350, 450, 550, and 650 ºC. Additionally, Martínez *et al.* (2022) heated soil samples up to 900 ºC to assess changes in various soil properties. It is important to note that these temperatures correspond to those recorded at the ground surface, depending on wildfire intensity and vegetation (Verdes and Salgado, 2011; Juárez-Orozco *et al.*, 2024). Since the severity of the 2017 wildfires was classified as moderate to high in some parts of the study area (Martins *et al.*, 2024b; Pinheiro *et al.*, 2025), 600 °C was assumed as the reference temperature in the present study. The two-stage burning process is adopted from the method used to determine the percentage of bitumen in bituminous mixtures through incineration, as stipulated in European standard EN 12697-39 (CEN, 2004). While furnace heating is commonly used to examine wildfire impacts on soils, it has notable limitations. In fact the uniform and gradual heating process does not truly mimic natural fire conditions, which feature asymmetric heating with rapid temperature rises and slower cooling (Shtober-Zisu and Wittenberg, 2021). This difference affects the variations in soil effects within the first centimetres (Alfaro-Leranoz *et al.*, 2023). The experimental procedures were, therefore, repeated twice for each soil sample. Photo 1c and 1d show the two soil portions after the burning process. The 'Nat' or 'Burn' index has been added to the designations previously introduced, depending on whether the soil is in its natural state or has been subjected to the burning process.

After the soils were prepared, the planned laboratory studies for their identification and classification commenced. Initially, the natural soils underwent identification tests aimed at their geotechnical classification. In this process, particle size analysis tests were conducted following specification E196-1966 (LNEC, 1966b) and tests to establish consistency limits. These tests adhered to British standard BS 1377-2 (BSI, 2022) and the Portuguese standard (NP143, 1969). Furthermore, assessments were performed to determine the density of solid particles (NP83, 1965), as well as tests to establish the minimum (ASTM, 2000a) and maximum (ASTM, 2000b; Araújo Santos, 2015) void indices. The classification of soils was carried out according to the procedure outlined by the unified classification (ASTM, 2006). Similar methods were utilised for the burnt soils to detect potential alterations in their physical condition due to the combustion process. The research proceeded with shear strength assessments, employing direct shear box apparatus for both the untouched soils and those impacted by burning. The tests followed the guidelines specified in the NP EN ISO 17892-10 standard (IPQ, 2018). For these assessments, all samples were prepared to achieve a relative density of around 50%. Finally, permeability tests were performed at this same relative density to evaluate changes in hydraulic conductivity for both types of soil samples.

Photo 1 - Soils collected at the case study site: a) Alva1$_{Nat}$; b) Alva2$_{Nat}$; c) Alva1$_{Burn}$ and d) Alva2$_{Burn}$.

Fot. 1 *- Solos recolhidos no local em estudo: a) Alva1$_{Nat}$; b) Alva2$_{Nat}$; c) Alva1$_{Burn}$ and d) Alva2$_{Burn}$.*

Experimental results and discussion

The first aspect to examine is the particle size distribution analysis of the two natural soils and those produced by the burning process. Initially, it appears that the Alva1$_{Nat}$ and Alva2$_{Nat}$ soils display slightly different grain sizes, especially for diameters under 0.3 mm, with Alva2$_{Nat}$ exhibiting a higher percentage of fines (fig. 2). Nonetheless, this distinction does not impact their classification as both are identified as coarse soils, classified as sands with fines and gravel. Regarding the fines, it was not possible to classify them using the Casagrande chart due to the inability to determine the plasticity limit. Analysing the grain size distribution of the two soils after the burning process reveals a significant reduction in the fine fraction (fig. 2). The grain size curves for Alva1$_{Burn}$ and Alva2$_{Burn}$ soils lie below those of the natural soils, with the most pronounced differences appearing in the initial and final segments of the curves. The burning process reduces the finest soil fractions (clays and silts), resulting in more granular and less cohesive soils, as Parise and Cannon (2012) noted. This reduction in the fine fraction is due to the fusion and aggregation of clay particles, which, according to Satín and Doerr (2016), starts at temperatures exceeding 500 °C, which include chemical changes in molecular bonds at a microscopic level. These changes result from the dehydroxylation, the initial stage of mineral disruption (Tan *et al.*, 1986). Mataix-Solera *et al.* (2011) note that soils tend to become coarser after fire events, especially at temperatures above 600 °C, based on both laboratory and field studies. This phenomenon is connected to the binding agents in soils and their mineral composition (Haake *et al.*, 2023), which, in this case, promote the formation of stable aggregates from clay and silt particles. Additionally, significant changes in granulometry for sizes larger than 1 mm also occur in Alva1 soil, making these soils more susceptible to erosion processes.

