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Mechanical Behavior of Soils Polluted by Olive Mill Wastewater – Case Bouladhieb Evaporation Pond Site, Sfax, Tunisia

Noureddine Hamdi[1*], Ali Ellouze[2], Haithem Ben Jamaa[3], Moncef Zairi[4]

[1] Laboratory RAE, Sfax National School of Engineers, University of Sfax, PB 1173, 3038 Sfax, Tunisia
[2] Unit GPMM, Sfax National School of Engineers, University of Sfax, PB 1173, 3038 Sfax, Tunisia
[3] Tunis El Manar University, National Engineering School of Tunis, Civil Engineering Laboratory, BP 37, 1002, Le Belvedere, 1002, Tunis, Tunisia
[4] Laboratory 3E, Sfax National School of Engineers, University of Sfax, PB 1173, 3038 Sfax, Tunisia
* Corresponding author's e-mail: noureddine.hamdi1975b@gmail.com

ABSTRACT

Several Mediterranean countries, including Tunisia, face significant soil contamination from olive mill wastewater (OMW) produced during olive oil manufacturing. This pollution poses major environmental risks, impacting soil dwelling organisms and humans through food chains, yet it remains poorly understood. This experimental study aims to understand the short and mid-term mechanical behavior of OMW contaminated sites. Conducted at an evaporation pond in the Bouladhieb area in the south-east of Tunisia, the research compared the physical, chemical, mechanical, and geotechnical properties of virgin soil with those of soil artificially polluted by OMW at contamination rates up to 15% of the virgin soil's weight. The study provided significant insights and data to forecast OMW's impact on soil and guide strategies for soil rehabilitation and environmental management in regions frequently generating olive mill wastewater.

Keywords: olive mill wastewater (OMW), contamination, geotechnical properties, mechanical behavior.

INTRODUCTION

Several countries have many sites polluted by the discharge of OMW generated during olive oil extraction, particularly in the Mediterranean region. For instance, Tunisia produces approximately one million tons of olives annually for which about 950.000 m^3 of OMW are made (Elkadri et al., 2023). The chemical composition of OMW varies greatly both in quality and quantity. It is influenced by various factors, including the climate, the type of olive, the maturity of the fruit and the method used to extract the olive oil (Bettazzi et al., 2006; Justino et al., 2010; Khdair and Abu-Rumman, 2017). OMW generally consists of water (60 to 70%), unextracted olive oil (30 to 40%), organic matter, and other substances such as polyphenols, fatty acids, sterols, and phenolic compounds (El Kafz et al., 2023). This composition leads to significant environmental issues by complicating biodegradation. Its resistant substances accumulate as pollutants, making environmentally friendly treatment and disposal more complex and costly (Mehdaoui et al., 2023). The presence of high levels of phenolic compounds, in particular, poses major challenges for its decomposition and environmental management (Hanafi et al., 2011).

In Tunisia, the storage and evaporation of OMW in collective basins remains the most common practice. Currently, 150 storage sites for OMW are identified, with approximately half of these sites being established individually on private land by oil mill owners, while the others are public facilities (Elkadri et al., 2023). However, the direct application of OMW to soils, though less common, remains an illegal disposal method. These two practices raise significant concerns due to their potential effects on the chemical, physical, and mechanical properties of soils. Such modifications can alter the soil structure, reduce its fertility, and compromise its mechanical behavior, thereby jeopardizing the sustainability of agricultural practices and the health of ecosystems.

Predicting the impacts of this type of pollutant on soils represents a major challenge for many researchers and engineers. This issue raises several critical questions:

- How do contaminated soils behave?
- Is the treatment of polluted sites essential? If so, which decontamination techniques should be employed?
- How much time is required to treat a specific site and what are the associated costs?
- Would it be more effective to treat OMW before its discharge rather than addressing the pollution at contaminated sites?

To answer these questions, research in several areas is needed. These questions have prompted many researchers to study both the short- and long-term impacts of OMW on various aspects of soil health. With results indicating varied impacts on soil structure, microflora, and overall fertility. The impacts of OMW application show that although it can temporarily improve some physical soil properties such as water-holding capacity, it can also lead to salt accumulation in clayey soils. This accumulation could impact the soil's structure by reducing its hydraulic conductivity, which is vital for determining the allowed amount of OMW to be applied to a given soil. These OMW induced changes can be detrimental to overall soil's health and structure, affecting soil's stability and potentially compromising the long-term viability of agricultural land (Barbera et al., 2013; Mahmoud et al., 2010). Furthermore, (Kavvadias et al., 2015) focused on the impacts of toxic substances contained in OMW, such as phenolic compounds, on soil microflora. They discovered that these compounds could have significant adverse effects on soil microflora, compromising essential ecological functions of the soil and thereby reducing agricultural productivity. Their research highlights the importance of carefully managing OMW application to protect vital soil ecological functions and maintain agricultural productivity.

Applying OMW at different doses to olive fields over three years significantly influenced the physicochemical and microbial attributes of the soil. This treatment enhanced the soil's composition, notably by increasing levels of organic matter, nitrogen, and potassium, which are crucial for fertility. Soil microbial activity is also improved without any noticeable negative effects, even after three years of application. Similarly, studying the extended impacts of applying OMW on the chemical and biological characteristics of soil in Campania, Italy, showed that yearly applications of 30 cubic meters per hectare of OMW had minimal effect on soil acidity, electrical conductivity, and organic content. A notable increase in microbial respiration during the summer months was observed. These results suggest that using OMW as a substitute for chemical fertilizers could be an effective and eco-friendly solution, preventing issues like soil salinization and sodification (Magdich et al., 2013; Vella et al., 2016).

