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Reuse of Tunisian excavated soil in urban green infrastructure

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Abstract

Among the most voluminous civil engineering wastes, consequence of urbanisation, is excavated soil or material, called MATEX. The study draws a methodology for assessing through selected standard tests the environmental, geotechnical, and agronomical features of excavated soil to highlight the most ecological way to reuse these soils. In view of making a constructed soil to be implemented within green infrastructure part of new urban landscape, imperative skills of soil are referred to as SWOFI: safety, workability, fertility, infiltrability.

As a practical case of the application of the methodology, a soil of low agricultural value excavated from industrial zone of Hached in Tunisia has been characterised. This excavated soil is a negligible source of pollution hazard by heavy metals. It classifies in a category very sensitive to compaction and strongly influenced by the clay content, so difficult to reuse in road applications. It is very poor in organic matter and alkaline with a sandy loam texture, so grape marc waste is used to improve its fertility, thus making a 'composite soil'. This allows the valorisation of local agriculture waste throughout the designed strategy.

Novelty resides in the selection of tests and the association of technics issued from usually separated disciplines – mainly geotechnique and agronomy – and the integrated workflow of the soil at three stages of the value-chain: excavated-homogenised, amended, then reconstituted at a given bulk density as a composite soil. A study of permeability was conducted to select the best pedotransfer functions (PTFs) for the excavated soil. Based on required intervals of permeability for the projected use in green infrastructure, a decision-making table is applied with, as input, the most probable value of permeability. Combining pollution hazard management, geotechnical

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improvement, agronomical amendment, an innovative approach leads to pedological and hydrological functionality for constructed soil, a nature-based solution.

Keywords Soil safety, Workability, Infiltrability, Green and blue framework, Urban landscape, Nature-based solution.

1 Introduction

In recent decades, global economic development has caused a significant increase in urbanisation. Colonisation of cultivated zones by construction projects, transport infrastructure, commercial facilities, waste storage or treatment areas, generates environmental impacts on soils such as destruction, sealing, alteration of soil properties, which could lead to degradation of health level and well-being for society, disruption of biodiversity balance, and global warming acceleration for the planet. Until recently, despite increasing awareness at the inter-State level, the European Commission rules did not properly address land loss resulting from urban expansion and the development of brownfield sites (OJEU, 2003), and so did Mediterranean States.

Besides, the need for green infrastructure in cities is increasing, especially under arid climate (González-Méndez and Chávez-García, 2020; Grant, 1981; Smagin and Sadovnikova, 2015), also in countries undergoing climate warming and precipitation regime decay, with rainfall rarer while higher intensity storms, as it is the case in the Mediterranean. Green infrastructure (GI) is an innovative solution for urban landscape shaping and can provide many environmental benefits such as improved water quality, removal of air pollution, and enhancement of valuable ecosystem functions (Artmann et al., 2019; Elliott et al., 2020; Hewitt et al., 2020; Ramyar et al., 2020). Creating a GI need high quality and structured topsoil for plant and fauna to grow (Sarah et al., 2015) while preventing soil compaction, to support pedestrian traffic, to improve infiltration, and for pollutions to boost their degradation. But topsoil is not a readily renewable resource which can be simply found, excavated, and transported from rural to urban areas (Walsh et al., 2019).

As a result of construction activities, civil engineering waste has become one of the largest sources of global waste, accounting for about 45% of European waste volume (Gálvez-Martos et al., 2018). Most common studies in civil engineering focus on construction and demolition wastes (Hale et al., 2021; Silva et al., 2019) such as metal, concrete, mortar, brick, wood, plastic (Suchithra et al., 2022), to recycle them as construction materials for reuse in cement (Priyadharshini et al., 2018), concrete, brick, in building or road construction (Zhang et al., 2022).

Nevertheless, the most voluminous civil works waste is excavated materials or soils (MATEX). A fraction of MATEX generated by infrastructure or superstructure earthmoving projects (Guo et al., 2022), tunnel (Oggeri et al., 2014) and underground network construction projects, foundations, trenches (Chittoori et al., 2012) or any type of excavation, is reused as aggregates (Alnuaim et al., 2021). However, large quantities often end up in municipal landfills or are disposed in illegal areas (Magnusson et al., 2015). Like all wastes, MATEX cause environmental problems such as air pollution, soil and water quality degradation or even landslides. One objective of all countries should be to reduce environmental and economic impacts of these wastes by reusing MATEX. Beyond testing the adequation of MATEX (in particular, content in pollutants) with geochemical background of the targeted place of reuse (Li et al., 2018), available guidelines are rare, and no recommendation has been proposed in the Southern Mediterranean countries.

Constructed soils are a viable solution for MATEX reuse. They are made up of real stockpiled soils, excavation materials, demolition wastes, mixed with grinded green wastes (composted to different degrees). It is common

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enhancing the mineral material by including a supply of recycled biomass. The goal to create constructed soils will lead to work on arrangements of waste-materials in soil profiles. While reusing excavated soil waste to build GIs in cities, the export of high-quality soil from agricultural land to cities will decrease. In this paper, the concept of an urban soil grid is put forward in the same line of thinking as (Burrow et al., 2018) to consider GIs connected by trenches of constructed soil as a support for thriving biodiversity in cities. Note that alternatively, "de-sealing" actions will resort to constructed soils in GIs as well, to compensate for the creation of new built-up areas (Ugolini et al., 2020). Construction of soil is done for specific land uses in GIs such as parks and square lawns, urban farming, or green buffers for storm water management (Deeb et al., 2018; Minixhofer et al., 2022). Soil properties of constructed soil to be considered for assessing ecosystem functions differ according to the projected land use of GI. Following the implementation of a constructed soil, these properties are likely to evolve under the influence of external and internal factors, such as aggregation (Deeb et al., 2017) and carbon storage in soil. The process will ultimately result in a constructed soil that can be classified as a type of Technosol in the World Reference Base (WRB). The main ecosystem services expected from this new soil are improving surface conditions such as drainage by water infiltration-retention, or refreshment by evapo-transpiration and solar ray interception in urban areas.

From the excavated soil to the constructed soil, it is advocated here that several steps are to get through. The combination of materials of different origins suggests introducing the intermediate notion of composite soil. Then, in a similar logical as previously outlined for constructed soil with respect to GI, the characteristics of the composite soil to be considered and evaluated could be different according to the properties to be fulfilled by the constructed soil. Each soil property may be used in a semi-quantitative quotation table to define good, medium, insufficient, ability of the soil for a specific use. For instance, it is often desired that the constructed soil fulfils some expected interval of hydraulic conductivity. Imperative skills of composite soil are safety, workability, fertility, and infiltrability (SWOFI). Workability will be represented by a mechanical property, compactibility.

In this study, to improve the process of valorising excavated soil into constructed soil, a full methodology based on three characterisation methods of the excavated soil is drawn: environment and health hazard characterisation to assess the potential risks posed by heavy metals; geotechnical characterisation to assess if the soil can be reused in some building process; and agronomical characterisation to determine the soil composition and evaluate its fertility. To improve the soil structure and fertility, the excavated soil is mixed with organic waste. Characterisation of the excavated soil and the composite soil (mix of excavated soil and grape marc waste) is performed, the saturated hydraulic conductivity (Ks) is measured using constant-head permeability tests, then estimated by eighteen pedotransfer functions from the literature. To justify this characterisation methodology of the MATEX and composite soil, some of their parameters should be used at a higher level of data integration, in a decision-making aid procedure intended for the developer or the contracting authority use to project GIs. Finally, a decision-making table is promoted with as input the most probable value of Ks. The methodology has been applied on materials excavated by earthworks for the industrial zone of Hached in Tunisia as a case study.

2 Problem and goal

MATEX can be soft or hard rocks, gravels, sands, loams, clays, organic materials, sediments, or any other type of soil or subsoil material. Each material has its own way of valorisations: rocks, sands and sediments are the most common materials to be reused either as building materials in superstructure and infrastructure, or as embankment in flood

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control dykes. Soil characterisation methods as concern soil reuse are extremely limited and focused on the reuse pathways targeted by researchers in civil engineering, which might not be the best way for recycling soils from the ecology viewpoint. For techno-economic reasons, when mass reuse in civil engineering is possible, *i.e.,* the examples given in (Haas et al., 2021), the option of valorisation in constructed soil shall not seriously be studied. Up to now, research on the recycling of excavated soils in a pedological perspective is rare.

The literature on basic principles and applied methodologies for constructed soils was dominated by the recovering of derelict lands (Bech et al., 2017, 2016), mostly of mining, industrial or military origin, and generally polluted. A milestone book with a focus on pedology was "The restoration of land" by (Bradshaw and Chadwick, 1980). Pedotechnologies were also termed as "Pedotechnique" (Van Ouwerkerk and Koolen, 1988; Wilson and van Ouwerkerk, 1987) obviously in reference to geotechnical. (Koolen and Rossignol, 1998) stated the fundaments for the "construction and use of artificial soils". Recently, (Buondonno et al., 2018) gave an overview of pedotechnologies for the reclamation of degraded and derelict lands, and through a study-case intervention, suggested a protocol to ad hoc designing and building Technosols suitable for a reclamation addressed to the agricultural reuse of limestone quarries (see also: Simón *et al.*, 2018; Ruiz, Cherubin and Ferreira, 2020).