Table I provides a summary of the results from the other identification tests, underscoring the low plasticity of the soils, both in their normal state and after the burning process. The liquidity limit (w_L) values shown were derived from applying the British standard utilising the cone penetrometer; this was necessary because the field application of NP143 (1969) was not confirmed precisely due to the percentage of particles smaller than 0.05 mm being less than 30%. Therefore, it was also not feasible to ascertain the soils' plasticity limits (w_p), as the British standard for this limit suggests no alternative. Following the burning process, a slight increase in the liquidity limits of both soil types was noted. Given the loss of fines illustrated in fig. 2, one would expect the opposite behaviour, as Noraini (2018) indicated that clayey soils could achieve non-plasticity at temperatures exceeding 400 °C. However, as stated by Awn *et al.* (2019), changes in the liquidity limit can occur based on the temperature achieved and the number of burning cycles, with a notable reduction generally only occurring from the third burning cycle onward. Further studies are needed to determine the soils' behaviour in this context question.

The laboratory tests carried out reveal a slight difference in the density of solid particles in Alva1$_{Nat}$ soil, as noted by Peduto *et al.* (2022). However, the literature does not reach a consensus on how wildfires affect soil density, with some studies indicating both increases and decreases in this property (Agbeshie *et al.*, 2022). Importantly, Peduto *et al.* (2022) highlight that the

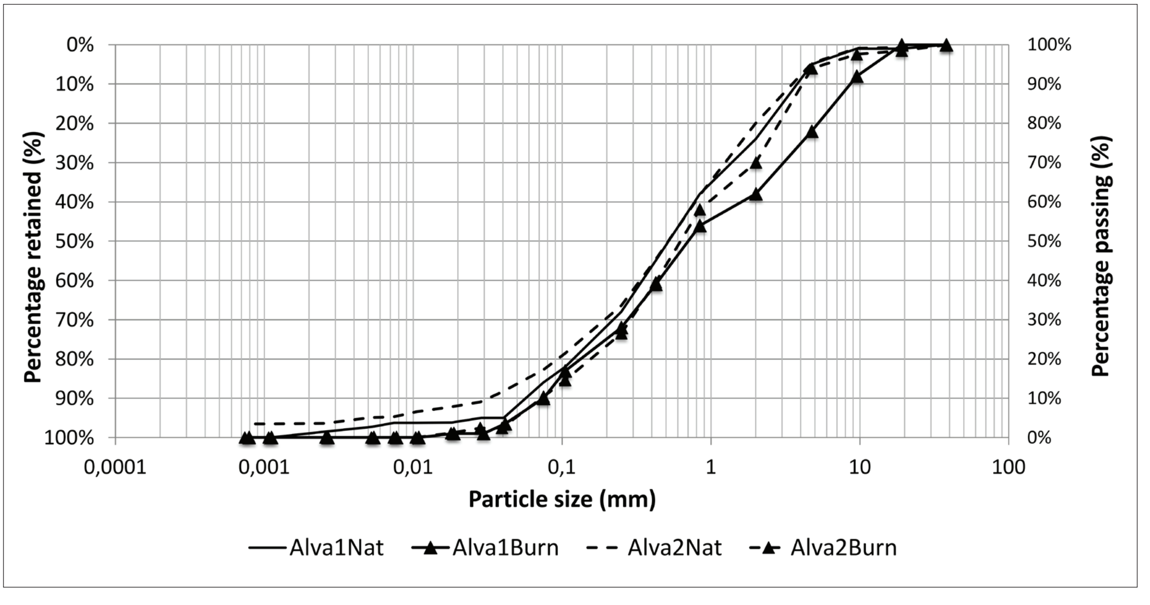

Fig. 2 - Grain size distribution of soil samples.

Fig. 2 - *Curvas granulométricas das amostras de solo.*

density of solid particles (*G*) is influenced by both the elapsed time post-test and the burning process itself. These authors propose that testing the density of solid particles in soil samples subjected to laboratory burning, as done in this study, generally yields significantly higher results. Contrary to this, the findings in the current research show a decrease in the density of solid particles in Alva2 soil, likely due to reduced fine fractions from the burning. In Alva1 soil, where a lower density of solid particles value is noted compared to Alva2 soil, the change in density of solid particles is minor, probably because the burning primarily impacts the coarser soil fractions. The reference void ratios display notable differences, specifically in their minimum values (e_{min}). Although Alva1$_{Nat}$ and Alva2$_{Nat}$ soils share the same maximum void ratio (e_{max}), their minimum void ratios are 0.329 and 0.479, respectively. Analysing the burned soils, both show an increase in reference values. The reduction in the minimum void ratios can be attributed to the loss of fine particles, leading to diminished packing capacity (Matos Fernandes, 2006). The rise in the maximum void index, especially in Alva2$_{Burn}$ soil, may be due to increased angularity (Pinto, 2009) of the particles resulting from breakage at temperatures exceeding 250 ºC (Satín and Doerr, 2016).