Another study investigated the use of OMW as biopesticides for crop protection. This study highlighted the antimicrobial properties of OMW, enriched with organic matter and minerals, to fight against plant pathogens. The results suggest that OMW can effectively reduce reliance on chemical pesticides, providing a sustainable alternative that promotes both ecological waste management and improved soil health (El-Abbassi et al., 2017). Similarly, another study focused on the environmental impact of using OMW and olive waste compost as soil amendments, particularly on the risks of groundwater contamination. The findings demonstrated that even when these wastes are applied at rates exceeding legal limits, the impact on groundwater quality remains minimal (Caputo et al., 2013).

The results of the study conducted using electrical resistivity tomography (ERT) to evaluate OMW disposal sites in the Sidi Bouzid region of Tunisia show that ERT effectively identifies OMW infiltration areas, revealing contamination in the porous underground layers. This allows for monitoring and managing contaminant movements, thereby limiting negative environmental impacts. Similarly, potassium concentrations in the discharge of karst springs have been demonstrated as reliable indicators of pollution from OMW, allowing for the estimation of infiltrated volumes. This method provides precise tracking of contamination and facilitates the environmental management of karst aquifers, which are vulnerable to rapid pollutant infiltration (Hamdan et al., 2020; Issaoui et al., 2023).

Research on the treatment of OMW through distillation followed by lime neutralization has revealed significant reductions in phenolic compounds, chemical oxygen demand (COD), biological oxygen demand (BOD), conductivity, and chloride levels. These findings suggest effective methods for mitigating the negative effects of OMW on soil (Ouabou et al., 2014). These impacts are further examined in another study, which indicated that the infiltration of wastewater into underlying layers causes salts to dissolve and alters the concentration of phenolic compounds, which can have consequences on soil quality (S'Habou et al., 2005).

Applying OMW to soils can enhance certain physical properties, such as water holding capacity. However, it can also result in soil salinization and reduced hydraulic conductivity, particularly in clay soils. Similarly, it can degrade the physical and hydraulic properties of soil, with the impact being more pronounced at higher application rates and primarily affecting the surface layer (Albalasmeh et al., 2019; Tamimi et al., 2016).

Pollution from similar pollutants, like hydrocarbons and industrial wastewater, poses a significant challenge for many industries. However, this issue has led to numerous innovative studies focusing on the mechanical properties of polluted soils and how to treat them. For example, bioremediation techniques have been successfully used to clean diesel-contaminated soils by adding amendments like coconut ash powder, biofilter-activated sludge, and NPK fertilizers to improve the removal of hydrocarbons (Rajamohan et al., 2019). Similarly, extensive research has been conducted on how soil contamination affects mechanical properties, especially how different contamination levels impact vertical and lateral movements under combined axial and cyclic lateral loads (Karkush, 2016). Furthermore, the use of pozzolanic leaf ashes and plastics have shown an improvement of geotechnical properties of soils, providing a sustainable and economical approach for soil stabilization (Yathushan and Puswewala, 2022).

However, research focusing specifically on the mechanical behavior of soils polluted by OMW, such as strength, compactness, bearing capacity, and compressibility, are rare. This highlights the need and the importance of our research, which aims to explore these understudied aspects to determine whether construction on these contaminated sites without treatment is possible, or whether these soils can be used as borrow materials for road projects, provided that their mechanical, physical and chemical characteristics are appropriate and that environmental standards are respected. The main objective of this research is to understand and predict the mechanical behavior of soils contaminated with OMW over the near and intermediate term. The experimental approach followed used samples, of the Aguareb evaporation pond on which series of chemical, physical and mechanical tests have been made. Based on the results obtained, hypotheses have been developed for the mechanical behavior of soils polluted by OMW.

MATERIAL AND METHODS

Site description

The studied site lies in the Bouladhieb area, within the Agareb delegation in the governorate of Sfax, southern Tunisia, at an altitude of 130 meters above the sea level, with geographical coordinates of 34.7302° N latitude and 10.4421° E longitude, approximately 30 kilometers from the city of Sfax (Figure 1).

It covers a total area of approximately 70 ha with evaporation ponds built without an impermeable layer. After the discharge of OMW into the reception basin and when they reach the 1.5 m level, the siphoning system begins to operate and the OMW is transferred by gravity flow through prefabricated siphons which cross the north and south dikes of each basin. This storage system

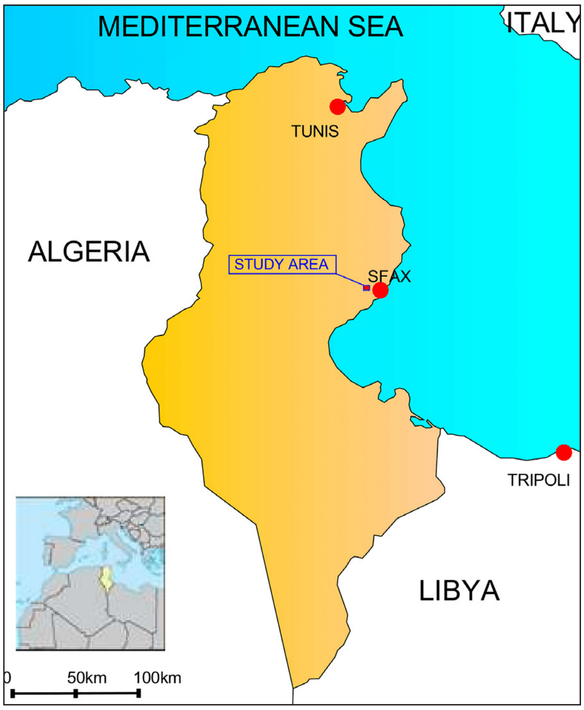

Figure 1. Location map of the study area

allows treatment of OMW by evaporation, especially since the arid climatic conditions of the region further help this phenomenon. The siphoning system accentuates evaporation, since the circulation of OMW takes place through the lower part of the basin and the majority of the oily phase will be trapped in the reception basin. This oily fraction is recovered by a manual scraping system. The storage basins feed the drying beds by pumping, the depth of which is limited to 30 cm. The part that remains after drying will be recovered by a shovel and stored on site. At the end of the campaign, the reception basin will be cleaned and the remaining contents will be moved into emptying bins.

