

Impact of mining waste incorporation as filler for *tout-venant* as road geomaterial

Maria Vitoria Vieira de Morais

Dissertação para obtenção do Grau de Mestre em
Engenharia Civil
(2^o ciclo de estudos)

Orientador: Prof. Doutor Luis José Andrade Pais
Co-orientador: Prof. Doutor Victor Manuel Pissarra Cavaleiro

junho de 2024

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Dedictory

To my grandmothers Nadir, Tereza e Luciola.

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Acknowledgement

I would like to express my deep gratitude to my parents, Airton e Neta, for their unconditional love and constant support. To Leonardo Marchiori for all his help, support and patience. My little dog, Pituca, for all the little bites while I was writing my dissertation. And I would also like to thank everyone who was truly by my side during this journey, personal friends, co-workers and college classmates.

To my supervisor Professor Doutor Luis José Andrade Pais and Professor Doutor Victor Manuel Pissarra Cavaleiro, for all the dedication, guidance, disponibility, and friendship.

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Resumo

A mineração gera uma quantidade de resíduos, denominados por rejeitos que não podem ser reaproveitados ou passar pelo processo de reciclagem. Assim, a única alternativa é serem direcionados a aterros sanitários. Contudo existem produtos inertes resultantes da actividade industrial, minas e outras que podem ser classificados como resíduos. Além dos riscos ambientais associados à geração de resíduos de mineração, como erosão do solo, contaminação da água e destruição de habitats, também existem custos económicos significativos relacionados à sua disposição. Para enfrentar esse desafio, métodos para reutilizar esses resíduos devem ser desenvolvidos. O uso de resíduos de mineração como mistura nos materiais rodoviários é uma estratégia sustentável para a indústria da construção.

A investigação pretende incorporar o resíduo de mineração granítica, sem uso de contaminantes, como enchimento para materiais granulares rodoviários, em agregado britado de granulometria extensa (ABGE) ou *tout-venant*, utilizando diferentes proporções de introdução de resíduo, considerando variações na percentagem de incorporação de resíduos (0%, 25%, 50%, 100%) e na granulometria dos resíduos (>0,063 mm, >0,400 mm). As amostras criadas têm a designação, por exemplo, MW25% (0,063) que corresponde a 75% de *tout-venant* mais 25% de resíduo de mineração passado pelo peneiro <0.063, etc.

A metodologia prevê testes de caracterização e identificação de resíduo de mineração de Pedreira da Devesa, Guarda - João Tomé Saraiva, realizando ensaios para determinação da composição química (fluorescência de raios-X, difração de raios-X, pH e lixiviação), identificação física (índice, densidade, limites de Atterberg e distribuição granulométrica, Proctor e condutividade hidráulica) e ensaios mecânicos (expansibilidade, edométrico e índice de suporte califórnia) de misturas e dos materiais puros.

Os resultados caracterizam as misturas como areias siltosas ou mal graduadas (USCS) e classificadas como A-1-b e A-2-4 (AASHTO), essas misturas têm potencial em aplicações geotécnicas devido à presença de quartzo, caulinita e muscovita. Em termos de composição granulométrica, as misturas MW25% (0,063), MW25% (0,400) e MW50% (0,063) são recomendadas para sub-base, enquanto apenas MW25% (0,063) atende aos limites de Atterberg para sub-base, sendo as outras misturas mais adequadas para corpos de aterro. Para o edométrico, MW25% (0,063) apresentou os

melhores resultados, e no ensaio CBR, apenas MW25% (0,063) superou o mínimo de 20% necessário para sub-base, com maiores valores em misturas com finos de 0,063. Misturas com materiais finos reduziram significativamente a permeabilidade. De modo geral, MW25% (0,063) é a melhor opção para sub-base granular, enquanto as outras misturas, exceto MW50% (0,063), são adequadas para a regularização do maciço, natural ou aterro de fundação e preenchimento de bermas.

Com isso, espera-se que os resultados possam contribuir para a economia circular, promovendo a reutilização de desperdício na construção, criando um equilíbrio entre desenvolvimento económico e conservação ambiental.

Palavras-chave

Resíduo de Mineração Granítica; *Tout-venant*; Caracterização Geotécnica; Sub-base Granular; Economia Circular.

Abstract

Mining generates a quantity of waste, known as tailings, that cannot be reused or go through the recycling process. Therefore, the only alternative is to send them to landfills. However, there are inert products resulting from industrial activity, mines and others that can be classified as waste. In addition to the environmental risks associated with the generation of mining waste, such as soil erosion, water contamination and habitat destruction, there are also significant economic costs related to your disposal. To face this challenge, methods for reusing these wastes must be developed. Using mining waste as a mixture in road materials is a sustainable strategy for the construction industry.

The research aims to incorporate granite mining residue (without the use of contaminants), such as filing for granular road materials, in large-grained crushed aggregate (ABGE) or *tout-venant*, using different proportions of waste introduction, considering variations in the percentage of waste incorporation (0%, 25%, 50%, 100%) and in the particle size of the waste (>0.063 mm, >0.400 mm). The samples created have the designation, e.g., MW25% (0.063) which corresponds to 75% *tout-venant* + 25% mining waste passed through a sieve <0.063, etc.

The methodology provides for characterization and identification tests of mining waste from Pedreira da Devesa, Guarda – João Tomé Saraiva. In addition to chemical (X-ray fluorescence, X-ray diffraction, pH and leaching) and physical identification (index, density, Atterberg limits, particle size distribution, Proctor and hydraulic conductivity), and mechanical testing (expansibility, oedometer and California bearing ratio) of mixtures and pure materials.

The results characterize the mixtures as silty or poorly graded sands (USCS) and classified as A-1-b and A-2-4 (AASHTO), these mixtures have potential in geotechnical applications due to the presence of quartz, kaolinite and muscovite. In terms of granulometric composition, mixtures MW25% (0.063), MW25% (0.400) and MW50% (0.063) are recommended for sub-base, while only MW25% (0.063) meets the Atterberg limits for sub-base, being the other mixtures more suitable for landfill bodies. For the oedometric, MW25% (0.063) presented the best results, and in the CBR test, only MW25% (0.063) exceeded the minimum of 20% required for sub-base, with higher values in mixtures with fines of 0.063. Mixtures with fine materials significantly reduced permeability. MW25% (0.063) is the best option for granular subbase, while

the other mixtures, except MW50% (0.063), are suitable for regularization and berm filling layers.

With this, it is expected that the results can contribute to the circular economy, promoting the reuse of waste in construction, creating a balance between economic development and environmental conservation.

Keywords

Granite Mining Waste; *Tout-venant*; Geotechnical Characterization; Granular Sub-base; Circular Economy.

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Acronyms List

A	Cross-section
AASHTO	American Association of State Highway and Transportation Officials
ABGE	Large-grained Crushed Aggregate
ABNT	Associação Brasileira de Normas Técnicas
Al ₂ O ₃	Aluminum Oxide
C	Clay
c	Number of Layers
CA	Clay Activity
CaO	Calcium Oxide
CBR	California Bearing Ratio
C _c	Curvature Coefficient
Cc	Compression Coefficient
Cd	Cadmium
CETO	Caderno de Encargos Tipo de Obra
CH	Clay with High Plasticity
CL	Clay with Low Plasticity
Cl	Chlorine
Cr	Recompression Coefficient
Cs	Swelling Coefficient
Cu	Copper
C _u	Uniformity Coefficient
c _v	Consolidation Coefficient
DECA	Department of Civil Engineering and Architecture
DNER	Design of Flexible Pavements Considering Mixed Loads and Traffic Volume
DOC	Dissolved organic carbon
EC	Energy of Compaction
EDS	Dispersive X-Ray Fluorescence
EP	Estradas de Portugal
FC	Load Factor
FE	Axis Factor
Fe ₂ O ₃	Ferric Oxide
F.V	Vehicle Factor
Gs	Specific Gravity
h	Height
h1	Hydraulic Load 1
h2	Hydraulic Load 2
HRB	Highway Research Board
IG	Group Index
IS	Index Support
k	Hydraulic Conductivity
K ₂ O	Potassium Oxide
L	Height of the Test Piece
LOI	Loss on ignition
M	Silty Sand

MgO	Magnesium Oxide
ML	Non-plastic Silts or Silty Sand with Low Plasticity
MnO	Manganese (II) Oxide
m_v	Oedometric modulus
MW25% (0.063)	75% tout-venant + 25% mining waste passed through a sieve <0.063
MW25% (0.400)	75% tout-venant + 25% mining waste passed through a sieve <0.400
MW50% (0.063)	50% tout-venant + 50% mining waste passed through a sieve <0.063
MW50% (0.400)	50% tout-venant + 50% mining waste passed through a sieve <0.400
MW100%	100% mining waste
n	Number of Blows
N	Number of Standard Axis Operations
Na ₂ O	Sodium Oxide
NCHRP	National Cooperative Highway Research Program
Ni	Nickel
NMC	Natural moisture content
NL	Non-liquid
NP	Non-plastic
P	Weight of the pile
P ₂ O ₅	Phosphorus Pentoxide
Pb	Lead
pH	Potential of Hydrogen
PI	Plasticity Index
S	Sand
SC	Clayey Sands
SDGs	Sustainable Development Goals
SEM	Scanning Electron Microscopy
SiO ₂	Silicon Dioxide
SM	Silty Sand
SO ₂₋₄	Sulphates
SO ₃	Sulfur Trioxide
SP	Poorly Graded Sand
SP-SC	Poorly Graded Sand with Clay
t	Time
t ₁	Initial Moment
t ₂	Final Moment
TiO ₂	Titanium Dioxide
Tv	Time Factor
TV100%	100% tout-venant
UBI	University of Beira Interior
UCS	Unconfined Compressive Strength
USACE	United States Army Corps of Engineers
USCS	Unified Soil Classification System
U _v	Average Degree of Consolidation
V	Internal Volume of the Mold
V _t	Total Traffic Volume
w _L	Liquid Limit
w _P	Plastic limit
w _S	Shrinkage Limit
XRF	X-ray fluorescence

XRD	X-ray diffractures
z	Depth
Zn	Zinc
Δu	Pore pressure
$\Delta \sigma$	Tension

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Chapter 1

Introduction

1. Scope and Justification

Mining activities bring economic benefits, however, requires processing to enable the commercialization of the extracted ore. Those processes generate several products, including rock powder, sludge, soil, and chemicals, representing potential environmental risks. These products can be classified as waste or rejects. Waste being that material that, after exhausting all possibilities of treatment and recovery through available and economically viable technological processes, does not present any other possibility than environmentally appropriate final disposal; and waste is that which is not suitable for its intended use, but can become raw material for a new product or process.

Portugal has a granite mining industry with extensive exploration areas throughout the country. Traditionally, this waste was discarded in areas of specific position, often resulting in negative environmental impacts, such as soil and possible water contamination and landscape manipulation. Considering this situation, it is necessary to develop effective methods for reusing disposed materials. One approach is to verify and quantify the hypothesis of chemical contamination and then use these mining by-products as components in road materials, representing a sustainable and innovative strategy for the construction industry. Waste from granite is mainly composed of granite rock fragments, which seem to have mechanical properties and durability that make them suitable for use as aggregates in pavements. Furthermore, the mineralogical composition of granite waste may include minerals such as quartz, feldspar, and mica (biotite and muscovite), which contribute to the strength and stability of roads.

This research aims to incorporate granitic mining waste, or mining waste (MW), as filler in road granular layers. The MW comes from a quarry called “Pedreira da Devesa” (Figures 1 and 2), located in Santana de Azinha, Guarda (Portugal). An extract from a geological map with the geographic and geological framework is presented in Figure 3.

The “Pedreira da Devesa” is recognized as an extractive unit for granite rocks in the region. Besides, this approach not only addresses the responsible environmental management of mining waste disposal, but also seeks to promote sustainability in the construction of road infrastructure, thus contributing to more eco-efficient practices in the sector.



Figure 1 - Pedreira da Devesa



Figure 2 - Granite mining residue from Pedreira da Devassa

This area has numerous roads and paths that facilitate access to the main towns, the region is also crossed by the “Beira-Alta” and “Beira-Baixa” railway lines, which converge to Guarda. Guarda corresponds to an area connecting different geomorphological units, its eastern region, quite regular, with altitudes around 800 meters, is part of the surface of the “Meseta”. This area is crossed by numerous watercourses, made up of the Côa river and its tributaries, such as the “Ribeira das Cabras”, the Noeme, the Diz, and the Seixo rivers, among other smaller ones, with valleys, in general, of very steep slopes. Downstream are progressively more embedded, as happens with “Ribeira das Cabras”, which has carved very deep gorges in the granite rocks it crosses. The western region, on the contrary, is a mountainous area, which represents the first elevations of the “Serra da Estrela”. The region studied is in a centralized area.

The mapped region is essentially granitic in nature (Figure 3), with small shale patches interspersed, numerous veins, mainly of quartz and basic rocks, and some recent alluvial deposits. Granite is, as far as its mineralogical composition is concerned, of a monzonitic type, made up of two micas with a predominance of biotite. However, it comes in different varieties in terms of texture. Quartz veins predominate, followed by basic rocks and aplite-pegmatites. The covering lands are formed by recent alluvium and valley bottom deposits. Although it presents variations in texture and granularity, from the point of view of mineralogical composition it is more uniform despite showing a markedly alkaline character in the western half of the map. As essential elements it usually contains quartz, oligoclase or oligoclase-andesine, microcline, microcline-perthite, micropertite, albite or albite-oligoclase, biotite and muscovite. Accessory minerals comprise apatite, zircon, magnetite, tourmaline, rutile, among others, besides, secondary minerals include kaolinite, sericite, chlorite, acicular rutile, sphene, etc (Teixeira, et al., 1963).

The theoretical justification for the research is mainly the lack of studies in the literature that explore the reuse of granite mining waste, which limits the understanding of its potential and applicability in different areas of civil engineering.

The practical justification is associated with the reuse of waste, considering its abundance, aiming to reduce the environmental impact of mining and promote a sustainable management of natural resources. Furthermore, the use of this waste can represent an economic opportunity for companies in the sector, while contributing to the preservation of the environment and the development of more efficient and eco-friendly solutions in civil engineering.

This initiative is aligned with the Sustainable Development Goals (SDGs), especially SDG 9 - Industry, Innovation and Infrastructure, and SDG 12 - Sustainable Consumption and Production, which aims to promote sustainable practices in industry and resource management to achieve inclusive and sustainable economic development.

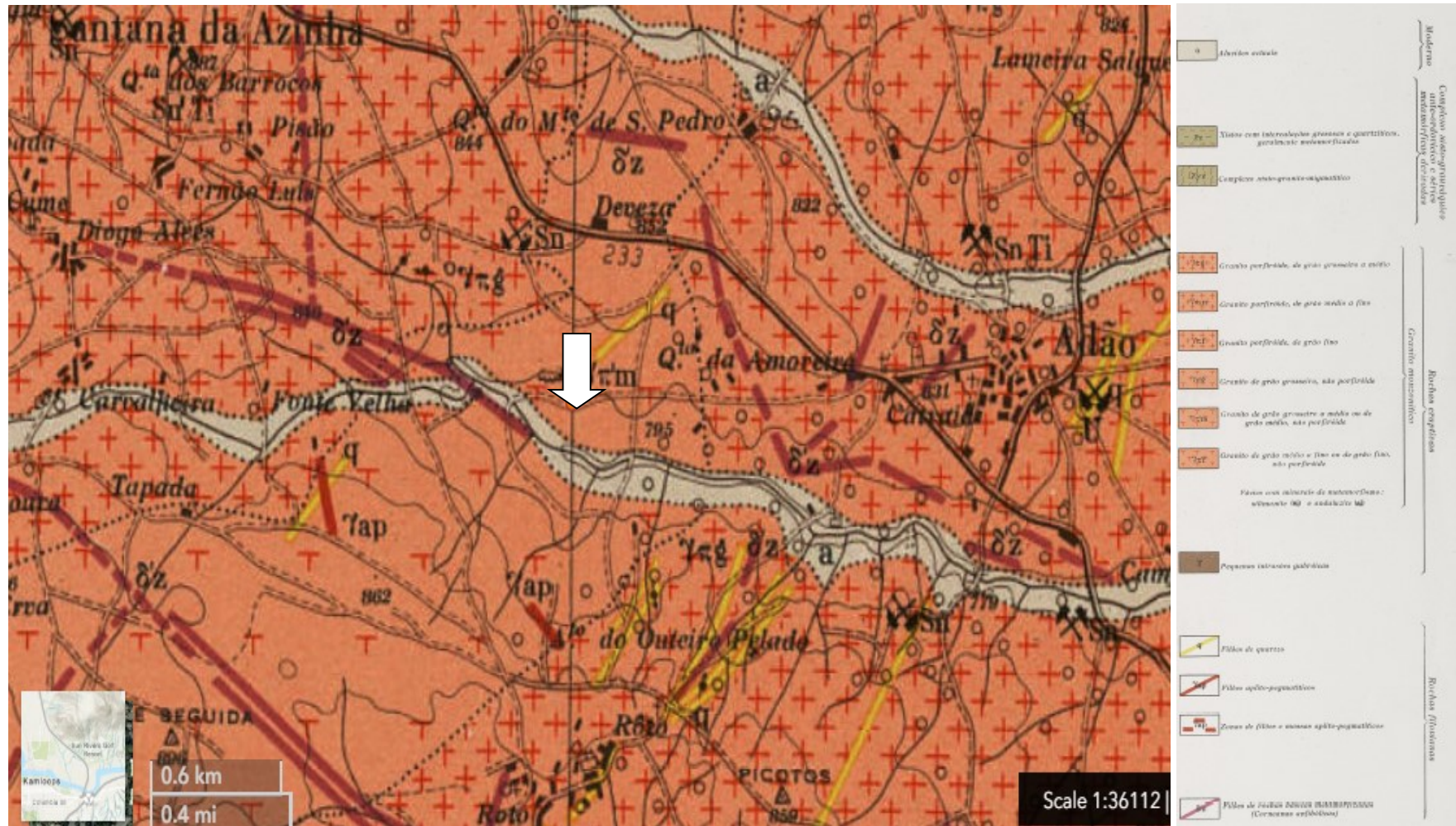


Figure 3 - Extract of geological map of Portugal, chart 18-C (Guarda), scale 1:50.000 (Source: https://geoportal.ineg.pt/pt/dados_abertos/cartografia_geologica/cgp50k/18-C)

2. Objectives

The general objective of this work is to analyze the viability of mixtures of granite mining waste as fillers for large-grained crushed aggregate (ABGE), or *tout-venant*.

The specific objectives are:

- Characterization and identification of granite mining waste: Carrying out an analysis of mining waste from Guarda (Portugal) through chemical and mineralogical composition, leaching potential, index, density, consistency, and particle size distribution to understand its properties and characteristics.
- Development of geomaterials for roads: Investigating the feasibility of using mining waste mixed with *tout-venant* in the production of new geomaterials using different ratios for waste introduction, considering variations in the percentage of waste incorporation (0%, 25%, 50%, 100%) and in the granulometry of the waste (particle sizes >0.063 mm, >0.400 mm, >2.000 mm), with the aim of evaluating the performance of materials for geotechnical applications.
- Geomechanical validation: Carrying out tests as Proctor compaction, hydraulic conductivity, expansibility, oedometric consolidation and California Bearing Ratio (CBR) for the mixtures developed.
- Contribution to Sustainable Development: Evaluate the results obtained from research in the context of the sustainable development of geomaterials, seeking to reduce environmental impact and promote more sustainable practices in civil engineering.

3. Dissertation Structure

This dissertation is composed of 6 chapters, following:

Chapter 1 – Introduction

In this first chapter, the research scope, justification, and objectives are presented, along with an overview of the dissertation structure. The importance of the study on the incorporation of granite mining waste as filler for base materials (*tout-venant*) in the composition of materials for road paving will be discussed.

Chapter 2 – State-of-the-art

In chapter 2, the structure of a pavement is described, with emphasis on granular layers. Furthermore, mining waste as geomaterial will be discussed, addressing the physical, chemical, and mineralogical characteristics of it from other works.

Chapter 3 – Methodology

In chapter 3, the materials, mixtures, and waste further analyzed throughout the research will be presented. Furthermore, the methodology used in the testing program and sampling for the trials will be detailed, aiming for a systematic approach to obtaining results.

