INDIAN INSTITUTE OF TECHNOLOGY (BHU) VARANASI

VARANASI, UTTAR PRADESH – 221005

A FINAL REPORT OF BTECH PROJECT

ON THE TOPIC

STUDY OF PROPERTIES OF ROCK FOR ROAD MATERIAL (UTILIZATION OF WASTE)

SUBMITTED BY

DIVYANSH KUMAR

ROLL NO: 16155027

B.TECH. PART-IV

SEMESTER VII

DEPARTMENT OF MINING ENGINEERING

CERTIFICATE

This is to certify that the work presented in this report entitled “Study of properties of rock for road material” by **Divyansh Kumar** (Roll no. 16155027) is a record of project carried out by him under my supervision and guidance.

To the best of my knowledge, neither this report nor any part of it has been submitted for any degree or diploma to any Institute or University in India or abroad.

Supervisor:

Dr. Aarif Jamal

Professor

Department of Mining Engineering

IIT (BHU) Varanasi

ACKNOWLEDGEMENT

The most pleasant point of presenting a thesis is the opportunity to thank those who have contributed to it. Unfortunately, the list of expression of thank no matter who how extensive is always incomplete and insufficient. Indeed this page of acknowledgement shall never be able to touch the horizons of generosity of those who tendered there help to me. First I foremost, I would like to express my gratitude and indebtedness to Prof. Arif Jamal for his kindness in allowing me to do work in the present topic and for his inspiration guidance, positive criticism and valuable suggestions throughout this project work. I am sincerely thankful to him for his able guidance and pain taking efforts in improving my understanding of this project.

An assemblage of this nature could never have been attempted without reference to and inspiration from the work of others. I acknowledge my obligations to all of them.

DIVYANSH KUMAR

16155027

Department of Mining Engineering

Indian Institute of Technology(BHU)

Varanasi - 221005

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Introduction

Mine rock waste, which is the rock material removed in order to access and mine ore, is free from gold processing chemical contaminants but presents a significant environmental challenge owing to the large volumes involved. One way of mitigating the environmental and safety challenges posed by the large volume of mine rock waste stockpiled in mining communities is to find uses of this material as a substitute for rock aggregates in construction. This article reports on a study conducted to evaluate the engineering properties of such a mine deposit to determine its suitability for use as road pavement material. The generation, handling, and safe disposal of solid wastes has become a major concern in the country. While the volume of wastes continues to grow, approval of facilities for waste processing and proper disposal is becoming more difficult to obtain. Many existing disposal facilities are approaching capacity. Furthermore, environmental regulations have become increasingly wide-spread and restrictive. As a consequence, the cost of waste handling and disposal has escalated significantly in recent years.

Many municipalities and industries are devoting an increasing proportion of their budgets to waste management expenditures. Stricter waste regulations have resulted in a commitment of substantially greater resources to waste management at all levels of society. Increasing waste volumes and escalating disposal costs have forced a reassessment of public attitudes regarding the way society handles its wastes. Furthermore, there is a growing public awareness of the importance of conserving and preserving our valuable natural resources.

This expanding awareness has given rise to a definite trend toward recycling or use of a wide variety of solid waste materials. Waste recycling in the 1990s has advanced from simple newspaper drives, motivated by a recognition of the resource value in high volumes of formerly discarded materials such as scrap tires, paving rubble, combustion by products, and mining wastes. Reusing such materials reduces disposal volumes and costs, conserves natural resources, and may even generate revenue. Because highways require huge volumes of construction materials, highway agencies have become frequent participants in efforts to recycle or reuse diverse waste materials.

Literature Review

The road construction sector is a worldwide high consumer of natural aggregates. The use of unusual industrial by-products in road techniques can contribute to the conservation of non-renewable natural resources and the reduction of wastes produced by some industries. Waste rocks could be considered as potential alternative secondary raw materials in road construction. The use and valorization of these wastes is currently limited according to the Moroccan guide for road earthworks (GMTR). The guide has classified these materials as waste products, which consequently, cannot be used in road construction. However, waste rocks (such as phosphate rocks) are mostly sedimentary natural rocks which have not been subjected to any transformation other than mechanical fragmentation.

The goal of this project is to discuss key-properties of various mine waste rocks (MWR) to be used as road materials. Solid waste materials differ vastly in their types and characteristics as well as in the applications for which they may be suited. Experiences with using waste materials in highways can vary considerably, depending on climatic differences, compositional fluctuations, material handling techniques, and construction procedures. Some waste materials and by-products (such as reclaimed paving materials, slags, and fly ash) have been used beneficially in the highway system for many years. Other materials have very little performance history from which to evaluate their potential for sustained use in highway construction. A number of waste materials may be suitable for use in constructing highways, but may have other, more economical or productive uses.

METHODOLOGY

Overview

A highway pavement is a structure consisting of superimposed layers of processed materials above the natural soil sub-grade, whose primary function is to distribute the applied vehicle loads to the sub-grade. The pavement structure should be able to provide a surface of acceptable riding quality, adequate skid resistance, favourable light reflecting characteristics, and low noise pollution. The ultimate aim is to ensure that the transmitted stresses due to wheel load are sufficiently reduced, so that they will not exceed bearing capacity of the subgrade. Two types of pavements are generally recognized as serving this purpose, namely flexible pavements and rigid pavements. This chapter gives an overview of pavement types, layers, and their functions, and pavement failures. Improper design of pavements leads to early failure of pavements affecting the riding quality.

Requirements of a pavement

An ideal pavement should meet the following requirements:

- Sufficient thickness to distribute the wheel load stresses to a safe value on the sub-grade soil,
- Structurally strong to withstand all types of stresses imposed upon it,
- Adequate coefficient of friction to prevent skidding of vehicles,
- Smooth surface to provide comfort to road users even at high speed,
- Produce least noise from moving vehicles,
- Dust proof surface so that traffic safety is not impaired by reducing visibility,
- Impervious surface, so that sub-grade soil is well protected, and
- Long design life with low maintenance cost.

Types of pavements

The pavements can be classified based on the structural performance into two, flexible pavements and rigid pavements. In flexible pavements, wheel loads are transferred by grain-to-grain contact of the aggregate through the granular structure. The flexible pavement, having less flexural strength, acts like a flexible sheet (e.g. bituminous road). On the contrary, in rigid pavements, wheel loads are transferred to sub-grade soil by flexural strength of the pavement and the pavement acts like a rigid plate (e.g. cement concrete roads). In addition to these, composite pavements are also available. A thin layer of flexible pavement over rigid pavement is an ideal pavement with most desirable characteristics. However, such pavements are rarely used in new construction because of high cost and complex analysis required.

Flexible pavements

Flexible pavements will transmit wheel load stresses to the lower layers by grain-to-grain transfer through the points of contact in the granular structure (see Figure 19:1). The wheel load acting on the pavement will be distributed to a wider area, and the stress decreases with the depth. Taking advantage of this stress distribution characteristic, flexible pavements normally has many layers. Hence, the design of flexible pavement uses the concept of layered system. Based on this, flexible pavement may be constructed in a number of layers and the top layer has to be of best quality to sustain maximum compressive stress, in addition to wear and tear. The lower layers will experience lesser magnitude of stress and low quality material can be used. Flexible pavements are constructed using bituminous materials. These can be either in the form of surface treatments (such as bituminous surface treatments generally found on low volume roads) or, asphalt concrete surface courses (generally used on high volume roads such as national highways). Flexible pavement layers reflect the deformation of the lower layers on to the surface layer (e.g., if there is any undulation in sub-grade then it will be transferred to the surface layer). In the case of flexible pavement, the design is based on overall performance of flexible pavement, and the stresses produced should be kept well below the allowable stresses of each pavement layer.