The characterisation of excavated soil, then the composite soil, is the most important step while so simple in appearance. One relevant illustration for this statement is given by (Obear et al., 2017) who observed clay lamellae neoformation in the sand putting green soils of a golf course less than ten-years after its settlement, which resulted in reduced water infiltration and a decline in turfgrass density. Clay did not originate from the breakdown of a calcined clay amendment that was used to construct the soil. They proposed that lamellae originated from clay that was initially present in the sand, which was translocated downwards and agglomerated at a textural interface of two horizons. This example highlights how much the initial characterisation of excavated soil may be crucial. However, a lack of characterisation methodology of soil parent materials and mixtures for soil construction is still noticed. To date, estimating the properties of a mixture from the characteristics of its constituents (Rokia et al., 2014), thus properties prediction of a composite soil, does not benefit from any straightforward procedure. Consequently, research in this field remains mainly empirical formulation of mixing ingredients. For instance, (Yilmaz et al., 2018) studied in situ five combinations of artefacts (urban and industrial wastes) in lysimeters, either as "growing material" (dedicated to plant growth) or "structural material" (as support for traffic), to see what it looks like. (Barredo et al., 2020) carried out a mesocosm experiment to assess the suitability for the reclamation of abandoned city plots, of six different Technosols resulting from the combination of four ingredients: construction and demolition wastes, bio-stabilised material from a municipal composting plant, recycled bentonites from a local industry, topsoil from vacant public plots.

The difference of the issue here with the main heuristics of this literature abstract is twice: first, the planned use of MATEX here is not reclamation of derelict land but the transformation of a sealed-soil urban environment; second, MATEX are not selected on purpose, they are not off-the-shelf solutions, rather they are imposed by contingency of civil works at the source of a long process towards valorisations. Our perspective is reuse of excavated soil into constructed soil for connecting GIs or to be implemented within GI. This perspective is undoubtedly attractive, but to convince decision-makers to choose this way of valorisations as a beneficial one, it is necessary to demonstrate that these excavated soils have characteristics suitable for the intended reuse. How can we demonstrate that without resorting to an empirical approach? As the targeted properties of the constructed soil depend on the final use and the values of properties themselves depend on the transformation process, there is no consensus about the intervals of needed characteristics of excavated materials. So, the suggestion is specifying the required properties of the composite

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soil that will be obtained from a transformation (homogenisation, amendment, arrangement) of MATEX, and this approach is illustrated by required intervals of permeability.

A characterisation methodology should distinguish between successive steps of construction the new soil. It is distinguished between five levels of consideration the term “soil”: i) the pre-existing in-situ soil from which were taken ii) the excavated parent materials at various points and depths, referred to soil by geotechnical engineers; iii) the composite material obtained from mixing excavated-homogenised parent materials with other wastes including organics; iv) the excavated-homogenised-reconstituted soil, which is man-made at the laboratory with horizons to mimic a real soil, will be called a composite soil; v) the constructed soil which is in-situ implemented composite soil within GI.

In this paper, we do not report any experiment on a constructed soil, nor do empirical research on mixture formulation. The vast subject of compost amendment is not focused either (see among other Deeb *et al.*, 2016; Kranz *et al.*, 2020): a local organic waste is used, from grape marc, to amend a poor excavated soil and go to the next step which is to evaluate the hydric properties of the mixture, composite soil. The main work here is to propose a methodology to characterise the soil at three stages of the value-chain: excavated-homogenised, amended, then reconstituted at a given bulk density as a composite soil. Most of tests used hereafter are standards. Novelty resides in the selection of tests and the association of technic issued from usually separated disciplines – mainly geotechnical and agronomy – and the integrated workflow from in situ soil to be excavated up to a composite soil to be implemented. Therefore, the goal is to define a strategy for a comprehensive laboratory characterisation of soil and organic waste, implement this strategy by assembling the components, and predict some mechanic and hydraulic properties of the composite soil, the compactibility, the retention capacity and permeability.

3 Materials and methodology

The assessment strategy of the parent materials, then mixed materials, is as follows. Evaluation of excavated soils should have four steps. The first step is an environmental characterisation, which provides the state of soil pollution: any reuse of this waste must comply with the environmental safety standards of each country. The second step is geotechnical characterisation, which is necessary to decide either reuse the excavated soil in civil engineering or study the soil behaviour in view of implementation into a constructed soil. The third step is agronomic characterisation to evaluate the fertility of excavated soil-organic waste mixture, a composite soil which allows us to qualify the excavated soil for the development of constructed soil within GI in urban areas. Second and third steps give insights in the retention properties of the investigated soil. As a fourth step, a full evaluation includes use of empirical relationship to predict hydraulic conductivity.

3.1 Study area, soil sampling and mixing, health safety characterisation

3.1.1 Geological and pedological context of the in-situ soil

The study area is in northeast Tunisia, half-way between the towns of Grombalia and Hammamet, governorate of Nabeul (Fig. 1), approximately 40 km from the capital Tunis, with approximate coordinates of 10°33' east longitude and 36°30' north latitude, using the WGS 84 geodesic system. The Grombalia plain is intensively, and unsustainably, cultivated for orange trees with the help of groundwater-based irrigation. According to the meteorological station at Lebna, near Nabeul, 75 mm/h is the intensity of a centennial rainfall event of one-hour duration. Geologically, the site

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is at the southward extremity of the Grombalia Quaternary graben infilled by continental deposits (aeolian, fluviatile) whose soils were lately encrusted. From the lithological viewpoint, the surrounding formations at the heights of the watershed are composed of marls, sandstone with calcite cement, conglomerates, sands and clays, heterogeneous association ranging from the Upper Miocene and continental Mio-Pliocene to the marine Pliocene. According to former pedological studies (Belkhodja et al., 1973), the soil of the study area is characterised by a high level of calcium carbonate, an alkaline pH, and a high level of active limestone. This type of soil is referred to as Calcisol in the WRB. The land cover of the study area is mostly composed of sparse vegetation, shrubs, and grassland. It includes relief domes and wadi branches and evidence that it has been left uncultivated for a long time. The industrial zone of Hached, covering an area of 82 hectares, will produce over 480,000 tons of excavated soil. The earthworks will be carried out in three sections, beginning in 2019, 2021, and 2023 for the first section of 20 hectares, the second section of 42 hectares, and the third section of 20 hectares, respectively.

3.1.2 Soil sampling and mixing

Soil was sampled at five locations at both sites so five samples for the first section in October 2019, and five samples for the second section in October 2021 (Fig. 1). Soil samples were taken with a backhoe loader to a depth of 0 to 400 cm. So, a total volume of two cubic meters at each section site was collected and immediately brought to the laboratory for further processing. Samples from each section site were combined to form two composite samples, thoroughly mixed. Each sample will be referred to as "soil 1" and "soil 2", used for the excavated soil of the first and second section sites, respectively. For the physical, chemical, mineralogical, environmental, agronomical, and geotechnical characterisation, a representative sample was reduced from each mixture of excavated soil, soil 1 and soil 2. For the laboratory analyses a sample splitter was used for the quartering procedures. The grape marc waste used in this research is found in large quantities in the region. To improve agronomical properties of both soils, excavated soil was mixed with a 5% volumetric fraction of organic waste (grape marc). Both materials were air-dried and sieved to 5 mm before being manually mixed. For both, a 20-litre mixture was prepared, and 2.5 litre of the mixture was placed in 3-litre containers. The mixture (95% excavated soil and 5% grape marc waste) was replicated five times, for five containers. During six months, each container was moistened three times a week with groundwater from the regional deep confined aquifer. To carry out the tests on the soil-organic waste mixture after a six month-period, samples were collected from the surface of each container using a cylindrical punch.

3.1.3 Environment and health safety characterisation

Evaluating the levels of trace metal contamination and associated ecological risk is important to determine if the projected reuse method for excavated soils is applicable. The environmental and health hazard characterisation was carried out by determining the total concentrations of heavy metals. Six metals, Cadmium (Cd), Chromium (Cr), Copper (Cu), Nickel (Ni), Lead (Pb), and Zinc (Zn), were measured in the excavated soil solution using an atomic absorption spectrophotometer after a total digestion procedure with a mixture of nitric, hydrofluoric, and perchloric acids. To assess the state of in-situ soil pollution, various indexes were suggested. The most common ones are the Geo-accumulation Index (I_{geo}), Contamination factor (C_F) and Degree of contamination (C_D), Ecological risk factor (E_r) and Potential ecological risk (RI). In this section, Müller (Müller, 1969) and (Hakanson, 1980) were chosen as references for environmental indexes as they made pioneer attempts to aggregate indexes of pollution impacts on aquatic media and soils together. This choice is honouring their holistic vision which has uppermost importance today. The details about each index (calculating formula, thresholds) are provided as an appendix.

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3.2 Geotechnical characterisation

Five samples were tested for each section site with the aim of determining the average bulk density of soil 1 and soil 2. A particle size distribution (for all particle fractions until 5 mm) was determined by a combination of dry sieving (after washing), for the fraction of soil more than 63 μm, and sedimentation using the hydrometer method for the fraction less than 63 μm according to standard ISO 17892-4. Wet sieving was performed to disjoint aggregates larger than 0.063 mm within samples. The consistency of the soil was estimated by using Atterberg limits: liquid limit w_L and plastic limit w_p were performed following standard ISO 17892-12. The Casagrande cup was used to determine the liquid limit (w_L); the plasticity limit (w_p) was assessed using the thread rolling method. The methylene blue test was performed according to the French standard NF P 94-068 to estimate the clay type content.

In order to complete the soil characterisation, mechanical and hydraulic tests were conducted. The Proctor standard test performed in this study is based on the French standard NF P 94-093: this test was used to find the compaction characteristics of soils by assessing the optimum moisture content and maximum bulk density, which is widely used for the study of soils and unconsolidated materials, in order to predict the stability of buildings or to determine the resistance of agricultural soils to compaction (Marshall et al., 1996). The normal energy was used in the Proctor test. Also, immediate bearing index (IBI) was measured for soil mixture compacted into CBR moulds using standard Proctor compaction at optimum moisture content according to the French standard NF P 94-078. The IBI test is a variant of the standard California Bearing Ratio (CBR) test, i.e., the immediate CBR test without surcharge (Mitchell and Soga, 2005). This index evaluates the aptitude of a soil to support the traffic of machines or vehicles. Hence, it is discriminant between several potential uses of a constructed soil. The IBI test is performed after the Proctor test, thus after compaction of the soil.