Chapter 4 – Results and Discussion

In chapter 4, the results are presented and discussed, highlighting the characteristics and behaviors of the materials studied, and an analysis is made regarding the desired application.

Chapter 5 – Conclusions and Proposals

Chapter 5 will present the main conclusions of the research, and suggestions for future investigation, aiming to contribute to the advancement of knowledge in the area.

Chapter 2

State-of-the-art

1. Introduction

In geotechnical works, such as embankment, roads, foundations, and others, high variations of soils can be found, which may be frictional soils (sands and gravels), cohesive soils (silts and clays), residual soils, or all other possible mixtures of these two, in different proportions. Besides, soils can be used in the paving layers of a road, however, the region's natural soils are not compatible with what is intended, establishing some limitations. In these cases, you can choose to buy new materials or apply stabilization techniques, such as additives like lime or hydraulic binders, due to medium to high plasticity of those materials, or granulometric stabilization, to improve the properties of the soil and make it suitable for roads.

For earthworks, to select the optimal mixture of waste-soil with the best characteristics for the intended purpose, it is necessary to carry out a complementary evaluation of its mechanical characteristics in an experimental plan, which serves as a comparison with the results obtained in the laboratory and are essentially used to optimize mixtures and develop standard compaction curves. The development of a project that involves the improvement and reinforcement of soils using the compaction method requires the definition of calculation parameters based on the compaction curve, which is normally the curve corresponding to that obtained in a small mold.

The lack of knowledge about the compaction characteristic due to the difficulty in defining the water content necessary to obtain the maximum degree of compaction, requires carrying out testing programs to analyze the influence of wastes on soils after compaction. The characteristic compaction curve obtained in the field will be used to define a laboratory compaction test approximating the obtained in situ, which will be used for control operations in the future use of materials during construction work (Marchiori, 2022).

Each layer of a pavement structure requires a different type of mechanical behavior, for flexible pavements, the upper layers are made up of bituminous materials and the lower layers are made up of granular materials above the foundations or sub-grade. While for rigid pavements, the upper layers are made up of materials stabilized with hydraulic binders and the lower layers are made up of stabilized granular materials (Morais, 2011, Santos, 2010).

The focus of this work is the granular layers, as it seeks to analyze the prediction of mixtures of granite mining waste as fillers for coarse-grained crushed aggregates in the context of the sustainable development of geomaterials, seeking to reduce the environmental impact and promote more efficient practices. sustainable development in civil engineering.

2. Granular Layers

The granular layers (sub-base and base) play a structural role by distributing vertical loads, relieving compressive stresses in the foundation, which corresponds to the critical failure zone, where, although vertical efforts are lower, the mechanical strength characteristics are reduced, ensuring the soil's capacity to support traffic. This occurs by reducing stress in the foundation soil and standardizing the mechanical properties of the circulation surface on site (Morais, 2011, Santos, 2009, Silva, 2005). In these layers, *tout-venant* are commonly used, or soils and aggregates with the addition of hydraulic binders.

The Type of Work Specification, or Caderno de Encargos Tipo de Obra (CETO) from Estradas de Portugal (EP) generally defines the structure of the granular layers of flexible pavements in accordance with Table 1 (E.P., 2014). This table provides the types of materials that can be used for sub-base, base and regularization layers. Furthermore, in Table 2, the minimum requirements are set out, in accordance with reference standards, for the acceptable values of granular materials with sub-base characteristics. These criteria define the physical and mechanical characteristics necessary to ensure adequate bearing capacity and stability of the pavement subbase.

Table 1 - Materials for unbonded layers

LAYER	MATERIAL
Sub-base	ABGE Recycled aggregates Selected soils
Base	ABGE Recycled aggregates
Regularization	Sandy aggregates, fine aggregates for sidewalk, or concrete blocks

Table 2 - Required properties for sub-base soils

REQUIREMENTS	STANDARD	VALUE	UNIT
Particle dimension, maximum	LNEC E 196	75	mm
Passing % of #200, maximum	LNEC E 196	15	%
Liquid limit, maximum	NP 143	25	%
Plastic limit, maximum	NP 143	6	%
CBR (Modified Proctor compaction degree of 95%), minimum	LNEC E198	20	%
Expansibility (CBR), maximum	NF P94-078	1,5	%

The current practice of constructing granular pavement layers is mainly based on mined rocks and aggregates. Natural aggregate (rolled or crushed) can be defined as that which is extracted from natural deposits, with mineral origin, such as gravels that have naturally fragmented from rocks, and sands, the final residue from the deterioration of rocks, crushed stone resulting from processing mechanic (Santos, 2010). However, extracted materials, normally from mines, for civil construction applications are becoming increasingly scarce (Yaghoubi, et al., 2023).

With the aim of improving the properties of granular layers, increasing their resistance and durability, reducing costs and environmental impacts associated with waste disposal, granular layers and binders have been intensively researched. The main insights are from development of new materials and methods, relying on the use of various mixtures of wastes, as mining wastes, agro-industrial ashes and shells, metallurgical slags, among others (Doan, et al., 2024, Yaghoubi, et al., 2023, Marchiori, et al., 2022).

Soil granulometric stabilization is a technique that aims to improve and stabilize the geotechnical properties of the soil, ensured by contact between particles. This technique involves using a material or mixture of materials to meet specific specifications. Soils with few fines have reduced workability, low density, and high permeability. Finer soils filling the voids result in low permeability, high density, and moderate difficulty in compaction due to the low void content. On the other hand, soils with a large percent of fines show very low density and permeability, presenting poor workability (Campanha, 2011).

Additionally, other techniques include proper soil compaction, controlling moisture during construction, using geotextiles and geosynthetics to reinforce soil and reduce erosion, in addition to apply strengthening techniques such as resin injection or the use of stakes or pillars.

To ensure field control of these layers, some tests are carried out, which may be Plate Load Test, Load Test with Impact Deflectometer, and/or Load Test with Portable Impact Deflectometer. All these tests follow a common principle, where a load is applied to the surface to be tested by means of a circular load plate, and the resulting vertical displacements are measured by deflectometers. In addition, in-situ density tests control the compaction degree of the layers, made by gamma densimeters or soil density gauge (Marchiori, 2022). These field tests complement the analyzes carried out in the laboratory, which include the identification and classification of soils for road purposes, granulometric analysis, consistency limits, Proctor compaction, CBR test (Morais, 2011).

2.1. Flexible pavement design approach

Among all the existing pavement design methods, two stand out: analytical method and empirical method. The first considers the analysis of stresses and deformations in non-perfect elastic media (soils and asphalt mixtures) and compares these structure responses with pre-established criteria to determine layer thicknesses. The empirical method is based on repeated experiences in the field. They are best based on the method originating from the work of O. J. Porter, an engineer at the California Department of Highways. Initially known as the California method, it was also later known as the United States Army Corps of Engineers (USACE) or “Design of Flexible Pavements Considering Mixed Loads and Traffic Volume” (DNER), based on the CBR (Alves, 2016, Souza, s.d.,Ferreira, 2021).

The support capacity of the subgrade and the constituent materials of the pavements is determined by the CBR, using the test method recommended by the DNER, on undisturbed or laboratory-molded specimens for the apparent density and humidity conditions specified for the service. The subgrade and the different layers of the pavement must be compacted according to the values established in the "General Specifications", ensuring that, in no case, the statistically calculated degree of compaction must be less than 100% of that specified. For coarse-grained granular soils, the compaction energy corresponding to the modified Proctor must be used. The subgrade materials must present an expansion, measured in the CBR test, less than or equal to 2% and a CBR \geq 2% (DNIT, 2006).

The method classifies the materials used in such a way, as follows: materials for reinforcing the subgrade are those with a CBR greater than that of the subgrade and expansion \leq 1% (measured with an overload of 10 lb); materials for sub-base, those with C.B.R. \geq 20% and expansion \leq 1% (measured with 10 lb overload); and base materials, those with: C.B.R. \geq 80% and expansion \leq 0.5% (measured with 10 lb overhead), Liquidity Limit (W_L) \leq 25% and Plasticity Index (PI) \leq 6% (DNIT, 2006).

The method also states that if the liquidity limit is greater than 25% and/or the plasticity index is greater than 6, the material can be used as a base (if the other conditions are met), as long as the sand equivalent is greater than 30.

In the case of sizing, a Support Index - IS is adopted, calculated with the arithmetic mean of two other indices derived, respectively, from C.B.R. and the Group Index -IG, given in Eq. 1:

$$IS = \frac{(IS_{CBR} + IS_{IG})}{2} \quad (1)$$

Where IS_{CBR} is the support index derived from the CBR (numerically it is the CBR itself), IS_{IG} is the support index derived from the group index, practically corresponding to an inversion of scale, causing good quality soils to have the highest IS_{IG} values.

To design the pavement, it is necessary to determine the traffic (Vt) and the equivalent number of operations of the standard single axis during the design period and the traffic parameter used in the design (N) (Eq. 2 e 3).

$$N = Vt * (FE) * (FC * FE) * FC \quad (2)$$

$$N = Vt * (F * V) \quad (3)$$

Where, FE is an axle factor, that is, a number that, multiplied by the number of vehicles, gives the number of corresponding axles; FC is a load factor, that is, a number that, multiplied by the number of axles that operate, gives the number of axles equivalent to the standard axle; F.V is a vehicle factor, a number that, multiplied by the number of vehicles operating, directly gives the number of axles equivalent to the standard axle; and Vt is the total traffic volume. To calculate these factors, it is necessary to know the traffic composition. To do this, it is necessary to count the traffic on the road being considered, studying a certain total volume of traffic, Vt , for the sampling period. Calculation of Vt can be done based on an economic study of the region. The total number of axes n is counted, and all these axes are weighed (Figure 4). With the weighing data, a table is organized by grouping the various axles by load intervals, which results in the index ($F * C$).

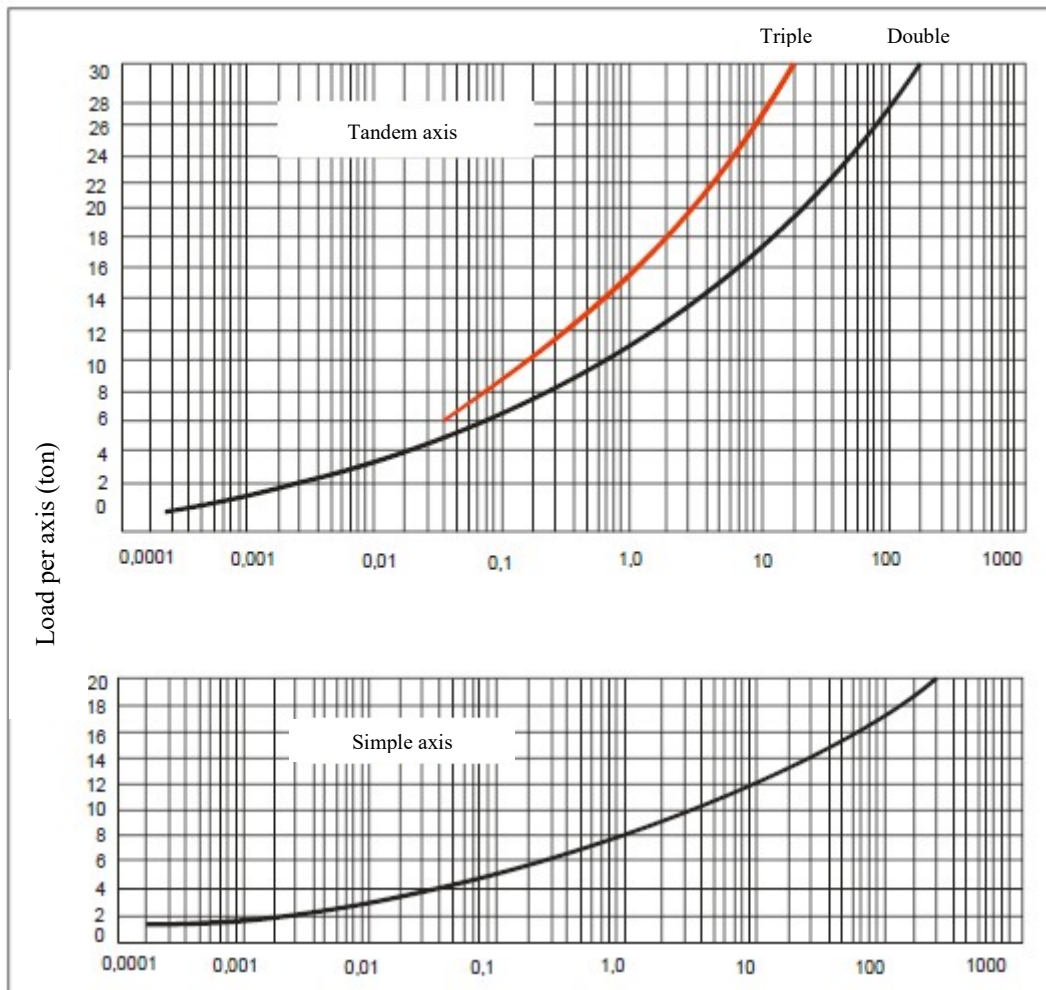


Figure 4 - Operation equivalence factors (DNIT, 2006)

The graph in Figure 5 gives the total thickness of the pavement, as a function of N and I.S. or C.B.R., so that entering the abscissa with the value of N , proceed vertically until finding the straight line representing the CBR and, proceeding horizontally, the thickness of the pavement is found, in ordinates. The maximum and minimum compaction thicknesses of the granular layers are 20cm and 10cm, respectively.

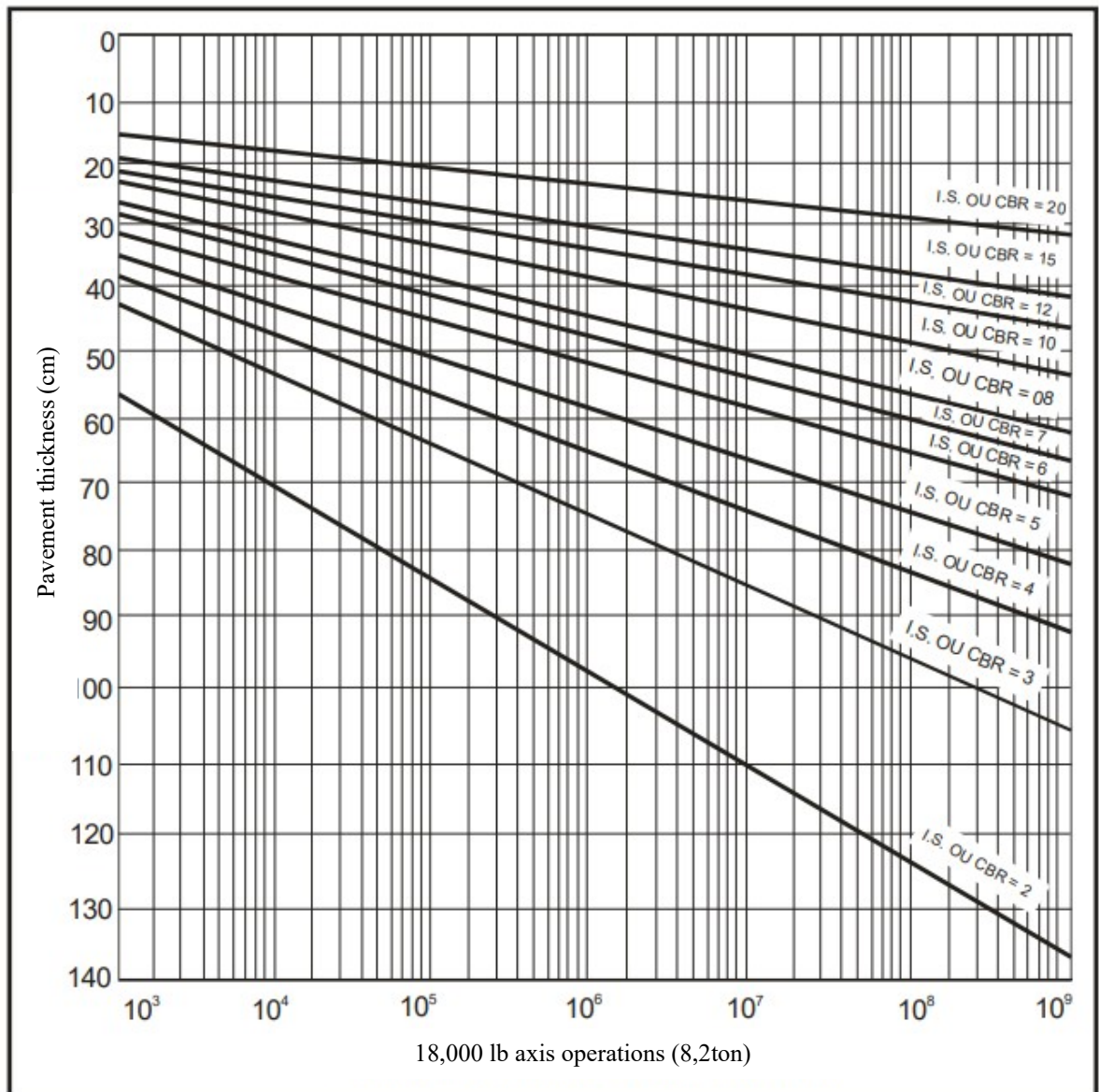


Figure 5 - Determination of pavement thickness (DNIT, 2006)

Figure 6 presents symbols used in pavement design. H_m designates, in general, the total thickness of pavement necessary to protect a material with C.B.R. or I.S. = CBR or IS = m, etc., h_n generally designates the layer thickness of the pavement with C.B.R. or I.S. = n, etc. Once the thicknesses H_m , H_n , H_{20} , the thicknesses of base (B), sub-base (h_{20}) and subgrade reinforcement (h_n) are obtained by successive resolution of the following Eq. 4, 5 and 6:

$$R_{KR} + B_{KB} \geq H_{20} \quad (4)$$

$$R_{KR} + B_{KB} + h_{20} K_s \geq H_n \quad (5)$$

$$R_{KR} + B_{KB} + h_{20} K_s + h_n K_{Ref} \geq H_m \quad (6)$$

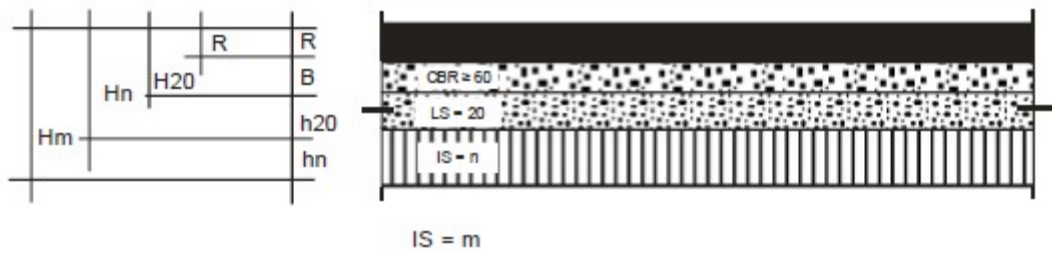


Figure 6 - Pavement sizing (DNIT, 2006)

3. Mining Wastes

In mining activities, ore is extracted from rocks made up of a specific mineral containing economic value (Campanha, 2011). The ore, when found in nature in its raw form, requires processing to purify, enrich and prepare the minerals for industrial use, using physical and/or chemical methods, thus, mining, despite bringing economic benefits, requires processing processes to enable the commercialization of the extracted ore. These processes generate wastes, known as mining waste or tailings (Lara, et al., 2018). Mineral exploration follows a rigorous technical process, starting with the deforestation activity, which involves the removal of the covering soil and the dismantling of the rock, resulting in the temporary production of sterile waste grouped in piles. Then, the extracted mineral then undergoes processing, where it is treated to improve its physical-chemical properties, which is the ultimate objective of the industrial activity, and are accumulated in dams having, initially, low economic value (Pinto, 2013).

Therefore, mining waste is a by-product generated from mineral extraction, where three types stand out in terms of volume: rock waste, tailings, and mine water, which are present during various stages of the extraction process. In the case of granite mining, the extraction process begins in the deposits, where waste is generated from the crushing of rock blocks. The accumulation of waste generated by mining and quarrying activities over the years has resulted in the formation of large deposits, representing a potential risk of environmental pollution and causing significant visual impacts, negatively affecting the quality of life of local communities (Castro-Gomes, et al, 2012). In the case of mining waste, its composition contains metallic ions, and sometimes radioactive substances, which enter the soil and water, destroying the balance of the ecological environment (Jing, et al, 2023a, Jing, et al., 2023b), needing evaluation of those parameters.