Table I - Phase relationships and consistency limits.

Quadro I - *Índices físicos e limites de consistência.*

	Alva1$_{Nat}$	Alva1$_{Burn}$	Alva2$_{Nat}$	Alva2$_{Burn}$
G (-)	2.64	2.66	2.69	2.64
e_{min} (-)	0.329	0.366	0.479	0.546
e_{max} (-)	0.874	0.914	0.875	1.238
w_L (%)	34	42	35.5	47
w_P (%)	*	*	*	*

* The low percentage of fines did not allow the determination of the soil's plasticity limit.

Soils Alva1 and Alva2 underwent shear strength testing with a direct shear box measuring 6 cm on each side. The soils' natural and burnt states were tested under four load ranges: 41.3, 68.6, 95.8, and 123 kPa. As depicted in fig. 3, the results for peak shear strength indicate a notable improvement in the peak resistance, namely in Alva2 soil. Two primary factors may lead to this increase: i) the decrease in fine particles caused by particle aggregation and ii) the fracturing of particles during combustion, resulting in a more angular shape that heightens friction between them. The resistance appears quite similar at the critical state (CS) and lacks a discernible pattern in the soil's response. For instance, the critical state shear strength angle for soil Alva1 decreases significantly by 2º, while Alva2 shows an opposite trend (Table II). It is important to note that the test conducted at a normal stress of 95.8 kPa yields an unusual result. If this result is excluded, the overall behaviour resembles that of Alva1. It's important to highlight that the findings of this study contrast with others, such as Peduto *et al.* (2022), which reported a decline in the mechanical response of the soils. The samples' differing initial conditions and the deformation levels reached may account for these discrepancies.

The evaluation of soil samples' hydraulic conductivity is influenced by their particle size distributions. Since the samples are classified as sands with fines and gravel, this parameter can be determined through constant head permeability tests. The tests were conducted using permeameters following the NP EN ISO 17892-11 standard (IPQ, 2019). Two samples of each soil type at a relative density of 50% were prepared, ensuring they were fully saturated. After this step, a constant elevation head of 20 kPa was applied, allowing water to flow through the sample. When a continuous flow was established, the test

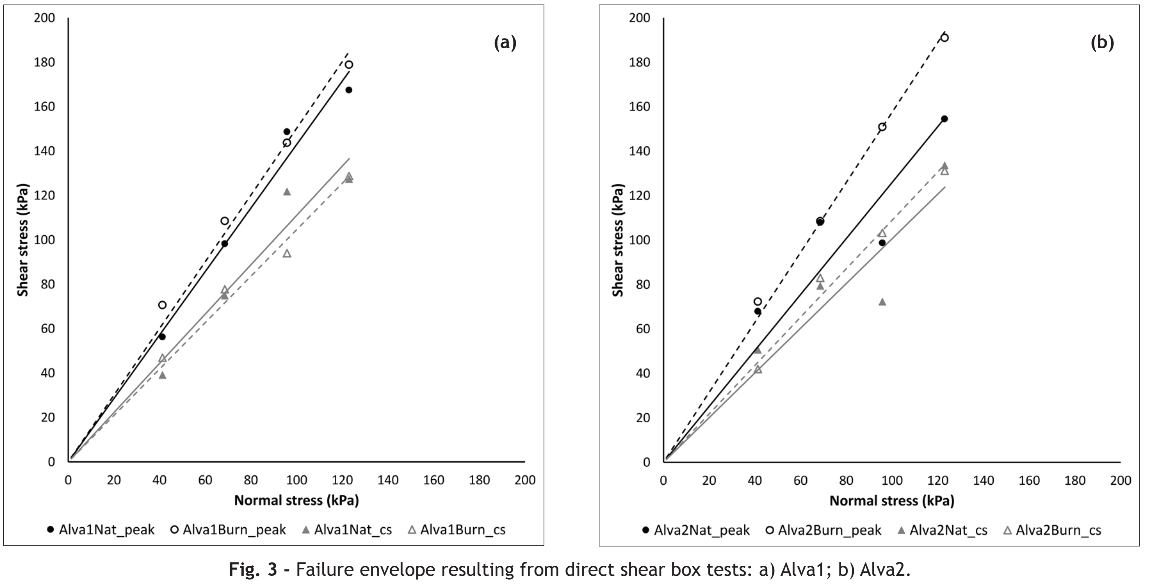

Fig. 3 - Failure envelope resulting from direct shear box tests: a) Alva1; b) Alva2.