3.3 Fertility characterisation of parent materials and the composite soil

This section includes physical, chemical, and mineralogical characterisation of parent materials, then agronomical characterisation of the composite soil. The fertility potential of parent materials is characterised by pH, organic carbon content (OC), the C/N ratio, total and active carbonate content ($CaCO_3$), and cation exchange capacity (CEC). An estimate of the retention capacity of soil is required as a basic property and a component of the soil fertility. This estimation will be done with texture-base empirical relationship chosen for their good reputation in the international or French literature. Textural analyses of the < 2 mm fraction of soil were performed using a sieve for the sand fraction and pipet methods (the so-called Robinson pipet) for the silt and clay fractions after the removal of soil organic matter by hydrogen peroxide (Mathieu and Pieltain, 1998). The mineralogical composition of our samples was found using powder X-ray diffraction (XRD) with PANalytical equipment, model X'Pert PRO MRD, system operated at 40 kV voltage and a current of 45 mA. The methods of determination of physical, chemical, and mineralogical characteristics of parent materials can be found in the appendix.

To evaluate the composite soil composed by 95% excavated soil 1 and 5% grape marc waste mixed by hand, textural analyses were carried out with the same method as for excavated soil, while the grape marc waste was dried at 40°C and particle size distribution was determined by sieving. Chemical characterisation was carried out for the grape marc waste and the mixture of excavated soil-grape marc waste: soil total carbonate and active carbonate, soil organic matter (OM), the organic carbon (OC) and total nitrogen (N) were performed 6 months after mixing, together with pH and electrical conductivity (EC). Measurements of the saturated hydraulic conductivity Ks have been performed using a

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constant head permeameter for the composite soil, i.e., 95% excavated soil 2 and 5% grape marc waste, at a reconstituted bulk density of 1.6 g/cm^3.

3.4 Estimation of Ks by pedotransfer functions

Experimental in-situ estimation of Ks would require special equipment, expensive and time-consuming work (Abdelbaki, 2021; Gupta et al., 2006; Nasri et al., 2015a, 2015b; Paige and Hillel, 1993; Reynolds et al., 2000). Alternatively, there are models to determine the porosity of mixed two granular materials, then the permeability (Zhang et al., 2011). However, these models become difficult to use in the case of three components, especially if one of them is organic waste because it does not meet the conditions of a granular material. Alternatively, pedotransfer functions (PTF) allow for predicting K_s values using available soil features as inputs such as soil texture (% sand, % silt, and % clay), bulk density (BD), soil porosity *n*, and/or organic matter content (OM).

To select the most suitable PTF for estimating saturated hydraulic conductivity Ks, a series of constant-head permeability direct measurements according to the ISO 17892-11 standard were carried out at laboratory based on a Darcy-like device. This task was done on repacked samples of the excavated soil for different bulk densities (BD) of 1.36 g/cm^3, 1.53 g/cm^3, 1.61 g/cm^3, and 1.78 g/cm^3, using a wet tamping method (Ladd, 1974). One advantage of this method is that it permits any specimen to be prepared within a wide range of void ratio. In this study, eighteen existing PTF were classified according to the input data into three groups: five TXT-Ks-PTF (soil texture), three TXTD-Ks-PTF (soil texture and bulk density), and ten TXTDO-Ks-PTF (soil texture, BD, porosity, and OM). All Ks-PTFs are listed in Table 1. To evaluate the performance of PTFs by comparing measured and predicted values of K_s two statistical measures were used, geometric mean of error ratio (GMER) and geometric standard deviation of error ratio (GSDER). Both statistical functions were calculated based on the error ratio (ε_i) of the predicted value K_{sp} to the corresponding measured K_{sm}.

4 Results on excavated and composite soil assessment

In this section, results are presented on the environmental, geotechnical assessment of excavated soil, then the agronomical characterisation of excavated soil and amended soil up to composite soil assessment. Some questions arising at each step of characterisation will be discussed on the potential of the approach in predicting soil properties such as compactibility and permeability.

4.1 Environmental assessment of excavated soil

To ensure that the reuse of excavated soil is not detrimental to human health, an environmental risk assessment of the soil must be carried out. The heavy metals concentrations results are summarised in Table 2. Based on the excavated soil standard values of heavy metals concentrations (level 1) in France (BRGM, 2020), here only the cadmium (Cd) and copper (Cu) concentrations are over the standard values. Indeed, Cd exceeds the limit values by 38% for soil 1 and by 88% for soil 2, while Cu greatly exceeds these values by 64% and 141% for soil 1 and soil 2, respectively. The geo-accumulation index (I_{geo}) results calculated for excavated soil are presented in Fig. 2a. Both excavated soils were uncontaminated to moderately contaminated by Cu and only soil 2 was uncontaminated to moderately contaminated by Cd. With regards to the other heavy metals, both soils were clearly uncontaminated.

The contamination factor (C_F) values are displayed in Fig. 2b. According to the classes proposed by (Hakanson, 1980), both soils are moderately contaminated by Cd and Cu. The degree of contamination value (C_D) includes all heavy

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metals in the soil: its value was calculated to be 3.80 and 5.03 for soil 1 and soil 2, indicating that our excavated soil has a low contamination risk. The single potential ecological risk index (Er) values for each metal in excavated soil are shown in Table 3. Based on the Er classification standard, heavy metals in the excavated soil represent a low potential ecological risk, except for Cd, which exceeds the grading standard by 3% in soil 1 and by 41% in soil 2, indicating a moderate potential ecological risk in the latter case. The potential ecological risk index (RI) was calculated for the excavated soil and was found to be 50.5 for soil 1 and 69.2 for soil 2. According to the standards, both soils have a low potential ecological risk.

4.2 Geotechnical assessment of excavated soil

The average bulk density values are 1.59 g/cm^3 and 1.61 g/cm^3 for excavated soil, soil 1 and soil 2, respectively. The soil particle density is 2.65 g/cm^3 for both. Fig. 3 presents the dry grain-size distribution of both excavated soils. The particle size curves have approximately the same shape and according to uniformity and curvature coefficients, the soils are well graded. Knowing that both soils include a gravel fraction (> 2 mm), and the accounted limit sand/silt is at 0.063 mm, the derived soil composition in texture triangle in a geotechnical standard (several classifications exist for different engineering applications) differs from the agronomical standard. According to the international standard ISO 14688-1, in geotechnical, the MATEX would be classified as **silty sand**. The plasticity index (PI) and soil methylene blue value (MBV) results listed in Table 4 are related to the amount of clay fraction. According to these results, the soils are at the highest end of the medium plasticity interval.

The results of the normal Proctor test show that the maximum dry density and optimum water content are, for soil 1, 1.96 g/cm^3 and 10.18%, for soil 2 respectively 1.95 g/cm^3 and 11.24%. Note that this result is consistent with the low-end of the BD vs. critical water content relationship found by (Paradelo and Barral, 2013). The maximum immediate bearing capacity index IBI results (all particles under 5 mm) are 8.16% for soil 1 and 8.09% for soil 2. Based on Fig. 4, IBI is quasi linearly dependent on BD and IBI would exhibit a significant gain (about 100%) in bearing capacity when implementing the soil from in-situ BD to maximum BD. The IBI is used to guide the choice of construction equipment and compaction techniques to improve soil bearing capacity or to compact soil to a desired density. The choice of the appropriate construction equipment to use will also depend on the compaction energy required. For us, it is not about gear traffic but bicycle, pedestrian traffic, and trampling. The concept of constructed soil connecting GIs raises the question of access for soft traffic. While the mentioned IBI results are low, they are significant as regards gentle mobility modalities.

According to the French classification edited by the Guide for technology of road, embankments and subgrades (GTR) (LCPC and SETRA, 2000), the class A2 is defined by $12 \leq PI$ and considered intervals of IBI within class A2 are: $IBI \leq 2$; $2 < IBI \leq 5$; or $5 < IBI \leq 15$. With measured IBI values about 8, the excavated soil here has medium value and is affected the suffix m. Note that in GTR class A1 defined by $PI \leq 12$, the top interval of the immediate bearing capacity is $8 < IBI \leq 25$. The GTR class of our excavated soil is clayey silty sand denoted by A_2m. The average character of the soils in this subclass makes them suitable for the use of the widest range of earthwork tools (water content must be low). This soil does not pose any problem for low value-added reuse as backfill or embankment, except under heavy or medium rainfall. However, this class gathers soils that are difficult to use as a road base (sub-base); they are sensitive to water and have a low load-bearing capacity at the time of application. So, the use of this excavated soil in road construction would be recommended only after heavy and costly treatment with cement or lime.

The ratio of the plasticity index to the clay fraction quantifies the electrochemical activity of clays (Skempton, 1953), called Skempton activity. The identification of clay is done via the following intervals: kaolinite for $0.33 < A_c < 0.46$;

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illite for A_c around 0.9; montmorillonite (Ca) for A_c around 1.5; montmorillonite (Na) for A_c around 7.2. The calculation of the Skempton activity of clay in the investigated soil suggests that the clay mineral is illite. The adsorption capacity of methylene blue MBV is the amount of methylene blue that can be adsorbed onto the specific surface of clay particles in a soil. The specific surface area is usually estimated by SA = 24.5 x MBV; the latter characteristic is relevant to estimate the CEC (Nasri, 2013).

Thus, beyond the viewpoint shades among the classifications that focus on different aspects of the soil behaviour, geotechnical characterisation leads to consider the soil as strongly influenced (sensitive to compaction) by the clay content, even while it is moderate and illitic in nature. Its mediocre performance for civil engineering applications fortunately paves the way to making another use of soil such as agronomical component within GI.

4.3 Fertility indicators, agronomical assessment, and soil amendment

4.3.1 Fertility indicators

Results of the physical and chemical properties of excavated soil are displayed in Table 5. Textural analyses show that the texture of both excavated soils is almost similar, with the sandy fraction dominating at 64% and 63% for soils 1 and 2, respectively, followed by 19% of the silty fraction and a 17% to 18% clay fraction. According to USDA soil texture classes, excavated soils 1 and 2 classify as **sandy loam**, and have in-situ a 40% total porosity *n*. Moreover, the water content at saturation for both soils is 25% (± 0.75%).