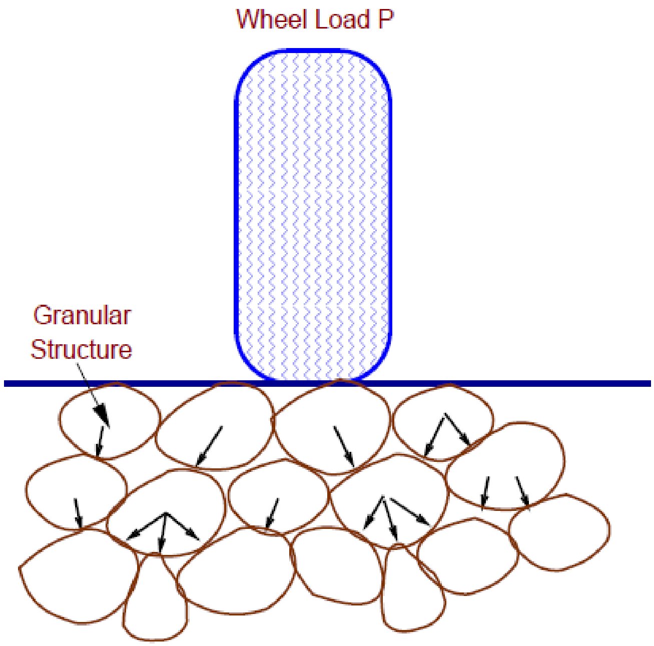

Figure 19:1: Load transfer in granular structure

Typical layers of a flexible pavement

Typical layers of a conventional flexible pavement includes seal coat, surface course, tack coat, binder course, prime coat, base course, sub-base course, compacted sub-grade, and natural sub-grade.

Seal Coat: Seal coat is a thin surface treatment used to water-proof the surface and to provide skid resistance.

Tack Coat: Tack coat is a very light application of asphalt, usually asphalt emulsion diluted with water. It provides proper bonding between two layer of binder course and must be thin, uniformly cover the entire surface, and set very fast.

Prime Coat: Prime coat is an application of low viscous cutback bitumen to an absorbent surface like granular bases on which binder layer is placed. It provides bonding between two layers. Unlike tack coat, prime coat penetrates into the layer below, plugs the voids, and forms a water tight surface.

Surface course
Surface course is the layer directly in contact with traffic loads and generally contains superior quality materials. They are usually constructed with dense graded asphalt concrete(AC). The functions and requirements of this layer are:

- It provides characteristics such as friction, smoothness, drainage, etc. Also it will prevent the entrance of excessive quantities of surface water into the underlying base, sub-base and sub-grade,
- It must be tough to resist the distortion under tra_c and provide a smooth and skid- resistant riding surface,
- It must be water proof to protect the entire base and sub-grade from the weakening e_ect of water.

Binder course
This layer provides the bulk of the asphalt concrete structure. It's chief purpose is to distribute load to the base course The binder course generally consists of aggregates having less asphalt and doesn't require quality as high as the surface course, so replacing a part of the surface course by the binder course results in more economical design.
Base course
The base course is the layer of material immediately beneath the surface of binder course and it provides additional load distribution and contributes to the sub-surface drainage It may be composed of crushed stone, crushed slag, and other untreated or stabilized materials.
Sub-Base course
The sub-base course is the layer of material beneath the base course and the primary functions are to provide structural support, improve drainage, and reduce the intrusion of fines from the sub-grade in the pavement structure If the base course is open graded, then the sub-base course with more fines can serve as a filler between sub-grade and the base course A sub-base course is not always needed or used. For example, a pavement constructed over a high quality, stiff sub-grade may not need the additional features offered by a sub-base course. In such situations, sub-base course may not be provided.
Sub-grade
The top soil or sub-grade is a layer of natural soil prepared to receive the stresses from the layers above. It is essential that at no time soil sub-grade is overstressed. It should be compacted to the desirable density, near the optimum moisture content.

Factors affecting pavement design

There are many factors that affect pavement design which can be classified into four categories as traffic and loading, structural models, material characterization, environment.

Traffic and loading

Traffic is the most important factor in the pavement design. The key factors include contact pressure, wheel load, axle configuration, moving loads, load, and load repetitions.

Contact pressure: The tyre pressure is an important factor, as it determine the contact area and the contact pressure between the wheel and the pavement surface. Even though the shape of the contact area is elliptical, for sake of simplicity in analysis, a circular area is often considered.

Wheel load: The next important factor is the wheel load which determines the depth of the pavement required to ensure that the subgrade soil is not failed. Wheel configuration affect the stress distribution and detection within a pavement. Many commercial vehicles have dual rear wheels which ensure that the contact pressure is within the limits. The normal practice is to convert dual wheel into an equivalent single wheel load so that the analysis is made simpler.

Axle configuration: The load carrying capacity of the commercial vehicle is further enhanced by the introduction of multiple axles.

Moving loads: The damage to the pavement is much higher if the vehicle is moving at creep speed. Many studies show that when the speed is increased from 2 km/hr to 24 km/hr, the stresses and detection reduced by 40 per cent.

Repetition of Loads: The influence of traffic on pavement not only depend on the magnitude of the wheel load, but also on the frequency of the load applications. Each load application causes some deformation and the total deformation is the summation of all these. Although the pavement deformation due to single axle load is very small, the cumulative effect of number of load repetition is significant. Therefore, modern design is based on total number of standard axle load (usually 80 kN single axle).

Structural models

The structural models are various analysis approaches to determine the pavement responses (stresses, strains, and detections) at various locations in a pavement due to the application of wheel load. The most common structural models are layered elastic model and visco-elastic models.

Layered elastic model: A layered elastic model can compute stresses, strains, and detections at any point in a pavement structure resulting from the application of a surface load. Layered elastic models assume that each pavement structural layer is homogeneous, isotropic, and linearly elastic. In other words, the material properties are same at every point in a given layer and the layer will rebound to its original form once the load is removed. The layered elastic approach works with relatively simple mathematical models that relates stress, strain, and deformation with wheel loading and material properties like modulus of elasticity and poissons ratio.

Material characterization

The following material properties are important for both flexible and rigid pavements.

- When pavements are considered as linear elastic, the elastic moduli and poisson ratio of subgrade and each component layer must be specified.
- If the elastic modulus of a material varies with the time of loading, then the resilient modulus, which is elastic modulus under repeated loads, must be selected in accordance with a load duration corresponding to the vehicle speed.
- When a material is considered non-linear elastic, the constitutive equation relating the resilient modulus to the state of the stress must be provided.

However, many of these material properties are used in visco-elastic models which are very complex and in the development stage. This book covers the layered elastic model which require the modulus of elasticity and poisson ratio only.

Environmental factors

Environmental factors affect the performance of the pavement materials and cause various damages. Environmental factors that affect pavement are of two types, temperature and precipitation and they are discussed below:

Temperature: The effect of temperature on asphalt pavements is different from that of concrete pavements. Temperature affects the resilient modulus of asphalt layers, while it induces curling of concrete slab. In rigid pavements, due to difference in temperatures of top and bottom of slab, temperature stresses or frictional stresses are developed. While in flexible pavement, dynamic modulus of asphaltic concrete varies with temperature. Frost heave causes differential settlements and pavement roughness. Most detrimental effect of frost penetration occurs during the spring break up period when the ice melts and subgrade is a saturated condition.