The capacity of this basin is 525.000 m^3, the OMW quantities produced by the region's oil mills far exceed this capacity, especially for high productibility seasons, from which a part is spread to the fields. Recognizing the environmental challenges and hazards resulting from ecosystem pollution by OMW, it is essential to conduct a study to evaluate the mechanical behavior of the contaminated soil.

Sampling

In December 2019, samples of OMW and virgin soils were collected from the described site to carry out this study. Representative samples of stored OMW were also obtained from the storage basin. For virgin soils, a manual sampling tube was used according to the ISO 18400-102 (2017) standard. The sample cores obtained measured between 0.5 and 1 meter in length (Figure 2).

Olive mill wastewater characterization

Olive mill wastewater, known as "OMW", is a liquid derived from the olive oil extraction procedure. Physically, it is characterized by a cloudy appearance with a color ranging from brown to black, and a viscous consistency. Chemically, it is abundant in organic matter, including phenols, polyphenols, oils, and fats contributing to its high COD and BOD. It also contains minerals such as potassium and phosphorus, along with significant levels of sodium and chloride, resulting in high salinity. This complex composition makes olive mill wastewater potentially polluting to the environment if not properly treated. The characteristics of OMW are heavily influenced by several factors, including the oil extraction method, the type and maturity of the olive fruit, the prevailing climate and soil's conditions.

The composition of OMW includes a variety of parameters with specific ranges, as summarized by (S'Habou et al., 2005). The pH of OMW ranges from 4.5 to 5.2, and its electrical conductivity is between 8 and 16 mS/cm. The COD varies from 45 to 130 g/L, while the BOD ranges

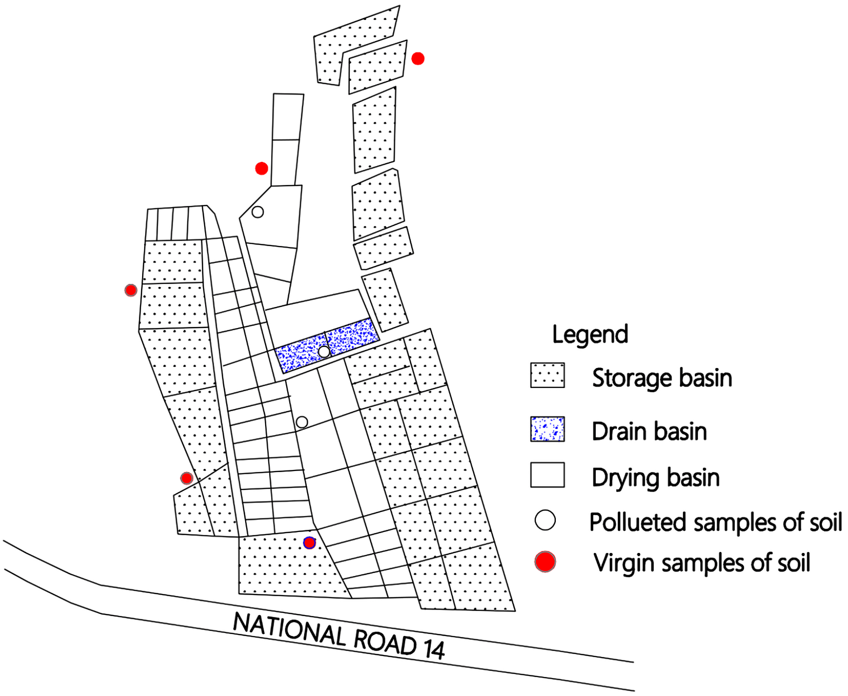

Figure 2. Locations of the soil samples taken around the study area

from 35 to 100 g/L. Suspended solids are present in concentrations from 1 to 9 g/L, and total solids range from 60 to 120 g/L. Mineral solids account for 5 to 15 g/L, and volatile solids are found in amounts ranging from 55 to 105 g/L. The sugar content of OMW is between 10 and 80 g/L. Pectins, mucilage, and tannins range from 3.7 to 15 g/L, while polyalcohol is present with concentrations ranging from 1.1 to 15 g/L. Polyphenols range from 5 to 24 g/L, and fats vary from 0.5 to 10 g/L. Organic acids are found in amounts from 5 to 10 g/L, and amino acids range from 2.8 to 20 g/L. The total concentration of various ions in OMW, such as phosphate, chloride, sulfate, sodium, potassium, calcium, magnesium, and manganese, amounts to approximately 23.0 g/L.

Soil characterization

In this study, physical, mechanical, and chemical characterization tests on a sample of virgin soil collected from the study site were conducted. The physical tests included measuring the particle density in accordance with ISO 17892-3 (2015) and the dry bulk density following ISO 17892-2 (2014). These tests provided crucial information on the density and compactness of the soil, which are essential for evaluating its stability. The water content was measured according to ISO 17892-1 (2014), a method for evaluating the humidity present, which influences the cohesion of the soil. The particle size analysis was performed following ISO 17892-4 (2016), while the sand equivalent was determined following the NF EN 933-8+A1 (2015) standard to estimate the quality and purity of the sand. Permeability was analyzed according to ISO 17892-11 (2019) to measure the water filtration rate through the soil, helping to predict the capacity of the soil to drain water, and the Atterberg limits, determined according to ISO 17892-12 (2018), revealed the plasticity of the soil. These tests provide a comprehensive overview of the soil's physical properties and structural stability.

The mechanical tests included a Proctor test carried out according to NF P94-093 to determine the optimal compactness of the soil, and a CBR test in conformity with NF P94-078 to measure its bearing capacity. The direct shear test, conducted in accordance with ISO 17892-10 (2018), assessed the shear strength of the soil. The odometer consolidation test, carried out according to ISO 17892-5 (2017), provided information on the compressibility of the soil. These mechanical tests are crucial for evaluating soil performance in terms of strength, bearing capacity, and deformation, providing essential data for the design and construction of foundations, embankments, and other civil engineering structures.