In the European Union in 2020, approximately 23.4% of waste generated came from the mining and quarrying industry (Eurostat, 2020). Certain mining wastes have been successfully used to improve soil properties while reducing the environmental impact of these wastes. Therefore, by integrating particle size stabilization with mining waste management, economic and

environmental benefits can be achieved, contributing to more sustainable and efficient construction.

Thus, the valorization of mining waste as a coating material for earthworks applications, such as geomaterials, appears as an innovation to prevent the accumulation of waste in the environment.

3.1. Physical, chemical, and mineralogical characteristics

The waste generated by mining activities has a complex physical, chemical, and mineralogical composition, resulting from the ore extraction, processing, and treatment processes. During this extraction, they can present a diverse composition, containing quartz, feldspar, mica, and other minerals, depending on the geology of the location.

As for chemical composition, according to (Malaoui, et al., 2023), rock mining waste mainly contains calcium oxide (CaO), silicon dioxide (SiO₂) and magnesium oxide (MgO). In terms of trace elements, very low concentrations of lead (Pb), zinc (Zn) and copper (Cu) were detected. Phosphatic limestone, in turn, has a significantly higher concentration of phosphorus pentoxide (P₂O₅) (22.66% by weight) compared to common limestone (0.89% by weight). As for mineralogical composition, the two phosphate residues share four main minerals: carbonate fluorapatite, calcite, dolomite, and quartz.

Lara, et al. (2018) presents a composition for iron mining waste, where the samples are predominantly composed of quartz, hematite and kaolinite, with quartz being the most abundant mineral, representing more than 50% of the total. Furthermore, scanning electron microscopy (SEM) shows a diversity of particle sizes and shapes, ranging from less than 10 µm to just over 100 µm, highlighting the heterogeneity of the samples. (Amaral, 2021) found goethite (42.6%), quartz (25.5%), hematite (19.5%), kaolinite (10.3%) and muscovite (2.1%) in different proportions.

For rock mining residue, (Dino, et al., 2020) reuses in the ceramics industry, where materials sampled in 2009 and 2016 present highly homogeneous geochemical characteristics ranging between aluminum oxide (Al₂O₃: 13–14%), ferric oxide (Fe₂O₃: 1–2%), titanium dioxide (TiO₂: 0.10–0.2%), CaO (0.5–2%), MgO (0.1–0.4%), potassium oxide (K₂O: 4–5%), Sodium oxide (Na₂O: 3–3.6%) for main elements.

Regarding physical and mechanical characteristics, mining waste can vary in particle size, from fine sediments to larger fragments of rock. This variation in granulometry can influence the compaction, permeability, and strength of the waste. Table 3 presents physical and mechanical

characterization parameters of some authors and Figure 7 presents some examples of mining waste studied by these authors.

Comparing the two materials used by (Campanha, 2011), the author says that the tests indicated superior mechanical performance in flotation tailings than concentration ones, due to the greater presence of fine fraction in its particle size composition, generating greater cohesion and better performance. (Amaral, 2021) analyzed the granulometric composition of iron mining waste and found that the pure waste was composed of silty sand. After the flotation process, the floating portion had a higher proportion of silt and clay, while the non-floating portion contained more sand.

Table 3 - Mining waste characterization

AUTHORS / INDEX		Gs	w_L	w_P	Fines	OMC	MDD	CBR
Unit	Waste Type	-	%	%	%	%	g/cm³	%
(Wurie, Zheng, & Traore, 2022)	Waste Rock	2.62	21.85	12.90	10.00	-	-	-
(Malaoui, et al., 2023)	Phosphatic Limestone	2.74	30.88	NP	2.78	12.30	1.85	10.55
	Limestone	2.63	33.41	23.81	3.27	14.15	2.00	18.29
(Andalicio, Pereira, & Oliveira, 2022)	Waste Rock	2.78	58.00	19.00	74.00	25.20	1.66	29.30
	Tailings	2.98	NL	NP	77.00	13.90	1.83	17.50
(Lara, et al., 2018)	Iron Mining Waste	2.98	NL	NP	10.00	-	-	-
(Sangiorgi, et al, 2016)	Tungsten Waste	2.73	-	-	-	-	-	-
(Galhardo, 2015)	Iron Mining Waste	2.96	NL	NP	36.00	-	-	-
(Campanha, 2011)	Iron mining flotation tailing	3,23	15.00	10.00	41.00	9.20	2,22	23.46
	Iron mining concentration tailing	3,62	NL	NP	10.00	12.24	1,85	18.23

NMC: Natural moisture content (%); Gs: Specific Gravity; w_L = Liquid Limit (%); w_P = Plastic limit (%); %Fines: Percentage of soil particles that are smaller than N°200; OMC: Optimal moisture content; MDD: Maximum dry density or dry bulk density.

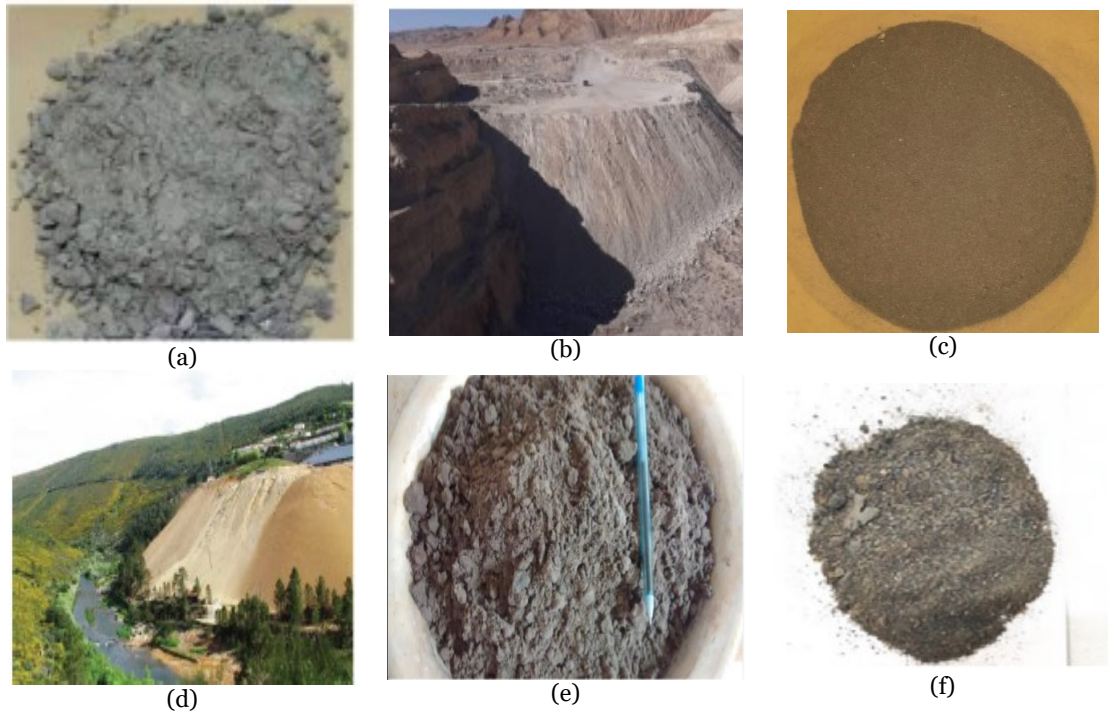


Figure 7 - Types of ore residue according to the authors (a) Wurie, Zheng, & Traore (2022) (b) Malaoui, et al. (2023), (c) Lara, 2018, (d) Sangiorgi, et al. (2016), (e) Galhardo (2015), (f) Jing, et al. (2023)

Generally, mining waste consists of particles ranging in size from clay to gravel, with the presence of sand and fines. They can be classified as non-plastic silts (ML) or silty sands (SM) by the Unified Soil Classification System (USCS). Generally, they have a w_L below 40% and a w_P ranging from 0 to 15%. The hydraulic conductivity (k) of tailings typically ranges from 10^{-7} to 10^{-9} m/s. In general terms, waste rock has low compressibility and high shear strength (Castillo, 2019).

Schnaid (2014) carried out the characterization of bauxite mining waste, where he concluded that the material disposed in the lagoons is mainly silty and low-plastic clay, with an average unit weight of 16 kN/m^3 and high specific gravity, reflecting the high iron content of the waste. Microscopy reveals well-rounded and angular grains, forming a loosely arranged structure that can result in relatively high drained shear strength. For pH values, Campanha (2011), Galhardo (2015) and Malaoui, et al. (2023) found values between 6 and 8.

3.2. Mining waste as geomaterials

The use of mining waste as geomaterials is a practice that is increasingly studied and applied in various areas of geotechnical and civil engineering. These materials, often considered by-products of mining activities, can be reused efficiently and sustainably in a variety of

applications. In this context, the exploration of these geomaterials offers not only economic benefits, but also contributes to reducing the environmental impact associated with the inadequate disposal of mining waste.

In 2018, Europe produced around 2.383 million tons of waste from various sources, while Portugal produced approximately 10.3 million tons, where the main destinations for waste treatment are landfill (37%) and recycling (39%). Romania and Bulgaria have the highest landfill rates (94% and 85%, respectively), while Italy and Belgium lead in recycling (79% and 77%, respectively). Portugal, in 2018, had a landfill rate of 34% and a recycling rate of 48%, both comparatively favorable, but there is still room to improve the circularity of materials in the country (Araújo, 2022).

In the area of paving, the use of mining waste seems to be a promising alternative. (Malaoui, et al., 2023) used waste rock from the Kef-Essenoun mine, between 2006 and 2017, it is estimated that the amount of waste rock produced varied from approximately 5.5 to 18.5 million tons per year. Mining waste is generally classified as a reasonable quality material for road applications. Some applications suggest the addition of mining residue with supplementary cementitious material, as oyster shell powder, partially or completely replacing cement to stabilize soils contaminated by heavy metals and improve soil resistance (Wurie, Zheng, & Traore, 2022).

Lara, et al. (2018) mixed mining residue in the proportions 50:50%, and 75:25% of soil:residue), verifying an increase in the maximum apparent dry specific mass and a decrease in the optimal water content of the mixtures using Normal and Intermediate compaction energy. This behavior is justified by the presence of hematite and quartz present in the mineralogical composition of the residue. CBR values increased according to the increase in the compaction energy was also observed individually for each energy in comparison to the pure soil. In this way, the maximum value of the CBR was 36%, reached for the mixture that incorporated 75% of waste, at the intermediate compaction energy, against an 13% obtained for the pure soil, an increase of more than 270%. The increase in the percentage of waste in the soil matrix caused a downward trend in the expansion values measured during the CBR tests.

(Galhardo, 2015) studied soil mixtures with sandy mining waste, in the proportions 80:20% waste, 60:40%, and 50:50% soil: waste. The addition of waste to natural soils reduces liquid and plastic limits, resulting in a decrease in plasticity index, especially at higher proportions of waste. Furthermore, the inclusion of tailings affects the compaction parameters, decreasing the optimum moisture content and increasing the maximum apparent specific mass. The combination of clayey laterite soil with 20% waste demonstrated the best mechanical performance and thicknesses suitable for pavements with low traffic, if the specific construction conditions of laterite soils are respected.

Regarding changes in physical characteristics, Andalicio, et al. (2022) evaluated the composition of the mixture 35% tailing + 15% waste rock + 50% canga of ore, verifying that the addition of

canga of ore to the mixture resulted in a reduction in the percentage of fines passing by sieves number 40 and 200 compared to pure mining waste. Furthermore, this mixture presents non-plastic characteristics, with adequate CBR, expansion and great values for the sub-base layer. (Marchiori, et al, 2022) presents in his research that the addition of granite mining residue in mixtures with clayey soils, promotes a reduction in their plasticity, in addition to indicating that, as it has a finer grain size, it can indicate good filling properties within the soils.

Sangiorgi et al (2016) carried out a study with tungsten mining waste, where coarse waste for road construction has proven viable if the installation of a stable asphalt concrete plant and crushing and screening of aggregates is implemented in the mine areas. Cold, hot and warm bituminous mixtures can be produced and transported within a profitable market range in the districts surrounding the mine. Rough estimates suggest that more than 3,000 tons of waste can be used to build 1 km of two-lane rural road in the asphalt concrete layers alone, which could double if used in the foundation layers as well.

Another type of mining waste is phosphate limestone waste, normally found in a very dry state and considered sensitive to water, it can be reused in the construction of landfills or capping layers after a humidification process to reach a dry or normal state. To improve their mechanical and physical properties, this waste needs to be treated with a hydraulic binder, such as cement, which can result in thinner subbase layers and possibly reduce the thickness of the pavement layer, bringing economic and environmental benefits. From the perspective of mechanical behavior and applicability in road construction, CBR and Unconfined Compressive Strength (UCS) values increase with MDD, and UCS increases with curing age (Rachida Malaoui, et al., 2023).

The practical application of using mining waste for paving layers was made by (Andalicio, et al, 2022), where field studies were conducted on an experimental stretch of BR 040, in Minas Gerais, Brazil. Based on validated laboratory results, specific mixtures were used in the base and sub-base, mainly composed of tailings, gravel and ore yoke. The results showed that the mixtures applied to the base and sub-base behaved differently from the characteristics observed in the laboratory. It was concluded that the composition applied to the base layer obtained consistent results in the field, indicating possible use in the sub-base layer.

Overall, granite mining waste has potential applications highlighting its usefulness in the construction and engineering of railways and roads, as well as in the production of hydrotechnical stones and lightweight aggregates. Furthermore, granite waste can be used as feldspar flours that improve soil quality, while basalt waste raw materials should be mainly used to improve soil quality as basalt flours (Kazmierczak, et al, 2019).

The reuse of mining waste can also be used in other applications. (Castro-Gomes, et al, 2012) presents the experimental use of sterile waste from Panasqueira mining in the creation of polymer-based composites. These composites take advantage of the natural characteristics of

waste rock, especially in terms of final appearance and visual impact, and are suitable for technical and artistic applications such as sculpture and architecture. Furthermore, it is possible to modify the color of the waste through heat treatment or other chemical processes. Based on their mechanical and physical properties, it is believed that these wastes can be reused as new construction materials, such as terrazzo tiles for exterior use, and in the development of new polymer composite products that combine technological and artistic concepts. However, the use of this type of materials basically composed of the extraction of ores and mineral waste resulting from the laundry process and in the case of tungsten mineralization, the so-called sterile materials may contain heavy metals and which, through reuse, will be disseminated and if there is no control.

(Aguiar, et al., 2024) uses three types of quartzite, which were crushed and combined into three different grain sizes: coarse, medium, and fine. Artificial stone slabs were manufactured using 15% by weight of vegetable polyurethane resin from castor oil and 85% by weight of ornamental stone waste (quartzite). The results demonstrated the technical feasibility of producing these artificial stones, also highlighting their contribution to a sustainable and environmentally conscious approach, in line with the principles of the circular economy. In the context of structural ceramics, (Amaral, et al., 2021), when adding waste or its fractions to the soil, observed improvements in certain characteristics of the ceramic specimens. Linear shrinkage decreased as the proportion of sedimentation and flotation fractions increased.

Another economical way of recycling is to use tungsten mining mud tailings to produce alkali-activated binders and mortars, which have been shown to be compatible with the region's shales. The manufacture of artificial aggregates using alkaline activation has obtained positive results, allowing the recycling of sludge into particles with special characteristics for paving. Finally, large volumes of waste rock can be recycled in the industrial production of prefabricated segments for transport infrastructure, with the alkaline activation of mud fines and other precursors forming the binding paste for these elements (Sangiorgi, et al., 2016).

Despite the high demand from the construction industry, which reaches 1.5 billion tons, the use of waste as construction material does not exceed 1% in volume. This is due to factors such as the low value of construction materials compared to higher value-added products and transportation costs. Successful or potentially implementable approaches have emphasized recovering resources in an environmentally friendly and low-cost manner compared to traditional materials. The literature highlights the application of mining tailings in construction and agricultural applications, despite low profitability, if the tailings have non-hazardous compositions and are in locations reasonably close to their final use (Araujo, et al., 2022).

3.3. Environmental Impacts

In the mining process, direct impacts affect the physical, chemical, and biological characteristics of the environment. These include the health issues of plant and animal communities, changes in topography, soil disruption, erosion, silting of drainage systems, loss of organic matter and changes in solar exposure and thermal amplitudes. In most cases, mining causes water pollution mainly due to the dumping of sludge. Although pollution from soluble chemical compounds also occurs and can be severe in certain areas, it is more limited in comparison. Mines of iron ore, limestone, granite, sand, clay, bauxite, manganese, cassiterite, diamond and many others generally result in pollution due to sludge disposal (Galhardo, 2015). Figure 8 summarizes the generation of iron waste and rock waste, showing the environmental effects at the different stages of mining. This includes the extraction and processing of iron ore, as well as the disposal of waste rock resulting from these operations.

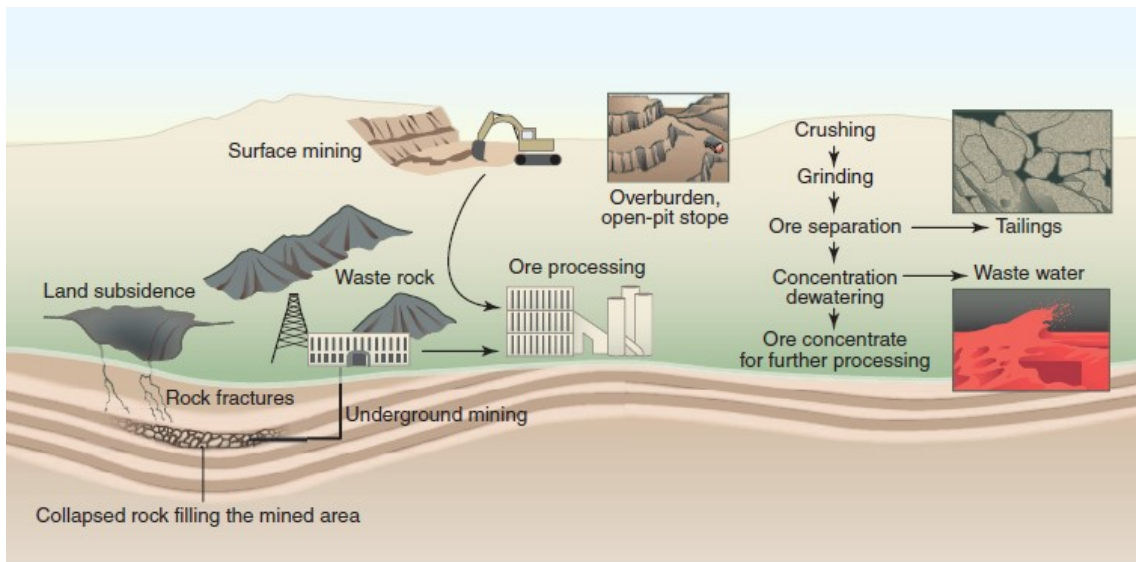


Figure 8 - Waste generated and environmental effects in the different stages of mining (Bian, et al., 2012)

Most of this waste is discarded directly into the ground or deposited in landfills. The first approach can result in adverse environmental consequences, such as destruction of vegetation, deforestation, changes in topography and increased risk of erosion. Furthermore, it can cause water and groundwater contamination due to the transport of pollutants through surface runoff and soil infiltration.

In cases of disposal in landfills and waste dams, the stability of these impoundments also requires a detailed investigation of the configuration of the water table, the limits of the aquifer, the characterization of the site and the determination of the short- and long-term properties of the waste. These studies are essential to ensure the safety and effectiveness of tailings impoundments over time. The most common type of embankment for tailings dams is the

upstream embankment, in which new sections are built on top of the sludge retained during the previous phase, moving the crest of the dam "upstream" during construction. Despite being a low-cost option, upstream landfills present high risk due to their susceptibility to liquefaction during seismic movements and the threat to dam stability when the rate of rise is high (Schnaid, et al, 2014).