Precipitation:_The precipitation from rain and snow affects the quantity of surface water infiltrating into the subgrade and the depth of ground water table. Poor drainage may bring lack of shear strength, pumping, loss of support, etc.

Pavement materials: Soil

Pavements are a conglomeration of materials. These materials, their associated properties, and their interactions determine the properties of the resultant pavement. Thus, a good understanding of these materials, how they are characterized, and how they perform is fundamental to understanding pavement. The materials which are used in the construction of highway are of intense interest to the highway engineer. This requires not only a thorough understanding of the soil and aggregate properties which affect pavement stability and durability, but also the binding materials which may be added to improve these pavement features.

Sub grade soil

Soil is an accumulation or deposit of earth material, derived naturally from the disintegration of rocks or decay of vegetation, that can be excavated readily with power equipment in the field or disintegrated by gentle mechanical means in the laboratory. The supporting soil beneath pavement and its special under courses is called sub grade. Undisturbed soil beneath the pavement is called natural sub grade. Compacted sub grade is the soil compacted by controlled movement of heavy compactors.

Desirable properties

The desirable properties of sub grade soil as a highway material are

- Stability
- Incompressibility
- Permanency of strength
- Minimum changes in volume and stability under adverse conditions of weather and ground water
- Good drainage, and

- Ease of compaction

Soil Types

The wide range of soil types available as highway construction materials have made it obligatory on the part of the highway engineer to identify and classify different soils. A survey of locally available materials and soil types conducted in India revealed wide variety of soil types, gravel, moorum and naturally occurring soft aggregates, which can be used in road construction. Broadly, the soil types can be categorized as Laterite soil, Moorum / red soil, Desert sands, Alluvial soil, Clay including Black cotton soil.

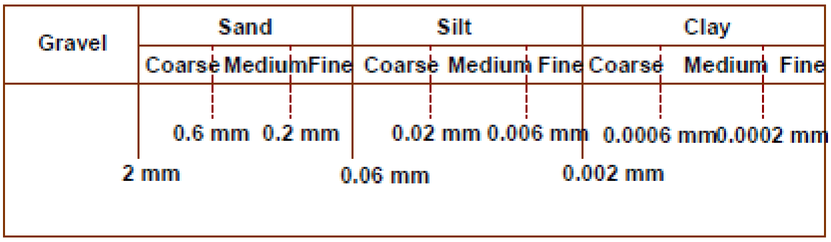

Figure 21:1: Indian standard grain size soil classification system

- **Gravel:** These are coarse materials with particle size under 2.36 mm with little or no fines contributing to cohesion of materials.
- **Moorum:** These are products of decomposition and weathering of the pavement rock. Visually these are similar to gravel except presence of higher content of fines.
- **Silts:** These are finer than sand, brighter in color as compared to clay, and exhibit little cohesion. When a lump of silty soil mixed with water, alternately squeezed and tapped a shiny surface makes its appearance, thus dilatancy is a specific property of such soil.
- **Clays:** These are finer than silts. Clayey soils exhibit stickiness, high strength when dry, and show no dilatancy. Black cotton soil and other expansive clays exhibit swelling and shrinkage properties. Paste of clay with water when rubbed in between fingers leaves stain, which is not observed for silts.

Tests on soil

Sub grade soil is an integral part of the road pavement structure as it provides the support to the pavement from beneath. The sub grade soil and its properties are important in the design of pavement structure. The main function of the sub grade is to give adequate support to the pavement and for this the sub grade should possess sufficient stability under adverse climatic and loading conditions. Therefore, it is very essential to evaluate the sub grade by conducting tests.

The tests used to evaluate the strength properties of soils may be broadly divided into three groups:

- Shear Tests
- Bearing Tests
- Penetration Tests

Shear tests are usually carried out on relatively small soil samples in the laboratory. In order to find out the strength properties of soil, a number of representative samples from different locations are tested. Some of the commonly known shear tests are direct shear test, triaxial compression test, and unconfined compression test.

Bearing tests are loading tests carried out on sub grade soils in-situ with a load bearing area. The results of the bearing tests are influenced by variations in the soil properties within the stressed soil mass underneath and hence the overall stability of the part of the soil mass stressed could be studied.

Penetration tests may be considered as small scale bearing tests in which the size of the loaded area is relatively much smaller and ratio of the penetration to the size of the loaded area is much greater than the ratios in bearing tests. The penetration tests are carried out in the field or in the laboratory.

California Bearing Ratio Test

California Bearing Ratio (CBR) test was developed by the California Division of Highway as a method of classifying and evaluating soil-sub grade and base course materials for flexible pavements. CBR test, an empirical test, has been used to determine the material properties for pavement design. Empirical tests measure the strength of the material and are not a true representation of the resilient modulus. It is a penetration test wherein a standard piston, having an area of 3 in2 (or 50 mm diameter), is used to penetrate the soil at a standard rate of 1.25 mm/minute. The pressure up to a penetration of 12.5 mm and it's ratio to the bearing value of a standard crushed rock is termed as the CBR.

In most cases, CBR decreases as the penetration increases. The ratio at 2.5 mm penetration is used as the CBR. In some case, the ratio at 5 mm may be greater than that at 2.5 mm. If this occurs, the ratio at 5 mm should be used. The CBR is a measure of resistance of a material to penetration of standard plunger under controlled density and moisture conditions. The test procedure should be strictly adhered if high degree of reproducibility is desired. The CBR test may be conducted in re-moulded or undisturbed specimen in the laboratory. The test is simple and has been extensively investigated for field correlations of flexible pavement thickness requirement.

Test Procedure

- The laboratory CBR apparatus consists of a mould 150 mm diameter with a base plate and a collar, a loading frame and dial gauges for measuring the penetration values and the expansion on soaking.
- The specimen in the mould is soaked in water for four days and the swelling and water absorption values are noted. The surcharge weight is placed on the top of the specimen in the mould and the assembly is placed under the plunger of the loading frame.
- Load is applied on the sample by a standard plunger with dia of 50 mm at the rate of 1.25 mm/min. A load penetration curve is drawn. The load values on standard crushed stones are 1370 kg and 2055 kg at 2.5 mm and 5.0 mm penetrations respectively.
- CBR value is expressed as a percentage of the actual load causing the penetrations of 2.5 mm or 5.0 mm to the standard loads mentioned above. Therefore,

$$CBR = \frac{\text{load carries by specimen}}{\text{load carries by standard specimen}} \times 100$$

- Two values of CBR will be obtained. If the value of 2.5 mm is greater than that of 5.0 mm penetration, the former is adopted. If the CBR value obtained from test at 5.0 mm penetration is higher than that at 2.5 mm, then the test is to be repeated for checking. If the check test again gives similar results, then higher value obtained at 5.0 mm penetration is reported as the CBR value. The average CBR value of three test specimens is reported as the CBR value of the sample.