For the chemical tests, the sulfate content was measured in accordance with NF EN 1744-1+A1, while the total organic carbon content was determined according to standard NF EN 15936 (2022), revealing the chemical components present likely to influence the reactivity and stability of the soil. These analyses provide essential information for assessing potential environmental impacts and risks associated with soil management, ensuring a thorough understanding of chemical characteristics that can affect its physical and mechanical properties.

Furthermore, we mixed OMW with the same virgin soil in proportions of 5%, 10% and 15% of the total soil mass to study the resulting changes in behavior. The retained OMW pollution rates were determined from the test results of the contaminated samples collected from various locations across the study site and the requirements of the laboratory tests. The soil was mechanically mixed using laboratory mortar mixer by gradually adding the OMW until obtaining a homogeneous polluted soil. All tests performed on the virgin soil sample were also conducted on the polluted soil samples. However, for physical tests, only permeability tests, particle size analyses, and Atterberg limits were applied.

RESULTS AND DISCUSSION

Virgin soil characterization

Virgin soil samples collected from carefully selected locations within the study site have undergone characterization tests and the obtained results will be compared with those from artificially contaminated soil samples. Based on the findings from the chemical identification tests, a sulfate rate of about 11.20% and a total organic carbon rate of nearly 14.80% were observed. The results of the physical identification tests conducted on the virgin soil samples are summarized in Table 1.

From the particle size distribution curve and the data presented in the table above, we notice that 47.76% of the elements have a diameter of less than 80 μm, while 97.80% have a diameter less than 2 mm and 95.75% of particles have a

Table 1. Summary of physical characterization test results for virgin soil

Test	Value
Water content	7%
Particle density	2.364 g/cm^3
Bulk density	1.23 g/cm^3
Sand equivalent	ESP = 9%; ESV = 7%
Atterberg limits	LL = 40%; PL = 18.5%
Permeability	K_{20} = 4.193.10^{-6} m/s

diameter greater than 80 nm. The virgin soil exhibits a liquid limit (LL) of 40% and a plasticity index (PI) of 21.5%.These findings confirm that the virgin soil under study is a clayey sand with low permeability, as classified by the French Central Laboratory of Bridges and Pavements (LCPC) for granular soils.

The results of the mechanical identification tests conducted on the virgin soil samples are summarized in Table 2. According to the results of the mechanical identification tests, we observe an immediate CBR rate of approximately 12.70%, a compression coefficient (Cc) of 0.1265, and a pre-consolidation stress (σ'_p) of 135 kPa, which is higher than the vertical effective stress (σ'_{v0}) of 25 kPa. These results clearly indicate that the soil studied is fairly compressible and over-consolidated.

Artificially polluted soil characterization

Chemical, physical and mechanical identification of polluted soil are carried out on samples of virgin soil to which OMW has been added at predefined rates, as indicated above.

Chemical characterization

Chemical identification results of artificially polluted samples are shown in Figure 3. Based on the results of the chemical identification tests, it was observed that adding 5% OMW to the virgin soil resulted in a decrease in sulfate content to 10.47%. However, when the OMW rate was increased to 10%, the sulfate content rose to 11.30%. Additionally, the percentage of total organic carbon consistently decreased with the addition of OMW, reaching a value of 13.1% at a 15% OMW rate.

Analysis of the chemical test results conducted on both virgin and contaminated soil with various rates of OMW makes it possible to deduce tendencies in the variations of the soil's chemical properties. The sulphate and total organic carbon contents are used to characterize the chemical

Table 2. Summary of mechanical characterization test results for virgin soil

Test	Value
Odometer consolidation	C_c = 0.1265; C_s = 0.013; e_i = 0.472; e_0 = 0.465; σ'_p = 135 KPa; σ'_{v0} = 25 KPa
Direct shear	C = 29.51 kPa; ϕ = 35.09°
Proctor	W_c = 17.70%; γ_d = 1.833g/cm^3
Immediate CBR	CBRi = 12.70

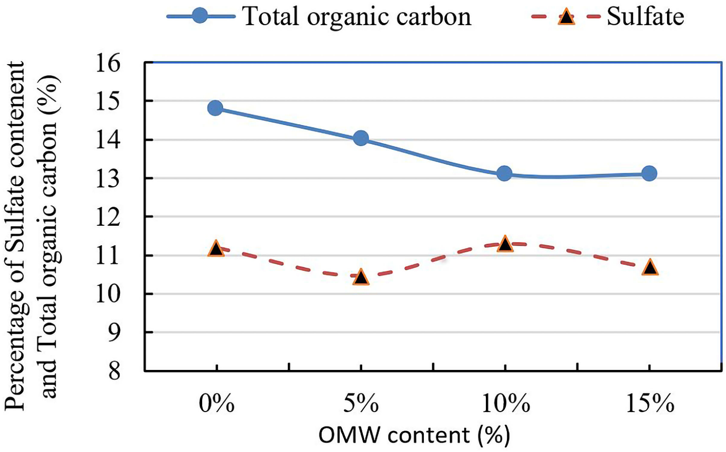

Figure 3. Evolution of the proportion of total organic carbon and sulphate content according to the OMW content added

nature of the soil and can reveal how OMW influences the chemical composition of the soil. For the sulphate content, there is no clearly defined trend concerning the variation of the sulphate level with the addition of OMW. However, a slight decrease in the sulphate rate is observed when the OMW is added to 5%, but this rate rises slightly to 10% and finally drops to 15%. This fluctuation could be due to the complexity of the chemical interactions between the olive margin and the soil. Unlike sulfate content, the trend for total organic carbon content is more evident. As OMW is gradually added, the TOC rate consistently decreases. This might seem counterintuitive since OMW supplies organic material. However, it is possible that introducing OMW dilutes the existing organic carbon in the soil or stimulates microbial processes that consume the organic carbon.

