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Geotechnical characterization of the US product AggreBind for use in road construction

A thesis submitted in partial fulfilment of the requirements for the degree Of Master of Engineering (MEng) in Civil Engineering

Curriculum: **Geotechnical Engineering**

Presented by:

NOUAYE Boris

Student number: 15TP21006

Supervised by:

Prof. Mbessa Michel

Prof. Simonetta Cola

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DEDICATED

I dedicate this thesis to my father **KENMOGNE ALBERT THIERRY**

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LIST OF ABBREVIATIONS

AASHTO: American Association for State Highway and Transportation officials

GA: Particle size analysis

ASTM: American Society for Testing and materials

CBR : Californian Bearing Ratio

CEBTP : Centre Expérimental des Recherches et d'Études du Bâtiment et Travaux Publics

CCTP : Cahier des Clauses Techniques et Particulières

PI: Plasticity Index

LL: Liquidity Limit

LP: Plasticity limit

LCPC : Laboratoire Central des Ponts et Chaussées

NF: French Standard

OPM: Modified Optimum Proctor

SETRA : Service d'Études Techniques des Routes et Autoroutes

UCS: Unconfined soil compression

USCS: Unified Soil Classification System

ABSTRACT

The quality of the road depends on the quality of the materials used. However, the issue of availability of good quality geotechnical materials is becoming more and more in road projects. Sometimes the soil in place has insufficient bearing capacity, hence the need to seek good soil with characteristics defined in the specifications. When such a material is not in the vicinity of the construction area, its transport makes the project more expensive and the implementation period very long. This has led to the development of various soil stabilization techniques for use in road geotechnics as an alternative solution. There are several stabilization techniques in road geotechnics depending on the soil type and the availability of stabilizers. The present research focuses on stabilization with AggreBind AGB-WT. To better understand the subject, a literature review on soil concepts, soil stabilization techniques and a presentation of the AggreBind product were carried out. The methodology used consisted of geotechnical laboratory tests on the natural soil to identify it and on the treated soil to characterize the new properties conferred by the AGB-WT product. The main results obtained from these tests identified the soil as a low plasticity clayey silt classified by AASHTO A-4 (2), with an immediate bearing capacity at 95% of the OPM equal to 30 (fairly good) but with a high fines content of 51.2%. The AggreBind treatment significantly increased the CBR of the soil from 30 to 156 in 28 days. From a compaction point of view (achieved at 95% OPM) an increase in dry density is observed up to a value of 1893 kg/m3 corresponding to a final compaction rate of 100.2%. According to the laboratory results, the improved soil can be used as backfill/soil, in subgrade, sub-base, and road base. In any case, before using the product it would be necessary to carry out a test panel (reference) test bed to see the effects of the treatment in real conditions.

Keywords: Characterization-Geotechnics-AggreBind-Road construction

RESUME

La qualité de la route dépend de la qualité des matériaux utilisés. Cependant, la question de disponibilité des matériaux de bonne qualité géotechnique se pose de plus en plus avec acuité dans les projets routiers. Parfois, le sol en place a une capacité portante insuffisante, d'où la nécessité de rechercher un bon sol dont les caractéristiques sont définies dans le cahier des charges. Lorsqu'un tel matériau n'est pas à proximité de la zone de construction, son transport rend le projet plus coûteux et la période de réalisation très longue. Cet état de fait a conduit aux différentes techniques de stabilisation des sols pour une utilisation en géotechnique routière comme une solution alternative. Il existe plusieurs techniques de stabilisation en géotechnique routière selon le type du sol et la disponibilité des stabilisants. La présente recherche s'intéresse à la stabilisation au produit AggreBind AGB-WT. Pour mieux appréhender le sujet, une revue de la littérature sur les notions des sols, techniques de stabilisation des sols et une présentation du produit AggreBind a été faite. La méthodologie utilisée a consisté à faire des essais géotechniques de laboratoire sur le sol naturel pour l'identifier et sur le sol traité pour caractériser les nouvelles propriétés conférées par le produit AGB-WT. Les principaux résultats obtenus lors de ces essais ont permis d'identifier le sol comme étant un silt argileux peu plastique classé par AASHTO A-4 (2), de capacité portante immédiat à 95% de l'OPM égale à 30 (assez bonnes) mais avec un taux de fines élevé de 51,2%. Le traitement au produit AggreBind augmente significativement l'indice CBR du sol allant de 30 à 156 en 28 jours. Du point de vue compactage (réalisée à 95% de L'OPM) une augmentation de la densité sèche est observée jusqu'à une valeur de 1893 Kg/m3 correspondant à un taux de compacité final de 100,2%. D'après les résultats au laboratoire, le sol amélioré peut être utilisé en remblai/Terrassement, en couche de forme, en couche de fondation, et en couche de base de la chaussée. Dans tous les cas avant d'utiliser le produit AggreBind il serait nécessaire d'effectuer une planche d'essais (de référence) afin de constater les effets du traitement en conditions réelles.

Keywords: Caractérisation-Géotechnique-AggreBind-Construction routière

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GENERAL INTRODUCTION

The road is a life-long infrastructure that allows the movement of people and goods from one point to another by various means of transport at any time, at a given cost and in comfortable and safe conditions. The field of road construction requires materials with better geotechnical characteristics because the durability of roads depends on the quality of the materials used. In nature, we encounter different types of soil depending on the source rock and the type of alteration of the latter (dissolution of certain salts by water, reaction with CO2, with organic acids, ionic exchanges, etc.). Not all soils are suitable for road use, hence the need for a geotechnical study before any use. Road construction always faces the problem of cost, as the acquisition of equipment and various materials such as graded aggregates, laterite, bitumen, wood, concrete, steel and others generally requires considerable financial resources. Borrowing in quantity and quality is not always available near project sites. Many long distance truck journeys are made every day on road construction sites, making projects more expensive. Improving the materials found on site for use in the pavement structure could reduce these costs.

Cameroon, in its objective to reach emergence by 2035, has embarked on the construction of large-scale infrastructures for the development of its territory. This will lead to the development of infrastructures such as roads, motorways and railways. These transit roads are becoming increasingly essential due to the growing volume of trade, and new constraints are emerging. These include the scarcity of materials that meet the requirements of the CCTP and the high cost of transporting these materials. That said, the use of certain soils, such as laterite, as construction materials in road geotechnics is beginning to make it a scarce resource in some parts of the country. This scarcity of the material also makes it necessary to study new improvement techniques.

This situation has led to the various researches that have found alternative solutions such as different soil improvement techniques. According to Habiba Afrin (2017), there are several methods of soil stabilization which can be grouped into two categories namely mechanical stabilization and stabilization by using different types of additives. Not all stabilization techniques are favorable for any type of soil and/or pavement layer as they have been tested, studied under the very specific conditions. This is why a technique may be effective in one layer of pavement but not in another, be suitable with one type of soil but not with another, etc. Each situation is unique and requires a technique that is suitable for all types of soil. Each situation is unique and requires a specific stabilization technique according to the CCTP, without forgetting that many of these stabilization techniques are polluting for the environment and therefore the degradation pollutes more. Thus, innovative techniques should be developed using innovative soil stabilization products, such as the AggreBind brand products, which are totally ecological (EPA compliant, non-toxic, flammable and do not degrade in the environment) and can be adapted to any type of soil, but also to non-cohesive materials such as desert sand.

The objective of this study is to determine the geotechnical parameters for the use of AggreBind treated soil in road construction. To this end, the present work is divided into four chapters. The first chapter presents the concepts of soils, highlighting their basic characteristics. The second chapter highlights the different stabilization techniques in road geotechnics. The third chapter is the methodology presenting the path followed to meet the expectations of our research. This chapter highlights the different geotechnical tests used for this study. Finally, the fourth chapter is a summary of the results and interpretations of the tests carried out in the framework of this research.

1 CHAPTER 1 : THE SOILS

INTRODUCTION

Pedology or soil science studies the formation, genesis, properties and classification of soils. It has many applications, particularly in the fields of agronomy and ecology. Soil is the support of microbial biodiversity, plant and animal life, as well as human activities. Thus, for civil engineers, soil is used for the construction of structures such as roads, building foundations, dams, etc. But it is not only that, it is also a living entity in its own right, a natural resource, little or slowly renewable. It is with this in mind that several soil stabilization techniques have been developed to limit the abusive and uncontrolled use of soil. Thus, Firoozi & al. (2017) define soil stabilization as a process that involves the addition of materials (binders or aggregate fractions) to improve the physical and mechanical properties of soils. As the appreciation of soil depends on its use, this chapter will therefore give a general presentation of soils through its definition in different contexts, its constituents, its mode of formation, its typology, its characterization, its use and finally present the different (best known) soil stabilization techniques.

1.1. SOIL DEFINITIONS

From a geotechnical point of view, the materials making up the earth's crust can be divided into two main categories: rocks and soils. Rocks (silica, feldspar limestone,) are hard materials that can only be broken up with great mechanical effort. Soil mechanics describes soil as the layer of loose material of mineral and organic origin that lies on the bedrock. Soil can be perceived in several ways depending on the field of study, pedology, soil geology, soil biology, agrology, botany, geochemistry, ecology, geotechnics etc... According to Albert Demolon (1932) soil is "the natural surface formation, with a loose structure and variable thickness, resulting from the transformation of the underlying parent rock under the influence of various physical, chemical and biological processes, in contact with the atmosphere and living beings". Duchaufour, (1997) defines soil as the outermost layer of the earth's crust resulting from the interaction between the lithosphere, atmosphere, hydrosphere and biosphere. Soil is the more or less friable material where plants, by means of their roots, find their food and other conditions for growth, (HILCARD, 1914). Soil means the outer horizons of rocks naturally modified by the mutual influence of water, air and living and dead organisms. It is an independent and varying natural body (Vassili Dokutschaïev, 1883). According to R. L'HERMINIER, (1967) soils result from the physical and chemical alteration of rocks, which are transformed into elements and particles of varying sizes based on silica, limestone, feldspar, mica and clay minerals.) Soil is a volume that extends from the Earth's surface to a depth marked by the appearance of hard or loose rock, little altered or little marked by pedogenesis (AFES & M.C. Girard&al.,2011). In soil biology, soil is a natural formation, an organised environment that is continuously changing under the influence of physical, chemical, biological and human processes. In soil mechanics, soil is the loose surface part of the earth's crust, usually considered to be up to 1.25 m thick (SCOHY, 1992). Soils are the materials that come from the weathering of rocks, (Muni Budhu, 2015). Soil is the layer of loose materials of mineral and organic origin that covers the bedrock (Vincent ROBITAILLE & Denis TREMBLAY, 1997). Soil is a complex of three elements: solid grains, water, air (or gas), (Gérard Philipponat & Bertrand Hubert, 2007).