Some projects are underway aiming at the biorecovery of metals from mining waste, such as Farias, Francisco, & Morais, (2022). We seek to innovate in waste treatment, promoting sustainability and contributing to the European Green Deal, developing biological techniques to recover valuable metals present in mining waste, using microorganisms to extract these metals in an efficient and environmentally responsible way.

Chapter 3

Methodology

1. Materials

Two materials were used for the research: *tout-venant* and granite mining waste.

Tout-venant, often used in road construction, is typically obtained from crushing and screening natural rocks such as granite, basalt and limestone. It is normally characterized by its variable particle size, which includes a mixture of fine to coarse particles and has high resistance due to the presence of hard minerals such as quartz (Teixeira, et al., 1963).

The granite mining waste from the construction company João Tomé Saraiva, from a quarry called "Pedreira da Devesa". Located in Santana de Azinha (Figure 9 and 10), Guarda (Portugal), Pedreira da Devesa is recognized as an extractive unit for granite rocks in the region, and the granite mining residues obtained is a by-product from the process of extracting and processing granite, a rock widely used in civil construction. From a mineralogical point of view, granite rock it is an intrusive, coarse-grained igneous rock, which forms from the slow cooling of magma at depth, allowing the growth of crystals large enough to be seen with the naked eye, being basically formed by quartz, feldspar and micas, you can also find other minerals such as pyroxenes, zircon, apatite and magnetite (Moura et al, 2000, Teixeira, et al., 1963).



Figure 9 - Location of the quarry mining

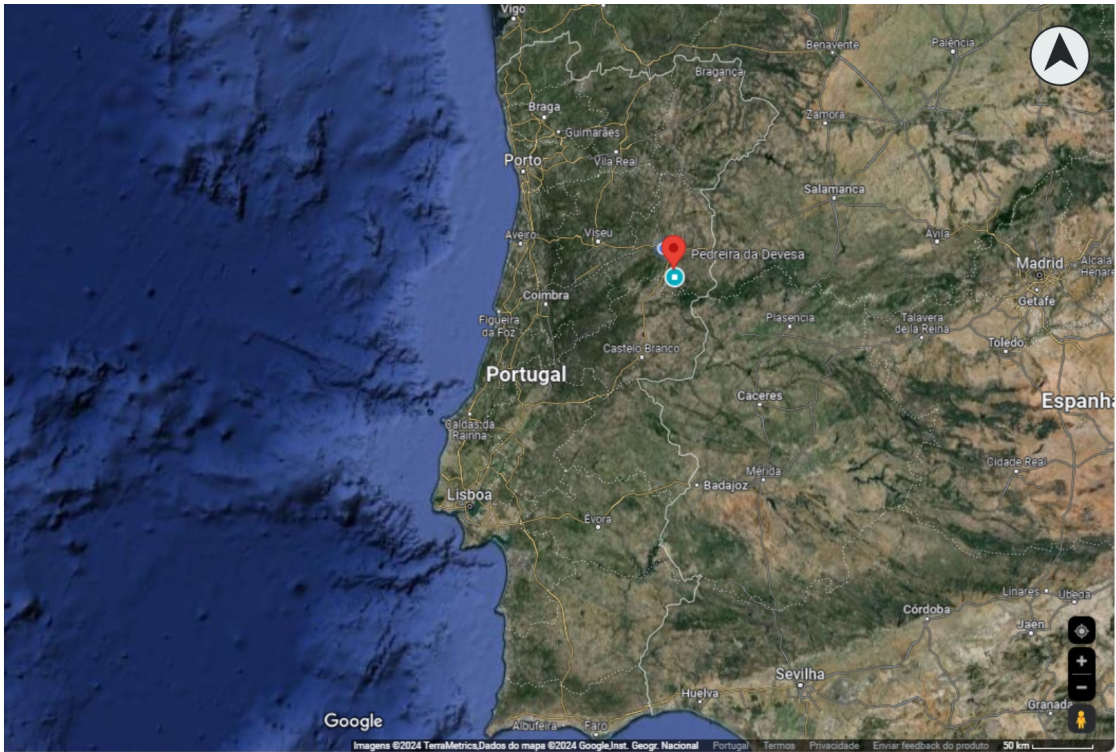


Figure 10 - Location of the quarry mining in the world

The choice of these materials for the research was based on their local availability, as well as their relevance for road engineering and other areas of construction, allowing a comprehensive analysis of their performance and potential for application in different road and structural contexts.

2. Laboratory Tests

To carry out the research, laboratory tests were carried out for the physical identification and characterization (particle size analysis, specific gravity, consistency limits, Proctor compaction and hydraulic conductivity), chemical and mineralogical composition (X-ray fluorescence (XRF), X-ray diffractures (XRD), pH and leaching), geotechnical and mechanical properties (load capacity with CBR test, compressibility and oedometric consolidation).

The tests were all carried out in the Soil Mechanics Laboratory of the Department of Civil Engineering and Architecture (DECA) of the University of Beira Interior (UBI).

3. Samples Preparation

According to the purpose of the research, mixtures with different percentages of residue and variations in particle size were defined, the samples presented in Table 4 were tested.

Table 4 - Residue and mixtures used in the research

SAMPLES	ACRONYM
100% <i>tout-venant</i>	TV100%
75% <i>tout-venant</i> + 25% mining waste passed through a sieve <0.063	MW25% (0.063)
75% <i>tout-venant</i> + 25% mining waste passed through a sieve <0.400	MW25% (0.400)
50% <i>tout-venant</i> + 50% mining waste passed through a sieve <0.063	MW50% (0.063)
50% <i>tout-venant</i> + 50% mining waste passed through a sieve <0.400	MW50% (0.400)
100% mining waste	MW100%

In Figure 11, mixtures as well as pure materials are shown side by side. In Figure 12 we have the materials enlarged, so that Figure 12a is the TV100% material, in Figure 12b it is the MW25% (0.063), in Figure 12c is the MW50% (0.063), in Figure 12d is the MW50% (0.063), in Figure 12e is the MW50% (0.400), and in Figure 12f it is MW100%.



Figure 11 - All samples, mixtures and pure materials (author)

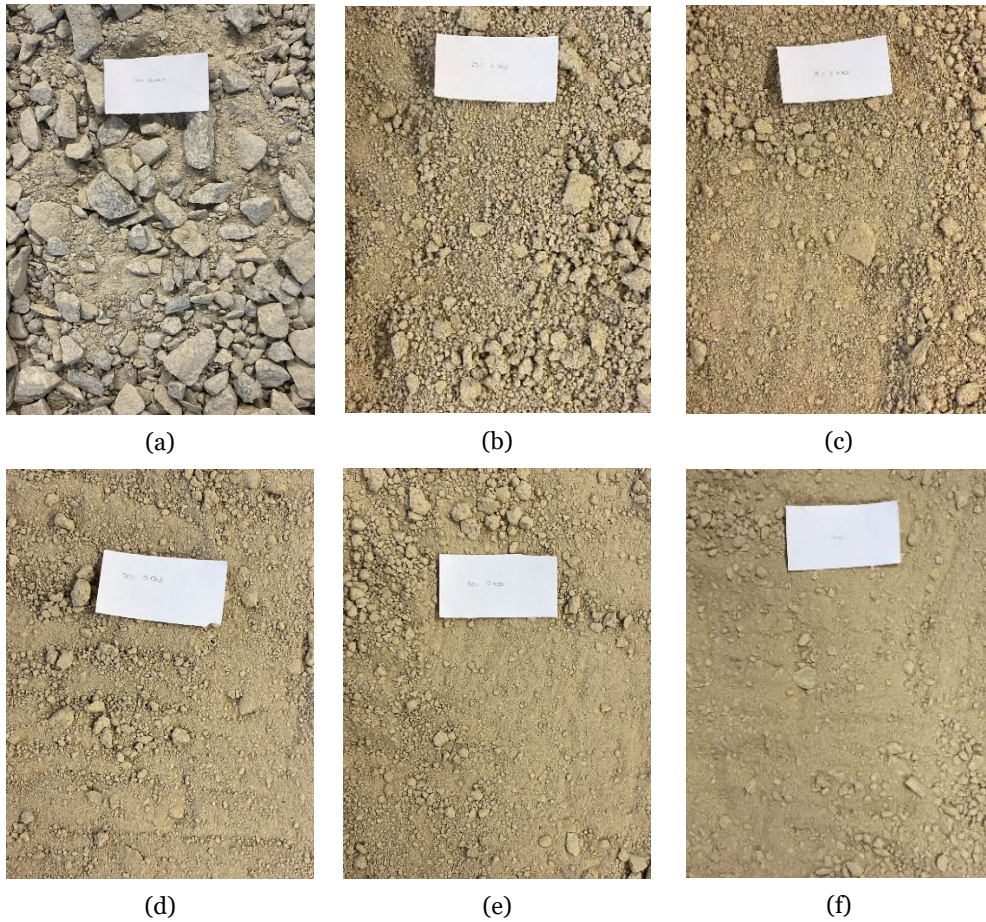


Figure 12 - Samples, mixtures and pure materials, enlarged (author)

In Table 5, there is a summary of the tests carried out and the corresponding quantity in each group of samples. Before carrying out the tests, each sample was mixed and homogenized in the aggregate distributor (Figure 13) below to ensure homogenization of the samples.

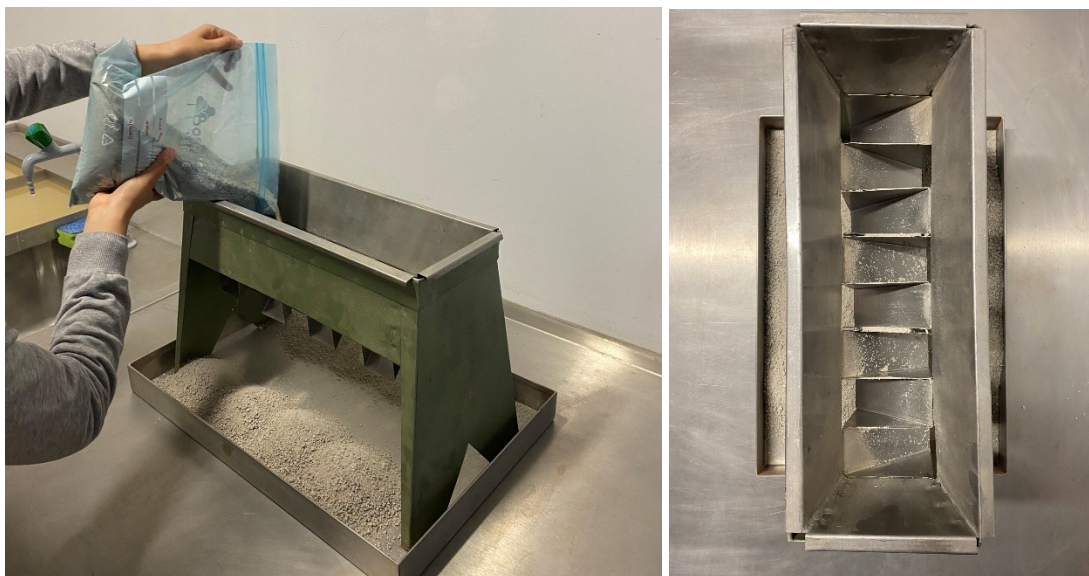


Figure 13 - Homogenization process of samples, mixtures and pure materials (author)

Table 5 - Tests carried out for the sample groups

TESTS	0%	25%		50%		100%
		<0.063	<0.400	<0.063	<0.400	
Physical Identification	Particle Size	1	1	1	1	1
	Specific Gravity	3	3	3	3	3
	Atterberg Limits	3	3	3	3	3
Chemical Composition	XRF	1	-	-	-	1
	XRD	1	-	-	-	1
	pH	1	-	-	-	1
	Leaching	1	-	-	-	1
Geomechanical Resistance	Proctor	1	1	1	1	1
	Oedometric	2	2	2	2	2
	Permeability	1	1	1	1	1
	CBR	1	1	1	1	1

4. Geotechnical Characterization

4.1. Granulometric Analysis

The particle size distributions, following specific established criteria according to constituent fractions of soils, are categorized using a series of sieves with gradate opening mesh. The granulometric curve is established by connecting points on a semi-logarithmic graph, as shown in Figure 14, an example of a curve following the granulometric scales of the Associação Brasileira de Normas Técnicas (ABNT) and the American Association of State Highway and Transportation Officials (AASHTO). On the horizontal axis, the logarithms of the particle dimensions are represented, while on the vertical axis, the percentages, by weight, of the material that have an average size smaller than the specific mesh are indicated.

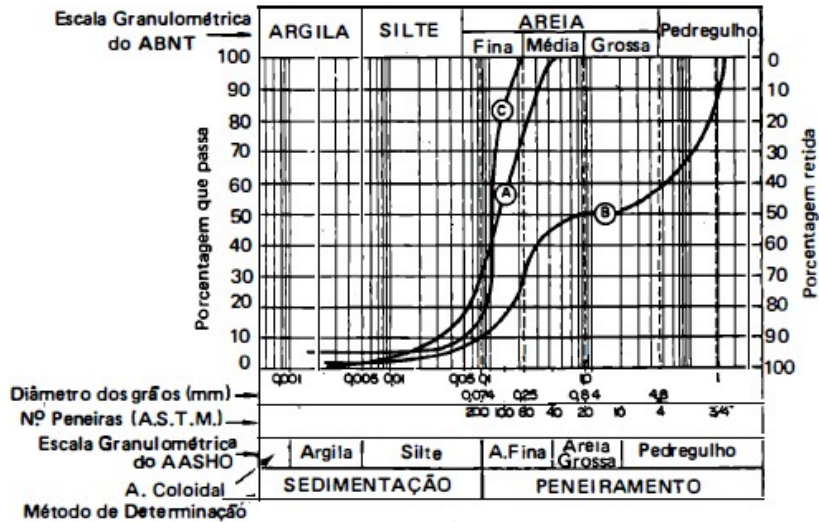


Figure 14 - ABNT and AASHTO particle size scales

There are several ways to classify soils, varying mainly in the definition of particle size ranges and the distinctions between silt and clay. The granulometric classification of soils can be done based on different international standards and methods established by specific organizations. Some of the recognized methods and standards will be discussed below.

(Caputo, 1988) makes a scheme for different grain sizes, which are presented in Figure 15a as well-graded soils, Figure 15b as uniformly graded soils and Figure 15c as open-graded soils. The same scheme is represented in graphic form in Figure 16.

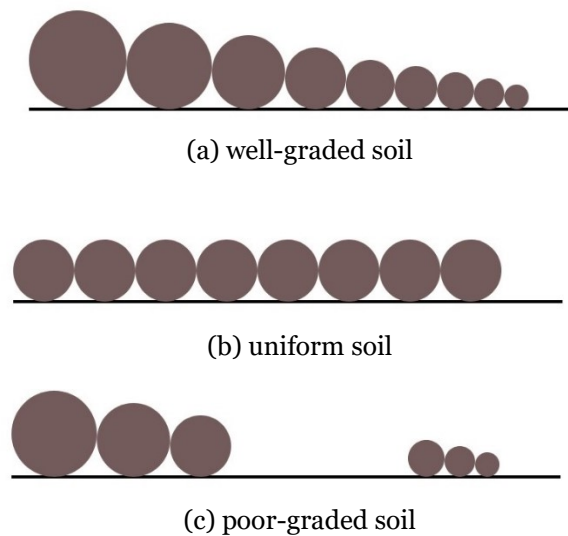


Figure 15 - Scheme of different particle sizes (author)

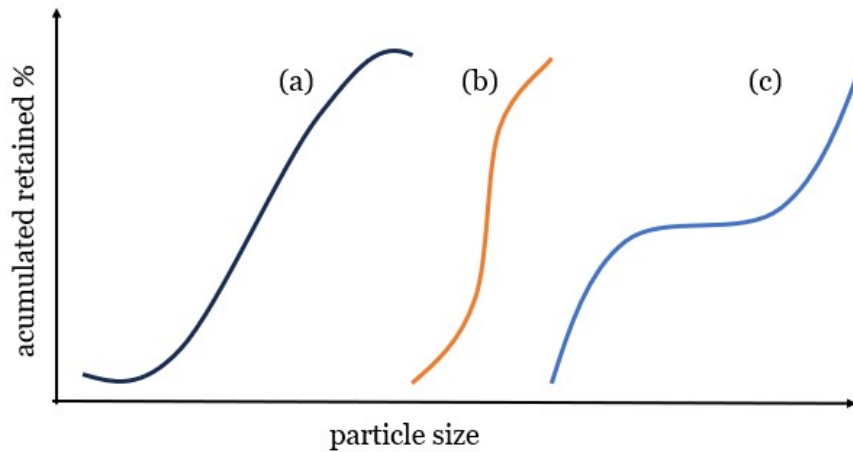


Figure 16 - Graph representing different particle sizes, where (a) well-graded soil, (b) uniform soil and (c) poor-graded soil (author)

The particle size analysis test was carried out in accordance with the guidelines or requirements established in EN ISO 17892-4. In Figure 17a and 17b, respectively, a visual representation of the sieving process by mechanical agitation and the various containers during the test are shown.



(a)



(b)

Figure 17 - Equipment (a) and sieves (b) used to analyze particle size distribution (author)

Several alternative methods for determining the particle size of the fine soil fraction have been proposed and tested, such as sedimentation, by laser and conventional, X-rays and by attenuation of gamma rays, which will be discussed later (Alexandre, 2000; Gonçalves, 2014).

4.2. Specific Gravity

The specific gravity test, also known as specific density of the grains test, aims to determine the relationship between the mass of a material and the volume it occupies. The resulting value is usually compared to the density of water to provide information about the relative compactness of the material. A specific gravity value greater than 1 indicates that the material is denser than water, while a value less than 1 indicates that it is less dense.

The method used to determine the specific gravity was EN ISO 17892-3, which uses a fluid pycnometer (Figure 18), where the difference in the weight of liquid required to fill the pycnometer with and without the presence of the sample. Initially, the pycnometer is filled with water, in such a way that there is no air, placing it in a temperature-controlled water bath. Next, the pycnometer is filled with water and the mass measured, then the pycnometer filled with water and sample are weighted. As for the sample, the particle size of the sample used for testing must be less than 4mm.



Figure 18 - Pycnometer (author)

4.3. Atterberg Limits

The characteristics of the fine fraction of a soil are not limited only according to the size of its particles (granulometry), as the water content, the shape of the particles and the chemical and mineralogical composition can influence the capacity of a soil to be molded, which is called plasticity.

Consistency limits refer to properties that characterize its state of plasticity and cohesion. Both w_L and w_P are defined by (Atterberg, 1911), while the shrinkage limit (w_s) is established by (Haines, 1923). Figure 19 shows an illustration of the four physical states of a soil sample in relation to the percentage of water.

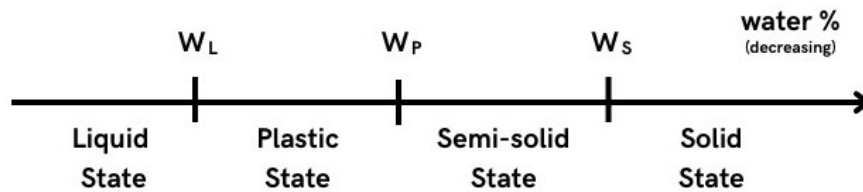


Figure 19 - Relation of water with the physical states of the soil (author)

The determination of the liquid limit is made using the Casagrande method, which consists of a shell-shaped device (Figure 20) where soil samples are deposited at different water content, then a cut is made in the middle of the sample with a chisel. After this, the device is mechanically hit and samples for water content determination are collected according to the number of blows that were necessary to join both sides of the cut. After, all the results are plotted, and the liquid limit is the water content for 25 hits.



(a)



(b)

Figure 20 - Equipment (a) Casagrande shell and (b) cinzel (author)

The plastic limit can be defined as the amount of moisture content in a soil at the point at which it transitions from the semisolid state to the plastic state. This test consists of a cylinder of soil moistened with distilled water, where it is rolled on a glass plane until a sample measuring 3 mm in diameter and 10 cm in length is formed. The final sample is cut into three parts. w_L is expressed as the average percentage of moisture content in the soil at these points.

For the tests, the ISO-17892-12 standard was followed, the samples were sieved and only material below 0.4 mm was used. With the values of w_L and w_P , it is possible to calculate the Plasticity Index (PI), which is the difference between the liquid limit and the plastic limit ($PI = w_L - w_P$). Jenkins classifies soils by plasticity using the intervals presented in Table 6.