In conclusion, adding OMW to the soil appears to impact its chemical characteristics, but in a non-linear way. While sulfate content fluctuates without a clear trend, the total organic carbon content decreases with increasing OMW rates, indicating a complex interaction between OMW and the soil.

Physical characterization

The physical identification tests revealed several key trends. First, there was a decrease in the coefficient of permeability up to an OMW addition rate of 5%, followed by an increase in this coefficient as more OMW was added (Figure 4). The Grain size distribution (Figure 5) shows a slight variation in which the percentage of particles with diameters less than 80 µm and those less than 2 mm both decreased with increasing OMW rate. This can be related to the fact that the oily character of the added substance plays a separating role for bigger particles and a cohesive one for small particles.

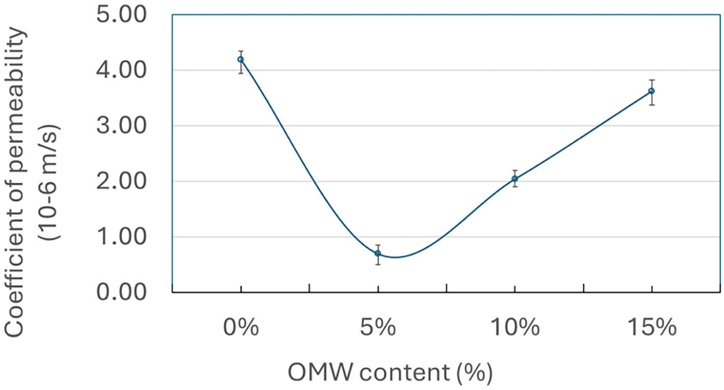

Figure 4. Evolution of the coefficient of permeability according to the OMW content added

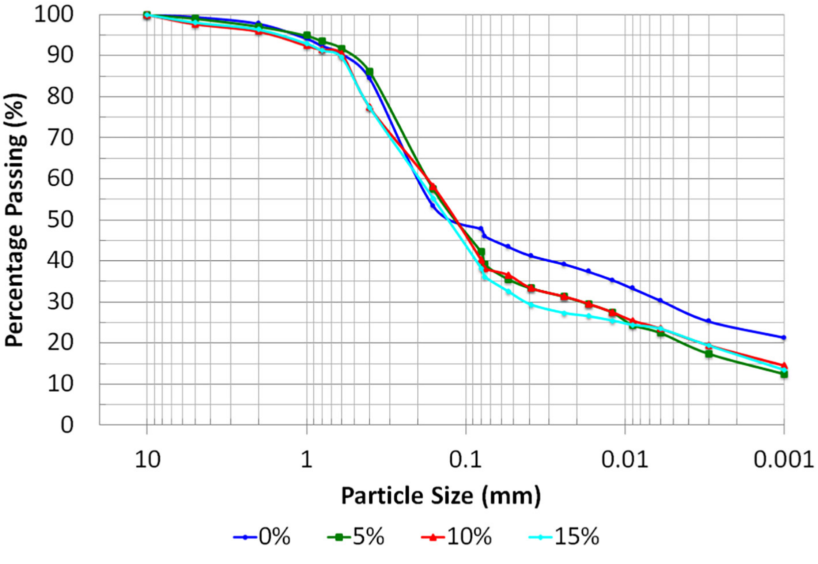

Figure 5. Grain size distribution for all the tested soils

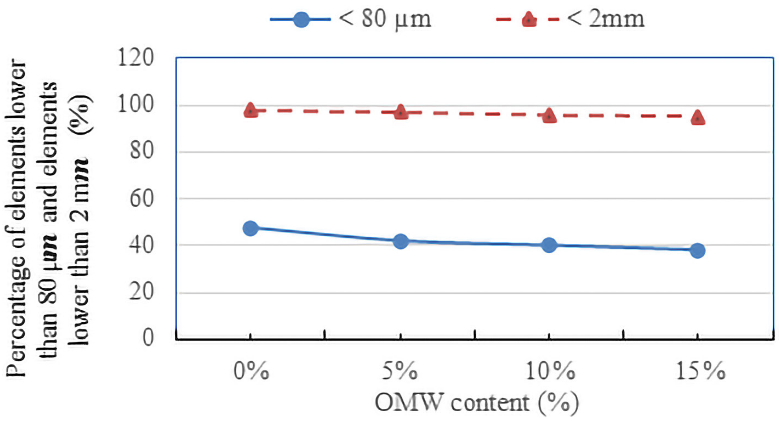

Figure 6. Evolution of the percentage of elements with a diameter lower than 80 µm and elements with a diameter lower than 2 mm according to the OMW content added

Furthermore, the liquid limit of the soil samples decreased with OMW additions up to 10%, but then increased at a 15% addition rate. Simultaneously, the plasticity index consistently decreased as more OMW was incorporated (Figure 7).

Analyzing the physical tests performed on soil samples, subjected to varying percentages of OMW, highlights the progressive physical effects of this substance on the soil's geotechnical properties. At 5% of OMW, the decrease in the liquid limit, indicating a decrease in cohesion, could result from the interaction between soil particles and the organic matter in the OMW, disturbing the inter-particle bonds. In addition, the significant drop in permeability suggests that organic matter and fine OMW particles clog soil pores, impeding water flow.

At 10% of OMW, although the permeability shows signs of improvement, it remains below the initial values. Soil plasticity increases, as indicated by the elevation of the plastic limit, suggesting that the organic matter in the OMW acts as a binder between soil particles, increasing its ability to deform without breaking. At 15% of OMW, the liquid limit returned to its initial level, which could indicate the saturation of the interaction sites between OMW and soil particles, thus stabilizing the interparticle bonds. However, even though the permeability is better than that observed at 5%, it remains lower than the initial value, still reflecting the presence of obstructions in the water flow ways. Moreover, with each increase in the OMW rate, the reduction in the proportion of particles passing through the 80 – micron sieve can be ascribed to the clumping of fine soil particles, likely caused by the organic matter in OMW acting as a binder. These results presented are in line with what can be expected when a soil is affected by the introduction of an external substance such as the OMW.