1.2. THE CONSTITUENTS OF A SOIL

A soil sample consists of three phases, solid, liquid and gas (see Figure 1.1a).

1.2.1. The solid phase

It can be minerals, organic matter or both. We have seen that soils result from the physical or mechanical alteration of rocks. It is easy to understand that the solid grains have the same mineralogical constitution as the parent rock. They are generally larger than 2µ. Soils smaller than 2µ are the result of chemical attacks that have been superimposed on physical or mechanical alteration. These chemical processes are dissolution by water, combination and recrystallisation. As a result, the particles of a fine soil do not have the same crystal structure as the parent rock. These smaller particles formed in this way constitute what will henceforth be called clays. Organic matter comes from the decomposition of living organisms (living or dead). These include carbohydrates, proteins and lipids. Unlike mineral matter, organic matter is often biodegradable. In addition to carbon and water, which are the essential constituents, it may also contain the elements hydrogen, oxygen, nitrogen, phosphorus, sulphur, etc. (Duchaufour, 2004).

1.2.2. The liquid phase

Generally, water. There are several categories of water: The water of constitution which is part of the chemical composition of the sheets. Bound or adsorbed water forms a film around each grain. It is not mobile and is only evacuated at very high temperatures (<300°C). Interstitial water which can be either free water or capillary water. Free water has the ability to circulate freely between the grains; capillary water is a part of the free water that rises by capillary action between the grains. Pore water evaporates completely if the soil sample is heated above 100°C.

1.2.3. The gas phase

It is usually air for dry soils or a mixture of air and water vapour for wet soils. Gases can be categorised into air gases (N, O2, CO2) and gases from respiration and decomposition of organisms: C02, H2, Ch4, NH. When all voids are filled with water the soil is said to be saturated.

1.2.4. Schematic representation of soil phases

We can idealise the phases of soil, as shown in Figure 1.1b. The physical parameters of soils are influenced by the relative proportions of each of these phases. The total volume of the soil is the sum of the volume of solids ($\boldsymbol{V_s}$), the volume of water ($\boldsymbol{V_w}$) and the volume of air ($\boldsymbol{V_a}$), i.e:

$$\boldsymbol{V = V_s + V_w + V_a} \qquad \text{EQ 1}$$

Where,

$$\boldsymbol{V_v = V_w + V_a}\text{, is the volume of voids.} \qquad \text{EQ 2}$$

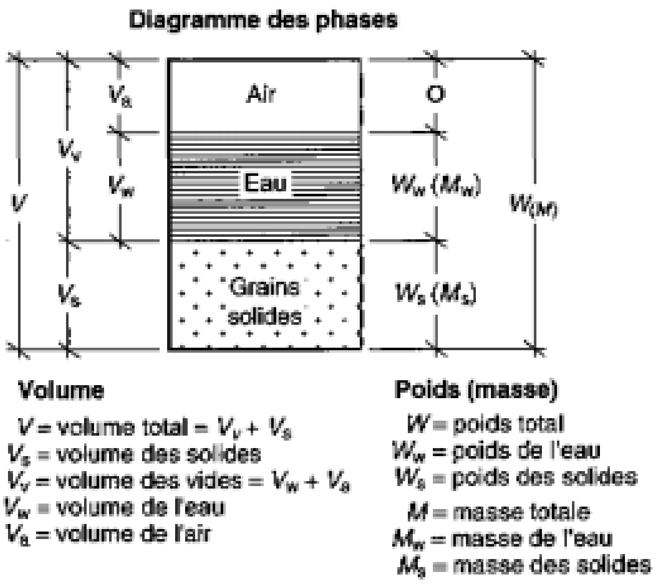


Figure 1. 1. Schematic representation of the phases of a soil (LA ROCHELLE, 1983

1.3. SOIL FORMATION

1.3.1. Training factors

Many factors interfere in the formation of soils, which explains the great diversity of soil types encountered. The most important factors are the nature of the parent rock or source material, climate, weather, vegetation and topography. Other factors such as the topology of the land and human intervention are also important.

1.3.1.1. The original material

Soil lies on top of its parent rock, its original material. The parent rock emerges on the surface of the globe as a result of geological mechanisms (plate tectonics, volcanism, glaciation, erosion, etc.). Of various geological origins (magmatic, metamorphic, sedimentary), the initial rock, known as parent rock, is a hard or loose rock that was formed thousands of years ago. Soil is formed by the physical fragmentation and chemical weathering of a material in-situ. Physical weathering breaks up the material without altering its nature and the rocks are gradually broken down into finer and finer pieces. At the same time, water and energy in the soil cause chemical reactions that alter the original (primary) minerals and produce new (secondary) minerals. Thus, the original material is progressively fragmented and altered into a material that is a mixture of the original constituents and new minerals, especially clays, which will play a very important role in soil fertility. Some environments favour physical weathering, others lead to strong chemical weathering and the production of an abundant quantity of secondary minerals.

1.3.1.2. The climate

Climate is of particular importance in the evolution of soils. On identical rocks, but in different climates, soils are not the same. Temperature and atmospheric precipitation are the primary causes of soil formation. Temperature influences the evolution in two ways: By its action on the speed and mode of alteration of rocks; very rapid in hot climates, this action progresses only slowly in cold climates. Thus, tropical soils are highly evolved and several meters thick, whereas in boreal regions the surface soils (a few decimeters) and their original minerals are little transformed; the crystallization forces of water being very important, they are sufficient to enlarge the slightest fault or fracture in the rock. Environments that experience strong physical weathering are therefore humid environments with several cycles of freezing and thawing per year; unlike relatively warm countries where the temperature never falls below zero. By its action on the speed of decomposition of organic matter. This decomposition takes place thanks to the living organisms present in the soil. Below a temperature of about 4°C, the bacteria and life in the soil no longer function or function only very slowly. There is no longer any decomposition of organic matter, which favours accumulation. Cold environments are therefore environments that favour the accumulation of organic matter and where chemical weathering is extremely low.

1.3.1.3. Biological factors

Of all the factors in soil formation, biological factors are the most important; it has even been said that without life there is no soil. Many soil scientists give biological factors top priority, because living beings contribute two fundamental new elements to the mineral environment through complex biological cycles: organic carbon and nitrogen. The biological factors are animals, plants, micro-organisms and man. The products of their activity, the residues they add to the mineral mass, evolve into humus and its various constituents (water-soluble organic products, fulvic acids, humic acids and humin) in proportions that depend on the conditions of climate, rock, topography and vegetation, whether natural or transformed by man. Animals cause the transport of material, mixing the horizons and making the soil more permeable to air and water. In particular, they contribute to the transformation of organic matter, first by pulverising it, then by mixing it intimately with mineral matter. Organic matter is often digested by small animals (springtails and other animalcules a few tenths of a millimetre in length) before being transformed into humus.

The role of vegetation is much better known. Plant types and above-ground biomass are strongly correlated with climate. Vegetation brings organic matter to the soil and organisms decompose the organic matter and structure the soil. In the context of soil formation, three roles of vegetation can be highlighted. Firstly, plants promote the physical weathering of parent material through root penetration. Secondly, the decomposition of organic matter, which is rich in C, H and O, releases H+ which promotes chemical weathering of the soil. Finally, the concentration of organic matter in the soil promotes soil fertility and allows for better plant density and growth: this accelerates the physical and chemical weathering processes described below.

The action of micro-organisms is predominant in the evolution of soil organic matter. They are essentially heterotrophs that act enzymatically on all the phenomena of degradation and synthesis of organic products. These phenomena are favoured by adequate humidity, soil aeration, heat and the presence of inhibiting substances. Generally speaking, organisms are transformers of many chemical substances and as such are involved in the cycle of important elements: nitrogen, carbon, iron, sulphur, etc.

The Man**,** through the modifications he imposes on the vegetation, exerts a powerful action on the evolution of the soil. He acts essentially through cultivation. Under the influence of the soil, the upper horizons of the profiles are transformed; they are homogenised. Man can also modify the nature and topography of the soil through his work: ripping, construction of banks, levelling, drainage, etc., and thus act on the mechanisms of erosion which he can control. He can also accumulate residues, in the vicinity of settlements for example, transform the environment by adding amendments, manure and mineral fertilizers and improve the fertility of the soil.

1.3.1.4. The relief

Knowledge of the relief factor is also important from different points of view. Indeed, it cannot be considered as an independent factor, comparable to the previous ones, because it depends on most of the other factors of soil formation. It is at the same time a particular manifestation of variations in rock, climate, time of evolution and a cause of the soil's own evolution. On small scales, relief is mainly related to tectonic phenomena and to the distribution of geological domains. There are mountainous regions, such as the Alps; flat areas, such as the Paris Basin, etc. But the shape of the terrain also depends on the parent rock. In the same climate, surfaces of identical age have different topographies depending on whether they are granitic outcrops (domes, flat valleys) or hard limestone (karst with dolomites).

The relief is also linked to the climate: in a temperate climate, a limestone will give a karstic morphology in hollows, whereas in tropical regions the same will present a topography in pitons. The relief also has a direct impact on the climate of the soil (pedoclimate). The effects of altitude, which increase the organic matter content in the surface horizons, are well known (rankers, montagnards). Slopes also play a role through their exposure, i.e. their orientation, which influences the thermal regime of the soil: south-facing slopes are warmer; west-facing slopes are more humid, etc. Relief is also related to the time factor. Indeed, the various parts of a given territory were formed at different times. An accentuated relief evolves by eroding and filling the hollows with excavated material. Large areas of erosion, glacis and river terraces are all traces of the shaping of the landform over time and under specific but varied soil and genetic conditions. But the relief is also a cause of the soil's own evolution. It exerts a direct action by bringing into play the action of gravity on sloping soils through its differences in levels. Two different processes can take place, namely erosion and oblique leaching. The result of this double process is a regular staggering of the soils from the top to the bottom of the slopes. This succession of continuously varying soils is called a soil chain (the Catena). The nature of the chains (their composition and proportions) depends on the climate, the parent rock, the length and the percentage of the slope.

1.3.1.5. The weather

Time is also a very important factor. In the life of a soil, different stages of temporal evolution can be distinguished: neo-formation, youth, maturity, senility. This evolution is quite slow, but its duration varies from one type of soil to another. Time allows the soil to form horizons that reflect local conditions. The time scale for soil formation is measured in thousands of years. However, it cannot be considered in relation to the intensity of weathering: hundreds of millions of years in an arid environment may have less significant effects than a few hundred years in a humid tropical environment. The more intense the weathering and pedogenesis conditions, the less time it takes to weather the parent material and form distinct horizons. For example, early observations in the U.S.S.R. showed that a rock about 15 cm thick could be formed in less than 800 years. It is interesting to have precise information on the different speeds of the processes involved which provide, in addition to the age of the soil, information on the phases of its evolution. The methods used for this purpose are more of an observatory of natural phenomena than experimental data.