Table 6 - Classification of soils based on plasticity

CLASSIFICATION	PLASTICITY
Weakly Plastic	$1 < PI < 7$
Regular Plastic	$7 < PI < 15$
Highly Plastic	$PI > 15$

From these parameters, it is possible to calculate Clay Activity, which is the equation that relates the Plasticity Index with the % of fine grains in the soil and used in Engineering as an index to identify the expansion potential of clay minerals. Eq. 7 presents the parameter.

$$CA = \frac{w_L - w_P}{\% \text{ clay}} \tag{7}$$

4.4. Soil Classification

To classify the materials studied, two best-known methods will be used, discussed below.

The ASTM D2487-17 - Unified Soil Classification System (USCS) is used to describe and categorize soils based on their physical characteristics and plasticity behavior. The method divides soils into two main categories: granular soils and cohesive soils. Granular soils are composed of predominantly sands, while cohesive soils are composed primarily of clay and silt particles. The method uses the letter system to differentiate soil groups, where S is used for sand, M for silty sand, ML for silty sand with low plasticity, C for clay, CL for clay with low plasticity, CH for clay with high plasticity, among others shown in Figure 21.

UNIFIED SOIL CLASSIFICATION AND SYMBOL CHART		
COARSE-GRAINED SOILS (more than 50% of material is larger than No. 200 sieve size.)		
Clean Gravels (Less than 5% fines)		
GRAVELS More than 50% of coarse fraction larger than No. 4 sieve size	GW Well-graded gravels, gravel-sand mixtures, little or no fines	
	GP Poorly-graded gravels, gravel-sand mixtures, little or no fines	
	Gravels with fines (More than 12% fines)	
	GM Silty gravels, gravel-sand-silt mixtures	
	GC Clayey gravels, gravel-sand-clay mixtures	
Clean Sands (Less than 5% fines)		
SANDS 50% or more of coarse fraction smaller than No. 4 sieve size	SW Well-graded sands, gravelly sands, little or no fines	
	SP Poorly graded sands, gravelly sands, little or no fines	
	Sands with fines (More than 12% fines)	
	SM Silty sands, sand-silt mixtures	
	SC Clayey sands, sand-clay mixtures	
FINE-GRAINED SOILS (50% or more of material is smaller than No. 200 sieve size.)		
SILTS AND CLAYS Liquid limit less than 50%	ML Inorganic silts and very fine sands, rock flour, silty of clayey fine sands or clayey silts with slight plasticity	
	CL Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays	
	OL Organic silts and organic silty clays of low plasticity	
SILTS AND CLAYS Liquid limit 50% or greater	MH Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts	
	CH Inorganic clays of high plasticity, fat clays	
	OH Organic clays of medium to high plasticity, organic silts	
HIGHLY ORGANIC SOILS	PT Peat and other highly organic soils	

LABORATORY CLASSIFICATION CRITERIA	
GW	$C_u = \frac{D_{60}}{D_{10}}$ greater than 4; $C_c = \frac{D_{30}}{D_{10} \times D_{60}}$ between 1 and 3
GP	Not meeting all gradation requirements for GW
GM	Atterberg limits below "A" line or P.I. less than 4
GC	Atterberg limits above "A" line with P.I. greater than 7
SW	$C_u = \frac{D_{60}}{D_{10}}$ greater than 4; $C_c = \frac{D_{30}}{D_{10} \times D_{60}}$ between 1 and 3
SP	Not meeting all gradation requirements for GW
SM	Atterberg limits below "A" line or P.I. less than 4
SC	Atterberg limits above "A" line with P.I. greater than 7

Determine percentages of sand and gravel from grain-size curve. Depending on percentage of fines (fraction smaller than No. 200 sieve size), coarse-grained soils are classified as follows:
 Less than 5 percent GW, GP, SW, SP
 More than 12 percent GM, GC, SM, SC
 5 to 12 percent Borderline cases requiring dual symbols

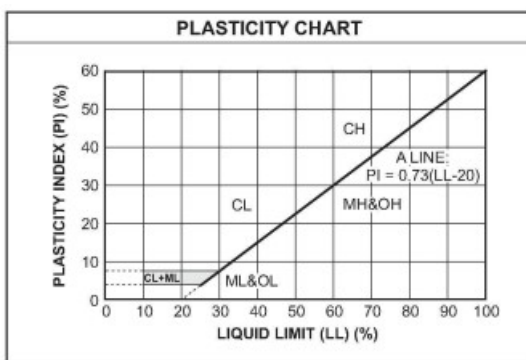


Figure 21 – Unified Soil Classification System in ASTM D2487-17

The soil classification according to the Highway Research Board (HRB) is a classification system developed by the National Cooperative Highway Research Program (NCHRP), which divides soils into main groups based on their properties and geotechnical characteristics, according to with Figure 22.

General Description	Granular materials (35% or less passing 75 micron IS sieve)							Silt clay materials (more than 35% passing 75 micron IS sieve)			
	A-1		A-3	A-2				A-4	A-5	A-6	A-7
Group Classification	A-1-a	A-1-b		A-2-4	A-2-5	A-2-6	A-2-7				A-7-5 A-7-6
Sieve analysis, percent passing											
2.0 mm IS sieve	50 max										
425 micron sieve	30 max	50 max	51 min								
75 micron sieve	15 max	25 max	10 max	35 max	35 max	35 max	35 max	36 min	36 min	36 min	36 min
Characteristics of fraction passing 425 micron sieve											
Liquid Limit				40 max	41 min	40 max	41 min	40 max	41 min	40 max	41 min
Plasticity Index	6 max		NP	10 max	10 max	11 min	11 max	10 max	10 max	11 min	11 min
Group Index	Zero					4 max		8 max	12 max	16 max	20 max
Usual type of significant constituent materials	Stone fragments gravel and sand		Fine sand	Silty or clayey gravel and sand				Silty soils		Clayey soils	
General rating as subgrade	Excellent to good					Fair to poor					

Figure 22 - AASHTO method

4.5. Proctor Compaction

(Matos-Fernandes, 1994) defines compaction as a process in which the reduction in the volume of the air phase of the soil achieved by the repeated application of loads, resulting in a reduction in the void ratio of the soil mass, composed of solid particles, water and air.

The Proctor-type compaction test consists of compacting a soil sample inside a cylindrical mold, where the number of layers and the volume of soil are factors that determine the energy of compaction (EC), which is calculated by Eq. 8, determined by LNEC E197-1966.

$$EC = \frac{P \cdot h \cdot n \cdot c}{V} \quad (8)$$

Where P is the weight of the pile, h is the height of the pile's fall, n is the number of blows, c is the number of layers and V is the internal volume of the mold.

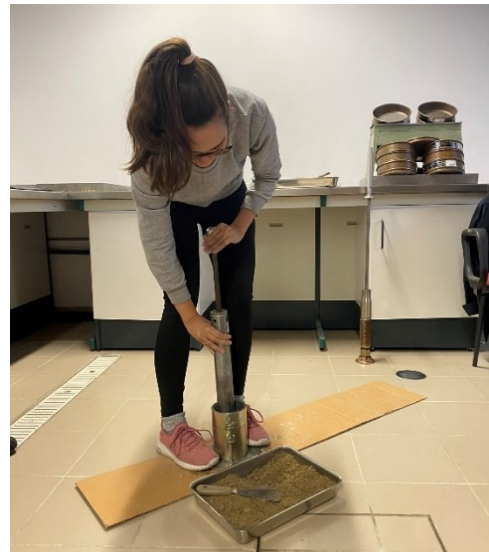
For the tests, standard BS 1377-4 procedures were followed. The procedure was to compact the sample in three successive layers in the cylindrical container, with an approximate volume of 1,000cm³, under the action of 25 blows from a socket weighing 2.5kg (Figure 23a), falling 30 cm high. The compaction tests in this study were conducted for Normal Proctor tests (with light

pressing in a small mold), through manual compaction (Figure 23b). The applied compaction energy, calculated according to equation (1), was $5.96\text{kg}\cdot\text{cm}/\text{cm}^3$.

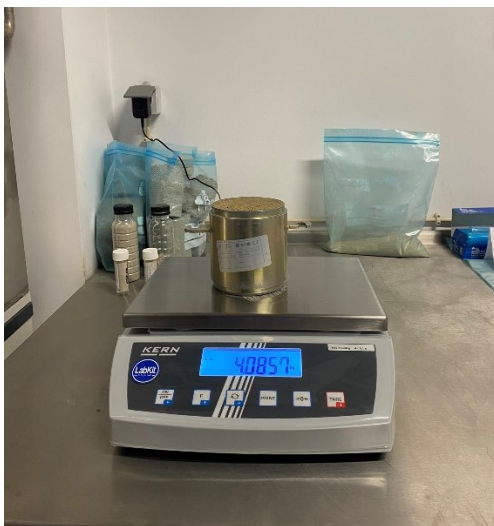
This process was carried out for different moisture contents, where the samples were subsequently weighed (Figure 23c) to determine the apparent specific weight. After drying, the water content of each sample is determined. With the values obtained, the curve water content versus dry density is where the values of OMC and MDD will be obtained. At the end of the test, a compacted sample is obtained as represented in Figure 23d.



(a)



(b)



(c)



(d)

Figure 23 - Proctor compaction test (author)

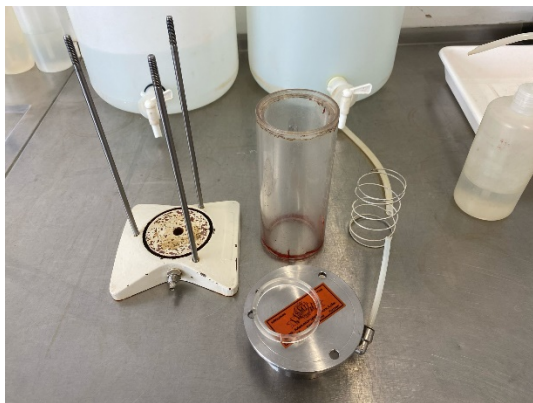
4.6. Hydraulic Conductivity

The k can be obtained through tests carried out in the laboratory, using semi-empirical formulas or correlations, as well as through tests carried out on site.

The ability of a soil to allow water flow, measured by the permeability coefficient, varies between different types of soil. In the case of the same type of soil, this capacity is mainly affected by temperature and void content. In warmer environments, water becomes less viscous, which makes it easier to move through the soil's porous spaces. This results in a proportional increase in the permeability coefficient. In summary, the k is inversely related to the viscosity of the water.

The EN ISO 17892-11 standard was followed in the work, following falling head procedure, with descending flow, calculated by Eq. 9. Where the sample studied is inserted into a cylinder of cross-section (A), as shown in Figure 24, and height of the test piece (L), this cylinder is connected through tubes to another graduated cylinder with cross section (a), with water up to a certain level. At an initial moment (t_1), there is a certain hydraulic load according to the height (h_1), at another moment (t_2) there is another hydraulic load (h_2).

$$k = \frac{a * L}{A * \Delta t} * \ln \left(\frac{h_1}{h_2} \right) \quad (9)$$



(a)



(b)

Figure 24 - Equipment used for the hydraulic conductivity test (author)

Hydraulic conductivity is a physical index that can also be obtained indirectly from the oedometric results, when k is low. More will be discussed about this in the Oedometric test session.

5. Chemical and Mineralogical Composition

5.1. X-ray Fluorescence and X-ray Diffraction

The XRF test is used to determine the chemical composition of materials, so that the atoms of the tested materials are excited with high-energy x-rays, thus emitting fluorescent radiation. This fluorescence can be given in two ways, the first being Energy Dispersive X-Ray Fluorescence (EDS) and Wavelength Dispersive X-Ray Fluorescence, the first one was used here.

In the XRD test, the crystalline structure of materials is characterized, where a beam of X-rays is directed to a sample, and the atoms in the sample scatter the X-rays, creating diffraction patterns that are recorded by a detector. From these standards, the crystalline structure of the material is determined, presenting the compounds and their proportions.

XRD and XRF tests were conducted mainly on pure materials (TV100% and MW100%) due being inert materials, when mixed no reactions are supposed to occur. This occurred because carrying out the tests on the mixtures would present the same minerals and compounds, just in different proportions or variations. Therefore, focusing on pure materials allowed a more precise and direct analysis of the individual characteristics of each substance, without the need to repeat tests for each mixture variation.

5.2. Potential of Hydrogen (pH)

The pH assessment was carried out in accordance with the guidelines of ASTM D4972-01 - Standard Test Method for pH of Soils, which aims to determine the level of acidity or alkalinity of soils suspended in distilled water or 0.01M calcium chloride solution. The use of calcium chloride, as the calcium displaces the exchangeable aluminum, results in a slightly lower pH than that obtained with distilled water.

To measure pH, you can use a potentiometer with a pH-sensitive electrode system or pH indicator paper. For the study, a potentiometer was used with CellOx 32 and SenTix 41 probes connected to a Multi 340i meter (WTW, Germany), where it was calibrated with buffer solutions of known pH.

pH is an important measurement for understanding the solubility of soil minerals and ion mobility, which is fundamental to ensuring soil-environment compatibility. For the procedure, the soil was air-dried, sieved with a 2mm mesh opening and water was prepared by distillation.

Approximately 10g of soil was added to a glass container containing 10mL of distilled water, mixed and left to rest for 1 hour, at a laboratory temperature between 15-25°C. The potentiometer was then introduced into the mixture suspension and the temperature and pH parameters were measured when the values stabilized.

For pH, only MW100% and TV100% were tested, due to the mixtures would present variations in values within the limits of values found between them, justified by being inert materials.

5.3. Leaching

The leaching test (EPA SW-846), sometimes referred to as the percolation test or leaching test, is a method for determining how well chemicals are released from solid materials into a liquid media, typically water. To assess the possible environmental impact of solid waste, such as mining tailings, industrial waste, and construction materials, this test is very crucial.

A sample of the solid material is put in contact with a liquid—typically water—during the leaching test, and the liquid is let to percolate or pass through the sample. Heavy metals, organic molecules, and other pollutants can be extracted from solid material by the liquid as it passes through the sample.

When conducting leaching tests, it is important to consider the concentration, makeup, and rate of release of pollutants in the leached liquid as well as their time-dependent release. Test results can be used to assess the material's leaching potential as well as any potential environmental effects, such as contamination of soil, groundwater, or surface water bodies.

For the research, only the residue alone was tested, since the TV100% material is already guaranteed to comply with leaching standards, being commercially used. Following pH procedures, the mixtures would present variations in values within the limits of values found between MW100% and TV100%, not being necessary to carry out leaching for the mixtures.

6. Mechanical Properties

6.1. Oedometric Consolidation

The one-dimensional consolidation (oedometric) test is used to determine soil compressibility and consolidation properties, where soil samples are placed and gradually compressed in

laterally confined cells with controlled loads. This test measures the deformation of a soil sample in response to vertical load increments while lateral conditions are constrained, simulating the one-dimensional compression typical of many geotechnical situations, such as the densification of soils under foundations.

For the study, the principles of the EN ISO 17892-5 standard were followed. The oedometric cells used have a diameter of 6.30 cm and a height of 2.00 cm. The samples were assembled manually, using a small pestle to compact them within the consolidation ring following optimal Proctor parameters abovementioned. Loads were applied to a range between 0kPa and 1260kPa, where each level was maintained under load for a period of 24 hours. The test was carried out under saturated conditions, with water inside the oedometric cell (Figure 25).



Figure 25 - Equipment used for the oedometric test (author)

To calculate the compressibility parameters, theories and equations determined by Terzaghi were followed, who developed an equation to describe how water pressure within the soil changes over time and depth when the soil is subject to a uniform load. The author relates the change in pore pressure (Δu), time (t) and depth (z) of a soil element subjected to tension ($\Delta \sigma$) uniformly distributed over an infinite area of soil, presented in Eq. 10.

$$\frac{\partial u}{\partial t} = c_v \frac{\partial^2 u}{\partial z^2} \quad (10)$$

The solutions to the consolidation equation are presented by two dimensionless quantities, the time factor (T_v) and the average degree of consolidation (U_v) within the consolidation coefficient (c_v), in Eq. 11 e 12.

$$T_v = \frac{e_v * t}{d^2} \quad (11)$$

$$U_v = \frac{\Delta h(t)}{\Delta h_{\text{max}}} \quad (12)$$

To determine the consolidation coefficient, there are two widely used traditional methods: the Taylor method and the Casagrande method. In the Taylor method, the square root of time is used on the horizontal axis to draw a tangent line through the 0% and 90% consolidation points. On the other hand, Casagrande's method uses a logarithmic scale for time and draws two tangent lines: one representing primary consolidation and the other secondary consolidation. The intersection between these lines is the point corresponding to 100% consolidation. Both methods seek to determine time and consolidation equivalent to 50%.

6.2. CBR Test

The CBR type test consists of determining the relationship between the pressure necessary to produce a penetration of a piston in a soil test specimen, and the pressure necessary to produce the same penetration in a standard mixture. In other words, it provides a measure of the soil's resistance to penetration and deformation under load. Furthermore, it is also possible to obtain soil expansibility values. AASHTO T193 procedures were followed.

Like the Proctor-type test, the compacted sample is placed in a metallic cylinder divided into layers, each compacted with a standardized energy. The soil sample is then placed in water and any significant increase in volume or deformation is observed. This soil expansion under humid conditions is an important indication for evaluating the potential for soil instability in the field, especially in regions where soil moisture variation is significant. After immersion for an established period, the sample is then taken for testing where a piston is used to gradually apply a vertical load, as shown in Figure 26.

The samples were molded manually using a cylindrical mold measuring 15.30cm in internal diameter and 17.80cm in height, where the material was at its OMC and MDD.



Figure 26 - Equipment used for the CBR test (author)

Folha em branco

Chapter 4

Results and Discussion

The results of the following tests will be presented in this chapter, regarding:

- Physical identification and characterization: particle size analysis, specific gravity, and consistency limits;
- Chemical and mineralogical composition: XRF, XRD, pH and leaching
- Geotechnical, physical and mechanical properties: proctor compaction, load capacity with CBR test, oedometric consolidation, and hydraulic conductivity (k).

1. Physical Characterization

For the physical characterization of granite mining waste, *tout-venant* and mixtures, particle size tests, consistency limits and specific gravity were carried out.

As reported in Chapter 3, mining waste was collected from Pedreira da Devesa and, in the laboratory, the samples were homogenized to better represent their particle size. The homogenization and quartering process was also adopted in the *tout-venant*, in addition to the mixtures to guarantee this aspect.

1.1. Granulometric Analysis

The particle size curves of all materials and mixtures involved in this research were determined in accordance with EN ISO 17892-4 standard, at the UBI Soil Mechanics Laboratory.

Figure 27 presents the particle size distribution curve of the raw materials (MW100% and TV 100%) and mixtures (MW25% (0.063), MW25% (0.400), MW50% (0.063) and MW50% (0.400)).