The introduction of OMW into the soil causes noticeable changes in its properties. Initially, with the increase in the rate of OMW, the organic matter present seems to play a "binder" role. This is evident by the tendency for fine particles to

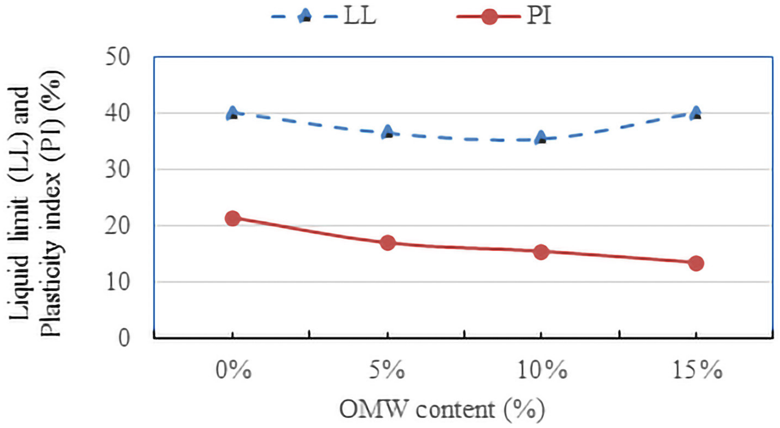

Figure 7. Evolution of the liquid limit (LL) and plasticity index (PI) according to the OMW content added

agglomerate, influencing the particle size distribution and causing a decrease in the elements passing through the 80 – micron sieve. This binding ability of OMW can be mainly attributed to its organic matter, which promotes cohesion between soil particles, leading to a more malleable soil, as shown by increased plasticity. However, exceeding a certain rate of OMW, it seems that it begins to manifest lubricating properties. This effect is noticeable by the variations of permeability, where the increase in the rate of OMW does not make it possible to return to the initial permeability of the soil. This lubricating phase suggests a significant alteration in the soil structure and a decrease in friction between the particles. At 15% OMW, the return of some parameters to their initial values might indicate a transition between these two distinct effects: initially as a binder, then as a lubricant.

Mechanical characterization

The results of the odometer consolidation test indicate several key trends. The in situ and initial void indicators rise as the amount of OMW added to virgin soil samples increases up to 10%, then both indicators decline at a 15% OMW rate. The compression indicator increases until reaching a 5% OMW rate before decreasing at higher rates (Figure 8). Pre-consolidation stress increases up to a 5% OMW rate and then declines at a 10% rate (Figure 9). Despite adding OMW, the soil remains relatively compressible and over-consolidated, except when 5% OMW is added, at which point the soil becomes moderately compressible but remains over-consolidated.

The odometer consolidation test results on virgin soil samples as well as soils contaminated with OMW reveal significant changes in their consolidation properties, providing essential information on the influence of organic contaminants on the soil behavior. The increase in compression index (Cc) at lower rates of OMW indicates an increase in soil compressibility. This improvement is likely due to the binding effect of the organic matter found in OMW, which enhances the interaction between soil particles, making the soil more compressible. This phenomenon resembles

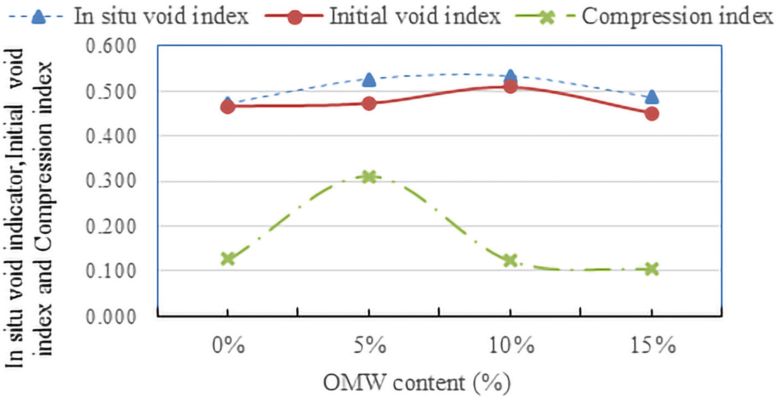

Figure 8. Evolution of the in-situ void indicator, Initial void indicator and compression indicator according to the OMW content added

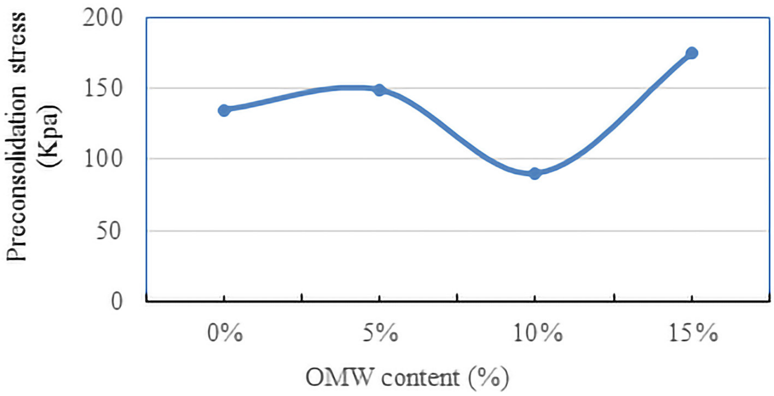

Figure 9. Evolution of the pre-consolidation stress according to the OMW content added

the findings reported by Authors in (AI-Sanad et al., 1995) in their studies concerning the impact of petroleum contamination on the geotechnical characteristics of sands. Additionally, a decrease in the compression index at higher OMW rates suggests an alteration in the internal structure of the soil. At these elevated contamination levels, OMW can function as a lubricating agent among soil particles, thereby reducing both the internal cohesion and bearing capacity of the soil. Furthermore, changes in the initial (e_0) and in-place (e_i) void indices, as well as the pre-consolidation stress (σ), suggest an overall alteration in the soil's ability to consolidate under loads. These results highlight the complex impact of organic pollution on soils and underline the importance of taking these effects into account in industrial waste management and geotechnical and environmental applications. Understanding these impacts is crucial for effective and sustainable management of contaminated soils and for developing rehabilitation strategies adapted to soils affected by organic contaminants.