Both excavated soils are alkaline with a pH of 8.1 to 8.5. The active carbonate content in both excavated soil is high, which may cause stunted growth and plant chlorosis. Organic carbon (OC) and total nitrogen (N) in excavated soil were below 0.15% and 0.10% for soil 1 and soil 2, respectively. In addition to pH, organic carbon (OC) is one of the best indicators of soil health. According to FAO classification (FAO, 2012) the organic carbon content here is very low, which induces low biological activity represented by the C/N ratio. Furthermore, the poverty of excavated soil fertility is characterised by low nutrient content. These results reflect and explain the absence of vegetation in the study area, which we observed by a land cover study using remote sensing and field visits (Snoussi et al., 2022). With these characteristics of low fertility, excavated soil must be amended with organic waste to be reused in constructed soil for GI in urban area.

According to the electrical conductivity values (1.030 mS/cm for soil 1 et 0.815 mS/cm for soil 2) the excavated soil is non-saline (AFES, 1965; Aubert et al., 1968; FAO, 1989, 2012). Moreover, CEC values are 14.5 meq/100g to 17.5 meq/100g, respectively, so in the 10-40 interval, which is indicative of their illite clay content (Meimaroglou and Mouzakis, 2019). Fig. 5 postponed to the appendix illustrates the XRD patterns of the two excavated soil samples. The XRD analysis shows that both soils have similar mineralogical composition which confirm that the homogenisation process was correctly done. According to the main mineralogical phases detected, excavated soil 1 and soil 2 respectively are very rich in calcite, 56% and 51%, followed by quartz 37% and 34%, and a clay content (illite) of 7% and 13%. Not surprisingly, the true mineralogical clay content is less than the granulometric clay fraction of texture analysis.

These results agree with the former physical and chemical characterisation. The high concentration of calcite, along with high pH value and high total calcium carbonate content (more than 35%), are consistent with the geological context of the study area.

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4.3.2 Agronomical assessment

Splash index (SI)

Under rainfall or irrigation, the a priori sensitivity of soil to droplet effects such as splash and encrusting, leading to porosity capping and erosion (Zhang et al., 2015), may be captured by an index based on the texture and OM content which also depends on pH. In France or in Tunisia for instance, the splash index (SI) in use by agriculture laboratories (Eq. 10).

$$SI = \frac{1.50\ \times\ \%\ \text{Fine Silt}\ +\ 0.75\ \times\ \%\ \text{Coarse Silt}}{\%\ \text{Clay}\ +\ 10 \times \%\ \text{OM}} - C \qquad (10)$$

pH [1/2.5] ≤ 7, then $C = 0$

pH [1/2.5] > 7, then $C = 0.2 \times (pH - 7)$

According to soil characteristics in Table 5, due to basic pH and low content in silt, the SI of soil 1 and soil 2 is respectively 1.0 and 1.1 which means an a priori non-sensitive soil to splash.

Total available water (TAW)

A first approach of the Total Available Water of the soil (TAW) using a value-field correspondence within the texture triangle (Baize, 2000; Bruand et al., 2004; Jamagne, 1967) provides the value 12.8%. This is to take as a maximum potential value of TAW. To go deeper, some authors evaluated the impact of the organic matter and organic carbon content, in addition to the soil texture, on TAW. To estimate the soil water contents corresponding to different values of the matric potential, (Rawls et al., 2003, 1982) worked on 12 000 soil samples of the U.S National Soil Database, and (Dobarco et al., 2019) took more than 1000 soil samples from three French soil characterisation databases i.e., SOLHYDRO, RMQS, and GEVARNOVIA. Both methods are applied on the excavated soil and composite soil to evaluate their retention capacity. The TAW obtained from (Rawls et al., 1982) for soil 1, soil 2, and the composite soil, was 8.35%, 8.18%, and 10.75%; the TAW from (Dobarco et al., 2019) is respectively, 9.83%, 9.62%, and 11.24%.

4.3.3 Soil amendment by organic waste: the composite soil

The chemical and mineralogical characterisation has shown that the excavated soil is very poor in organic carbon, and clearly alkaline. The soil hydraulic characterisation has shown that the permeability in soil 2 is lower than in soil 1. Soil 1 was chosen for testing soil amendment to improve soil fertility. Results of physical and chemical characterisation of the composite soil are listed in Table 5. In the grain size distribution of organic waste (Fig. 3), 70% of the organic waste particle size is between 2 and 4 mm, which could have a positive influence on Ks.

After 6 months, the texture of the composite soil has evolved, with silt fraction increasing by 45% (9 or 13.5 points according to the classification thresholds), sand fraction decreasing by 13%, and clay fraction decreasing by 6% compared to parent material (Table 6). Some physico-chemical transformation was involved in this change of the particle size repartition. Moreover, the soil pH value decreased by 16%, and the total and active carbonate content decreased by 15% and 3%, respectively. Soil fertility characteristics have been improved significantly, with organic matter (OM) and organic carbon (OC) doubled, total nitrogen (N) and C/N ratio multiplying by 16 and 2 times, respectively. The cation exchange capacity (CEC) increased by 80%, due to the increase in nutrient exchange caused by the decrease in pH value.

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Saturated hydraulic conductivity Ks is 5.64 10^{-6} m/s for soil 1 and 3.59 10^{-6} m/s for soil 2. Soil 1 has greater Ks and porosity, larger stone content (here the particle fraction from 2 to 5 mm), lower bulk density and clay content than soil 2. The measured Ks of the composite soil was 4.32 10^{-6} m/s when formed from soil 2 with a 1.61 g/cm^3 bulk density: compared to soil 2 without organic waste repacked at the same bulk density, Ks (6 months after amendment) increased by 19%.

To sum up, as regards the structural stability, the excavated soil is a priori non-sensitive to splash. As regards its retention capacity, the excavated soil has significant total available water allowing for plant growing and resilience. With the addition of 5% organic waste, there is considerable improvement both in the fertility indicators and permeability of the composite soil.

4.4 Permeability fitting and prediction – Excavated soil repacked

The saturated hydraulic conductivity Ks results for different BD values of excavated soil repacked are presented in Table 7 and Fig. 6. The results show that Ks decreases with increasing bulk density (i.e., decreasing soil porosity, *n*) which was expected. To predict Ks of the excavated-repacked soil using bulk density input is possible through an exponential function with residue $R^2 = 0.994$ (Eq. 11). Obviously, it will deserve more data to be inaugurated as a new PTF. However, it is already a promoting result and interesting hypothesis to be tested in future work.

$$K_s = 0.0008 \times exp^{(-3.388 \times BD)} \quad (11)$$

When BD approaches its maximum around 1.9 g/cm^3, the hydraulic conductivity reaches to a minimum about 10^{-6} m/s. The rationale of this relationship is as follows: by increasing BD, the expected gain in retention capacity of pollutants is paid by a decrease in conductivity and infiltration capacity. Despite the loss in conductivity, increasing the bearing capacity is another motivation to increase BD as already illustrated by Fig. 4.

The results of the evaluation of the eighteen Ks-PTFs as applied to the excavated soil data are summarised in Table 8. For the TXT-Ks-PTF group, the GMER results fall in a range from 0.59 for F1.1 to 2.16 for F1.2. The GSDER value is constant at 1.78 for all functions in this group since it does not depend on BD, thus regardless of the state of compaction of soil. In this study, the TXT-Ks-PTF group is unable to adequately predict Ks. Results of the TXTD-Ks-PTF group, where input data are soil texture and bulk density, decrease as bulk density values increase. The F2.1 predicted by (Jabro, 1992) underestimates Ks (GMER = 0.62), the F2.2 of (Ottoni et al., 2019) overestimates Ks (GMER = 1.51). Both functions have GSDER close to 1. Results of the TXTDO-Ks-PTF group decrease with increasing bulk density, similarly to the measured Ks. Results show that eight Ks-PTFs underestimate Ks and the predictions of the other two PTFs show an overestimation of Ks.

Among eighteen Ks-PTFs, the statistical evaluation of the pedotransfer functions showed that F3.9 developed by (Wösten et al., 1999) had the best performance (GMER = 0.81, GSDER = 1.54) which used a large database of 1136 soil samples from the European HYPRES database. This Ks-PTF was developed in terms of clay, silt, and organic matter contents, BD, and one categorical toggle with the value of 1 for "topsoil" and 0 for "subsoil". In this study, choosing topsoil provided the best prediction of Ks.

4.5 Decision-making aid procedure

To valorise this methodology of characterisation of the materials and composite soil, some of their parameters should be used at a higher level of data integration, in a decision-making aid procedure intended for the developer or the contracting authority use. Here, a concept of urban soil grid is put forward to consider GIs (green spaces based on imported topsoil) connected by constructed soil trenches as a support. Alveolate engineered soils inserted in sidewalks

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will be constructed with texture and constituent specifications for being both permeable and support of vegetation and soil organisms. Planted with grass species, pathways to cross streets and connect sidewalks will contribute to ecological continuity of habitat for soil biodiversity. Equivalent to the green and blue grid in peri-urban environment (Daudin et al., 2022), an urban soil grid of vegetated pathways in the streets are a nature-based solution for soil biota access to dense urban environment. Thus, they will contribute to provide several ecosystem services: driving biodiversity back to the city, reducing stormwater rates and improving human well-being.

By taking inspiration from the decision tree map, proposed for the infiltration of treated wastewater reaching from on-site sanitation (Fouché et al., 2019) the same approach can be applied to rainwater (less loaded in suspended matter and different water quality). Then, assuming that this approach can be generalised to a majority number of the construction projects involving the infiltration of rainwater, it is considered that a project of constructed soil set-up requires determining land's aptitude for the infiltration of rainwater and urban runoff. In the decision tree map, the first input table, involving the parameters of the soil and study site (Table 9 and Table 12), crosses the two main parameters: saturated hydraulic conductivity of the soil (Ks) (Table 10) and the thickness of the unsaturated zone (USz) under the bottom of GI (Table 11). In the case where the determination of the thickness of the unsaturated zone under the bottom of GI is not possible, a known statistical piezometric parameter such as minimal water table depth could be used.