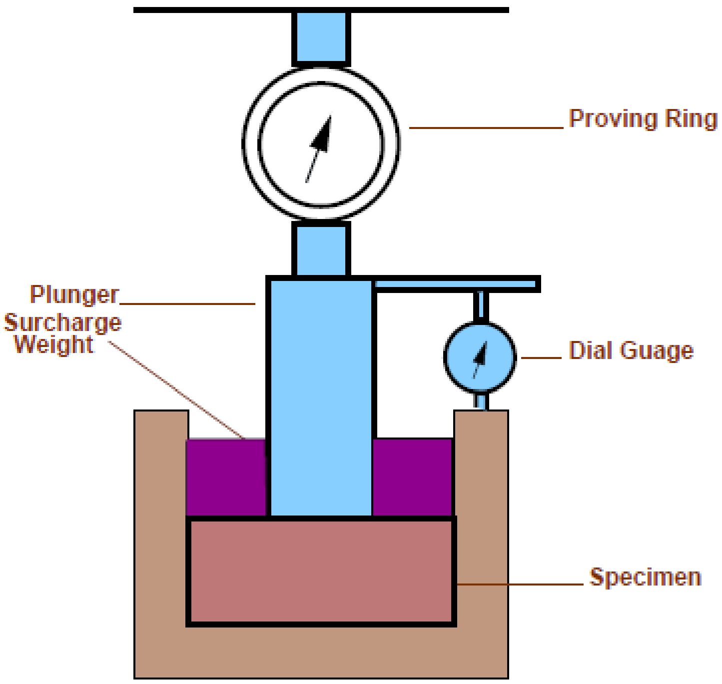

Figure 21:2: CBR Test

Plate Bearing Test

Plate bearing test is used to evaluate the support capability of sub-grades, bases and in some cases, complete pavement. Data from the tests are applicable for the design of both flexible and rigid pavements. In plate bearing test, a compressive stress is applied to the soil or pavement layer through rigid plates relatively large size and the detections are measured for various stress values. The detection level is generally limited to a low value, in the order of 1.25 to 5 mm and so the deformation caused may be partly elastic and partly plastic due to compaction of the stressed mass with negligible plastic deformation. The plate-bearing test has been devised to evaluate the supporting power of sub grades or any other pavement layer by using plates of larger diameter.
The plate-bearing test was originally meant to find the modulus of sub grade reaction in the Westergaard's analysis for wheel load stresses in cement concrete pavements.

Test Procedure

- The test site is prepared and loose material is removed so that the 75 cm diameter plate rests horizontally in full contact with the soil sub-grade. The plate is seated accurately and then a seating load equivalent to a pressure of 0.07 kg/cm2 (320 kg for 75 cm diameter plate) is applied and released after a few seconds. The settlement dial gauge is now set corresponding to zero load.

- A load is applied by means of jack, sufficient to cause an average settlement of about 0.25 cm. When there is no perceptible increase in settlement or when the rate of settlement is less than 0.025 mm per minute (in the case of soils with high moisture content or in clayey soils) the load dial reading and the settlement dial readings are noted.
- Deection of the plate is measured by means of deection dials; placed usually at one-third points of the plate near it's outer edge.
- To minimize bending, a series of stacked plates should be used.
- Average of three or four settlement dial readings is taken as the settlement of the plate corresponding to the applied load. Load is then increased till the average settlement increase to a further amount of about 0.25 mm, and the load and average settlement readings are noted as before. The procedure is repeated till the settlement is about 1.75 mm or more.
- Allowance for worst subgrade moisture and correction for small plate size should be dealt properly.
- Calculation A graph is plotted with the mean settlement versus bearing pressure (load per unit area) as shown in Figure 21:3. The pressure corresponding to a settlement is obtained from this graph. The modulus of subgrade reaction is calculated from the relation.

$$K = \frac{P}{0.125} kg/cm^2/cm.$$

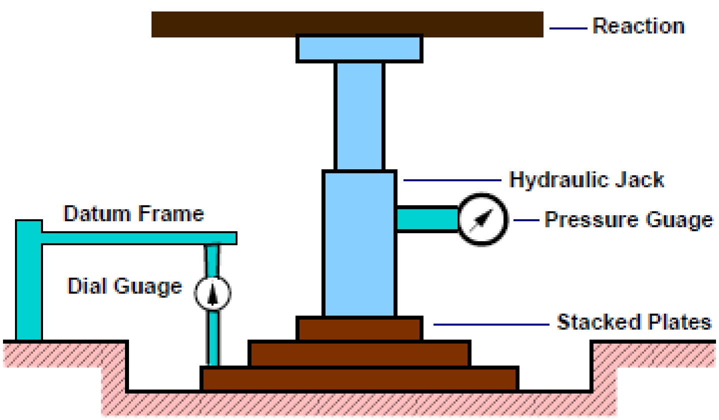

Figure 21:3: Plate load test

WASTE ROCK MATERIAL

Introduction

Various stakeholders in the road construction sector have to deal with the increased demand of raw materials used in road infrastructures. The flexible pavement structure is generally composed of several layers of materials: embankment materials, capping layer, pavement aggregate (base and sub-base course) and surfacing (surface and binder course) course.

Recently, an increasing attention has been given to the potential use of alternative aggregates, particularly, in the road construction sector . Several factors must be considered before using a waste or by-product in road engineering. The use of industrial wastes as secondary and alternative materials in the infrastructure sector depends on their availability, on the transport costs and their physical, geotechnical and chemical properties. The toxicity and solubility in water is a relevant factor to be considered with other factors The use of alternative materials in road construction provides several economic and ecological advantages. When waste materials with acceptable properties are available, it is possible to avoid the costs related to the extraction, and to minimize the transport distance, energy consumption and consequently the greenhouse gas emissions .

Many examples have been studied in detail in the literature. Fly ash and other agricultural wastes were used as soil admixture to improve the CBR values of soil in lower layers of road construction. Incinerated bottom ashes were also investigated in road construction. When stabilized with binder additives, these materials could be used successfully in embankment and pavement layers. Construction or demolition wastes have been used in the construction of embankments and pavement layers. It was also demonstrated that steel-slag fly ash and phosphogypsum as a solidified material can be used as road materials with competitive characteristics. It has been established that the use of fly ashes could improve the natural and mechanical characteristics of soils. Dredged sediments mixed with binders (cement and/or lime) and other products (steel slag, fly ash) were compatible with the requested standards for their use as base or embankments course material. According to the inventory carried out by

OCDE, about twenty types of waste and by-products, to be used in road engineering, has been studied. A classification according to the origin, the main characteristics, the current and the potential uses has been proposed.

In Morocco, phosphate mines produce millions of tons of phosphate mine waste rocks (PMWR) which are stockpiled on surface in waste rock piles covering large areas (several thousand hectares). These waste rocks represent mainly the intercalation layers (limestones, marls and flintstone) and the cover layer (topsoil, clays and marls) occurring within the phosphate sequence. During the extraction of phosphate ore, intercalation layers and the cover layer are blasted and stripped away. Due to their high calcite and dolomite content, the PMWR are inert geochemically. Hakkou, et demonstrated that PMWR could be used as materials for the passive treatment of acid mine drainage, and had the appropriate properties for a store-and-release cover component in a semiarid climate. Although they have characteristics similar to the natural aggregates used as building materials, PMWR are classified by the Moroccan Guide for Road Earthworks in the organic soils and industrial by-products class and particularly in the phosphate wastes sub-class F3 and cannot thus, be used in road construction.