1.3.2. Training process

Under the action of environmental factors, a series of transformations takes place that lead to the formation of soil. Three examples of phenomena contribute to this evolution: the alteration of rocks, the decomposition of organic matter, the transfer and organization of the materials formed. These phenomena involve complex mechanisms that are highly dependent on each other. They are not successive, but simultaneous; their effects add up and it is often difficult to dissociate them.

1.3.2.1. Weathering of rocks

Two mechanisms of rock transformation come into play, a physical process (fragmentation, disintegration) which separates the primary minerals of the rocks (e.g. quartz, feldspar, micas which are the primary minerals of granite) and produces fragments of the same chemical composition as the original rock and a chemical process (chemical alteration, mainly hydrolysis and neoformation) which transforms the primary minerals such as quartz and feldspars, micas,... into secondary minerals (clays, oxyhydroxides,...) In physical processes, the main mechanisms for fragmentation and disintegration of rocks are: high temperature variations causing expansion, contraction, cracking and splitting of rocks; and freezing where water penetrates cracks, freezing, loosening and disintegrating the rock. In chemical processes (chemical weathering, hydrolysis, neoformation), the most important chemical weathering mechanism is hydrolysis, i.e. the attack of minerals by pure or water loaded with $\mathbf{CO_2}$. Water is the main vector for this action, so rock weathering is particularly important in humid regions. However, other conditions favor hydrolysis: the nature of the minerals, their size, bacterial activity, temperature and soil drainage. The mineral particles resulting from weathering are mainly silicates. Moreover, weathering leads to the dissolution of soluble ions (neoformation) and the main secondary minerals that are neoformed are: clays, iron, aluminum, manganese and silicon oxyhydroxides. Organic matter also plays an important role in the transformation and solubilization process (chemical weathering).

1.3.2.2. Decomposition of organic matter

When deposited on the soil, fresh organic matter is gradually decomposed. The decomposition mechanism will transform the organic matter into carbon dioxide ($\mathbf{CO_2}$) and release the organic mineral elements it contains. The soil contains a large number of living organisms (bacteria, fungi, mites, earthworms, slugs, snails, beetles, ants, larvae, moles, field mice, etc.) which will decompose the fresh organic matter, releasing its compounds which will undergo a process of mineralization or humification.

Mineralization consists of the release of soluble mineral compounds: sulfates ($\boldsymbol{SO_4^{2-}}$), phosphates ($\boldsymbol{PO_4^{3+}}$), ammonium ($\boldsymbol{NH_4^+}$), nitrates ($\boldsymbol{NO_3^-}$) or gaseous: carbon dioxide ($\boldsymbol{CO_2}$).

Another part of the compounds gives new complex molecules, of a colloidal nature, which will constitute humus: this is the humification process. Humus is composed of several humic compounds, the main ones being fulvic acids, humic acids and humin. Humus, like mineral clays, plays an important role in soil fertility and plant nutrition by releasing mineral elements during its decomposition ($\boldsymbol{SO_4^{2-}}$, $\boldsymbol{PO_4^{3+}}$, $\boldsymbol{NH_4^+}$, $\boldsymbol{NO_3^-}$, $\boldsymbol{CO_2}$, …).

1.3.2.3. The transfer of formed materials

Mineral and organic decomposition leads to the formation of more or less soluble compounds that can move. In the alteration mantle, the movements of water, linked to the laws of gravity and evaporation, carry these elements away and initially cause a loss of matter. The concentration of elements in solution varies according to the nature of the water. While continental waters are not very mineralized, generally around 100mg/l, seawater reaches very high concentrations that can, exceptionally, exceed 200g/l. Dissolved ions are also different, $\boldsymbol{CA^{+}}$, $\boldsymbol{HCO_3^{-}}$, being predominant in the case of freshwater, while $\boldsymbol{Cl^{-}}$ et $\boldsymbol{Na^{+}}$ are largely dominant in sea water. Precipitation, i.e. the deposition of minerals, can occur as soon as the saturation threshold is reached. The transport of solid elements depends on two types of parameters: parameters specific to the elements themselves, i.e. their size, shape, density, surface properties, etc.; and parameters dependent on the transport agent such as its nature (water, wind, ice, its speed, force, etc.). Transport is accompanied by shaping and sorting of the elements. When the transport energy is no longer sufficient, the elements are deposited according to an organization that depends on the sedimentation conditions, an organization that is at the origin of the great diversity of sedimentary structures (ripples, granoclasements, stratifications, etc.).

1.4. SOIL CHARACTERISTICS

Soil is a porous medium with three phases: the solid phase, the liquid phase and the gas phase. The solid phase consists of mineral particles, and the gas and liquid phases consist of air and water that occupy the voids between the solid particles. The voids communicate with each other, creating a network of pores of varying sizes. This porosity determines many of the physical characteristics and mechanical and hydraulic properties of the soil (Vincent ROBITAILLE & Denis TREMBLAY, 1997.

1.4.1. Physical properties of soils

1.4.1.1. Definition of the physical properties of soils

Table 1.1 shows the physical characteristics of soils by their definitions and the equations to obtain them.

Tableau 1. 1. Physical characteristics of soi

Caractéristique	Définition	Équation
Masse volumique du sol	$\frac{\text{Masse totale}}{\text{Volume total}}$	$\rho = \frac{M}{V}$
Poids volumique du sol	$\frac{\text{Poids total}}{\text{Volume total}}$	$\gamma = \frac{W}{V}$
Masse volumique de l'eau	$\frac{\text{Masse de l'eau}}{\text{Volume de l'eau}}$	$\rho_w = \frac{M_w}{V_w}$
Poids volumique de l'eau	$\frac{\text{Poids de l'eau}}{\text{Volume de l'eau}}$	$\gamma_w = \frac{W_w}{V_w}$
Masse volumique sèche	$\frac{\text{Masse des solides}}{\text{Volume total}}$	$\rho_d = \frac{M_s}{V}$
Poids volumique sec	$\frac{\text{Poids des solides}}{\text{Volume total}}$	$\gamma_d = \frac{W_s}{V}$
Masse volumique des solides	$\frac{\text{Masse des solides}}{\text{Volume des solides}}$	$\rho_s = \frac{M_s}{V_s}$
Poids volumique des solides	$\frac{\text{Poids des solides}}{\text{Volume des solides}}$	$\gamma_s = \frac{W_s}{V_s}$
Masse volumique déjaugée	Masse volumique du sol − Masse volumique de l'eau	$\rho' = \rho - \rho_w$
Poids volumique déjaugé	Poids volumique du sol − Poids volumique de l'eau	$\gamma' = \gamma - \gamma_w$
Densité relative des grains solides	$\frac{\text{Masse volumique des solides}}{\text{Masse volumique de l'eau}}$	G_s ou $D_r = \frac{\rho_s}{\rho_w}$
Porosité	$\frac{\text{Volume des vides}}{\text{Volume total}}$	$n\,(\%) = \frac{V_v}{V} \times 100$
Indice des vides	$\frac{\text{Volume des vides}}{\text{Volume des solides}}$	$e = \frac{V_v}{V_s}$
Teneur en eau	$\frac{\text{Masse de l'eau}}{\text{Masse des solides}}$	$w\,(\%) = \frac{M_w}{M_s} \times 100$
Degré de saturation	$\frac{\text{Volume de l'eau}}{\text{Volume des vides}}$	$S_r\,(\%) = \frac{V_w}{V_v} \times 100$

1.4.2. Geotechnical properties of soils

It is usual to characterise soils by means of relatively simple tests. These tests are called identification tests. These include particle size analysis, determination of Atterberg limits, blue value, sand equivalent, and organic matter content. (Cf. Gérard Philipponat & Bertrand Hubert, 2007).

1.4.2.1. Grain size

The purpose of grain size analysis is to determine the proportions of different grain sizes in the soil. It is carried out by :

- Sieving (standard NF P 94-056) for grains with a diameter greater than 80 µm;
- Sedimentometry (standard NF P 94-057) for the finest grains.

The results are expressed as a curve called a sieve curve, which gives the cumulative percentage of items smaller than each diameter. Figure 1.2 shows some typical sieve size curves. $D_{60}, D_{30}, et\ D_{10}$ Being respectively the diameters corresponding to 60%, 30% and 10% of elements of lower dimension. Two parameters are used to characterize the shape of the particle size curve of a material:

The uniformity coefficient C_u such that

$$C_u = \frac{D_{60}}{D_{10}} \qquad \text{EQ 3}$$

The curvature factor C_c such that

$$C_c = \frac{(D_{30})^2}{D_{30} * D_{60}} \qquad \text{EQ 4}$$

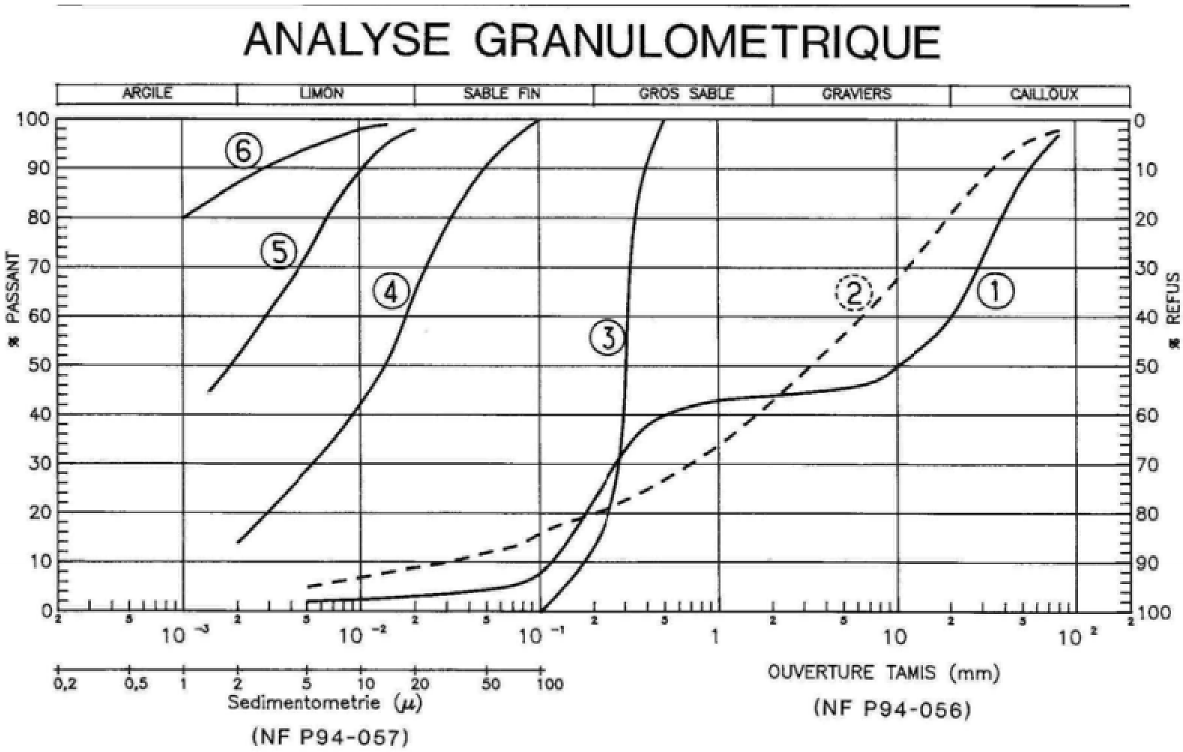


Figure 1. 2. Particle size distribution of different soil types

1.4.2.2. The limits of Atterberg

The Atterberg limits are determined only for the fine elements of a soil (fraction passing through the 0.4 mm sieve), as these are the only elements on which water acts by modifying the consistency of the soil. The test therefore consists of varying the water content of this soil fraction and observing its consistency. Given their structure, clays have the property of absorbing very large quantities of water or, on the contrary, of drying out, depending on the humidity conditions to which they are subjected. Whatever the nature of the clay, when mixed with increasing amounts of water, it eventually turns into mud. Clay has a liquid behaviour. On the other hand, if the clay is sufficiently dried out, the grains are very tightly packed and the bonds become intense. The clay behaves as a solid. Between these two extreme states, the clay is malleable: it has a plastic behaviour. The Atterberg limits are intended to define the moisture states corresponding to the limits between these three states, the moisture state of the soil being expressed by its water content. (See Figure 1.3)

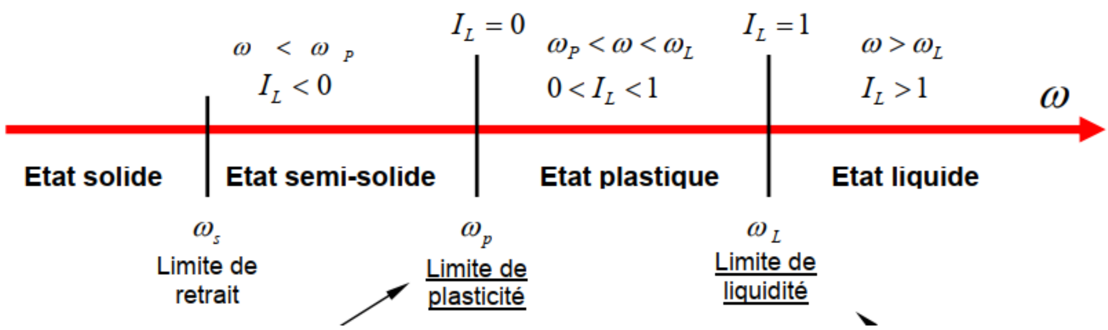


Figure 1. 3. Atterberg limits, natural water content and plasticity index

The liquidity limit w_L, is the transition between the liquid and plastic state.

The plasticity limit w_P, is the transition from the plastic to the solid state.

These characteristics are complemented by

The plasticity index I_P, which is expressed in % and is given by the following formula:

$$I_P = w_L - w_P \quad \text{EQ 5}$$

The liquidity index I_L which allows to quickly know if a soil is in a liquid, plastic, semi-solid or solid state. It is expressed by the formula:

$$I_L = (w - w_P)/I_p \quad \text{EQ 6}$$

Where w is the natural water content of the soil.

Atterberg limits are measured using the cup and roller method (standard NF P 94-051).

1.4.2.3. The blue value (spot method)

This test (standard NF P 94-068) is an indirect measurement of the specific surface of solid grains by adsorption of a methylene blue solution until saturation. The result, VBS, is expressed in grams of blue per 100 g of soil. The orders of magnitude are as follow:

$VBS \leq 0{,}2$: sandy soils (water-insensitive soil)
$0{,}2 < VBS \leq 2{,}5$: silty soils (soils that are not very plastic and sensitive to water)
$2{,}5 < VBS \leq 6$: Clayey-silt soils (medium plasticity soil)
$6 < VBS \leq 8$: clay soils
$VBS > 8$: Very clayey soil

1.4.2.4. The equivalent of sand

The sand equivalent (standard NF P 18-598) is only of interest for characterizing sandy soils containing very few fine particles. It is therefore mainly used for road aggregates and sand for concrete. The sand equivalent designated by ESP or ESV, depending on the measurement method (piston or visual measurement), varies practically between 10 and 100.

A sand equivalent of 100 corresponds to a soil that contains no clay or silt.

The value of the sand equivalent drops very quickly as soon as there is a small percentage of silt and clay in the powdered soil.

As an example, a minimum ES value is imposed for sands used in the manufacture of concrete; this minimum value is 60 to 75 depending on the sand used and the type of concrete.

1.4.2.5. Organic matter content

The presence of significant amounts of organic matter considerably modifies the behavior of soils and calls into question their volumetric stability over time. Organic soils include in particular mud, peat, recent alluvium and topsoil. The weight percentage of organic matter (OM) is measured by chemical analysis (standard NF P 94-055). A soil can be considered as organic when OM > 3%.

The Von Post test (standard NF P 94-058) is used to assess the state of decomposition of organic matter. It applies to soils containing more than 10% OM.

1.4.3. Mechanical properties of soil

They are best used to describe the behavior of soil as a load-bearing material. In particular, these include the optimum moisture content and maximum dry density, CBR, shear strength, and compressibility of soils.

1.4.3.1. Optimal moisture content and maximum dry density

When a material is to be used as a subgrade or foundation layer, it is necessary to know its maximum dry density. In order to answer this question, the Proctor test is used to determine the optimum moisture content (W_{opt}) of a soil that will result in a maximum dry density (γ_{max}) for a given compaction energy. The expected results of this test are the optimum moisture content (W_{opt}, expressed as a percentage) and the maximum dry density (γ_{max}, expressed as KN/m^3). According to NAVFAC, (1982) the results of Proctor tests for different soil types are listed in Table 1.2.

Tableau 1. 2. Proctor test results for different soil types

Type de sol	Symbole	Proctor normal*		Proctor modifié	
		ρ_{dmax} (g/cm³)	w_{opt} (%)	ρ_{dmax} (g/cm³)**	w_{opt} (%)***
Gravier bien mou mélange gravier-sable, peu ou pas de grains fins	GW	2,00 à 2,16	8 à 11	2,00 à 2,24	5 à 8
Gravier mal gradué ou mélange gravier-sable, peu ou pas de grains fins	GP	1,84 à 2,00	11 à 14	1,76 à 2,24	7 à 10
Gravier-silt, gravier-sable-silt	GM	1,92 à 2,16	8 à 12	1,84 à 2,32	5 à 8
Gravier argileux, mélange gravier-sable-argile	GC	1,84 à 2,08	9 à 14	2,08 à 2,32	6 à 10
Sable bien gradué ou mélange sable-gravier, peu ou pas de grains fins	SW	1,76 à 2,08	9 à 16	1,76 à 2,08	6 à 12
Sable mal gradué ou sable graveleux, peu ou pas de grains fins	SP	1,60 à 1,92	12 à 22	1,68 à 2,16	8 à 17
Sable silteux, mélange sable-silt	SM	1,76 à 2,00	11 à 16	1,60 à 2,16	7 à 12
Sable argileux, mélange sable-argile	SC	1,68 à 2,00	11 à 19	1,60 à 2,16	7 à 14
Silt inorganique et sable très fin, sable fin silteux ou argileux, ou silt argileux de faible ou moyenne plasticité	ML	1,52 à 1,92	12 à 24	1,44 à 2,08	8 à 18
Argile inorganique de plasticité faible ou moyenne, argile graveleuse, sableuse, silteuse	CL	1,52 à 1,92	12 à 24	1,44 à 2,08	8 à 18
Silt organique et mélange silt-argile organique de faible plasticité	OL	1,28 à 1,60	21 à 33	1,44 à 1,68	15 à 25
Silt inorganique, sol sableux très fin ou silteux, micacé ou diatomacé, silt élastique	MH	1,12 à 1,52	24 à 40	1,28 à 1,68	18 à 31
Argile inorganique de haute plasticité, argile silteuse	CH	1,20 à 1,68	19 à 36	1,44 à 1,84	14 à 28
Argile organique de haute plasticité, silt organique	OH	1,04 à 1,60	21 à 45	1,28 à 1,76	15 à 35

1.4.3.2. The CBR Index

In view of the requirement for low deformation in road works and much more so in the execution of embankments and subgrades, the suitability of this material should be ensured. To achieve this, the soil compacted in a test piece is punched at a constant speed of 1.27 mm/minute with a piston with a cross-section of 19.3 cm². The soil bearing capacity of a soil is determined with the C.B.R. test. (Californian Bearing Ration) test. The higher the C.B.R., the better the bearing capacity of the soil. As the material under test is to be used in an environment where it will be exposed to the weather and in particular to rainfall, it must be put under unfavourable conditions. This justifies the immersion of the test specimen for four days in water before it is punched. Apart from the fill layers and the subgrade, whose materials must have a bearing capacity that meets the requirements of the project owner, the pavement platform must also have good bearing capacity. To this end, it is recommended to check the bearing capacity of the last 30 centimeters of the roadbed.

CEBTP, (1984) identifies five soil classes (see Table 1.3) corresponding to the soil types found in tropical countries.

Tableau 1. 3. Soil classes in road geotechnics (CEBTP, 19

GROUND CLASSES	CBR INDEX	SOIL QUALITY
S1	CBR < 5	Very bad
S2	5 < CBR < 10	Bad
S3	10 < CBR < 15	Moderately good
S4	14 < CBR < 30	Good
S5	CBR > 30	Very good

1.4.3.3. Soil compressibility

The compressibility of a soil is the property that it has of reacting to an increase in effective stress by a tightening of its solid particles and a reduction in its void index, which corresponds to an increase in its density (according to LA ROCHELLE, 1983). This is only possible if the water and air occupying the soil voids are expelled. Thus, soils with a lower void index are a priori less compressible than those with a higher index. Thus, the notion of compressibility is linked to the notion of settlement, so we speak of immediate settlement in coarse-grained soils and consolidation settlement in fine-grained soils.