This decision-making table is applied with as input the most probable value of Ks determined with our estimation Ks-PTFs approach. Note however that beforehand, it is necessary to have checked that the soil of the GI construction is not polluted and that the zone meant to the GI is not located:

- Inside a water catchment protection perimeter of a drinking water supply resource;
- On soluble soils or rocks or on an unstable substratum.

According to the results and referring to the decision tree map approach, the soils 1 and 2 could be placed in Class II (intermediate) for their aptitude to infiltrate the urban runoff under the GI (Ks of the Soils 1 et 2 equal to $5.64.10^{-6}$ m/s and $3.59.10^{-6}$ m/s respectively). This is given the deep water-table, > 30 m depth, according to the well data in the Grombalia plain marked by over irrigation.

4.6 Discussion

In this section, beyond the evaluation of the case study site for its geochemical background, two main questions are discussed: how the approach is useful in predicting the soil behaviour, not only excavated but composite, with regards to compactibility, not only long-term but short-term, and permeability.

Discussion of local relevance on the geochemical background

According to the results of the environmental characterisation, excavated soil from the industrial zone of Hached can be safely reused. The I_{geo} and C_F indexes indicated that Cd and Cu were the most hazardous metals in the excavated soil. However, the concentrations of Cd and Cu exceeded the limit values at low levels. According to several studies, for some soil classes the limit values of heavy metals concentrations can be exceeded with moderation. Indeed, the concentrations of those metals depend on some soil features such as mineralogical composition (Horckmans et al., 2005; Salminen and Tarvainen, 1997; Tack et al., 1997), or particle size with the concentration being generally higher in fine granulometry than in coarse (Tack et al., 1997). Also, pH value influences the mobility of many pollutants in the soil by influencing the rate of their biochemical degradation and solubility, more precisely on cadmium (Cd) which

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is more mobile in acid soils than in alkaline soils (Chaudri et al., 2007; Jordan-Meille et al., 2021; Khan et al., 2017; Liu et al., 2015).

For more safety reasons, the excavated soil can be used in areas where the cadmium (Cd) and copper (Cu) values of the in-situ soil are higher than 0.75 mg/kg and 96.3 mg/kg, respectively, which is likely to occur in cities. If excavated soil was to be used in agricultural fields (Liu et al., 2021), the results compared with the Tunisian soil standard for water treatment sludges (INNORPI, 2002) (Cd = 3 mg/kg, Cr = 150 mg/kg, Cu = 140 mg/kg, Ni = 7 mg/kg, Pb = 150 mg/kg, Zn = 300 mg/kg) demonstrate that no obvious heavy metal pollution was found in this area. All heavy metal values were below the threshold limits.

Discussion on long-term compactibility and immediate bearing capacity

The compactibility has been studied on the excavated soil, not on the composite soil, which could be felt as a weakness in our workflow. In fact, to develop good practices in this field, it is an objective to optimise the characterisation program by valorising previous systematic results on composite soils. (Paradelo and Barral, 2013) studied the effect produced by adding increasing rates of a municipal solid waste compost (about 3%, 7% and 14% dry weight) to reduce maximum bulk density and the susceptibility to compaction of three mineral materials close to homogeneity, quartz sand (85% sand), slate processing fines (78% silt), and bentonite (75% clay). Using the Proctor test as we did, they confirmed the linear negative relationship between the maximum bulk density and the critical water content for their whole set of data, very similar to that reported by (Aragón et al., 2000) for a total of 105 real soils. They also confirmed the statement made by (Zhang et al., 1997) that the higher is the maximum bulk density of a soil, the more effective organic matter will be in reducing its compactibility. At the highest tested rate of 14% their addition of compost increased the critical water content (i.e., the moisture at maximum bulk density reached by the Proctor test), while at compost rates in the 0-7% range, the effect was negligible (excepted for quartz sand). Generalising these results, the critical water content of composite soil around a 5% organic waste rate is not prone to be dependent on the precision of this rate, let say roughly +-50% error of mixing rate or point variations (in space, time) of this rate after implementation would still be admissible. This information about admissible heterogeneity is crucial not only for compactibility (maximum, long-term) in general, but also for our focused concern, the immediate bearing capacity and practical implementation of composite soil at field. Moreover, the potential relationship of IBI as a function of BD was not studied before and the outlined linear relationship is an original result. It means that, when engineering a constructed soil, a required (or needed) immediate bearing capacity is reachable by tuning the BD during emplacement of the composite soil. This result, here found on one soil, takes the value of an assumption to be tested on a diversity of soils in future work.

Discussion on soil permeability

For hydro-pedological characterisation the aptitude of the soil to retention and infiltration functions has been quantified. A compromise between these two functions is necessary to qualify the soil as ‘good’ for the projected use. Of course, the evaluation of retention capacity could go deeper by determination of the soil water retention curve, as in (Willaredt and Nehls, 2021) who worked on mixtures of compost and crushed brick. This level of precision could be relevant to evaluate the maturation upon time of the constructed soil, but it is not necessary for the objective of this work, being the proposition of the technical-based decision-aid method to valorise the given low-quality excavated soil into a composite soil, assemblage of organic waste and excavated soil to GI use.

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Like compactibility, the permeability has been studied on the excavated soil, not on the composite soil. Again, we optimise the characterisation program by valorising previous systematic results on soils, here not specifically on composite soils since a large spectrum Ks-PTFs in hydro-pedology was used. The variability of the permeability results is because the Ks-PTFs only consider fractions smaller than 2 mm. Yet at least 6% of the study soil grain size varies between 2 mm and 8 mm, which tends to increase permeability compared to an average from Ks-PTF results. Moreover, a gap between 0.010 mm and 0.035 mm is noted from the grain size analysis.

The good performance of the (Wösten et al., 1999) PTF on this Mediterranean soil (study site) is highlighted, which also confirms the quality of the European HYPRES database. However, the OM content as a variable, which has very low values in the excavated soil, requires an amendment, so it cannot play in the short term the structuring role, which it plays in a mature topsoil. As an alternative, to optimise the fit of a function for this soil and keep it independent of the OM variable, two PTFs could be combined as follows: 0.55xF2.1+0.45xF2.2 where F2.1 and F2.2 are the PTFs of (Jabro, 1992) and (Ottoni et al., 2019) reported in Table 1. This choice would be better justified as a tool to estimate the permeability of an embryonic constructed soil from poor MATEX than directly taking the Wösten PTF with case 1 (Topsoil). Nevertheless, as soon as the soil will be amended with organic waste and a composite soil is considered with time evolution, the Wösten PTF will be required to predict Ks. Moreover, considering that the selection of this PTF has been validated on the considered excavated soil, a Ks prediction of the composite soil may be computed with the help of Wösten PTF (case 1) according to the composite soil analyses at 6 months, this Ks being 4.26 10^{-6} instead of measured 4.32 10^{-6} m/s.

5 Conclusion and perspective

The general frame of this research is adapting to climate change by reusing excavated soil considered as waste into urban anthropogenic soil, designed with specific features to promote soil formation, plant growth, urban landscape shaping, and drain rainwater in green urban areas. A method has been developed to test the potential of a soil improper to cultivation and of low value for road engineering to serve as a main component of a future constructed soil with targeted pedological properties: higher porosity and water-holding capacity, higher nutrient availability, lower or higher bulk density compared to the parent materials according to desired workability and infiltrability.

Imperative skills of composite soil are safety, workability, fertility, and infiltrability: these SWOFI items are steps within a decision tree; they are not at the same level and should not be crossed between. This framework will guide a characterisation workflow to reuse excavated soils. It is the first time that a comprehensive strategy of characterisation linking the three approaches – pollution hazard, geotechnical feasibility, agronomic potential – is proposed within the heuristic of constructed soils. It is also the first time that a proposal of valorisations of mineral waste / excavated soil for realising green infrastructure in cities is proposed in Tunisia. The selection of pedotransfer functions adapted to constructed soils in the south of the Mediterranean is as crucial for stormwater management as the design of rainfall Intensity-Duration-Frequency curves.

In perspective, once a straightforward process of characterising the excavated and composite soil has been applied, the design of a constructed soil may be assisted by numerical modelling. This way, (Snoussi et al., 2020) explored some properties of a patented constructed soil: a multiphysics software was used to couple a soil hydraulic model with a thermal model of a porous medium in unsaturated state. The main result of running transfer functions through the composite soil was production of realistic initial conditions of temperature and humidity profiles. Knowing these

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conditions and ensuring numerical stability of the model are requested for future hydrological simulations (infiltration, runoff, recharge) with real material, rainfall, and temperature data.

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APPENDIX

Environmental and health safety characterisation

Geo-accumulation index

In order to assess the degree of contamination by heavy metals in aquatic sediments and solid wastes, Müller (Müller, 1969) proposed the geo-accumulation index (I_{geo}), calculated by Eq. (1). Due to its reliability, this index has been widely used to evaluate soil heavy metal pollution.

$$I_{geo} = log_2\left(\frac{C_i}{1.5 \times B_i}\right) \quad (1)$$

Where C_i is the measured heavy metal concentration in the excavated soil and B_i is the geochemical background value of the corresponding metal. However, because the Tunisian national standard does not have a geochemical background rule for the excavated soil, the level 1 limit values of excavated soils in France (BRGM, 2020) were selected in this study (Cd = 0.4 mg/kg, Cr = 90 mg/kg, Cu = 40 mg/kg, Ni = 60 mg/kg, Pb = 50 mg/kg, Zn = 150 mg/kg). The constant 1.5 is the factor compensating for the geochemical background content due to lithogenic actions (Haris et al., 2017). According to (Förstner and Müller, 1981), the geo-accumulation index admits seven classes: uncontaminated ($I_{geo} \leq 0$), uncontaminated to moderately contaminated ($0 < I_{geo} \leq 1$), moderately ($1 < I_{geo} \leq 2$), moderately to heavily ($2 < I_{geo} \leq 3$), heavily ($3 < I_{geo} \leq 4$), heavily to extremely ($4 < I_{geo} \leq 5$), extremely contaminated ($5 < I_{geo}$).