To our knowledge, very limited scientific research on the valorization of PMWR in road construction has been published. Ahmed and Abouzeid investigated the use of phosphate waste rocks in road construction. The work consisted of geotechnical characterization, which led them to conclude an interesting potential of these by-products as road aggregates; similar to natural ones. The substitution of conventional aggregates by PMWR for the construction of road infrastructures might be considered as a promising and ecofriendly solution. A scientific approach of valorization of these mining wastes in road technique is, therefore, necessary to ensure the transition from a "waste" to "building materials". The aim of this paper is to focus on PMWR and its use in the construction of road embankments and to discuss their status in Moroccan Guide for Road Earthworks. Laboratory tests were performed in order to determine the chemical, mineralogical characteristics, physical and geotechnical properties and the environmental behavior of the PMWR. In addition, in situ tests were realized in order to access the behavior of these materials during and after embankments construction using the wet process. These waste rocks represent mainly the intercalation layers (limestones, marls and flintstone) and the cover layer (topsoil, clays and marls) occurring within the phosphate sequence. During the extraction of phosphate ore, intercalation layers and the cover layer are blasted and stripped away. Due to their high calcite and dolomite content, the PMWR are inert geochemically. Hakkou, et demonstrated that PMWR could be used as materials for the passive treatment of acid mine drainage, and had the appropriate properties for a store-and-release cover component in a semiarid climate.

Materials and Methods

Material Sampling

The studied materials were sampled from the mining site located in the central part of the sedimentary phosphate deposits in the Guantour region. The deposit is characterized by phosphate series of late Cretaceous–Eocene age consisting of alternating layers of phosphate separated by gangue silico-carbonate levels. The upper phosphate layer is overburdened by an alternation of different layers (topsoil, siliceous marl, clays, flintstone, calcareous marl and alluvium). The mine produces millions of tons per year of phosphate mine waste rocks (PMWR). The various rock lithologies are scattered in the mine site. Five different waste rocks piles referenced hereafter as I1, I2, I3, I4 and I5 were investigated. To ensure a representative sample, attention was given to the mode, history of storage, geological and petrographic lithology description to identify the parameters likely to impact the characteristics of the sampled materials. Given the heterogeneity of the waste rock piles, a rigorous technique was used to obtain the most representative sampling. The approach consisted of collecting 3 samples from the five stockpiled waste rocks of approximately equal size at different points, respectively at the base, at the middle and at the top of the pile depending on the actual segregation status. The field samples were collected, homogenized in the laboratory, and riffle-split into smaller sub-samples which were stored for further testing.

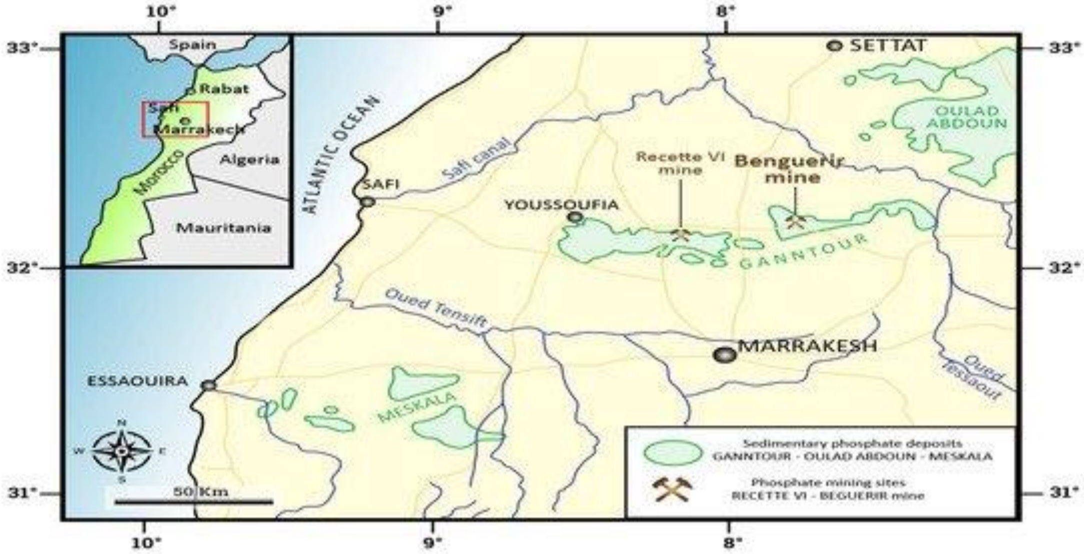

Figure 1. Geographical location of the studied mine site.

Figure 2. Phosphate mine waste rocks dumps.

Research Methodology

The GMTR guide does not include PMWR specifications and conditions of use, therefore, the geotechnical characterization in the laboratory has been completed by conducting in situ tests in a trail embankment and identifying other specific parameters (consolidation, shear strength, chemical and environmental properties) which are not provided by the NF P11-300 standard and which may affect their functional behaviour. Figure 3highlights a summary of the methodology used in this work.

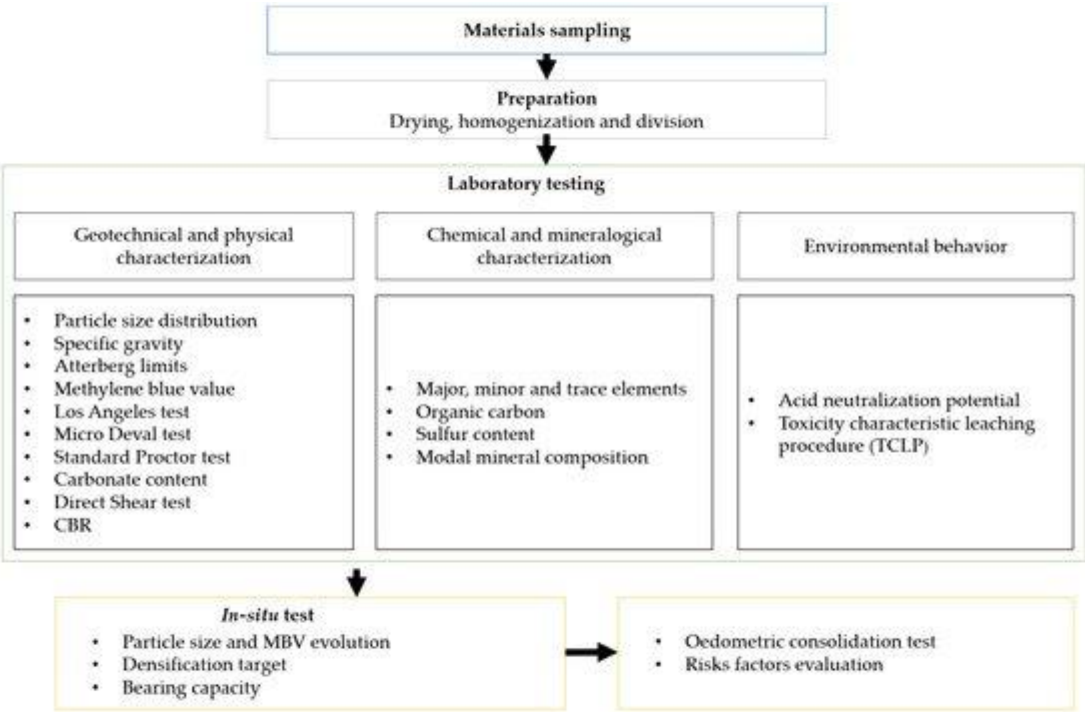

Figure 3. Summary of the followed methodology.