1.4.3.4. Shear strength

This is sliding between solid particles of a soil at the moment of its failure. The resistance to sliding (τ_{rupt}) is caused by friction, entanglement and cohesive forces between the particles. Its parameters are the internal friction angle (ϕ) and the cohesion (c). The greater the angle of friction and cohesion, the higher the shear strength should be. The coulomb equation allows us to express the shear strength in terms of these two parameters:

$$\tau_{rupt} = c + \sigma_{nrupt} * tan\phi \qquad \text{EQ 7}$$

Where τ_{rupt} is the normal soil stress at failure (expressed in KN).

C, expressed in Kpa.

Φ, expressed in degrees.

For powdery soils, cohesion is zero.

1.4.4. Hydraulic properties of soils

The most important hydraulic property of a soil is its permeability. This is its capacity to let water through. The coefficient of permeability (k) depends on its grain size, nature, structure, void index and temperature. The finer the soil, the smaller the pores, the greater the friction and pressure drop and the smaller the permeability coefficient. Table 1.4 gives the order of magnitude of the permeability coefficient of soils.

Tableau 1. 4. Permeability coefficient of different soil type

Nature	Ordre de grandeur de k en m/s	Degré de perméabilité
Graviers moyens à gros	10^{-3} à 10^{-1}	très élevé
Petits graviers, sable	10^{-3} à 10^{-5}	assez élevé
Sable très fin, sable limoneux, loess	10^{-5} à 10^{-7}	faible
Limon compact, argile silteuse	10^{-7} à 10^{-9}	très faible
Argile franche	10^{-9} à 10^{-12}	pratiquement imperméable

1.4.5. Chemical properties of soils

Among the chemical properties of the soil we have the absorbent complex, the acidity and the redox potential. The pH characterizes the degree of acidity of a soil, i.e. the quantity of H+ ions present in the soil solution. The more H+ ions, the more acidic the soil and the lower the pH. The variability of the pH is due to the nature of the rocks (sandy and silty soils are more acidic than calcareous soils).

1.5. SOIL TYPOLOGY

HOUGH, B.K. (1957) identifies the different types of soils according to the size of their particles (their texture), it is a fairly rapid method which provides basic information on the hydraulic and mechanical properties of soils. According to their behavior through the notion of soil shear strength. The shear strength is produced by friction, entanglement and cohesion of the particles and depends, among other things, on the size, shape, specific surface and surface characteristics of the particles.

1.5.1. According to their texture

In soil mechanics (Muni Budhu, 2015), the simplest division is to group soils into two broads classes: coarse-grained and fine-grained soils.

1.5.1.1. Coarse-grained soils

These are soils whose particles are visible to the naked eye. The value of their equivalent diameter is normally greater than 0.08 mm, since below this limit the human eye is practically unable to discern shapes.

Pebbles and boulders, or riprap, have an equivalent diameter greater than 80mm. They are characterized by a very high permeability. These rock fragments are very difficult to handle because of their size and weight, and are used mainly for large engineering works, such as earth dams or harbor developments, for which heavy mechanical equipment is available.

Gravel and sand consist of rock particles with an equivalent diameter ranging from 0.08mm to 80mm. In general, they have good permeability. They are soils that compact fairly easily and remain stable once compacted; they can then support heavy loads without settling.

Because of their smaller size than blocks and their excellent characteristics, gravel and sand are used as foundation materials in a large number of civil engineering structures, such as roads, viaducts, railways, runways and buildings. They are also used as drainage and filtration material.

1.5.1.2. Fine-grained soils

They include all soils with particles that are invisible to the naked eye. The equivalent diameter of these particles can vary from about 1nm ($\mathbf{10^{-6}}\boldsymbol{mm}$) to 0.08mm.

Silt is made up of fine rock particles with an equivalent diameter of 0.002 mm to 0.08 mm, the shape of which can be seen with a magnifying glass or optical microscope. Silt cannot support as high a load as gravel or sand. Its compressibility is greater than that of gravel or sand, which leads to increased settlement. Its permeability is very low.

Clay is made up of crystalline particles that originate from the chemical decomposition of rock constituents. Their equivalent diameter varies from approximately 1nm to 0.002mm.

Because clay is virtually impermeable, it is often used as a sealing material in the core of earth dams or embankments. However, its compressibility is high and, in general, the loads it can support are much lower than those supported by gravel and sand. Clay particles, unlike those of other soil types, are attracted to each other and cluster together. This attraction, which is called cohesion, is the source of consistency. Under these favorable moisture conditions, the consistency is such that the clay becomes plastic and cannot be shaped.

1.5.2. According to their behaviour

1.5.2.1. Uncohesive soils

Uncohesive soils include gravel, sand and silt. They are made up of large particles, and their shear strength is provided by friction and the interlocking of the particles. Friction results from the surface roughness of the grains, which come into contact with each other. The entanglement is mainly caused by the more or less angular edges of certain particles which, by fitting into the interstices between the other particles, create a resistance to movement.

1.5.2.2. Cohesive soils

Cohesive soils are made up of sheet-like clay particles, and their shear strength is derived from the friction and entanglement of the particles, as well as from the cohesion between the particles. Cohesion, also known as cohesive forces, refers to the set of attractive forces that bind clay particles together, giving them shear resistance along a plane of failure, even when no load P is applied. This cohesion is related to the presence of electrical charges on the surface of the clay particles that generate attractive forces between the particles through the impurities contained in the water that often saturates cohesive soils. Some of these impurities are electrically charged atoms or groups of atoms; they are called ions. As coherent soils are made up of particles that adhere to each other, they can be shaped when the water content is adequate. This is why they are called plastic soils. Soils containing only a certain amount of clay can also show cohesion: a soil is considered cohesive when it contains more than 50% clay particles. In contrast, powdery soils with no clay at all are not cohesive.

Consistency, which can be defined as a state of firmness, is linked to the cohesive forces between particles and therefore only concerns cohesive soils. In particular, the consistency of a fine soil varies greatly according to its water content. More precisely, when operating with decreasing water content, the following four states/behaviors are encountered:

- Liquid state : the soil has very little cohesion. It has the appearance of a fluid. It tends to spread out if placed on a horizontal surface.

- Plastic state: the soil has a higher cohesion. When placed on a horizontal surface, it does not tend to spread out but does not offer any resistance to the action of even very light loads.
- Solid state with shrinkage: the deformability of the body is much lower. When subjected to desiccation, it loses some of its pore water while contracting by an appreciable amount.
- Solid state without shrinkage: the stiffness of the body increases further and its volume does not change when its water content decreases. The transition from one state to the other is obviously gradual.

1.6. SOIL CLASSIFICATION

Soil classification systems arose from the need for civil engineers to have sufficiently reliable information on soil behavior to make quick and effective decisions. Many classification systems have been developed to meet the needs of engineers, including the triangular classification, the unified classification (USCS) and the AASHTO classification.

1.6.1. The triangular classification

Soil deposits can be assigned a designation based on the relative proportions of the various soil types (clay, silt, sand, and gravel) obtained in the sieve analysis. The triangular classification system is based on the same principle. They take the form of triangles with scales on the sides representing the proportions of sand, silt and clay measured on a soil sample (see Figure 1.3).

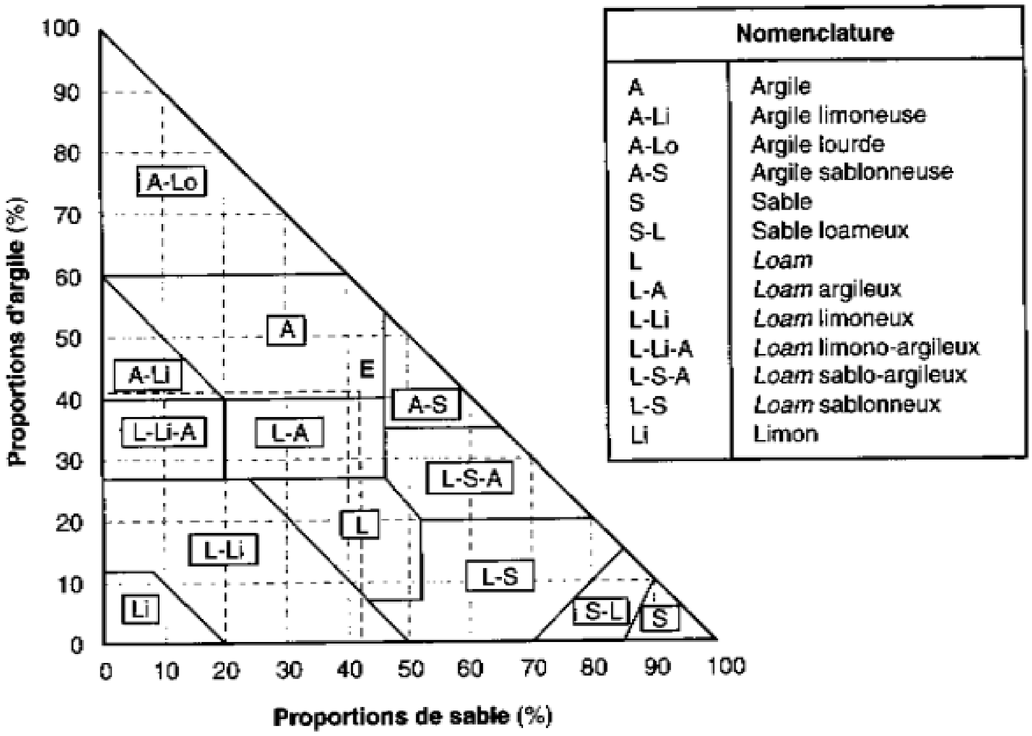


Figure 1. 4. Example of a triangular classification: the textural classes of the Canadian soil classification system. (Vincent Robitaille & Denis Tremblay, 2001)

1.6.2. The Unified Classification System (USCS)

Designed in 1948 by Arthur Casagrande, it is the best known and most widely used classification system in North America. The USCS system and its classification procedure are the subject of the American standard ASTM D 2487, the Quebec Ministry of Transport standard 1101 and the draft standard NQ 2501-007 of the Quebec Bureau of Standards. The system is based on the granulometric classification of soils, especially for coarse-grained soils, and on the determination of consistency limits for fine-grained soils. The unified classification system consists of 15 soil groups, each identified by a two-letter symbol, conventionally referred to as a prefix and a suffix (as shown in Table 1.5).