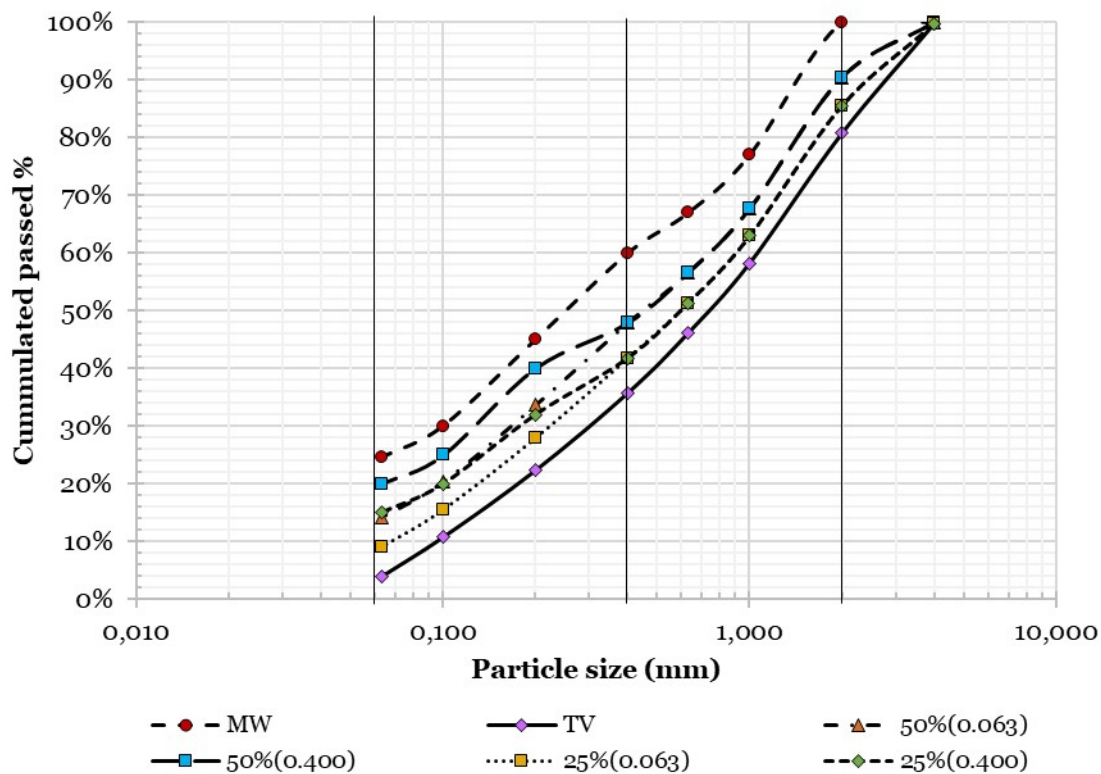


Figure 27 - Results of granulometric curves for pure materials and mixtures

MW and TV are well-graded materials, but with different fines percentages. Thus, the mixtures present different curves, following the addition of fines, but always varying between the limits of MW and TV.

From the granulometric curve, the Uniformity Coefficient (C_U) and Curvature Coefficient (C_C) parameters can be obtained according to Figure 21. Table 7 presents the results of C_U and C_C for the studied materials.

Table 7 - C_U e C_C of pure materials and mixtures

SAMPLE	C_U	C_C
MW100%	4.00	1.30
MW25% (0.063)	4.10	0.90
MW25% (0.400)	5.00	0.90
MW50% (0.063)	4.20	1.10
MW50% (0.400)	5.80	0.90
TV100%	4.00	0.80

As expected, the mixtures have also well-graded granulometric curves, varying only the proportions of fines. The granulometric curves of the mixtures are within the ranges recommended by the CETO from EP LNEC E 196, for use in granular subbases where the percentage of material that passes sieve No. 200 ASTM maximum is 15%, excluding MW100% and MW 50% (0.400) due to higher fine portions.

1.2. Specific Gravity

The results obtained for the specific gravity are listed in Table 8.

Table 8 - Specific gravity of pure materials and mixtures

SAMPLE	G_s
MW100%	2.50
MW25% (0.063)	2.58
MW25% (0.400)	2.63
MW50% (0.063)	2.56
MW50% (0.400)	2.59
TV100%	2.70

MW is a lighter material than TV, and by including a greater percentage of MW in TV, the mixtures present variations in G_s values in between those limits. The analysis becomes more visual with Figure 28.

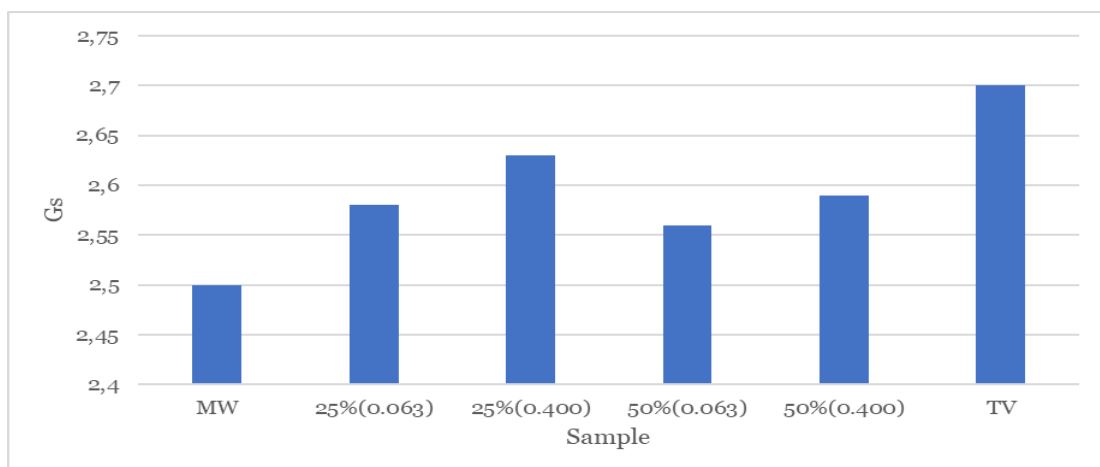


Figure 28 - Specific gravity of pure materials and mixtures

1.3. Atterberg Limits

Table 9 presents Atterberg limits and clay activity (CA) for the studied materials.

Table 9 - Results of Atterberg limits for pure and mixed materials

SAMPLE	w_L (%)	w_P (%)	PI (%)	CA
MW100%	33.90	11.90	22.00	0.90
MW25% (0.063)	23.50	19.00	4.50	0.50
MW25% (0.400)	29.70	21.20	8.50	0.57
MW50% (0.063)	29.70	19.40	10.30	0.72
MW50% (0.400)	29.70	27.60	2.10	0.10
TV100%	18.50	NP	NP	-

MW100% can be characterized with a high plasticity; and finally, TV100% during the test did not present plastic characteristics for its execution. Furthermore, MW25% (0.063) and MW50% (0.400) can be classified as having low plasticity; and the mixtures MW25% (0.400) and MW50% (0.063) with medium plasticity. This occurs due to the different introduction of finer material, smaller particles usually present higher plasticity. As for the mineralogical clay activity (CA), TV100% does not present mineralogical activity. The highest index is MW100%, as expected.

According to CETO from EP, for use in granular sub-base layers, the maximum permissible liquidity limit is 25%, where only the MW25% mix (0.063) would be applicable. For the regularization, filling, and berm layers, the maximum acceptable for the liquidity limit is 35%, with all mixtures being applicable for this use.

For the plasticity index, CETO determines as 6% the limit value for applications in granular sub-base layers, where only the MW25% sample (0.063) meets this criterion, and 6 to 10% for the regularization and berm filling layers, of the mixtures, with MW50% (0.063) being the only one not applicable.

1.4. Soil Classification

According to particle size distribution and Atterberg limits evaluation, the classification of soils is permitted, and were following USCS (ASTM) and AASHTO standards. Those classifications are exposed in Table 10.

Table 10 - Classification the materials according to USCS (ASTM) and AASHTO

SAMPLE	ASTM	AASHTO
MW100%	SC	Clayey sand A-2-6
MW25% (0.063)	SP-SC	Poorly graded sand with clay A-1-b A-2-4
MW25% (0.400)	SC	Clayey sand A-1-b A-2-4
MW50% (0.063)	SC	Clayey sand A-1-b A-2-4
MW50% (0.400)	SM	Silty sand A-1-b A-2-4
TV100%	SP	Poorly graded sand A-1-b A-2-4

For the USCS (ASTM) classification, samples MW100%, MW25% (0.400) and MW50% (0.063), were classified as clayey sands (SC), indicating the significant presence of clay, which was already expected since percentages of fines were added to TV. These fine particles can provide good cohesion but can also result in drainage problems and susceptibility to swelling and shrinkage with humidity variations. The MW50% (0.400) is a silty sand (SM), combines sand with silt, offering good drainage, but with potential for erosion and less stability. Besides, MW25% (0.063) is a poorly graded sand with clay (SP-SC), suggesting a soil with particles of varying sizes and the presence of clay, which may imply a lower support capacity. On the other hand, this soil may offer good initial stability after compaction, which is useful during the construction phase. Finally, the TV100% sample, poorly graded sand (SP), presents a less uniform distribution of particles, resulting in less compaction effort, but with high permeability.

For the classification of soil samples according to AASHTO, MW100%, classified as A-2-6, is a silty-clayey sand with intermediate properties that offer a combination of moderate drainage and some cohesion, which can be advantageous in certain layers of the road structure, although it may require additional treatment to improve bearing capacity. The rest of the mixtures and TV100%, all classified as A-1-b and A-2-4, represent soils with a predominance of sand, which are considered ideal materials for road construction due to their excellent drainage, high support capacity and stability under cyclic loads.

1.5. Proctor Compaction

This item presents the results of the compaction tests carried out with samples with a Proctor Normal mold with light compaction energy, following the LNEC E197-1966, aiming to define the optimal moisture content and the dry bulk density, which are used to carry out the CBR and oedometric tests. The compaction curves of the pure materials and their mixtures are

represented in Figure 29. Table 11 presents a summary of the parameter values obtained in the tests: optimum moisture content (OMC) e dry bulk density or maximum dry density (MDD).

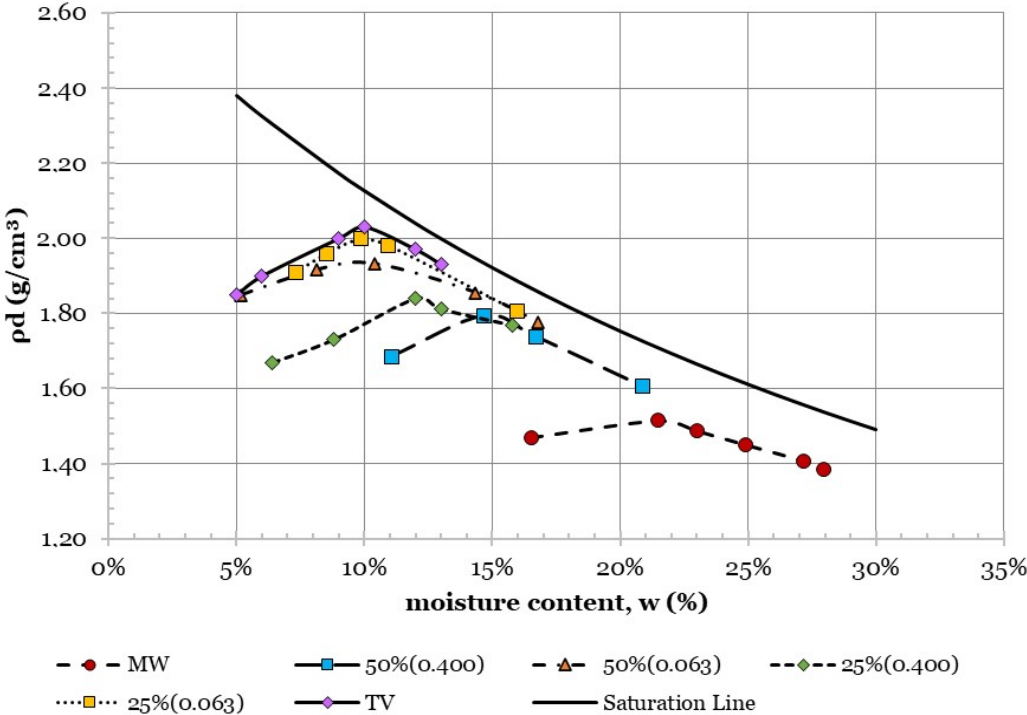


Figure 29 - Results of the compaction curves of the materials

The MW25% (0.063) mixture had an OMC of 9.85%, while the MW25% (0.400) had a slightly higher OMC of 10.51%. The usual behavior, that the finer material retains more moisture compared to the coarse material, and for those mixtures, given due to the quantity of introduced residue, the 0.400 incorporation uses more fine material than the 0.063, corroborating with the usual behavior. When increasing the mixing ratio to 50%, MW50% (0.063) had a moisture content of 10.40%, and MW50% (0.400) had the highest moisture content of 10.67% among mixtures. These results indicate that, at larger proportions, the thicker material continues to retain more moisture than the finer material.

This may be due to the greater ability of thicker materials to create interstitial spaces that retain water, thus increasing optimal humidity. Furthermore, the mixtures do not show significant modification of OMC related to TV100%, which seems to be great regarding the utilization of consolidated compacting procedures.

Table 11 - Results of the OMC and MDD indices of pure materials and their mixtures

SAMPLE	OMC (%)	MDD (g/cm³)
MW100%	21.60	1.50
MW25% (0.063)	9.85	2.00
MW25% (0.400)	10.51	1.73
MW50% (0.063)	10.40	1.93
MW50% (0.400)	10.67	1.79
TV100%	10.00	2.03

From Figure 29 it can also be seen that with the increase in residue content there is a tendency to reduce the specific dry mass of the mixtures in relation to TV100%, this can be explained by the fact that MW is a lighter material than the TV studied. Showing good potential regarding lowering the transportation costs of the materials due to lighter materials.

For laboratory and characterization purposes, for the CBR, oedometric and hydraulic conductivity tests, the degree of compaction at 100% was used considering the OMC and MDD for each mixture.

1.6. Hydraulic Conductivity

The results of the hydraulic conductivity test are shown in Figure 30. To carry out the test, the degree of compaction at 100% was calculated.

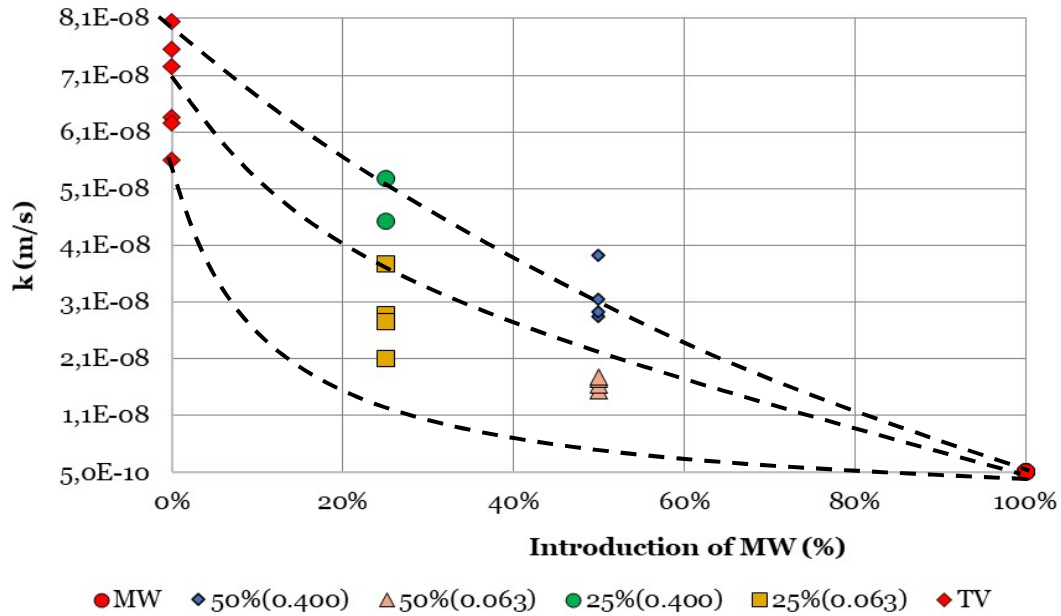


Figure 30 - Hydraulic conductivity results

The results of the permeability test show variations depending on the percentage of incorporation and the MW fines mixed with the TV. MW100% has the lowest permeability with an average value of $6.6E-10$, indicating an extremely low ability to allow water to pass through, which suggests that this material is very dense or very fine in texture, proved by compaction and granulometric results. For the MW25% (0.063) mixture, the permeability increases substantially to an average of $2.8E-08$, and MW25% (0.400) the permeability increases further to $6.8E-08$, like TV100%. This demonstrates that both types of mixture, but especially for material with larger grain sizes, increase the soil's permeability. For MW50% (0.063) the average k is $1.6E-08$, lower than with 25%, indicating that a greater amount of fine material reduces permeability compared to a smaller amount. With MW50% (0.400), the average k is $3.2E-08$, which is lower than MW25% (0.400), but still more permeable than the residue itself. These results indicate that mixing MW into TV tends to reduce permeability following fine materials introduction ratio. The black dashed lines were done to differentiate 25% and 50% MW content and impact in k behavior.

2. Chemical and Mineralogical Composition

2.1. X-ray Fluorescence and X-ray Diffraction

The elements found in the XRF test are presented in Table 12. The results found by the XRD test are shown in Figures 31 and 32.

Table 12 - Results of XRF

OXIDES (%)	MW 100%	TV 100%
Na ₂ O	0,64	0,70
MgO	2,59	2,00
Al ₂ O ₃	22,37	26,00
SiO ₂	58,85	59,00
P ₂ O ₅	0,39	0,05
SO ₃	0,57	0,01
K ₂ O	4,18	4,00
TiO ₂	0,89	0,90
CaO	1,78	0,01
MnO	0,08	0,01
Fe ₂ O ₃	7,27	7,00
LOI	6,91	6,00
Total	100	100

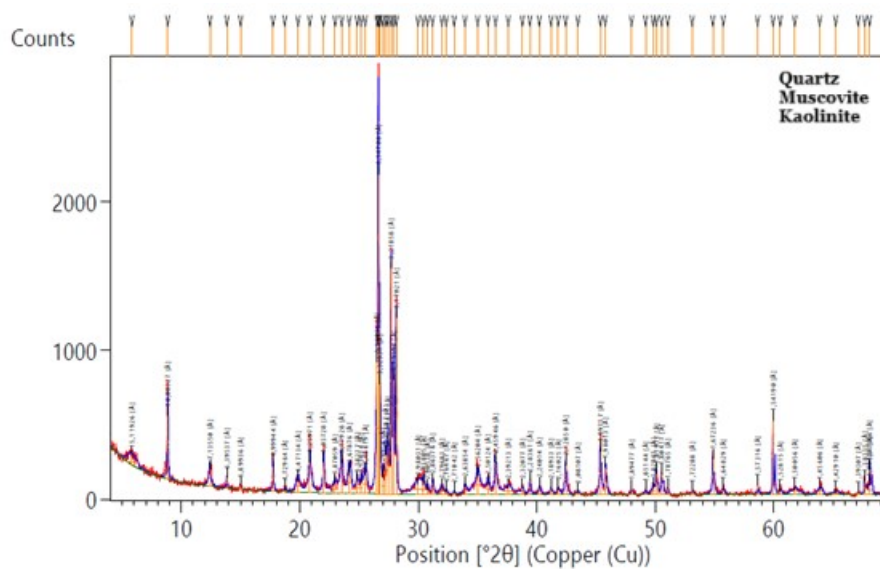


Figure 31 - Results of the XRD of the MW100% samples

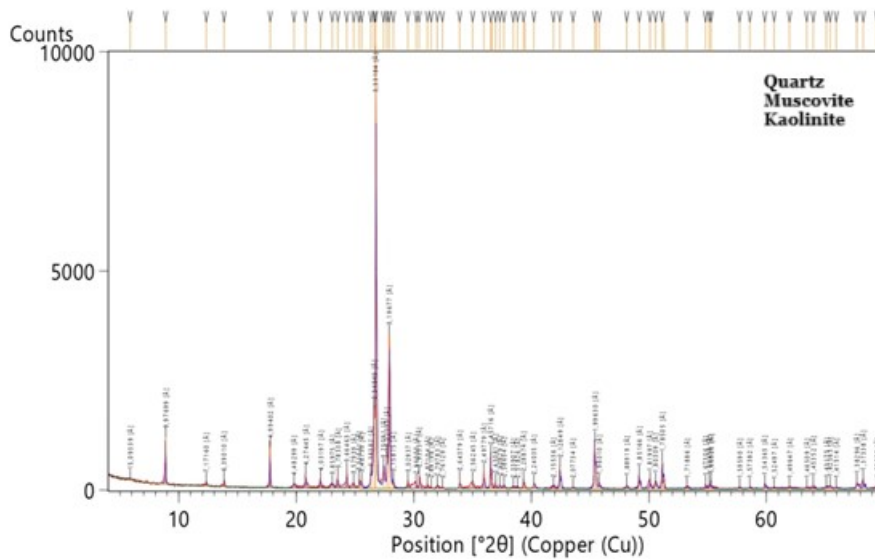


Figure 32 - Results of the XRD of the TV100% samples

The XRD tests carried out on MW100% and TV100% revealed the presence of Quartz, Kaolinite and Muscovite. The identification of quartz, one of the most abundant and hardest minerals, suggests that the residue has potential for applications in civil construction, as aggregate in concrete and pavements, due to its strength and durability. Kaolinite, a clay with high plasticity and adsorption capacity, can be used to improve the cohesion of sandy soils, increasing the stability of foundations and support structures, and in road cuts it can be applied to reduce soil erodibility, preventing landslides, and ensuring the safety of infrastructures. The good particle size distribution seen in section 1.1 of results allows a good degree of packing (particle imbrication). In addition to this, the heterogeneous structure of the minerals generates greater resistance.