Laboratory Test

Laboratory tests have been conducted to determine the chemical characteristics, the environmental behavior, the mechanical and physical properties and the geotechnical properties. The laboratory tests were carried out in accordance with the relevant AFNOR standards. The leaching behavior of waste rocks was assessed using the Toxicity Characteristic Leaching Procedure (TCLP). The leaching solution used has a pH of 4.93 ± 0.05. The obtained results are compared with US-EPA thresholds. This test is used to verify a potential release of impurities and contaminants. The chemical composition of the solid samples was analyzed using an X-ray Fluorescence (Panalytical, Epsilon 4 Model, Malvern Panalytical, Malvern, UK) and liquid solutions were analyzed by inductively coupled plasma with atomic emission spectroscopy (ICP-AES) (Perkin Elmer Optima 3100 RL, PerkinElmer Waltham, MA, USA). The organic carbon content (Corg) was determined by dichromate oxidation in the presence of concentrated sulphuric acid according to ISO 14235 standard. The crystalline phases were determined by the X-ray diffraction (Bruker AXS Advance D8. Bruker, Billerica, MA, USA), Cu Kα radiation. The DiffracPlus EVA software (Bruker, Billerica, MA, USA) was used to identify mineral species and TOPAS software (Bruker, Billerica, MA, USA) implementing Rietveldt refinement to quantify the abundance of all identified minerals. Due to the presence of calcareous rocks, the carbonate content was determined on −400 µm of crushed samples in accordance with the NF P 94-048 standard.

The classification of the PMWR has been codified in relation to the nearest standardized materials, it will be therefore called to standard NF P 11-300 for the geotechnical characterization. Prior to the characterization, the moisture content of the samples was measured. The fraction 0/400 µm of the studied samples have been subjected to the plasticity test using the Atterberg limits method. Also, dimensional properties tests were investigated using granularity method by dry sieving after washing. The methylene blue test value (MBV) was measured on the 0/5-mm fraction taken from the 0/50-mm dry material according to the standard NF P 94-068. For compaction aptitude, the samples were compacted, in three layers, in a CBR standard mold using normal compaction. When the proportion of elements greater than 20 mm exceeds 30% of the mass of the material, the Proctor test was performed on the 0/20-mm fraction, but its interpretation is then limited to the assessment of its moisture content w_{opn}. In this case, the real dry density was measured in a full trial scale. To complete the knowledge of the petrographic features of the original rocks, evaluate the resistance of the material regarding the fragmentation, the wear and the particle size distribution evolution under the effect of mechanical solicitations, several tests were carried out using: NF P 94-064 standard for the density of a rock element by the hydrostatic weighing method. For better representativeness, the fraction 25/50 mm was chosen for the determination of Los Angeles abrasion value (LA) and Micro Deval value (MD) using NF P18-573 [35] and P18-572 [36] standards. To measure the sensitivity of these materials to fragmentation under the effect of mechanical stresses and climatic cycles, the fragmentation coefficient and degradability coefficient of samples were measured on the 40/80-mm fraction according to the standards NF-P94-066 [37] and NF-P94-067 [38], respectively. To determine the load bearing capacity of the materials after compaction and to assess their resistance to punching and heavy machines traffic, Californian bearing ratio (CBR) tests were carried out according to standard NF-P94-078 [39]. The shear strength parameters were investigated under the drained conditions, on the 0/20-mm fraction of the studied waste rock samples on the waste rocks samples [40].

In order to evaluate the vertical deformation (settlement) under the effect of the charges after saturation, an oedometric test was carried out on the 0/20-mm fraction of material I2 according to the standard XP-P94-090-1 [41] with a water content close to the optimum moisture content (w_{opn}) and with a dry density equal to the reference dry density (γdr) determined by the in situ tests.

In-Situ Test

In situ tests were performed with sample I2 which is the most abundant material among the PMWR. The objective was to determine the optimal conditions that offer the best results in terms of material compaction. These are related to: water content, thickness of compacted layer, speed and number of compactor passes. The ability of these materials to achieve the targeted compaction level for the embankments (q4 level) was also assessed. The dry densities of the materials were measured in situ using a membrane densitometer [42], while the measurement of the bearing capacity of the materials was evaluated through the determination of the module under static loading at the plate EV_2 (standard NF P 94-177-1).

A full-scale of trial embankment was constructed on 30 m length and 8 m width reinforced with around 1 m of embankment high. Three layers of 0.30-m thickness were constructed by wet method using a loading machine, a grader, a sprinkler vehicle and vibratory road roller (Figure 4). The trial test was carried out on a stable platform whose bearing capacity at the time of completion was greater than 50 MPa. The layers were compacted with a calibrated vibratory road roller with a single drum [43]. The speed was fixed at 4 km/h and the compaction energy of the machine was controlled. The representation of the three layers pile is shown in Figure 4. Many parameters were fixed during these tests: the speed of the compactor, the vibration amplitude of the compactor, the average water content range (between 0.9 and 1.1 of w_{opn}) and the layer thickness.

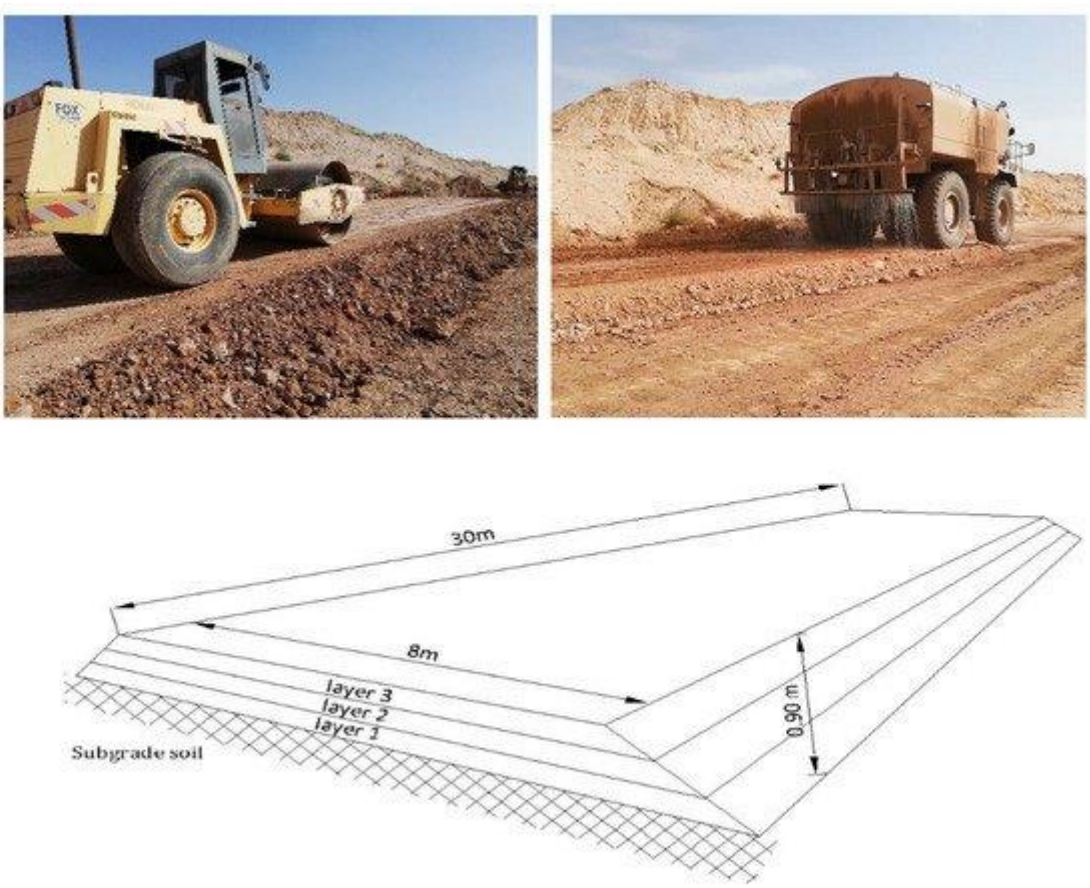

Figure 4. Photos and scheme illustrating the field trial embankment construction.