Contamination factor and degree of contamination

The contamination factor C_{Fi} was defined by (Hakanson, 1980) to evaluate a level of contamination for each individual metal in soil, using Eq. (2):

$$C_{Fi} = \frac{C_i}{B_i} \quad (2)$$

There are four contamination levels based on C_F values: low ($C_F < 1$), moderate ($1 \leq C_F < 3$), considerable ($3 \leq C_F < 6$) and very high ($C_F \leq 6$). Then, the degree of contamination in soil C_D is the sum of contamination factors of selected elements, as Eq. (3).

$$C_D = \sum_{i=1}^{n} C_{Fi} \quad (3)$$

There are four degrees of contamination according to C_D: low degree ($C_D < 8$), moderate ($8 \leq C_D < 16$), considerable ($16 \leq C_D < 32$), and very high degree of contamination ($32 \leq C_D$) which is an indicator of serious anthropogenic pollution.

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Potential ecological risk

Defined by (Hakanson, 1980), the ecological risk factor E_r allows for the quick quantification of the ecological risk of a contaminant. E_r can be obtained using Eq. (4)

$$E_r = T_r \times C_F \tag{4}$$

Where T_r represents the toxic factor of the heavy metal element, after normalisation with respect to the element Zn. The basic material for the evaluation of T_r is based on the abundance of various elements in different types of media: igneous rocks, soils, fresh water, land plants and land animals. T_r values are 30, 2, 5, 5, 5, and 1, for Cd, Cr, Cu, Ni, Pb, and Zn, respectively. The ecological risk factor E_r is divided into five ranges as follows: low ($E_r < 40$), moderate ($40 \leq E_r < 80$), considerable ($80 \leq E_r < 160$), high ($160 \leq E_r < 320$) and very high ($E_r \leq 320$). The potential ecological risk index (RI) was defined as the sum of the ecological risk factors of several elements Eq. (5).

$$RI = \sum_{i=1}^{n} E_{r.i} \tag{5}$$

Four categories of the potential ecological risk index (RI) are distinguished, low (RI < 150), moderate (150 ≤ RI < 300), considerable (300 ≤ RI < 600) and very high (RI ≤ 600).

Geotechnical characterisation

For the geotechnical characterisation, water content was determined by oven drying samples at 105°C for 48 h, according to the standard ISO 17892-1. Soil particle density ρ_s was determined by the fluid pycnometer method according to ISO 17892-3. The standard ISO 17892-2 was used to determine the bulk density (BD) from which porosity n may be easily estimated by Eq (6).

$$n = 1 - \frac{BD}{\rho_s} \quad (6)$$

The sample soil volume was determined by linear measurement method using a cylindrical cutter.

Grain size analysis and Atterberg limit tests allow for identification of soil within the Unified Soil Classification System (USCS), the French Laboratoire Central des Ponts et Chaussées (LCPC), and the American Association of State Highway and Transportation Officials (AASHTO), three classifications in use in geotechnical engineering. According to USCS and LCPC, the excavated soil is a "*clayey* silty sand". For the AASHTO system part of the ASTM standard D3282, it belongs to the A-6 group (of the total soil, a fraction exceeding 35% passes through a sieve with an aperture of 75 μm, then PI ≥ 11, then $w_L \leq 40$), said of "*clayey* fine soils: mediocre performance".

Fertility characterisation

Soil pH was measured in a 1:2.5 water suspension using a standard electrode and pH-meter. The total carbonate content as $CaCO_3$ was determined by measuring the emitted volume of CO_2 gas produced by the addition of HCl in a Dietrich-Fruhling calcimeter according to the French standard NF P94-048 (NF ISO 10693), and the active carbonate was measured by the Drouineau method after French standard NF X31-106. The saturated paste extract method was used to measure electrical conductivity (EC). The soil organic matter (OM) and organic carbon (OC) were determined by the Walkley-Black method (Walkley and Black, 1934). Total nitrogen (N) was determined by the Kjeldahl method. The cation exchange capacity (CEC) was determined at pH 7 using the ammonium acetate solution according to the NF X 31-130 French standard.

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TABLES

Table 1. Pedotransfer functions for estimating saturated hydraulic conductivity (Ks-PTF).

Ks-PTF, saturated hydraulic conductivity (m/s); SA, sand content (%); SI, silt content (%); CL, clay content (%); BD, bulk density(g/cm^3); n, total porosity (cm^3/cm^3), ρ_s, soil particle density, and for PTF F3.9 (Topsoil): 1 for « Topsoil », 0 for « Subsoil ».

Ks-PTF	Reference	Formula (m/s)	Development Dataset	
			Size	Region
TXT-Ks-PTF				
F1.1	(Adhikary et al., 2008)	K_s - PTF $= 4,816 \times 10^{-4} \times ((SI) + (CL))^{-1,48}$	564	India
F1.2	(Cosby et al., 1984)	K_s - PTF $= 7,0556 \times 10^{-6} \times 10^{(-0,6+0,0126\times(SA)-0,0064\times(CL))}$	1448	USA
F1.3	(Ferrer Julià et al., 2004)	K_s - PTF $= 2,5556 \times 10^{-7} \times exp(0,0491 \times (SA))$	2178	Spain
F1.4	(Ottoni et al., 2019)	K_s - PTF $= 1,15741 \times 10^{-7} \times 10^{(2,039-0,00874(SI)-0,00723(CL))}$	425	Brazil & Europe
F1.5	(Saxton et al., 1986)	K_s - PTF $= 2,778 \times 10^{-6} exp[12,012 - 0,0755 \times (SA) + (-3,895 + 0,03671 \times (SA) - 0,1103$ $n = 0,332 - 7,251 \times 10^{-4} \times (SA) + 0,1276 \times log(CL)$	230	USA
TXTD-Ks-PTF				
F2.1	(Jabro, 1992)	K_s - PTF $= 2,778 \times 10^{-6} \times exp^{(9,56-0,81\times log(SI)-1,09\times log(CL)-4.64\times(BD))}$	350	International
F2.2	(Ottoni et al., 2019)	K_s - PTF $= 1,15741 \times 10^{-7} \times 10^{(3,998-0,0101\times(SI)-0,0152\times(CL)-1,163\times(BD))}$	425	Brazil & Europe
F2.3	(Ottoni et al., 2019)	K_s - PTF $= 1,418981 \times 10^{-7} \times (0,582 - 0,00216 \times (SI) - 0,00232 \times (CL) - 0,03 \times (BD))^{1,853}$	425	Brazil & Europe
TXTDO-Ks-PTF				
F3.1	(Brakensiek, Rawls and Stephenson, 1984)	K_s - PTF $= 2,778 \times 10^{-7} exp(19,52348(n) - 8,96847 - 0,028212(CL) + 1,8107 \times 10^{-4}(SA)^2 -$ $-8,395215 \times (n)^2 + 0,077718 \times (SA) \times (n) - 0,00298 \times (SA)^2 \times (n)^2 - 0,019492 \times$ $+1,73 \times 10^{-5} \times (SA)^2 \times (CL) + 0,02733 \times (CL)^2 \times (n) + 0,001434 \times (SA)^2 \times (n) - 3,5 \times 1$	230	USA
F3.2	(Ferrer Julià et al., 2004)	K_s - PTF $= 2,778 \times 10^{-7} \times (-4,994 + 0,56728 \times (SA) - 0,131 \times (CL) - 0,0127 \times (MO))$	2178	Spain
F3.3	(Nemes et al., 2005)	K_s -PTF $= 1,15741 \times 10^{-7} \times 10^{(0,571+0,96\times Z_4)}$; Z4 =f(SA, CL, BD, MO)	886	USA
F3.4	(Patle and Vanlalnunchhani, 2020)	K_s - PTF $= 1,15741 \times 10^{-7} \times (-3581,42 + 36,78 \times (SA) + 36,58 \times (SI) + 36,8 \times (CL) - 44,4$	29	India
F3.5	(Shwetha and Prasanna, 2018)	K_s - PTF $= 2,778 \times 10^{-6} sinh(-1,272 - 0,0433 \times (SI) + 0,693 \times (MO) + 13,04 \times n + 0,0009$ $-0,0074 \times (SI) \times (MO) - 0,091 \times (SI) \times n - 0,0036 \times (MO)^2 - 1,128 \times n \times (MO) - 3,204$	101	India
F3.6	(Vereecken et al., 1990)	K_s - PTF $= 1,157407 \times 10^{-7} \times exp(20,62 - 0,96 \times ln(CL) - 0,66 \times ln(SA) - 0,46 \times ln(MO)$	127	Belgique
F3.7	(Wösten, 1997)	K_s - PTF $= 1,15741 \times 10^{-7} exp(9,5 - 1,471 \times BD^2 - 0,688 \times (MO) + 0,0369 \times (MO)^2 - 0,332$	88	Netherlands
F3.8	(Wösten, 1997)	K_s - PTF $= 1,15741 \times 10^{-7} exp(-43,1 + 64,8 \times (BD) - 22,21 \times (BD)^2 + 7,02 \times (MO) - 0,156$ $-0,1332 \times (CL) \times (MO) - 4,71 \times BD \times (MO))$	88	Netherlands
F3.9	(Wösten et al., 1999)	K_s - PTF $= 1,15741 \times 10^{-7} exp(7,755 + 0,0352 \times (\%SI) + 0,93 \times topsoil - 0,967 \times (BD)^2 - 0$ $- 0,001 \times (SI)^{-1}$ $-0,0748 \times (MO)^{-1} - 0,643 \times ln(SI) - 0,01398 \times (BD) \times (CL) - 0,1673 \times (BD) \times (MO) + 0$ $\times topsoil \times (SI))$	1136	Europe
F3.10	(Wösten et al., 2001)	K_s - PTF $= 1,15741 \times 10^{-7} exp(-42,6 + 8,71 \times (OM) + 61,9 \times (BD) - 20,79 \times (BD)^2 - 0,210$ $- 5,382 \times (BD) \times (OM))$	832	Netherlands

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Table 2. Heavy metal pollutants in excavated soil.