Fig. 3 - *Envolventes de rotura resultantes dos ensaios de resistência ao corte em caixas de corte direto: a) Alva1; b) Alva2.*

commenced, recording the volume of water collected in a container over a specified duration. Table II summarises the average value of the two tests for each soil. For both samples, the burned specimens exhibit higher hydraulic conductivities, nearing a twofold increase. These findings correspond with the effects of particle sizes and reference void ratios. A reduction in fine content creates more space between particles, resulting in increased hydraulic conductivity. However, not all soils demonstrate this behaviour. In fact, Neary's (2011) literature review indicates that no consistent pattern can be identified based on depth, coverage, or other factors. Additionally, the presence of water repellency affects the influence of wildfire on hydraulic conductivity. Lower temperatures (200 – 250 °C) can enhance the water effect, whereas higher temperatures (450 – 500 °C) can degrade the water repellency layer, potentially increasing hydraulic conductivity (Wieting *et al.*, 2017).

Table II - Angle of shear resistance and hydraulic conductivity.

***Quadro II** - Ângulos de resistência ao corte e coeficientes de permeabilidade.*

	$Alva1_{Nat}$	$Alva1_{Burn}$	$Alva2_{Nat}$	$Alva2_{Burn}$
(°)	55	56.3	51.5	57.6
(°)	48	46.3	45.2	47.4
k (m/s)	1.37×10^{-2}	2.44×10^{-2}	2.10×10^{-2}	3.98×10^{-2}

Conclusions

Every year, wildfires in Portugal burn an average of 100,000 hectares. Following the October 2017 wildfires and extreme weather events like droughts and storms, numerous soil instability phenomena were observed in Oliveira do Hospital, Coimbra district, in subsequent years. To explore the geotechnical implications of soils affected by wildfires- specifically changes in shear strength and hydraulic conductivity- samples were collected from landslide-affected slopes and taken to the laboratory for analysis. Initial assessments confirmed the on-site visual inspections, and the samples were categorised into two different soils, Alva1 and Alva2.

Each soil sample was prepared following Portuguese and international standards and divided into two: one remained in its natural state, while the other was subjected to a burning process. The burned sample was heated to 600 °C for 30 minutes in a muffle furnace to mimic wildfire effects, then cooled to room temperature. Afterwards, all four samples underwent identification and classification, shear strength, and hydraulic conductivity tests. The last two categories of tests were conducted on specimens with a 50% relative density. From the first set of tests, one may conclude that:

- A loss of fines resulting from the burning process is observed, particularly in the Alva2 soil, in which it ascends to 10%.
- In Alva1 soil, changes in granulometry also occur for particle sizes higher than 1 mm, resulting in coarser soils.

These findings align with previous research and are due to the fusion and aggregation of clay particles occurring above 500 °C. This process relates to the binding agents in soils and their mineral composition, which help form stable aggregates from clay and silt particles. The alterations in grain size distribution also influence the reference void ratios (e_{min} and e_{max}), particularly in soil Alva2. Besides the loss of fines, there is an increase in particle angularity caused by breakage at temperatures over 250 °C.

To assess whether these modifications influence the geotechnical behaviour of the soils studied, shear strength and hydraulic conductivity tests were performed on samples with a relative density of 50%. It becomes evident that reducing fines and increasing particle angularity significantly enhance the soils' peak resistance and the hydraulic conductivity of samples, namely in Alva2.

- By plotting the failure shear stress against the four normal stresses on the Mohr-Coulomb plane. Consequently, the angle of shear resistance increased by 2.4% and 11.8% for soils Alva1 and Alva2, respectively. These findings contradict recent studies that report a decrease in the mechanical response of burned soils.
- However, when examining the critical state parameters, no clear pattern emerges.
- On average, both soils exhibit an 85% increase in their coefficient of hydraulic conductivity. This increase is associated with the rise in the reference void ratio of both soils.

This work emphasises the geotechnical changes in soils caused by burning processes. Although using the furnace heating method to simulate he effects of real wildfires has limitations, the study confirms that soils' mechanical and hydraulic responses are significantly affected by wildfires. However, relying solely on a geotechnical approach without accounting for external factors is insufficient for predicting slope stability affected by wildfires and fully understanding the failure mechanisms observed in the area of study. Factors like root decay and water-repellent layers associated with local vegetation should be considered in geotechnical analyses. Future research should include shear strength tests on soils with roots at various decomposition stages induced by heating, and slope stability assessments that account for water-repellency effects.

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