The shape of the granulometric curve obtained before compacting showed a continuity of the granularity, in addition, to have a better representativity, the water content was realized on the entire fraction of soil-rockfill mixture (0/80 mm).

Before compacting, the grain-size distribution curve, the MBV, the fine fraction (having a size less than 80 µm), the particles having a size less than 2 mm (determined on the 0/50-mm fraction) and the water content were measured. In addition to the same parameters followed before compacting, the layer thickness, the dry density and the bearing capacity for the three compacted layers with the different energy proposed (2, 4 and 8 of roller passes) were

measured after compacting. The average of six samples will be selected for each monitored parameter before and after compaction.
The optimum dry density will be the one that corresponds to the maximum value of the six points of dry densities recorded on the compacted thickness and the control of the homogeneity of the distribution of compaction forces was verified by determining the maximum deviation from the mean value on the same compacted layer. In other words, the determination of the compaction energy which makes it possible to have the maximum dry density. It is this which will be taken as reference dry density (γdr) for the calculation of the compaction rate and evaluation the ability of these materials to achieve the required compaction levels for embankments.

Results and Discussion

PMWR Characterization

Physical and Geotechnical Properties

Results of the geotechnical identification tests are summarized in Table 1. All the studied PMWR samples display approximately the same water content and very dry moisture content due to the arid climate of the region and the storage at the mine site. In addition, the tested materials show generally similar properties with a slight difference in grain size distribution results (Figure 5). The 0/20-mm fraction is important as it is considered in the Proctor and CBR tests. Only materials whose +20 mm particles weight proportion under 30% have been the subject of CBR and Proctor tests (it is the case only of I3 material). Also, the granulometry has a direct impact on plasticity of the studied materials. The materials with the highest content of fine fraction (I3, I4 and I5) showed the most plasticity features. The degree of plasticity that remains low for all these materials is particularly related to the mineralogical composition of the clays (illite). A difference was founded in mechanical properties of the studied PMWR samples. Unlike other materials with low values, I2 and I1 samples showed satisfactory values of LA, MD, degradability and fragmentability coefficients. The analysis of the results of the various physical tests indicates that the degradation of particles is related particularly to the presence rate of clay and flintstone in the studied samples. With a maximum particles diameter less than 150 mm, a non-zero cohesion (4–7 kPa), a plasticity index less than 16%, a specific (particle) density around 26 kN/m^3 and a percentage of fine elements less than 23%, the PMWR studied as shown in Table 1 could be classified in the category C1B5 (friable soil); a gravelly coherent materials with a fine fraction [24] and the category of mixture of limestone and siliceous sandstone (for the case of the rocky origin). Thus, these materials can be used in the construction of road embankments. This is illustrated in the synoptic table of classification according to the nature of the materials proposed by the NF P11-300 standard (Figure 6).

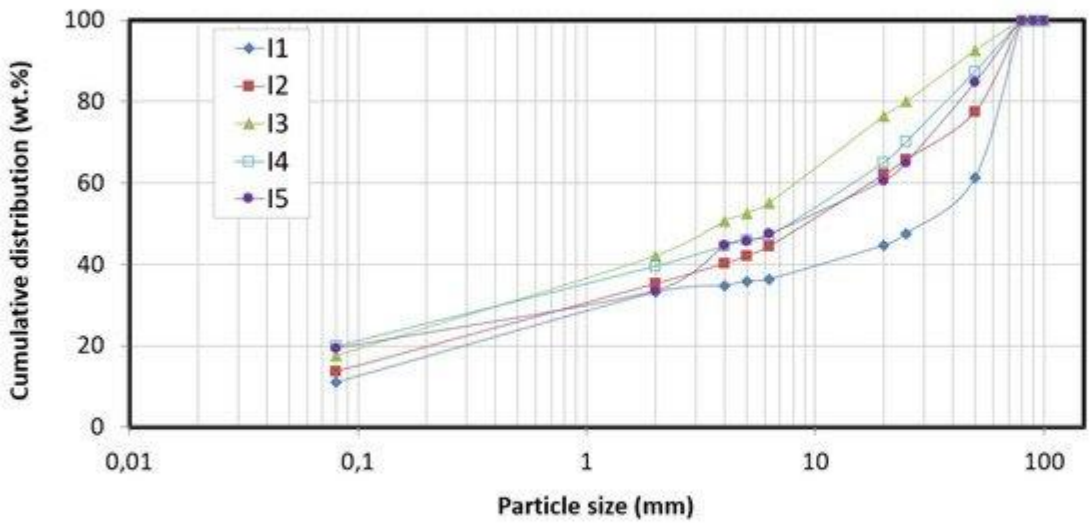

Figure 5. Particle size distribution of the five collected materials.

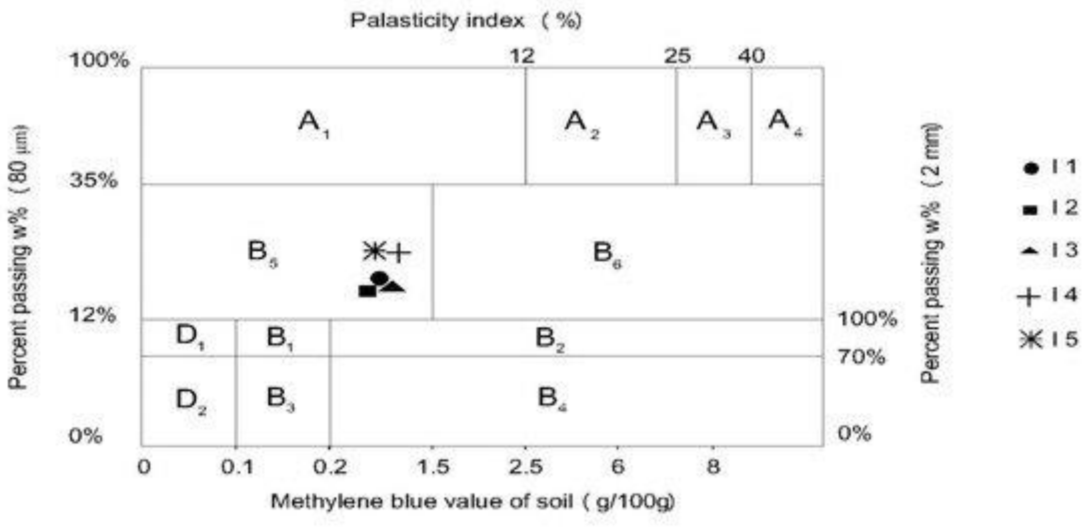

Figure 6. Classification of studied PMWR according to the soil classification table of the NF P11-300 standard (fraction 0/50 mm). A: fine soil; B: Sandy and gravely soil with fine particle and D: Soil insensitive to water.

Chemical and Mineralogical Properties

The chemical and mineralogical composition of PMWR are presented in Table 2. All the samples contain mainly SiO_2 (41–57 wt. %), CaO (12–19 wt. %), MgO (4.9–9.1 wt. %), P_2O_5 (4.2–5.4 wt. %). Alkali and alkali earth oxides are present in low concentrations (less than 1 wt. %). The amounts of detected sulfur and organic carbon were generally below 0.5 wt. %. The PMWR could be classified easily as non-generating of acid mine drainage with a very neutralization potential, as already demonstrated [18]. In terms of trace element occurrence, only a very low concentration of Cr, Cd, Cu and Mo were detected. The relative abundance of minerals identified by XRD and quantified using a Rietveld refinement method is illustrated in Table 2. All materials contain a siliceous fraction represented by quartz and cristobalite, and carbonaceous fraction represented mainly by dolomite and little amount of calcite. Fluorapatite was also detected varying between 6 and 8.5wt. %. The mineralogical composition of the studied materials showed also plagioclase (albite and anorthite) and clays (illite which was observed only in samples I3, I4 and I5, that is why they showed the most plasticity features).