Heavy metal	Unit	Soil 1	Soil 2
Cd	mg/kg	0.55	0.75
Cr	mg/kg	18.5	11.6
Cu	mg/kg	65.6	96.3
Ni	mg/kg	0.05	0.05
Pb	mg/kg	0.25	0.50
Zn	mg/kg	85.6	90.6

Table 3. The single potential ecological risk index (Er) in excavated soil.

Heavy metal	Er	
	Soil 1	Soil 2
Cd	41.25	56.25
Cr	0.41	0.26
Cu	8.20	12.04
Ni	0.00	0.00
Pb	0.03	0.05
Zn	0.57	0.60

Table 4. Geotechnical characterisation of excavated soil.

Test	Unit	Soil 1	Soil 2
Uniformity coefficient (Uc)	-	266.7	200.0
Curvature coefficient (Cc)	-	1.98	1.02
Liquid limit (w_L)	%	29.40	32.00
Plastic limit (w_p)	%	14.22	14.03
Plasticity index (PI)	%	15.18	17.97
Methylene blue value (MBV)	g	1.17	1.18

Table 5. Physical and chemical characterisation of excavated soil and composite soil.

Test	Unit	**Soil 1**	**Soil 2**	**Composite soil**
Sand	%	64	63	56.5
Silt (Fine + Coarse)	%	19 (15 + 4)	19 (14 + 5)	27.5
Clay	%	17	18	16.0
pH	1:2.5	8.50	8.16	7.13
Total carbonate ($CaCO_3$)	%	44.3	35.3	37.6
Active carbonate	%	14.0	9.2	13.6
Organic matter (OM)	%	0.26	0.10	0.78
Organic carbon (OC)	%	0.15	0.05	0.45

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Total nitrogen (N)	%	0.098	0.091	1.64
C/N ratio	-	1.53	0.57	2.74
Electrical conductivity (EC)	mS/cm	1.03	0.81	2.19
Cation exchange capacity (CEC)	meq/100g	14.5	17.5	26

Table 6. Agronomical and geotechnical thresholds and analyses for soil texture.

Characterisation		Agronomic classification			Geotechnical classification		
Standard		Sieve for the sand fraction pipet methods for the silt and clay Sand (2 mm > D > 0.05 mm) Silt (0.05 mm > D > 0.002 mm) Clay (0.002 mm > D)			ISO 17892-4 Grave (D > 2 mm) Sand (2 mm > D > 0.063 mm) Silt (0.063 mm > D > 0.002 mm) Clay (0.002 mm > D)		
Test	**Unit**	**Soil 1**	**Soil 2**	**Composite soil**	**Soil 1**	**Soil 2**	**Composite soil**
Granulometric fractions							
Grave	%	-	-	-	11	6	5.5
Sand	%	64	63	56.5	55	56	45.6
Silt	%	19	19	27.5	18	21	32.9
Clay	%	17	18	16.0	16	17	16.0

Table 7. Measured values of saturated hydraulic conductivity Ks of excavated soil for different bulk densities BD, including replication tests.

BD (g/cm^3)	**Ks (m/s)**	**Mean Ks (m/s)**
1.36	$7.57\ 10^{-6}$	$7.57\ 10^{-6}$
1.53	$4.56\ 10^{-6}$	$4.55\ 10^{-6}$
1.53	$4.55\ 10^{-6}$	
1.61	$3.62\ 10^{-6}$	$3.59\ 10^{-6}$
1.61	$3.65\ 10^{-6}$	
1.61	$3.50\ 10^{-6}$	
1.78	$1.90\ 10^{-6}$	$1.89\ 10^{-6}$
1.78	$1.88\ 10^{-6}$	

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Table 8. Geometric mean of error ratio (GMER) and geometric standard deviation of error ratio (GSDER) for a series of Ks-PTFs.

Ks-PTF	Reference	GMER	GSDER
TXT-Ks-PTF			
F1.1	(Adhikary et al., 2008)	0.59	1.78
F1.2	(Cosby et al., 1984)	2.16	1.78
F1.3	(Ferrer Julià et al., 2004)	1.44	1.78
F1.4	(Ottoni et al., 2019)	1.64	1.78
F1.5	(Saxton et al., 1986)	0.64	1.78
TXTD-Ks-PTF			
F2.1	(Jabro, 1992)	0.62	1.27
F2.2	(Ottoni et al., 2019)	1.51	1.12
F2.3	(Ottoni et al., 2019)	0.01	1.74
TXTDO-Ks-PTF			
F3.1	(Brakensiek, Rawls and Stephenson, 1984)	0.15	1.77
F3.2	(Ferrer Julià et al., 2004)	2.02	1.78
F3.3	(Nemes et al., 2005)	0.02	1.48
F3.4	(Patle and Vanlalnunchhani, 2020)	0.47	1.10
F3.5	(Shwetha and Prasanna, 2018)	6.96	1.78
F3.6	(Vereecken et al., 1990)	0.36	2.45
F3.7	(Wösten, 1997)	2.57	1.26
F3.8	(Wösten, 1997)	0.11	2.04
F3.9	(Wösten et al., 1999)	0.81	1.54
F3.10	(Wösten et al., 2001)	0.51	1.71

Table 9. Water characteristics of the lixiviate from excavated and composite soil compared to tap water.

	Tap water	Lixiviate Soil 2	Lixiviate Soil 2 + 5% organic waste
Turbidity (NTU)	40	5.5	4.3
Total Dissolved Solids TDS (mg/s)	1200	1470	1620
Conductivity (µs/cm)	2000	2450	2700
pH	8.1	7.9	7.6

Table 10. Threshold and intervals of saturated hydraulic conductivity (Ks) to insure the transfer and retention functions of a green infrastructure.

Ks threshold in m/s	Attributed Score for Ks
$Ks \leq 2.0\ 10^{-6}$	C = Low

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$2.0\ 10^{-6} < Ks \leq 8.0\ 10^{-6}$	B = Medium (adequate)
$8.0\ 10^{-6} < Ks \leq 4.0\ 10^{-5}$	A = High (adequate)
$4.0\ 10^{-5} < Ks$	C = Very high

Table 11. Threshold and intervals of thickness of the unsaturated zone under the bottom of a green infrastructure, useful for the plant root growth, water transfer and retention. The feasibility of rainwater deep percolation in the soil is evaluated flowing 3 scores.

Unsaturated zone thickness (USz) interval	**Attributed Score for USz**
USz ≤ 50 cm	c = Insufficient thickness
50 cm < USz ≤ 100 cm	b = Medium thickness
100 cm < USz	a = High thickness

Table 12. Range of the derived scores for the deep percolation service of the soil.

<table>
<tr><td colspan="3" rowspan="3">Hydraulic conductivity (Ks) \ Unsaturated Zone thickness (USz)</td><td colspan="3">USz</td></tr>
<tr><td>High</td><td>Medium</td><td>Insufficient</td></tr>
<tr><td>a</td><td>b</td><td>c</td></tr>
<tr><td rowspan="3">Ks</td><td>High</td><td>A</td><td>Aa</td><td>Ab</td><td>Ac</td></tr>
<tr><td>Medium</td><td>B</td><td>Ba</td><td>Bb</td><td>Bc</td></tr>
<tr><td>Low</td><td>C</td><td>Ca</td><td>Cb</td><td>Cc</td></tr>
</table>