2.2. pH

The results for pH values indicate an average value of 6.8 for MW100% and 6.0 for TV100%. Pessoa (2004) classifies soils with a pH between 6.0 and 6.5 as slightly acidic to neutral. Both soils are within a favorable range for most paving applications. MW100% with pH 6.8 is ideal as it offers a neutral condition that minimizes adverse chemical reactivity with stabilizing materials, facilitating the stabilization and durability of the pavement. When mixed, it should ensure better stabilization of the slightly acidic pH of TV100%. The results are consistent with what is presented in the literature (Campanha, 2011, Galhardo, 2015, Malaoui, et al., 2023). It is understood that the mixtures would present variations in values within the limits of values found between MW and TV, and it is not necessary to carry out this analysis for the mixtures.

2.3. Leaching

The leached extracts were obtained in accordance with EPA SW-846 (Method 1313). Table 13 presents the results of the inorganic constituents leached from the samples and the limits established by “Decisão do Conselho 2003/33/EC”, provided for in (E.P., 2014).

Table 13 - Results of the levels of organic constituents leached from the MW100%

PARAMETERS	Decisão do Conselho 2003/33/CE	MW100%
Dissolved Organic Carbon, DOC (mg/kg)	≤ 500	14.3
Cd (mg/kg)	≤ 0.04	0.0004
Cu (mg/kg)	≤ 2	0.0257
Cr (mg/kg)	≤ 0.5	0.0023
Ni(mg/kg)	≤ 0.4	0.0330
Pb (mg/kg)	≤ 0.5	0.0095
Zn (mg/kg)	≤ 4	0.1300
Cl (mg/kg)	≤ 800	-
Sulphates, SO ₂₋₄ (mg/l)	≤ 1000	57.0

The results of the leaching test carried out on MW100% showed that the leaching levels meet all limits set by Council Decision 2003/33/EC. This compliance with the waste acceptance criteria demonstrates that granite mining waste is safe for use in paving, posing no significant risk to human health or the environment. Compliance ensures that potential leachate components will not leach into the soil or groundwater, preventing contamination. According to MW100% results, the mixtures are qualified to meet the same limits mentioned above due to low ratio introduction of the residue.

3. Mechanical properties

3.1. Oedometric Consolidation

The oedometric test carried out on the six samples resulted in the graphics presented together in Figure 33, in the left is exposed with the actual void ratio of the samples, and in the right the

void ratio was normalized in y-axis to better analyze the curves. A steeper slope in the consolidation curves suggests a more compressible soil, as is the case with MW100%, while a gentler slope indicates a less compressible soil (TV100%). Mixtures exhibit varying behaviors between these two ranges. Table 14 presents the values of the compressibility coefficient (C_c), recompression coefficient (C_r) and swelling coefficient (C_s). For the tests, the degree of compaction at 100% was calculated. Tables 15 to 20 show the loading loads (without unloading) and the oedometric modulus (m_v), consolidation coefficient (c_v) and k values for each material.

Table 14 - Results of oedometric tests for compressibility parameters

SAMPLE	C_c	C_r	C_s
MW100%	0.109	0.030	0.020
MW25% (0.063)	0.045	0.030	0.012
MW25% (0.400)	0.058	0.011	0.019
MW50% (0.063)	0.058	0.013	0.015
MW50% (0.400)	0.078	0.008	0.011
TV100%	0.001	0.033	0.009

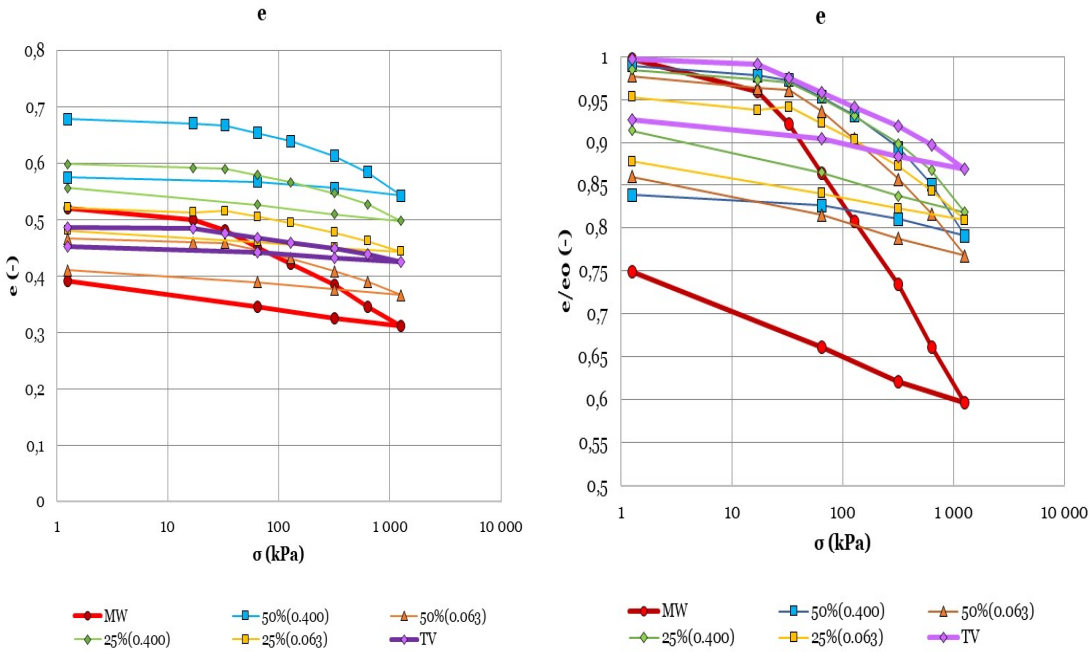


Figure 33 - Compressibility curves from oedometric tests

MW100% has a relatively higher compression coefficient (C_c) than the other samples, indicating that it is a very compressible material under normal consolidation loads. This suggests that, unmixed, the residue is the least suitable for use in road granular layers as it can lead to large settlements over time. For the MW25% sample (0.063), C_c decreases significantly, making this

soil less compressible and more stable, while recompression coefficient (C_r) remains constant, suggesting that the structure recovery capacity is not affected by the addition of fine material. For MW50% (0.063) and MW25% (0.400), the C_c is the same, while the MW50% (0.400) mixture presents the worst value among mixtures, but still stable. Analyzing the table, the MW25% (0.063) mixture is one of the best options, with a very low C_c and swelling coefficient (C_s). Considering that the compressibility index is dependent on the density and initial void index, Sanglerat et al., (1978) in Andrade Pais (2007) classifies the type of soil according to values found for C_c . The results found in this research classify all samples in Table 14 as “sand”.

Table 15 - Results of parameters m_v , c_v and k for MW100%

MW100%	c_v (m²/s)	m_v (m²/MN)	k (m/s)
0 kPa	-	-	-
1 kPa	4.68 E-07	1.14	5.48 E-09
17 kPa	4.30 E-07	0.96	4.42 E-09
33 kPa	3.91 E-07	0.87	3.36 E-09
64 kPa	3.53 E-07	0.66	2.30 E-09
127 kPa	5.93 E-07	0.32	1.90 E-09
316 kPa	9.11 E-07	0.17	1.55 E-09
631 kPa	1.08 E-06	0.09	9.60 E-10
1260 kPa	9.70 E-07	0.04	3.87 E-10

Table 16 - Results of parameters m_v , c_v and k for MW25% (0.063)

MW25% (0.063)	c_v (m²/s)	m_v (m²/MN)	k (m/s)
0 kPa	-	-	-
1 kPa	7.88 E-07	2.15	1.66 E-08
17 kPa	1.52 E-06	0.71	1.07 E-08
33 kPa	1.52 E-06	0.27	4.07 E-09
64 kPa	3.43 E-06	0.21	7.31 E-09
127 kPa	1.06 E-05	0.11	1.17 E-08
316 kPa	2.44 E-07	0.06	1.44 E-10
631 kPa	8.56 E-07	0.03	2.84 E-10
1260 kPa	9.78 E-07	0.02	2.00 E-10

Table 17- Results of parameters m_v , c_v and k for MW25% (0.400)

MW25% (0.400)	c_v (m^2/s)	m_v (m^2/MN)	k (m/s)
0 kPa	-	-	-
1 kPa	8.08 E-07	0.75	6.00 E-09
17 kPa	1.60 E-06	0.56	8.84 E-09
33 kPa	1.60 E-06	0.35	5.52 E-09
64 kPa	3.60 E-06	0.22	8.00 E-09
127 kPa	1.11 E-05	0.13	1.40 E-08
316 kPa	2.55 E-07	0.06	1.67 E-10
631 kPa	8.77 E-07	0.04	3.40 E-10
1260 kPa	1.00 E-06	0.03	3.08 E-10

Table 18- Results of parameters m_v , c_v and k for MW50% (0.063)

MW50% (0.063)	c_v (m^2/s)	m_v (m^2/MN)	k (m/s)
0 kPa	-	-	-
1 kPa	7.88 E-07	0.94	7.32 E-09
17 kPa	1.55 E-06	0.57	8.72 E-09
33 kPa	1.55 E-06	0.33	5.14 E-09
64 kPa	3.50 E-06	0.25	8.72 E-09
127 kPa	1.08 E-05	0.17	1.84 E-08
316 kPa	2.46 E-07	0.08	2.02 E-10
631 kPa	8.43 E-07	0.04	3.60 E-10
1260 kPa	9.63 E-07	0.02	2.58 E-10

Table 19- Results of parameters m_v , c_v and k for MW50% (0.400)

MW50% (0.400)	c_v (m²/s)	m_v (m²/MN)	k (m/s)
0 kPa	-	-	-
1 kPa	8.00 E-07	0.54	4.27 E-09
17 kPa	1.58 E-06	0.62	9.71 E-09
33 kPa	1.58 E-06	0.44	6.90 E-09
64 kPa	3.55 E-06	0.26	9.08 E-09
127 kPa	1.10 E-05	0.14	1.52 E-08
316 kPa	2.52 E-07	0.08	2.11 E-10
631 kPa	8.37 E-07	0.05	4.81 E-10
1260 kPa	9.57 E-07	0.04	3.97 E-10

Table 20- Results of parameters m_v , c_v and k for TV100%

TV100%	c_v (m²/s)	m_v (m²/MN)	k (m/s)
0 kPa	-	-	-
1 kPa	2.00 E-06	0.26	9.74 E-07
17 kPa	7.89 E-07	0.05	1.10 E-09
33 kPa	2.25 E-07	0.41	2.12 E-06
64 kPa	1.30 E-06	0.18	1.90 E-07
127 kPa	1.10 E-06	0.10	1.08 E-07
316 kPa	3.16 E-06	0.04	2.06 E-08
631 kPa	7.24 E-06	0.02	1.27 E-08
1260 kPa	7.24 E-06	0.02	1.19 E-08

The one-dimensional compression for each sample was plotted against the square root of time or the logarithm of time to deduce c_v for each load, besides, m_v was calculated for the same load interval according to the deformation measured, and in addition to k , which was calculated according to the Darcy's law for the same load stage of those coefficients (Matos-Fernandes, 1994). Those parameters behave as expected for all samples, decreasing within load increase.

The results from Tables 15 to 20 are summarized for better understanding in Figures 34 to 36, where Figure 34 presents the result values for the consolidation coefficient (c_v), Figure 35 the values found for hydraulic conductivity (k) and Figure 36 the oedometric modulus (m_v).

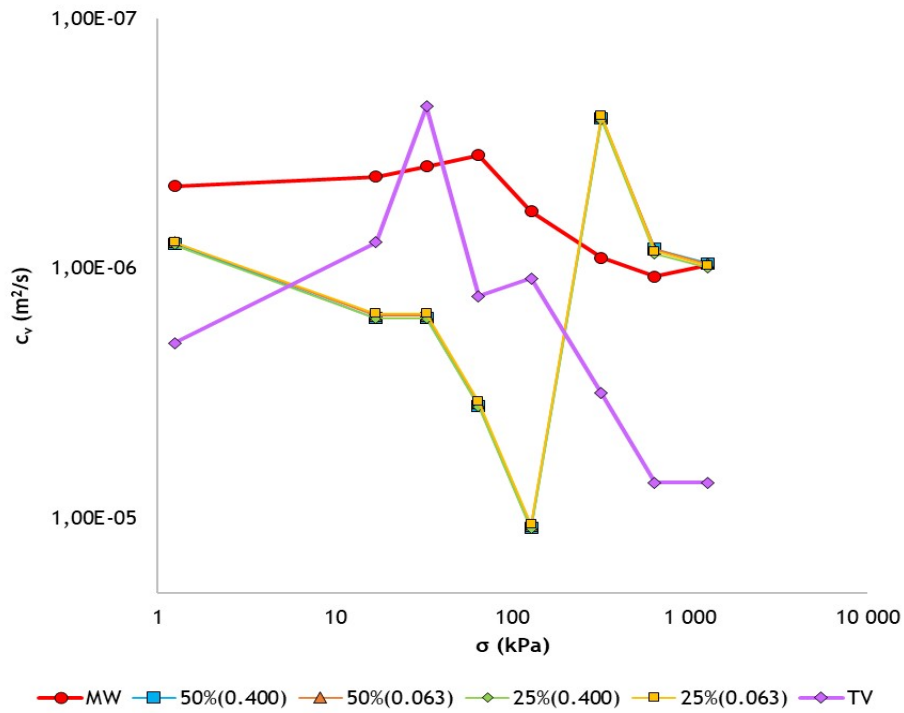


Figure 34 - Consolidation coefficient results for the samples

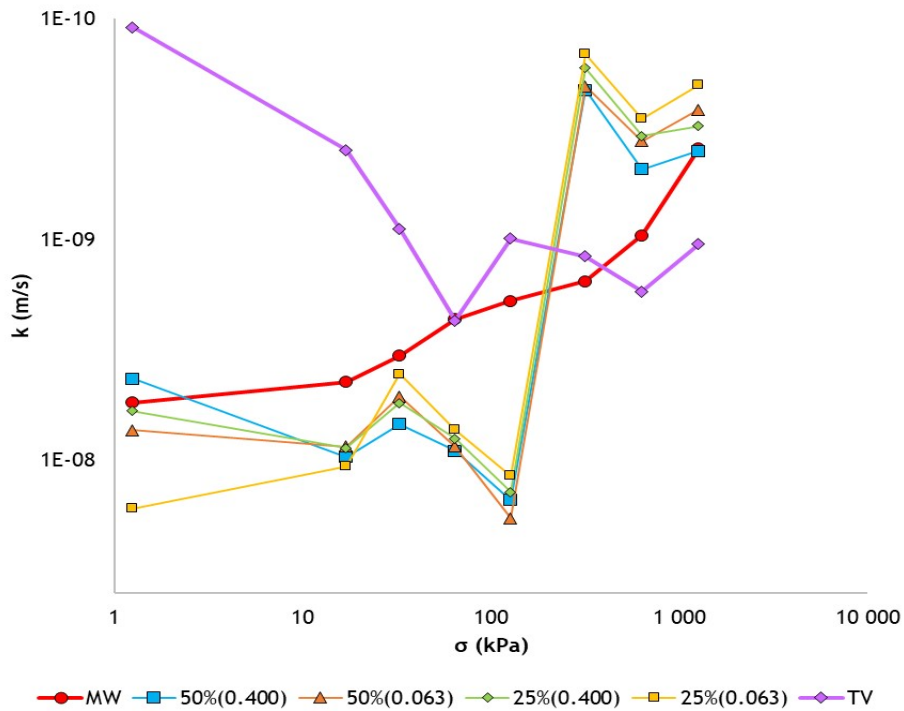


Figure 35 - Hydraulic conductivity results for the samples

As expected, the c_v values for the mixtures are practically the same, TV100% and MW100% present slightly different behaviors, where MW100% has a more constant horizontal line, showing no impact according to the load. Similar behavior to c_v is found for k , where the mixtures show similar behavior to each other, obtaining a peak after structural yield stress. This

behavior indicates that, regardless of the specific composition of the mixtures, the variation in k remains within a predictable and consistent range. TV100% and MW100% have a more constant k and are like each other. However, for the mixtures, near 100 kPa seems to have an anomaly in the behavior after reaching the structural yield stress. This rearranged the samples due the residues introduction, generating a new void filling composition for the structures.

The volumetric compressibility coefficient and the permeability coefficient are not constant throughout the applied stress, they are dependent on small variations of vertical load. Therefore, the m_v and k are considered constant for each load level. The permeability coefficient values (obtained indirectly through Darcy's law) show that the soil microstructure creates preferential paths for flow. Furthermore, when the soil is unloaded, a significant part of the plastic deformation does not recover, due to the increase in compactness which occurs within rearrangements in the solid skeleton, resulting in new stability between the particles that are more stable (Andrade Pais, 2007). The k naturally decreases along with the void ratio due to increase in vertical effective stress, however, as observer for c_v , near 100 kPa seems to have an anomaly in the behavior after reaching the structural yield stress, rearranging the samples.

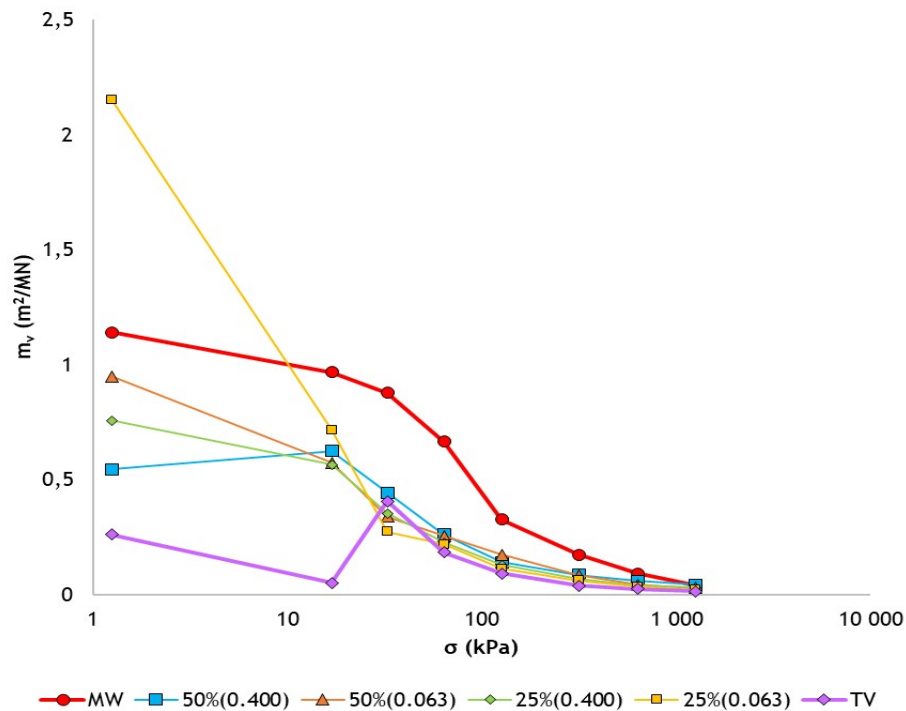


Figure 36 - Oedometric modulus results for the samples

The variation in the m_v can be understood as a linear reduction after the structural yield stress, but for lower stresses, this does not happen. For completely unstructured soils, the compression rate will be practically constant. The results found for the samples are as expected, where after structural yield stress all samples demonstrate the same behavior, the most different being MW100%, starting with higher values, but reaching the same m_v when increasing the load.

Other coefficients should be exposed to interpretate oedometric consolidation. For example, the inverse of the m_v parameter, the one-dimensional compressibility modulus ($M=1/m_v$), is also adopted to estimate the structural yield stress, due to the possibility of defining a law of variation with the applied vertical effective stress. For stresses below the structural yield, this situation does not occur, the compression rate will be practically constant in completely unstructured soils. The representation of stress *versus* compressibility modulus (Figure 37) of the tests carried out, under saturated test conditions, defines the probable yield limit of inter-bonds, in addition to a mathematical law for the variation of the compressibility modulus. TV and MW trend line were exposed in Figure 37, being the exponential curve of MW more accurate with R^2 of 0.92, but the objective here was design the limits for the mixtures' behavior. The other mentioned objective was to delineate or suppose where the structural yield stress was for the samples, and all of them were in between the purple zone, among 30 and 120 kPa, those values justified the anomalous results around 100 kPa for the tested materials.