Table 2. Chemical and mineralogical composition of PMWR samples.

No montmorillonite has been detected, which eliminates the risk of swelling of the clayey fraction contained in these materials once used in road construction. The I2 sample exhibit low content of clays (illite) and high content of siliceous minerals (flintstone occurrence), which explain the best mechanical features: Los Angeles (LA = 46 wt. %), Micro Deval (MD = 50 wt. %), Degrability and Fragmentability coefficients respectively 9.1 and 7.5 as shown in Table 1.

Environmental Behavior of Materials

The results of trace elements leaching from PMWR using the TCLP test are summarized in Table 3. The mobility of heavy metals depends on several factors such as heavy metals bearing minerals and the pH of the leaching solution. All concentrations were in agreement with the limits for non-hazardous waste fixed by US-EPA regulation. Therefore, the studied PMWR cannot be listed as hazardous waste, in fact they should be considered as natural aggregates. The observed limited metal release is explained by the low initial content within PMWR and the relative high stability of the occurring inert minerals (silice and aluminosilicates) and high neutralizing capacity minerals such as dolomite and calcite. The fluoroapatite need strong acidity to be solubilized.

Table 3. Results of the Toxicity Characteristic Leaching Procedure (TCLP) of PMWR.

In situ Full Trial Tests

The evolution criterion (in the granulometric approach) considered in this on-site study concerns fragmentation under the action of mechanical solicitation before and after compaction. This parameter was demonstrated during the essays in true size by the measurement of the particle size analysis and MBV before and after compacting by means of different compaction energies. The results show (Table 4) that the maximum particle size evolution of 18.39%(explained by the presence of friable limestone and marly rocks characterized by low mechanical resistance) was recorded with eight passes, almost identical evolution of 18.23% was recorded in the case of four passes which concerns the evolution towards the fine fraction, this explains that the production of the fine elements is stopped under the effect of compaction energy of four passes, it was also noted that MBV values increased slightly with increasing compaction energy; even with these evolutions, the material always keeps the same classification family after compaction (C_1B_5) according to the NF-P11-300 [24] standard.

Table 4. Granulometric and Methylene Blue value (MBV) evolution according to the compaction energy.

The in situ tests have shown that with a very important compaction energy of 8 passes, the process of alteration of the blocks has been almost stopped (granulometric evolution less than 0.9% for fine elements and less than 3% for other diameters found by adding four additional passes of the compactor to get to 8 passes). The results of the dry density according to the compacting energy at the surface and at the bottom of the compacted layer have been summarized in the Table 5. Embankment dry density was examined as a function of roller passes.

Table 5. The compaction rate according to the compaction energy.

The results showed that the maximum dry density corresponding to 19.5 kN/m^3 was recorded for the compaction energy of four passes, the reference dry density is therefore taken equal to 19.5kN/m^3.The calculation of the compaction rates (at the surface and at the bottom of the layer) makes it possible to show that the application of a compaction energy of two passes does not satisfy the required compaction levels for embankments contrary to four and eight passes (Table 5). After application of each compaction energy, the bearing capacity test was carried out just after the compaction of the third layer by ensuring the average water moisture of the material at the time and after compaction, this has been verified by sampling during the entire duration of the measurements by realizing a sounding through the three layers (Table 6).

Table 6. Results of lift tests.

With k (EV_2 / EV_1) < 2 (which makes it possible to appreciate the quality of the compaction) and an average EV_2 module > 80 MPa, material I2 has very satisfactory lift results. According to the LCPC-Setra guide [41], these materials, which are also sensitive to water, can therefore, be classified as Top part of the earthworks (PST3) from a class (AR2) formation if the constructive drainage arrangements make it possible to evacuate the water and prevent its infiltration.

The aforementioned criteria of grain size evolution, densities and bearing capacity justify the choice to be limited only to the compaction energy of four passes for the construction of embankments with PMWR. this retained energy, which remains more important than that required by the LCPC-Setra guide (limited to only three roller passes and for the same compaction parameters), allows to have a maximum fractionation especially for the marly rocks recognized by their evolving behavior and therefore avoid having two fractions with clearly differentiated granulometry (large particles and very fine fraction), this has been demonstrated by the realization of in situ trenches which show that the compacted material is coherent (the fines perfectly fill the voids between the blocks), resistant, and has a homogeneous appearance (a reduced standard deviation found during densities and lift measurements over the entire thickness of the compacted layer).

In view of the aforementioned results, the optimal compaction conditions which make it possible to obtain the compaction level required for embankments (by humidification), to ensure the minimum bearing capacity for the embankment materials and to avoid possible disorders due to the phenomenon of grain size evolution under the effect of mechanical stresses are the following (Table 7).

Table 7. Optimal compaction conditions of I2 material.

Risks Factors Evaluation

The results of the oedometric test showed that the material I2 has An average oedometric modulus of 10,045 kPa, a low compressibility index of 0.125 and a very low swelling index of 0.04, considering that the contracting regulations in Morocco often require settlements of less than 10 cm in 25 years on ordinary road embankments, an evaluation study of embankment settlements (in case of construction with I2 materials) was carried out to determine the maximum height beyond which stability will be questioned, the results make it possible to conclude that this material can be used for embankments up to a height of 15 m respecting a minimum rate of compaction of 95% of γdr and a water content close to w_{opn} without any significant risk of instability. With an organic matter content well below 3% threshold required by the NF P11-300 standard, these releases are therefore far from the category of organic materials, with the availability of deposits, the passage of this materials from the status of waste to an alternative material can therefore be pronounced. This leads back to identifying and evaluating the possible risk factors resulting from this study (Table 8).

Table 8. Risk assessment.

Conclusions

This study is the first of its kind consisting of a physicochemical, mineralogical, environmental and geotechnical characterization of phosphate mine waste rocks. The main conclusions from the laboratory and in situ trial tests to assess the potential use of these materials for road construction are the following:

- The mechanical behavior of these materials depends essentially on their flintstone and clay content.
- The chemical and mineralogical composition and leaching tests on PMWR suggests that they are chemically inert.
- The in situ full trial testing has defined the optimal compaction condition for the use of PMWR in ordinary embankment construction (used in a wet way). It consists of a compaction energy of four passes, a speed of a V4 vibratory roller compactor of 4 km/h and a thickness of the compacted layers of 30 cm.
- Embankments up to 15 m height can be built with PMWR without any significant physical instability risks. The respect of the constructive provisions is necessary.

Considering the results of the leaching tests, the organic content and geotechnical properties, the PMWR can be assimilated to the category of conventional natural aggregates. The use of these materials will have a very important impact on the preservation of the use of natural resources (avoiding the use of borrowing materials) and the recycling of PMWR.

Even with an important level of heterogeneity linked to several scales: the extraction mode, the storage method, and the petrography of the original rocks. It may be recommended that PMWRs be considered as alternative aggregates to be sorted according to a pre-defined zoning map in order to simplify their reuse in civil engineering. The Moroccan guide for road (GMTR) should be updated to allow PMWR to be classified as natural aggregates.

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