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FIGURES and CAPTIONS

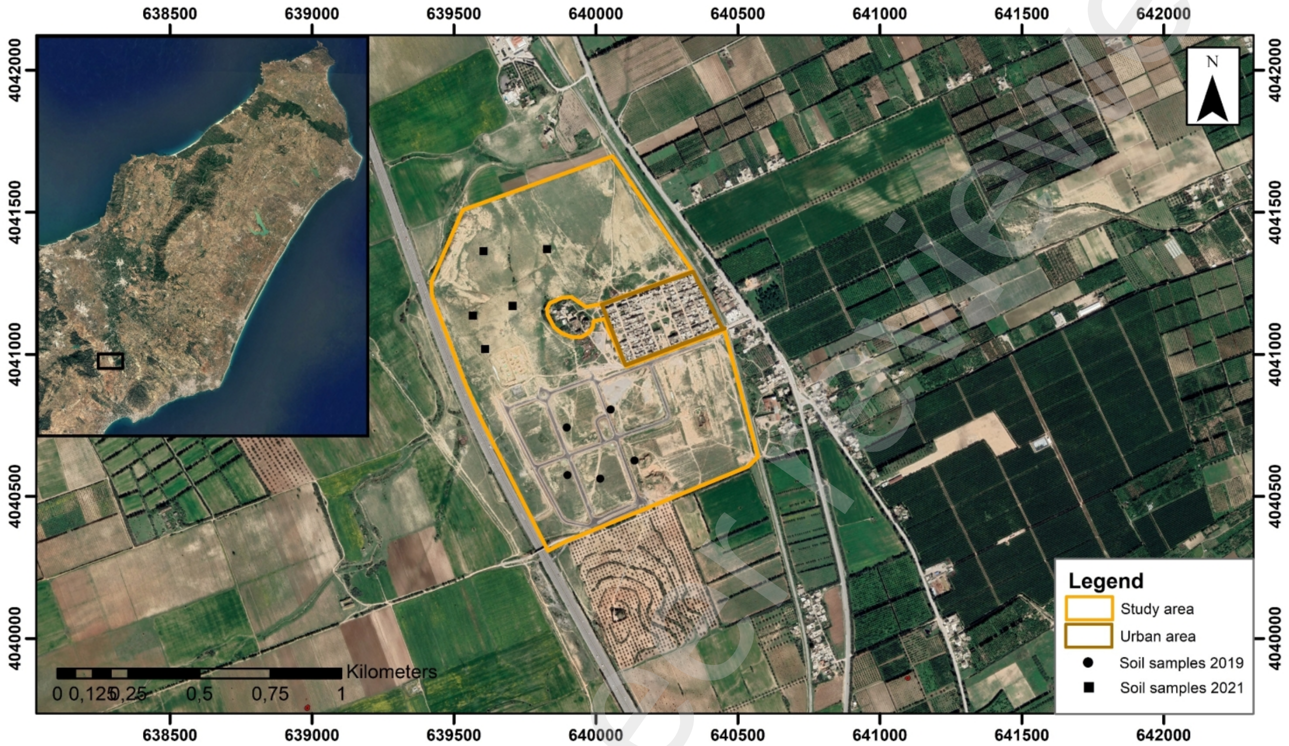
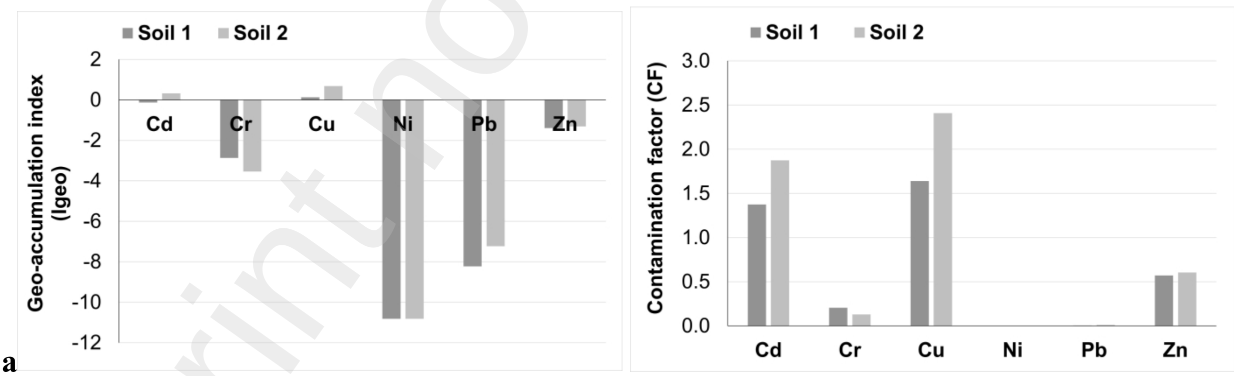


Fig. 1. Study area: coordinates are in m according to the Carthage UTM projection Zone 32 N.

COLOR should be used.



a b

Fig. 2. (a) The geo-accumulation index of heavy metals in excavated soil. **(b)** The contamination factor of heavy metals in excavated soil.

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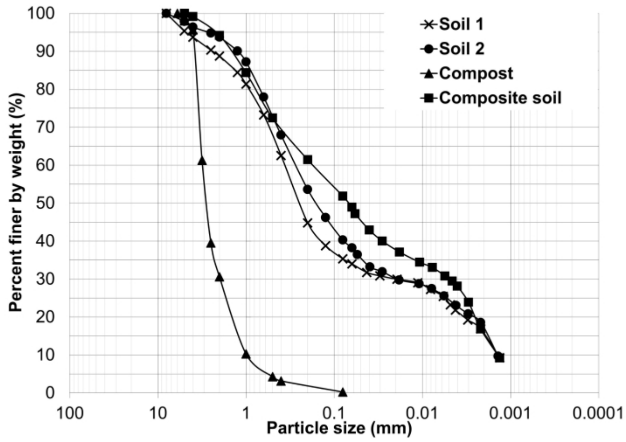


Fig. 3. Grain size distribution curves of grape marc organic waste, soil 1, and soil 2, according to results reported in Table 6.

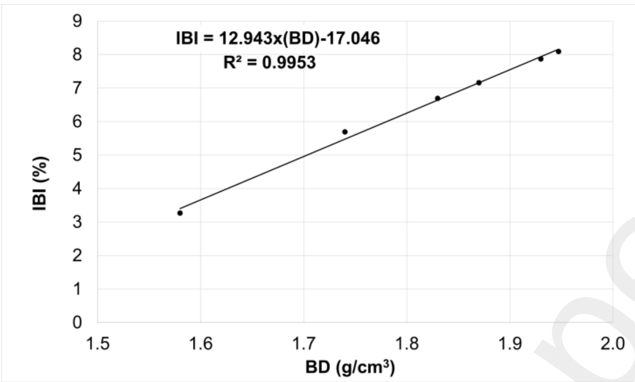
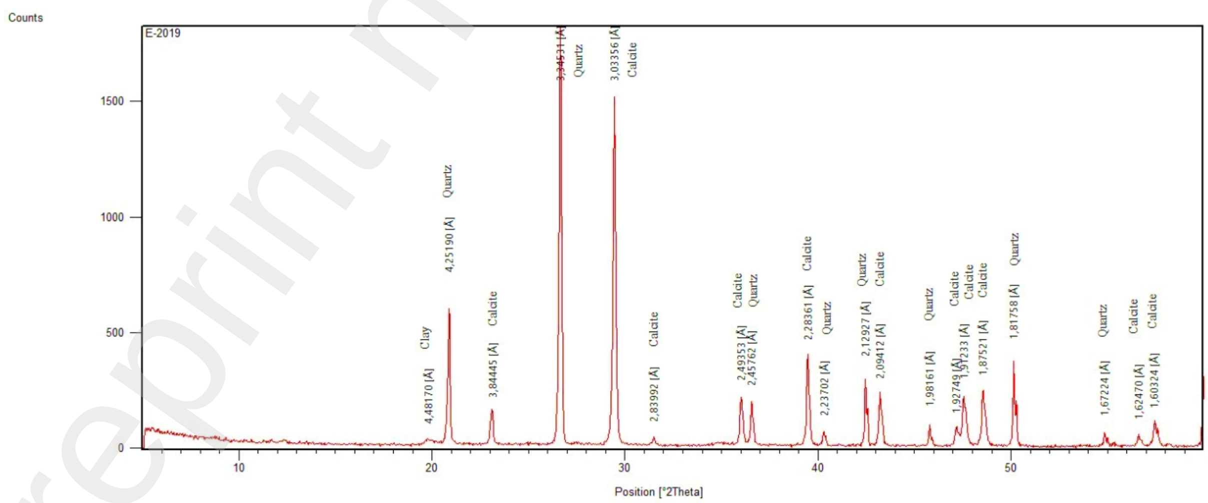


Fig. 4. Quasi linearity of the immediate bearing capacity index IBI as a function of BD.



a

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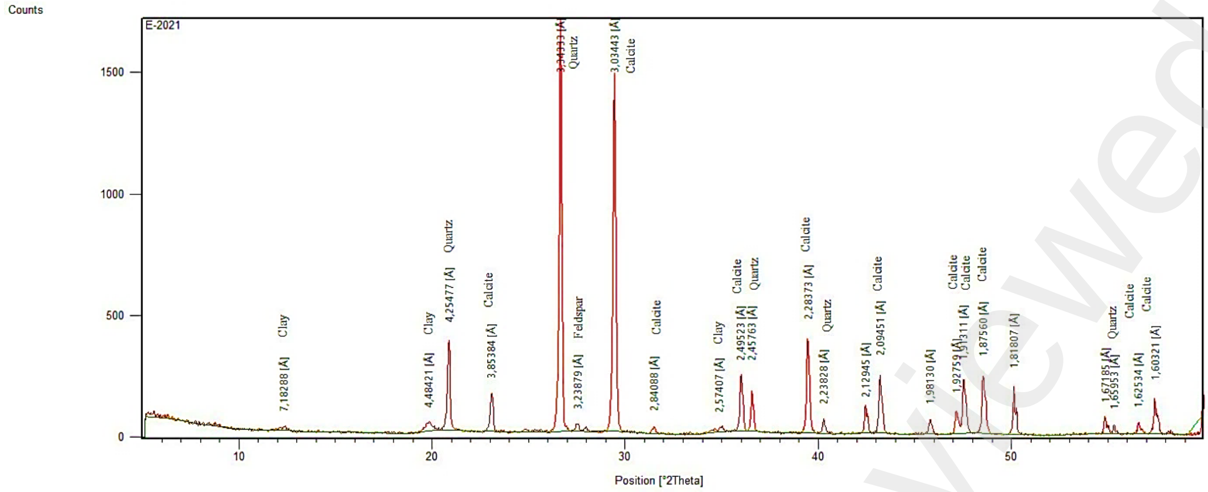

b

Fig. 5. X-ray diffraction patterns of excavated soil: **a)** soil 1, in 2019; **b)** soil 2, in 2021.

(TO POSTPONE TO THE APPENDIX)

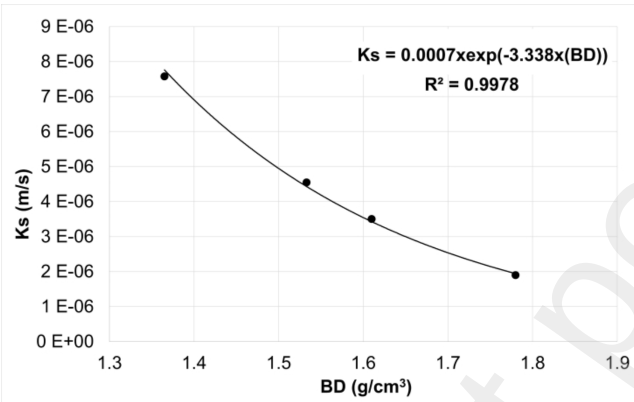

Fig. 6. For different bulk densities BD of the excavated-reconstituted soil, measured values of saturated hydraulic conductivity Ks.

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