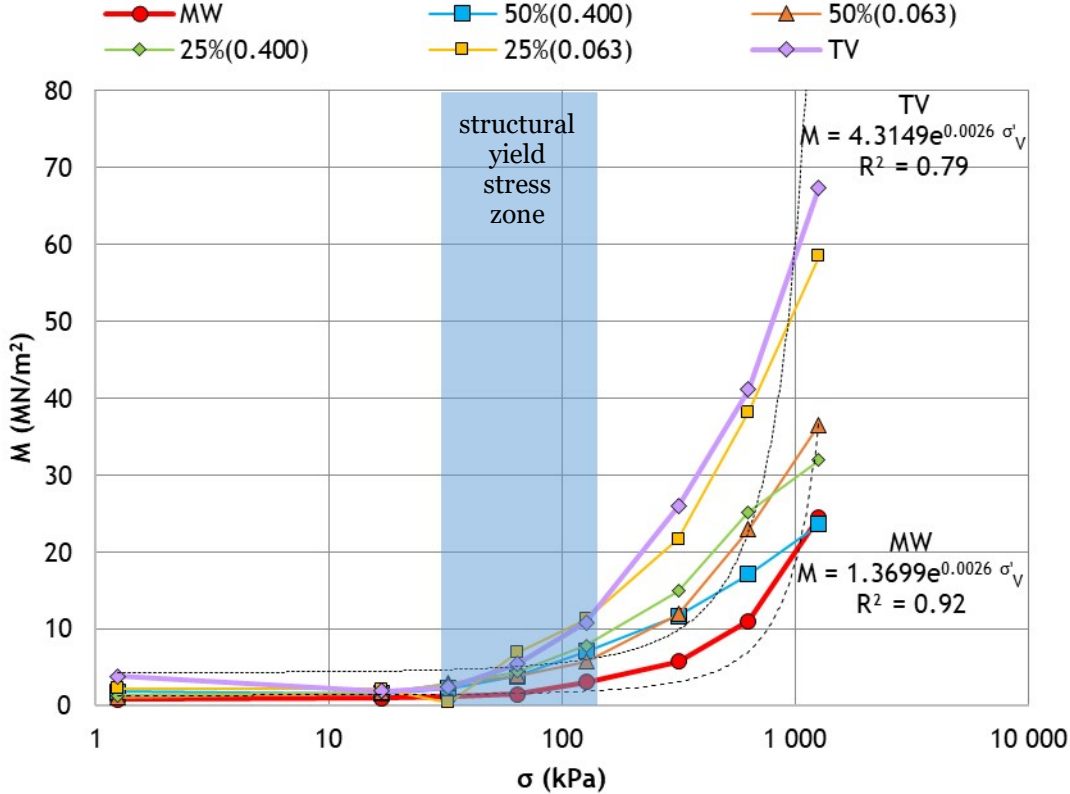


Figure 37 - Stress versus compressibility modulus

3.2. CBR Test

Figure 38 presents the results obtained from the CBR for expansion *versus* time of the residue, the *tout-venant* and their mixtures. For the tests, the degree of compaction at 100% was calculated.

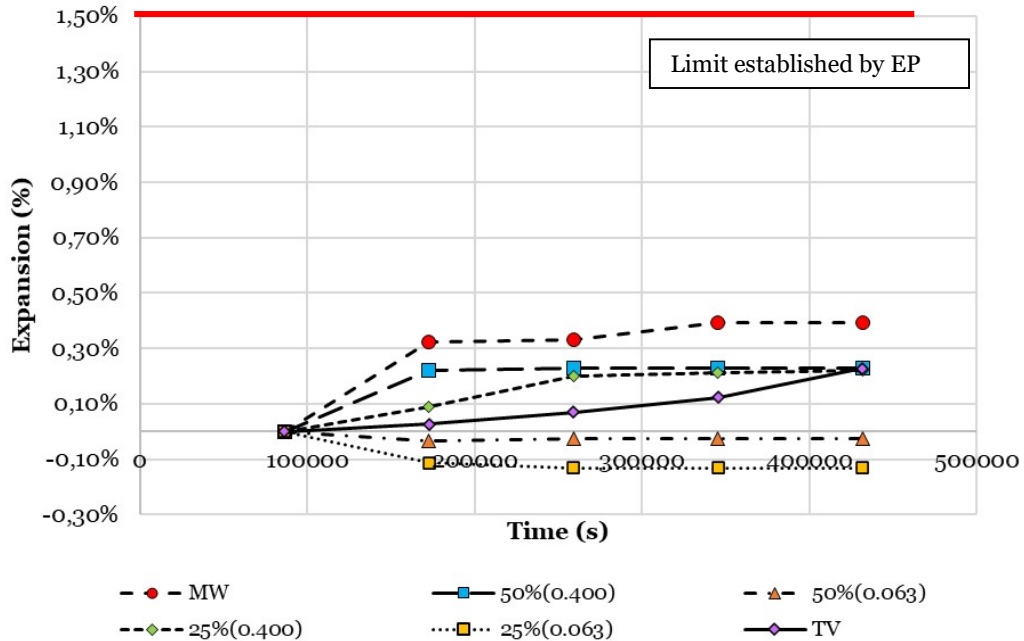


Figure 38 - Expansion vs time (CBR)

MW100% presents the highest expansion of the materials studied, 0.39%, but still very low expansion. The MW25% (0.063) and MW50% (0.063) mixtures present almost zero expansion, slight contraction, due to the introduction of a low quantity of silty clay material which could fill the voids, suggesting a stable material, which may indicate an improvement in volumetric stability when compared to other mixtures with particle size 0.400. Samples with 50% mixture show interesting results, MW50% (0.063) has an almost neutral expansion, indicating that the increase in the amount of fine material continues to reduce the expansion, while at MW50% (0.400) maintains an expansion of 0.23%, like TV100%. The MW25% (0.400) presents an expansion of 0.22%, which is lower than that of the pure residue.

These results suggest that adding finer material to soil or waste can reduce expansibility, improving material stability. The expansion limit established by CETO (E.P., 2014) is 1.5% for sub-base layers, and there are no required expansibility values for regularization and berm filling layers.

Figure 39 presents the results obtained from CBR for force *versus* penetration and in Table 21, CBR values for 2.5- and 5.0-mm penetration.

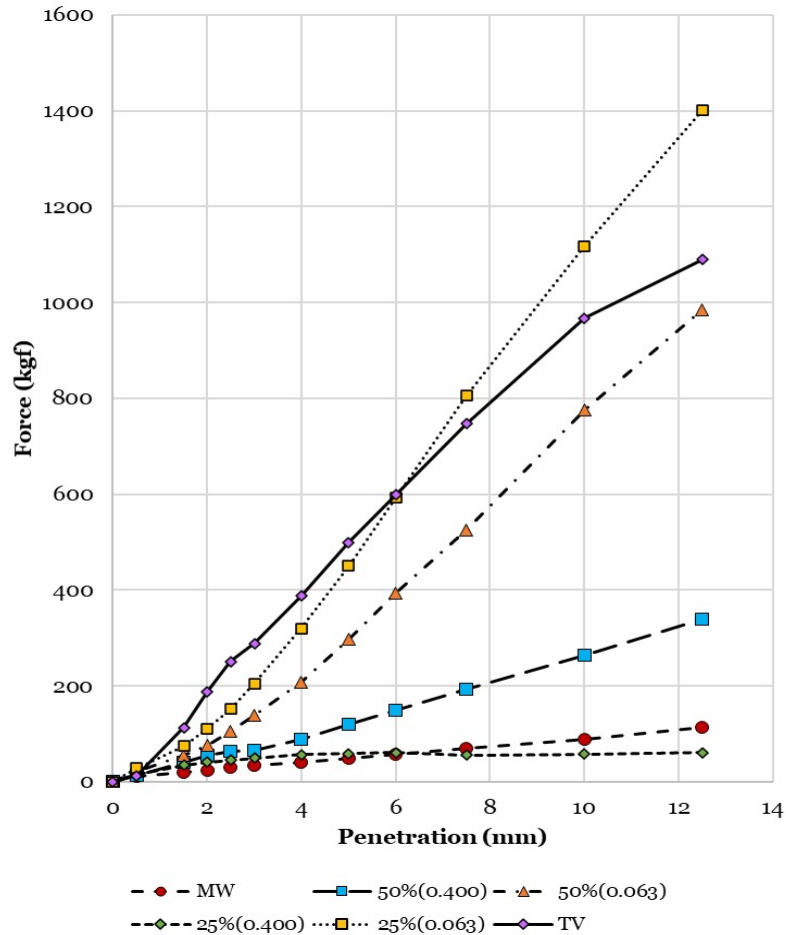


Figure 39 - Force vs Penetration (CBR)

Table 21 - CBR values of the materials

SAMPLE	2.5 (mm)	5.0 (mm)	CBR
MW100%	2.2%	2.4%	2.4%
MW25% (0.063)	11.2%	22.1%	22.1%
MW25% (0.400)	3.3%	2.9%	2.9%
MW50% (0.063)	7.7%	14.7%	14.7%
MW50% (0.400)	4.6%	5.9%	5.9%
TV100%	18.5%	24.6%	24.6%

MW100% presented a CBR value, of 2.4%, while TV100% presented 24.6%. Lower CBR values were found in mixtures with a particle size of 0.400, reinforcing the idea of expansion values. The mixtures with 0.063, with a greater presence of clay-silty material, presented higher CBR values, especially the mixture with 25%. For the sub-base layer, (E.P., 2014) requires a

minimum of 20% for the CBR value, with the MW25% (0.063) mixture being the only one that meets this parameter. For regularization and filling layers there are no minimum values required, and all mixtures can be applicable.

For an example of sub-base layer design following the DNIT (2006), A standard pavement design was established: subgrade, sub-base, base, and surface layer. For design, the only mixture that met the sub-base requirements (CBR greater than 20% and expansion of up to 1%) was MW25% (0.063) with a value of 22.1%.

To determine the N number, it would be necessary to know the composition of vehicles by type and class, the region's climatic factor, the traffic factor, among other factors. To design the model, a specific project established by EP for a National Road in the “Beira Alta” region in Portugal was considered, adopting a pavement with bituminous coating with a height of 12.5cm thick, where N number greater than 5×10^7 are typically found in the standard. For the present study, the N number of 6×10^7 was adopted, and a subgrade with an ISC =6% was estimated.

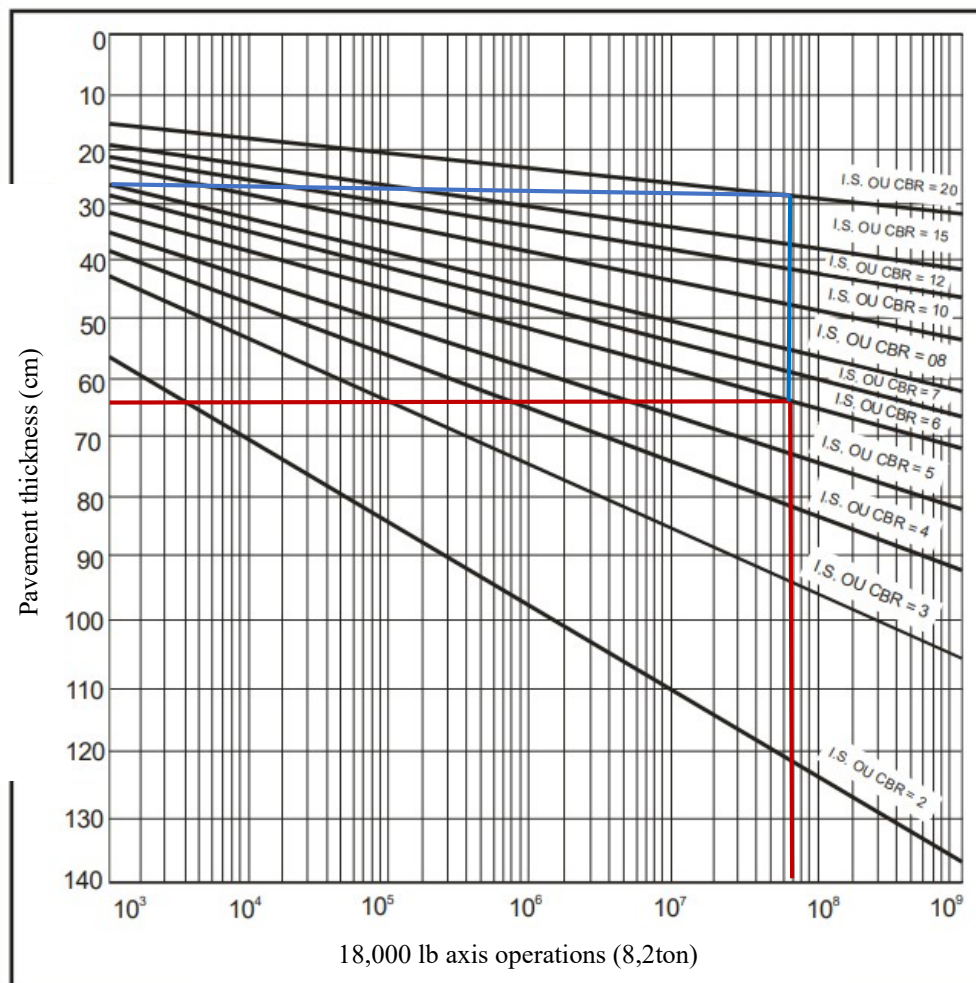


Figure 40 - Example for sub-base layer design

From the values mentioned above, a line was drawn with the value of the number N up to the CBR curve of the subgrade in red in Figure 40, resulting in a value of $H_m=65\text{cm}$, and another in blue for the CBR found in the mixture MW25% (0.063), finding a value of $H_{20}=30\text{cm}$ (estimated height). For coating values, bituminous concrete with a thickness of 12.5 was adopted (DNIT, 2006). Using Eq. 04, commented on in Chapter 2, the value below was found, where K_r and K_b are equivalence coefficients, determined by standard for the type of bituminous treatment chosen, and using a safety coefficient of 1.2, required for N number values greater than 10^7 .

$$RK_r + BK_b \geq H_{20} \quad (4)$$

$$12,5 * 2 + B * 1 \geq 30 * 1,2$$

$$B \geq 11\text{cm}$$

For base height, a value of $B \geq 11\text{cm}$ was found, however the minimum established by the standard is 15cm. Using Eq. 05 to determine the height of the sub-base layer, a value $\geq 25\text{cm}$ was found.

$$RK_r + BK_b + H_{20}K_s \geq H_m \quad (5)$$

$$12,5 * 2 + 15 * 1 + H_{20} * 1 \geq 65$$

$$H_{20} \geq 25\text{cm}$$

It is important to note that the minimum thickness for compacting granular layers is 10 cm and the maximum is 20 cm. The height value found for the sub-base (25cm) must be executed in two layers. Assuming a second dimensioning with a minimum number N (10^4), and following the calculations above, $H_{20} \geq 18\text{cm}$. If the axis operation increases up to 10^9 , the thickness will no surpass 30cm. This seems to characterize that mixture as a good material according to bearing capacity, and the workability for future construction should be good due to the use of low quantities for that thickness.

The values mentioned above were selected for a standard pavement model, already used by EP in a specific project. For each new project to be developed, it is essential to know factors such as the vehicle factor, the region's climate factor, the traffic distribution factor, among others, to correctly size the N number.

For mixtures using mining waste, CBR values close to 20% were also found in the literature by (Campanha, 2011; Lara, et al., 2018), who also differentiated the CBR for normal and intermediate energy, being an interesting application in this research, however, due to scheduling issues, they were not carried out, being an option for future research. The CBR results contrasted with other studies (Andalicio, Pereira, & Oliveira, 2022), which found CBR values of 29.30 for waste rock, due to different particle size distribution of the waste.

Chapter 5

Conclusions

The present study aimed to evaluate the potential use of granite mining waste from the “Pedreira da Devesa” located in Santana de Azinha, Guarda (Portugal). The natural residue analyzed, from a mineralogical point of view, is an intrusive igneous rock, basically formed by quartz, feldspar, and micas, which suggests its potential for applications in geotechnical engineering. The choice of these materials for the investigation was based on their local availability and combined with this situation, the large volume of waste generated in the mining company has motivated the search for using this material as an alternative element for works.

In this sense, this research proposed carrying out laboratory investigations, seeking the feasibility of using mining waste mixed with *tout-venant* in the production of new geomaterials using different proportions of waste introduction, considering variations in the percentage of waste incorporation (0%, 25%, 50%, 100%) and in the granulometry of the waste (particle sizes >0.063 mm, >0.400 mm, >2,000 mm).

After completing the technical analysis covered in the previous chapters, in the development of this research it is possible to highlight some of the main conclusions and future recommendations regarding the behavior of these materials.

- In terms of granulometric composition, the changes that mixing the waste causes in the *tout-venant* are in terms of particle size and a function of the percentage of waste. According to the parameters recommended by CETO (E.P., 2014), the mixtures MW25% (0.063), MW25% (0.400) and MW50% (0.063) are recommended for application in sub-base. The MW50% (0.400) mixture is recommended for the regularization and berm filling layers.

- Regarding Atterberg limits, CETO (E.P., 2014) recommends that the maximum liquidity limit be 25% for sub-base and 35% for regularization layer and berm filling. As for the plasticity index, 6% for sub-bases and 6 to 10 for the regularization layer and filling of verges. The only applicable subbase mixture for both parameters is MW25% (0.063). The mixtures MW25% (0.400) and MW50% (0.400) can be used in other applications, even in landfill bodies, while MW50% (0.063) exceeds all established limits.

- Regarding the USCS (ASTM) classification, mixtures are generally characterized by silty sands or poorly graded sands. For AASHTO, all mixtures are types A-1-b and A-2-4. CETO (E.P., 2014) does not specify anything regarding these classifications.

- Regarding chemical and mineralogical composition, quartz, kaolinite, and muscovite were found. Quartz is one of the most abundant and hardest minerals, suggesting that the residue has potential for applications in geotechnical engineering. In relation to pH, both the residue and the *tout-venant* presented neutral conditions. Regarding the leached inorganic constituents, in environmental terms, the parameters established by CETO (E.P., 2014), in relation to the document “Council 2003/33/CE”, the residue complies.

- For the oedometric test, the MW25% sample (0.063) is one of the best options, with a low Cc and Cs index, while the MW100% presents the worst value, however all the materials have very low consolidation ration, classifying as potential stable road materials.

- For the CBR type test, in sub-base layers, (E.P., 2014) requires a minimum of 20% for the CBR value, with the MW25% (0.063) mixture being the only one that meets this parameter. For leveling and filling layers there are no minimum values required, and all mixtures can be applicable. It was also possible to observe that higher CBR values were found in mixtures with fines introduction lower than 0.063.

- Regarding hydraulic conductivity, the results indicate that mixing with MW tends to reduce permeability, and the mixing proportion has a considerable impact, with greater proportions of fine material reducing permeability significantly. CETO (E.P., 2014) does not establish minimum or maximum values for this parameter.

In general, it can be concluded that the MW25% mixture (0.063) presented the best parameters in relation to those established by “Estradas de Portugal” for application in granular sub-base layers. The other mixtures, except for MW50% (0.063), can be applied in a leveling layer and filling berms.

In terms of practical application, the environmental advantages of reusing granite mining waste are emphasized, instead of giving it the traditional destination (deposition in landfills).

Future Investigation

In addition, the investigation should further address some other points, like:

– Analyze the behavior of other grades with the tailings and other particle sizes, to obtain more results and other optimal mixtures;

- Carry out tests on the equivalent type of sand, methylene blue value, shear box and triaxial to complement the analysis carried out in this study, since it was not possible to carry out due to the schedule;
- Carry out CBR-type tests with different types of energy (modified and intermediate) and analyze whether there are changes in the behavior of the mixtures;
- Carry out a study on the economic viability of using waste in mixtures with the soils of this research, in comparison to traditional materials commonly used in paving;
- Use the mixtures in experimental sections such as granular layers of pavements, monitoring and managing the performance of these sections in the long term.

Folha em branco

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