Tableau 1. 5. Prefixes and suffixes of group symbols in the USCS system (Vincent Robitaille & Denis Tremblay, 2001)

Préfixes	Signification	Suffixes	Signification
G S	Gravier Sable	W P M C	Bien gradué Mal gradué Silteux Argileux
M C O	Silt Argile Sol fin organique	L H	Faible plasticité $W_L < 50$ % Forte plasticité $W_L > 50$ %
Pt	Sol fortement organique : terre noire, tourbe	(pas de suffixes)	

The USCS classification procedure is shown graphically in figure 1.5.

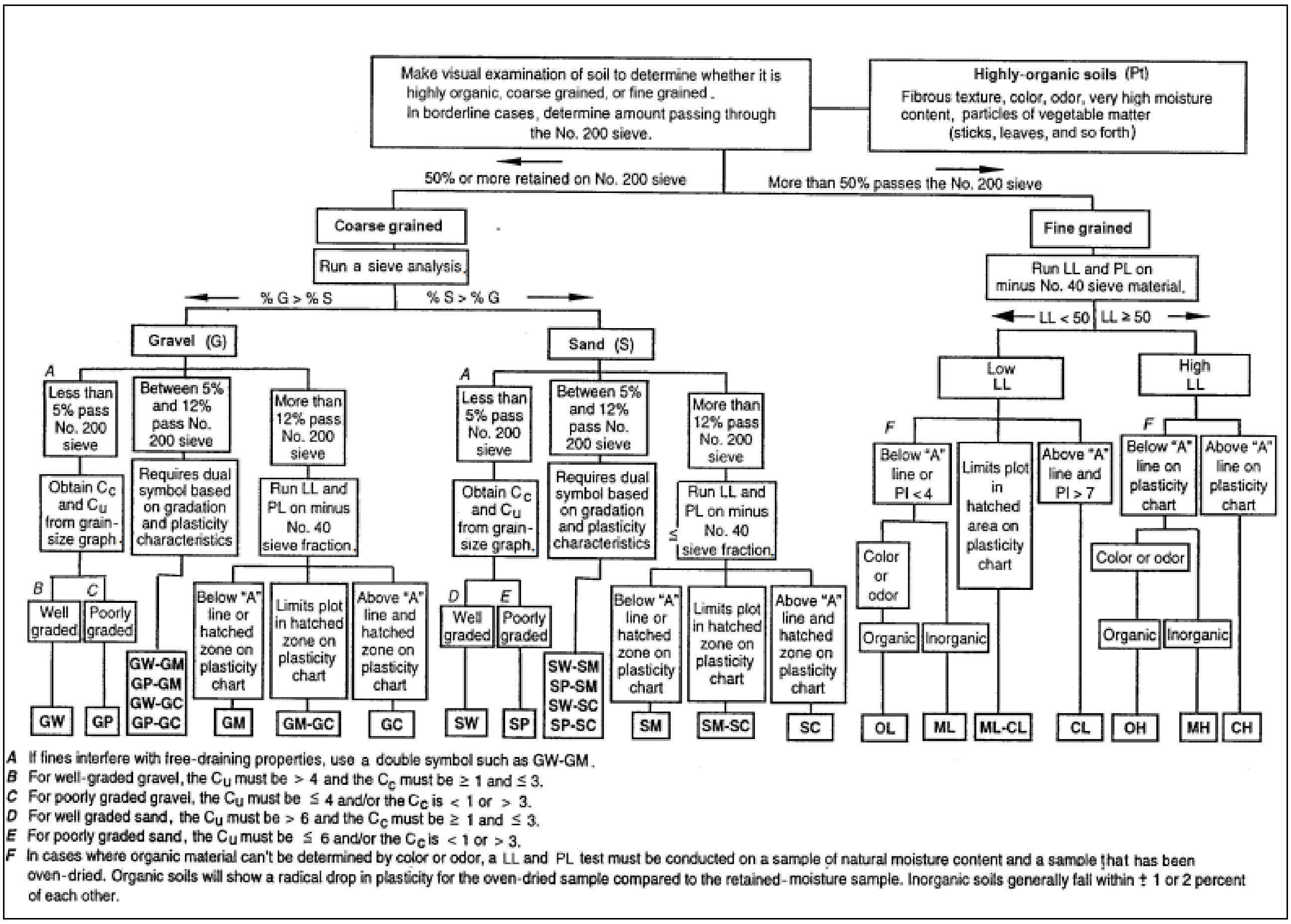


Figure 1. 5. Unified classification - identification procedure for coarse-grained soils (Vincent Robitaille & Denis Tremblay, 2001)

1.6.3. The AASHTO classification (HRB)

Like the unified system, the AASHTO (American Association for state highway and transportation officials) classification system, better known in our context as the HRB classification, meets the needs of American civil engineering, particularly in the field of road construction. Developed in 1929 by Terzaghi and Hogentogler from the study of the performance of various soils in pavement infrastructure and revised several times thereafter, this system is the subject of the ASTM D 3282 standard. The AASTHO system is based on the results of sieve analysis and the determination of the liquidity and plasticity limits of fine soils.

Table 1.6 shows the 8 main groups numbered from A-1 to A-8 with group A-3 occupying rather the second position at the expense of group A-2. Also, only groups A-3, A-4 and A-6 are not subdivided.

Tableau 1. 6. Group numbers and their names (according to the AASHTO classification).

Type of soils	Numbers	Name
Coarse-grained soils	A-1	Rocks fragments, gravel and sand
	A-3	Fine sand
	A-2	Silty or clayey gravels and sands
Fine-grained soils	A-4	Silty soils
	A-5	
	A-6	Clay soils
	A-7	
	A-8	Black earth

A soil can easily be classified using the data from the particle size analysis and the Atterberg limits, using the model in Figure 1.6. The soils are divided into two main branches: on the left, the groups of rather powdery soils; on the right, the groups of silty and clayey soils.

Group A-8 is completely separated from the rest of the groups, as it is not identified by the same tests.

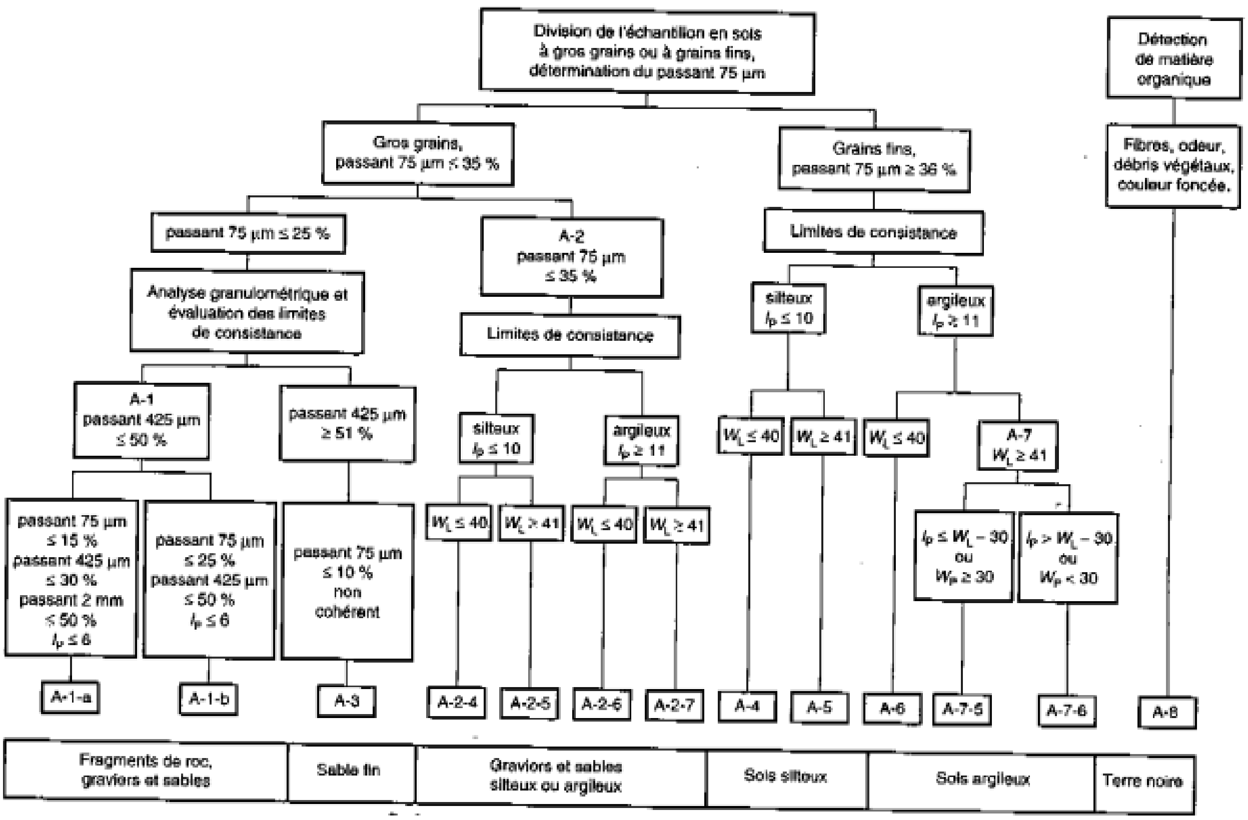


Figure 1. 6. AASHTO classification - identification procedure (Vincent Robitaille & Denis Tremblay, 2001).

1.7. USE OF SOILS

Soils are part of our daily environment and therefore have different functions that can be classified into three main categories: support function, production function and environmental function according to (www.alterre-bourgogne.fr, accessed on 28/02/2021).

1.7.1. The support function

Soil is the support of all terrestrial, plant and animal life. First of all, plants anchor themselves in very poor soils, thanks to their roots. In addition to anchoring themselves, plants draw the nutrients and water necessary for their growth from the soil. Some plants have developed specific adaptations to different types of soil. Thus, the diversity of soils is matched by a plant diversity that shapes natural ecosystems and landscapes. This function also concerns human activities, through the various structures built in the different sectors of civil engineering, transport, construction, hydraulics and public hygiene. Soils support our cities, villages and all our infrastructures and this is possible through their use in: the foundations of structures (superficial foundations, deep foundations), embankments and road foundations, earth retention structures and earth dams.

1.7.2. The production function of soils

This function consists of the production of food resources through agriculture, biomass for energy production (through energy crops and forestry) and materials for construction (wood, soil, aggregates, rocks).

Trees and plants grow on soils, which are the source of important economic sectors. While the indispensable role of soils in our food supply is well known, they are also the basis for important non-food production such as fibers, medicines, organic solvents, etc. Forests are also a very diversified source of production because wood is also used as a material (construction wood, timber, etc.) or as fuel.