Compaction curves according to the OMW content added are assembled in Figure 10. Based on the Proctor test results, the optimum water content decreases from 17.70% to 8.50% as OMW rate increases up to 10%. Beyond this rate, the optimum water content rises sharply to 17.60% at a 15% OMW rate (Figure 11). Meanwhile, the optimum dry density rises from 1.833 g/cm³ to 1.957 g/cm³ up to a 10% OMW rate before dropping rapidly to 1.783 g/cm³ at a 15% OMW rate (Figure 11).

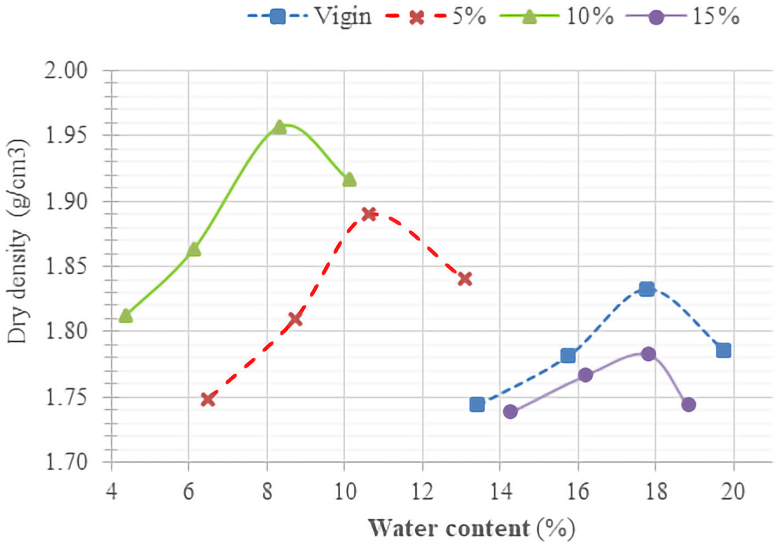

Figure 10. Compaction curves according to the OMW content added

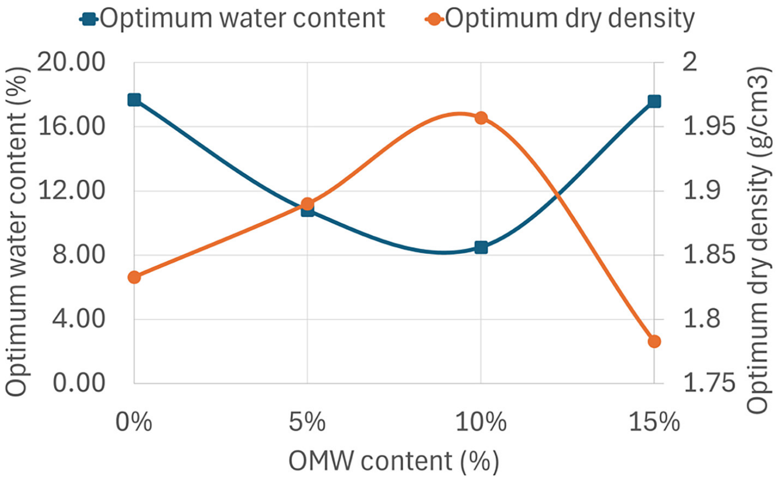

Figure 11. Evolution of the optimum water content and the optimum dry density according to the OMW content added

Analysis of Proctor test results on virgin soil samples and soils affected by OMW reveals a complex interaction between OMW and soil compaction properties. A notable drop in optimal water content for an OMW rate less than or equal to 10% indicates that moderate addition of OMW potentially improves soil compaction. This improvement could be due to the binding effect of organic materials which increase cohesion between soil particles, thus allowing effective compaction at lower moisture levels. This is consistent with the increase in cohesion coefficient observed in direct shear tests, where OMW at low concentration appears to strengthen interparticle bonds. Simultaneously**,** the increase in maximum dry density observed up to an OMW rate of 10% confirms the hypothesis according to which OMW, at moderate rates, contributes positively to strengthening soil structure. This improvement might be due to the binding effect of the organic matter in OMW, which solidifies the interparticle bonds and optimizes compaction. However, beyond this rate, a drop in dry density suggests a disturbance in soil architecture. This overload of organic matter seems to create an imbalance in the soil structure, thus compromising its compaction and mechanical.

CBR test results show that the bearing capacity increases with the addition of OMW, the immediate CBR indicator increases from 12.70% to 18.46% with the addition of a rate of 10 % then it decreases with a rate of 15% of OMW and reaches the value of 8.79 % (Figure 12).

CBR tests on virgin soils and those polluted by OMW show notable fluctuations with increasing OMW concentrations, indicating a significant alteration in the soil's load-bearing capacity. At concentrations of around 10% OMW, an improvement in CBR values is observed, suggesting soil reinforcement, likely due to the binding effects of organic matter, as noted in similar contexts in (Choura et al., 2009) for soils contaminated with crude oil. However, at higher OMW concentrations, a decrease in CBR values is noted, attributable to the supersaturation of the soil with organic matter, thus reducing its bearing capacity. This pattern aligns with the general understanding of soil behavior under the influence of pollutants, where moderate levels of organic contamination can improve soil properties, while excessive contamination leads to a decrease in mechanical strength.