Most food crops can be used for energy to produce fuel to run engines, such as ethanol, rapeseed or sunflower to make diester for diesel. Biomass is also a source of energy, either through direct combustion or indirectly through the production of methane via the methanation of crops such as miscanthus, straw, short rotation black locust and wood. The soil is also a source of thermal energy through geothermal energy, and the installation of networks containing water or other fluids makes it possible to recover and transport this thermal energy to buildings, and thus save on heating costs.

Earth is probably the oldest building material in human history. It has long been used raw, mixed with straw, and then fired in the form of mud bricks. Other types of material are taken from the ground: this is the case of certain aggregates intended for the manufacture of public works or civil engineering works, which are loose rocks extracted from alluvial deposits. Gravels, on the other hand, are taken from the weathered layer of the parent rock. Soils also provide materials such as ochres and pigments used for painting. They may also contain mineral resources such as gold, aluminum or iron.

1.7.3. The environmental function of soils

Soils are intimately linked to other environmental compartments such as water, air and the biosphere. It plays an important role in the water cycle, through its capacity to store, regulate and purify water. As a key component of the carbon cycle, soils can store or emit greenhouse gases and thus influence climate change. In soils, organic matter is degraded by numerous micro-organisms to produce mineral elements that can be assimilated by plants and other living beings. As such, soils are at the crossroads of the biogeochemical cycles that govern life on Earth. Finally, soils are a formidable reservoir of biodiversity. It is home to nearly a quarter of the species living on earth, all of which are essential to the functionality of the soil.

1.8. SOIL STABILIZATION TECHNIQUES

1.8.1. Mechanical stabilization

Mechanical stabilization can be achieved by densification or compaction, addition of granular material and compaction, mechanical remediation and lithostabilisation. It can be applied to embankments, subgrades and foundations. Mechanical stabilization is carried out by means of mechanical operations such as: mixing (correction of size distribution), wetting and compaction.

1.8.1.1. Densification or compaction

Compaction is an important step in stabilization. Compaction leads to an increase in strength or stiffness and a decrease in permeability and compressibility. Simple compaction reduces soil porosity by expelling trapped air. The optimum compaction characteristics of the soil are determined by the normal Proctor test. The measured characteristics, i.e. the optimum water content (w_{opm}) to achieve the highest dry density of the soil (ρ_{opm}) are used in the stabilization studies and also during construction.

Soil particle size, morphology, abrasiveness and clay content influence the behavior of the soil during compaction. Due to their small size (a few microns) clay particles increase the dry density of the soil by filling its porosity. The behavior of the soil depends on the clay content. Thus Faure A. (1978), Daskalova L.B. (1980) and many others define different behaviors (variation of w_{opm} and ρ_{opm}) for reconstituted soils depending on the sand and clay content. These authors show that soils can have a behavior (Figure 1.7) :

- Sandy, if it contains more than 90% sand. In this case, the density of the mixture is not very dependent on the water content and the density optimum is relatively low.
- Sand-clay, if it contains between 80 and 70 % sand. The density optimum is better marked.
- Clay-sand, if it contains less than 70% sand. In this case, the density of the mixture is strongly dependent on the water content and the optimum density is high.

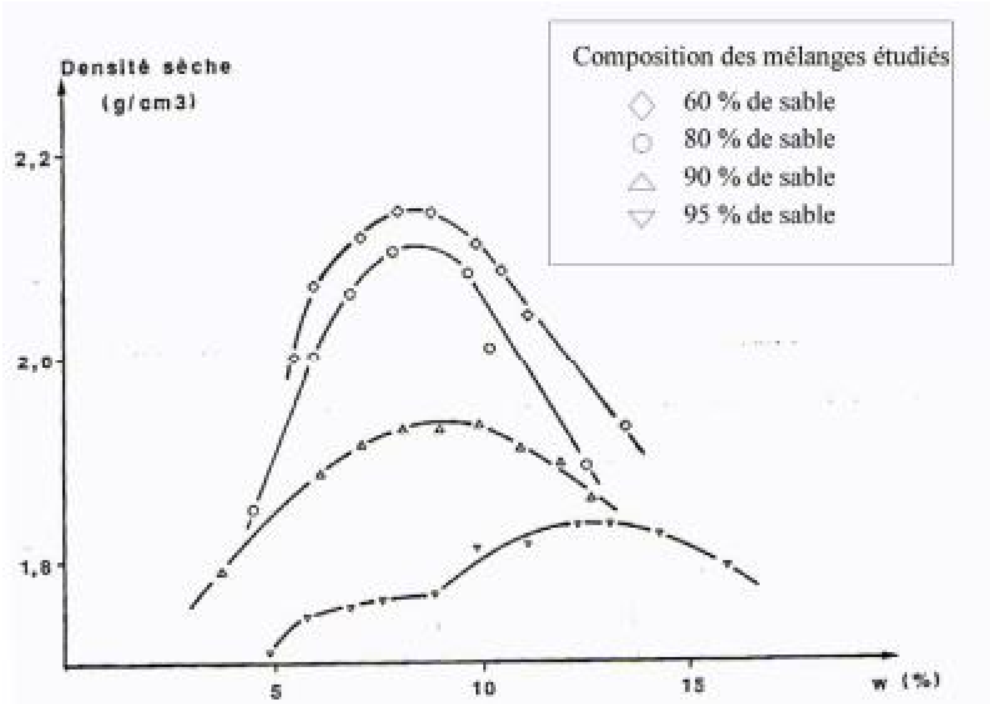


Figure 1. 7. Influence de la teneur en eau sur la densité de différents mélanges de sables et d'argiles selon le protocole du Proctor modifié.

1.8.1.2. Stabilization by adding aggregates

A common method of improving the engineering characteristics of the soil is to add certain aggregates that give the soil desirable attributes, such as increased strength or reduced plasticity. This method saves materials, improves the supporting capabilities of the subgrade and provides a working platform for the remaining structure.

1.8.1.3. Lithostabilization

Lithostabilization is a form of mechanical stabilization of poor-quality laterite by the addition of crushed material (often more than 10%). Its main objective is to obtain from the mixture a material with better geotechnical performance (mainly bearing capacity). The crushed materials often used are granite, basalt, sandstone and flint crushed materials.

1.8.1.4. Stabilization by mechanical sanitation

Traditionally, mechanical remediation is the accepted practice for dealing with soil contamination. It is a technique that involves physically removing contaminated soil and moving it to a designated hazardous waste treatment facility away from human population centers. Recently, however, chemical and biological remediation has proven to be a better solution, both economically and environmentally. It is often cheaper to solve the problem where it exists than to move it elsewhere and possibly have to treat it again in the future.

1.8.2. Stabilization by using different types of additives

Among the methods mentioned above, other little-used methods can be added, such as thermal stabilization, electrical stabilization, rice ash and rice husk stabilization. But these methods will not be discussed in this chapter.

1.8.2.1. Criteria for choosing the type of additive

The use of additives leads to a change in the basic properties of the soil (the addition of lime and cement reduces plasticity, cementitious agents such as asphalt help to develop bonds between soil particles, thus increasing cohesive strength, and decreases water absorption. Chemical stabilization with lime can be applied on embankments, subgrades and foundations; with cement on foundations (pavements); with bitumen on base courses and foundations (pavements). The choice of additive type and dosage depends on several factors, such as:

- The nature and characteristics of the soil;
- The objective of stabilization (improvement of short and/or long-term properties);
- The final requirements of the stabilized mix (strength, stiffness);
- Environmental costs and factors.

Tableau 1. 7. Guide pour le choix d'un stabilisant, (Overseas road Notes 31, 4th Edition, 1993)

Guide to the type of stabilisation likely to be effective

Type of stabilisation	Soil properties: *More than 25% passing the 0.075 mm sieve*			*Less than 25% passing the 0.075 mm sieve*		
	PI≤10	10<PI≤20	PI>20	PI≤6 PP≤60	PI≤10	PI > 10
Cement	Yes	Yes	*	Yes	Yes	Yes
Lime	*	Yes	Yes	No	*	Yes
Lime-Pozzolan	Yes	*	No	Yes	Yes	*

Notes. 1. * Indicates that the agent will have marginal effectiveness
2. PP = Plasticity Product (see Chapter 6).

1.8.2.2. Lime stabilization

Lime is often used for soil stabilization (especially for clay soils). The required lime content usually varies between 3 and 5% (by weight of soil). The main advantage of lime is the reduction of plasticity, and thus the reduction of the effect of water. The volume change and swelling potential are also reduced. This leads to an improvement in the constructability and performance of the pavement. The cementing action leads to an increase in strength. Limestone is broken down at high temperatures to form lime. As a result, three forms of lime are produced: quicklime (calcium oxide-CaO), hydrated lime (calcium hydroxide-$Ca[OH]_2$), and hydrated lime slurry, all of which can be used for soil treatment. Quicklime is made by chemically converting calcium carbonate (limestone-) into calcium oxide.$CaCO_3$) into calcium oxide. In addition, hydrated lime is created when quicklime chemically reacts with water. When hydrated lime is mixed with clay particles, it permanently forms strong cementitious bonds. Hydrated limes are commonly used for soil stabilization in temporary road pavements and for road sub-base layers, particularly where the subsoil has a high percentage of cohesive fine aggregate and/or clay (from M. R. HALL et al., 2012). Soils classified according to the USCS as CH, CL, MH, ML, OH, OL, SC, SM, GC, GM, SW-SC, SP-SC, SM-SC, GW-GC, GP-GC, ML-CL, and GM-GC should be considered as potentially capable of being stabilized with lime. Lime should be considered for all soils with a PI of greater than 10 and more than 25% pass through No. 200 sieve [FM 5-472/NAVFAC MO 330/AFJMAN 32-1221].