The direct shear tests results show that the addition of OMW to the soil had an effect on both the shear resistance angle and the cohesion. Specifically, the shear resistance angle remains almost constant until a rate of 5% OMW, then increased to 35.75° at a rate of 10% of OMW before decreasing to 32, 59° at a rate of 15% of OMW. At the same time, the cohesion increased from 29.51 kPa to 41.83 kPa at a rate of 5% of the OMW and remained almost constant before decreasing to 25.63 at a rate of 15% of OMW. These findings indicate that the incorporation of OMW can both enhance and alter the soil shear resistance properties, depending on the content of the OMW (Figure 13).

By adding OMW to the soil, a complex interaction is revealed between the cohesion coefficient and the shearing resistance angle. At a rate of 5% of OMW, the cohesion increases, while the angle of shearing resistance remains almost constant. This increase in cohesion can be interpreted as the result of the "binding" effect of OMW. The organic substance probably functions as a binding agent, strengthening the interparticle bonds, similar to the soil strength improvement observed with oil contamination (AI-Sanad et al., 1995). At a rate of 10% of OMW, the cohesion remains

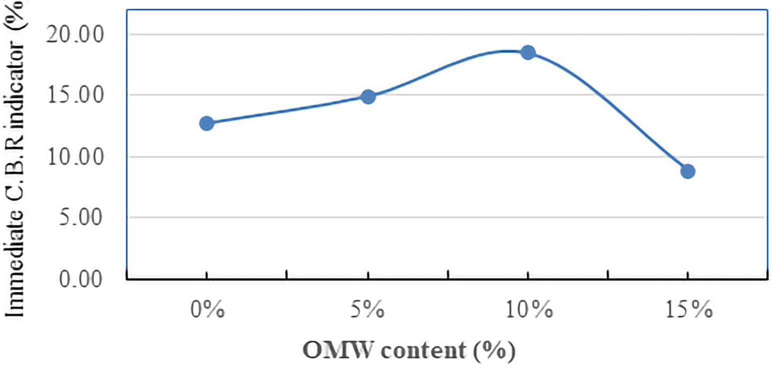

Figure 12. Fluctuation in the immediate CBR indicator according to the OMW content added

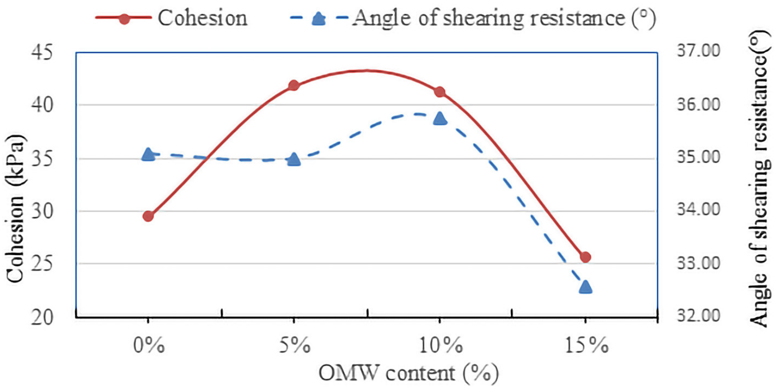

Figure 13. Fluctuation in the angle of shearing resistance and cohesion according to the OMW content added

roughly stable, but the angle of shearing resistance increases slightly, suggesting a slight increase in soil shear strength. This observation aligns with the conclusions of Authors in (Khamehchiyan et al., 2007), who documented similar trends in soils contaminated with other types of organic matter. However, at rate of 15% OMW, a significant drop in cohesion and angle of shearing resistance occurs. This reversal suggests a potential "lubricating" effect where excess OMW reduces friction between particles, thereby compromising soil shear strength. In conclusion the addition of OMW to the soil seems to have a double effect. At low to moderate rate (up to 10%), it acts primarily as a binding agent, improving soil cohesion and, therefore, its shear strength. However, above this rate, OMW appears to exhibit a lubricating effect, reducing soil strength.

The findings from analysis conducted on both virgin and contaminated soil samples revealed that the addition of OMW at a rate less than or equal to 10% of its weight had a positive impact on certain soil mechanical properties in the short and medium term, such as compression indicator, optimum water content, optimum dry density, shearing resistance angle, cohesion and immediate CBR indicator. These positive impacts result from the role played by a thin film of OMW which covered the soil grains, acting as a binder and contributing to the formation of more compact and resistant aggregates.

CONCLUSIONS

This study investigated the impact of OMW on soil characteristics, evaluating both virgin and contaminated samples. Notably, an OMW concentration of up to 10% improved several mechanical properties such as compression indicators, optimal water content, dry density, shearing resistance, cohesion, and immediate California Bearing Ratio (CBR). These benefits arise because OMW acts as a binder, forming compact and resilient soil aggregates. Chemical analyses revealed varying impacts of OMW on soil chemistry, with sulfate content showing slight fluctuations and total organic carbon consistently decreasing with increasing OMW, likely due to dilution or microbial degradation. Physical tests indicated that OMW progressively modifies soil structure; at a 5% concentration, it reduces liquid limit and permeability, disrupting inter-particle bonds and potentially blocking pores.

This improvement is likely attributed to the effect of the organic compounds in OMW, which serves as a binder, enhancing the interactions between soil particles. This paves the way for the valorization of this product by exploiting it for other applications, such as using it as a watering agent for filling materials in road projects while respecting environmental standards. However, the research also reveals that higher OMW rates start to produce harmful effects, disrupting soil structure and reducing its strength. This trend is particularly explained by the lubricating effect of OMW at these high rates, which reduces cohesion between soil particles. These observations emphasize the importance of careful management of OMW rates in the soil.

The future prospects of this research highlight the importance of additional studies to assess the long-term effects of OMW on the characteristics of the soil. Understanding biodegradation processes and their long-term environmental impacts is crucial for developing effective strategies for managing contaminated soils. This study provides essential information to guide soil rehabilitation practices and environmental management in contexts where OMW is a frequent by-product, enriching the knowledge of the interactions between soils and organic contaminants while paving the way for sustainable and informed practices.

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