1.8.2.3. Cement stabilization

a. In-situ cement stabilization

In-situ cement stabilization is usually carried out by means of a recycling train. A relatively low dose of cement (1.5% to 3.5%) is used for marginal soils, granular material in unbound subgrades, crushed material in cement-bound subgrades or a combination of these (from Sherwood P, 1993). The recycling train usually consists of a vehicle equipped with volumetric feeders for spreading cement, a recycler coupled to a tanker for adding water, a vibrating smooth drum roller, a tyre roller and a grader for shaping and levelling. On the one hand, in situ cement stabilization is the most cost-effective and environmentally friendly method. On the other hand, the quality of the constituent materials can be quite poor, which affects the mechanical properties of the final mix, and the homogeneity of the production can hardly be controlled. For these reasons, in-situ cement stabilization is applied as a precautionary measure to deep layers (sub-base, base or base courses), where the effects of tyre pressure are less critical, or to the base course for low volume roads.

b. In-situ cement stabilization

Cement-treated mixtures (CTM) are usually produced in a factory and consist of selected aggregates, cement, which varies from 2 to 5 % by weight of aggregates, and a defined percentage of water, which plays an important role in the compaction and hydration of the cement. Factory production is carried out in mixing plants (concrete mixers) that do not require any equipment for heating and selecting aggregates, nor any filtration or exhaust system. These are often mobile systems that can be easily installed in or near the construction site. Cement can be applied to stabilize any type of soil, except soils containing a percentage of organic matter greater than 2% or which have a pH lower than 5.3 (ACI 230.1R-90, 1990). The use of cement in granular soils has proven to be economical and effective because smaller quantities of cement are required. In addition, soils with a PI (plasticity index) greater than 30 are difficult to mix with cement. To avoid this problem, lime can be added before mixing the cement; this initial step will make the soil more workable.

1.8.2.4. Bituminous soil treatment

Bituminous treatment of soils is usually carried out by a cold process of mixing asphalt emulsion with soil. Clean sand and natural gravel are usually used (IP <= 12). The bituminous treatment provides impermeability (the soil particles are covered with asphalt, and water does not come into contact with the soil particles, making the soil less sensitive to water and reducing water absorption) and better cohesion of the mixture (cementing mechanism). The bitumen content depends on the function required (higher if both waterproofing and cementing are required).

Bitumen increases the cohesion and load-bearing capacity of the soil and makes it resistant to water action. Most bituminous soil stabilization has been carried out with asphalt cement, mastic asphalt and asphalt emulsions. Soils that can be effectively stabilized with bituminous materials generally contain less than 30% of the material passing the No. 200 sieve and have a PI below 10. Soils classified by the USCS as SW, SP, SW-SM, SP-SM, SW-SC, SP-SC, SM, SC, SM-SC, GW, GP, SW-GM, SP-GM, SW-GC, GP-GC, GM, GC, and GM-GC can be effectively stabilized with bituminous materials, provided the aforementioned particle size and plasticity requirements are met (AYININUOLA Gbenga Matthew & al., 2018). There are two main types of bitumen emulsion: Cationic bitumen emulsion and anionic bitumen emulsion.

1.8.2.5. Stabilization with fly ash

Fly ash is one of four coal combustion products that are produced as a by-product of coal combustion, two main groups are produced, Class C and Class F fly ash. The combustion of lignite and sub-bituminous coal produces Class C fly ash. However, the burning of anthracite, another bituminous coal, produces Class F fly ash. Class F fly ash is not used as often because it requires an activator, either lime or cement, to form stabilized pozzolanic mixtures (SPMs) as it is not a self-bonding material. Zulkifley & al (2014) evaluated the effect of off-spec fly ash on the engineering properties of tropical soils in Hawaii. They observed that fly ash reduced the liquid limit and plasticity index, and improved the California Bearing Ratio (CBR) and unconfined compressive strength. Rupnow et al (2015) used Class C fly ash with lime to develop guidelines for estimating the structural layer coefficient for the base layer of a flexible pavement. The thickness of the required base layer decreased with the addition of the two additives. Fly ash, when mixed with lime, can be used effectively to stabilize most coarse and medium grained soils; however, the PI should not be greater than 25. Soils classified by the USCS as SW, SP, SP-SC, SW-SC, SW-SM, GW, GP, GP-GC, GW-GC, GP-GM, GW-GM, GC-GM, and SC-SM can be stabilized with fly ash.

1.8.2.6. Stabilization through the use of geosynthetics

The use of geosynthetic properties for road infrastructure is a state-of-the-art technique because geosynthetics significantly improve the mechanical behavior of soft soils. Due to their ability to deform and their high mechanical strength, it is possible to combine the behavior of certain soils with that of fabrics to obtain a soil with specific behavior. The geosynthetic reinforcement used in pavement layers are mainly geogrids, geotextiles and polymer geocomposites (WATN, 2011). Reinforcement is installed in the pavement structure under, and sometimes in, the base layers, sub-base, subgrade or stabilized subgrade. Its role is to significantly increase the bearing capacity of the soft soil by distributing traffic loads over a wider area, resulting in reduced pressure on the soft soil and thus less deformation during construction and service life.

However, the design methods for such reinforced structures are far from perfect and major research efforts are still required, particularly on the puncture resistance of geotextiles.

1.8.2.7. Stabilization with fibers

The use of hair-sized polypropylene fibers in soil stabilization applications has been common in soil stabilization projects because of their low cost compared to other stabilizing agents. These materials have high resistance to chemical and biological degradation and do not leach into the soil. Sharma & al (2015) studied the improvement of swelling clay properties using hay fibers. They found that there was no considerable or reasonable change in Atterberg limits due to the introduction of hay fibers. The optimum moisture content, maximum dry density, shrinkage limit, unconfined compressive strength to soil decreased with increasing hay content up to 1.0%. The direct shear strength and tensile strength of the air-dried mix increased especially with the addition of hay. Mirzababaei & al. (2017) investigated the unconfined compressive strength (UCS) of clays reinforced with waste carpet fibers. They found that carpet waste fibers mixed with clay soils, prepared at the same dry unit weight, can significantly increase the unconfined compressive strength (UCS), decrease the strength loss after peak, and change the failure behavior from brittle to ductile. The results also indicated that the relative advantage of fibers in improving the unconfined compressive strength of clay soils depends largely on the initial dry unit weight and the water content of the soil.

1.8.2.8. Stabilization with chemical solution

Chemical soil stabilization involves changing the physical synthesis around and within the clay particles, where the soil needs less water to overcome the static imbalance. Calcium chloride, which is hygroscopic and deliquescent, is used as a water retention additive in bases and mechanically stabilized floor coatings. The vapor pressure decreases, the surface tension increases and the evaporation rate decreases. The freezing point of pure water is lowered, which prevents or reduces frost heave. By lowering the electrical double layer, the salt reduces the absorption of water and thus the loss of strength of fine-grained soils. Calcium chloride acts as a soil flocculant and facilitates compaction. Frequent application of calcium chloride may be necessary to compensate for the loss of chemical through leaching action. For the salt to be effective, the relative humidity of the atmosphere must be above 30%. Sodium chloride is the other chemical that can be used for this purpose with a stabilizing action similar to that of calcium chloride. Sodium silicate is another chemical used for this purpose in combination with other chemicals such as calcium chloride, polymers, chromelignin, alkylchlorosilanes, siliconites, amines and quaternary ammonium salts, sodium hexametaphosphate, phosphoric acid combined with a wetting agent.

1.9. CONCLUSION

At the end of this chapter, it was a question of presenting the state of the art of soils by highlighting their constituents, their characteristics, the factors and processes of soil formation, soil typology, soil classification and their use in everyday life, and finally concluding with the different soil stabilization techniques. It emerges from this that soils originate from the degradation of their parent rock and are formed by a slow process of alteration (physical or chemical) under the action of climate, relief, vegetation, etc.... followed by erosion, transport and sedimentation. Soil can therefore have different characteristics from one region to another. Soil will be used in several sectors of activity including agriculture, civil engineering, mining, etc. In road construction, the soil will have to serve as a support for the pavement layers and have a good bearing capacity to allow traffic during its lifetime. Soil treatment will therefore be applied to soils that do not have the required characteristics to be used as pavement layers, in order to recover materials with unsuitable characteristics that cannot be used in their natural state. Several soil treatment techniques will be developed in road geotechnics and are grouped into two categories by Habiba Afrin, (2017) namely mechanical stabilization and stabilization by adding additives.

2 CHAPTER 2 : THE AggreBind PRODUCT

INTRODUCTION

AggreBind soil stabilization is an innovative technique for soil stabilization by adding additives (according to Habiba Afrin, 2017). AggreBind uses innovative techniques to facilitate the design and rehabilitation of the current road system at lower costs and reduced construction time compared to conventional construction methods. It is a patented soil stabilizer and when used correctly creates a strong, waterproof, load-bearing sub-base layer. In this chapter, the product AggreBind will be described in detail, its properties will be analyzed, the areas of use of the product will be described, the advantages of its use will be explained and the procedure for in-situ soil stabilization will be presented.

2.1. AGGREBIND PRODUCT OVERVIEW

AggreBind soil stabilization is an innovative technique for soil stabilization by adding additives, (according to Habiba Afrin, 2017). AggreBind uses innovative techniques to facilitate the design and rehabilitation of the current road system at lower costs and reduced construction time compared to conventional construction methods. It is a patented soil stabilizer and when used correctly creates a strong, waterproof, load-bearing sub-base layer. In this chapter, the product AggreBind will be described in detail, its properties will be analyzed, the areas of use of the product will be described, the advantages of its use will be explained and the procedure for in-situ soil stabilization will be presented.

2.1.1. Product description

AggreBind is a proprietary formulation of uniquely cross-linked styrene acrylic polymers. It is produced and sold by AggreBind Inc. AggreBind polymer has been developed and modified for use in the construction industry. AggreBind manufactures the following soil stabilization products:

- AGB – WT AggreBind: which is a concentrated water-based polymer liquid of white color, used for soil stabilization by connecting the base to the pavement, rehabilitation of urban roads, rehabilitation of rural tracks and also for the manufacture of bricks, paving stones and for the use of different kinds of concrete.
- AGB - BLK AggreBind: which has the same characteristics as AGBWT but is rather black in color.

The AggreBind product is placed in sealed drums and containers for shipment (see Figure 2.1). All products are under our direct supervision until they are shipped. AggreBind is produced in batches of 20,000 to 40,000 liters. Each batch has a distinct number: batch number, production date, sample of the batch taken and kept at the factory.

Figure 2. 1. Imported AggreBind products

- Tariff code

3906.90.90 ou 3906-90-10

Check your local regulations for the best number/ranking.

1 liter of 'AGB weighs 1,0487 kg.

- Drums

1 drums = 205 litres

Weight of a drum = 215 Kg

Dimension of a drum = 88 cm high X 58cm of diameter

4 drums = 1 pallet

Pallet size = 1,2m x 1,2m

Pallet weight = 17,5 kg

- Tote

1 tote = 1000 litres

Tote size = 120cm X 100cm X 116cm ;

Total weight of the tote including pallet = 1065 Kg

- Containers

1 ft = 30,48 cm

A 20ft container = 40 fûts en 10 palettes = un total de 8 200 litres

= 10 réservoirs en 10 palettes = total de 10 000 litres

40 ft container = 80 fûts en 20 palettes = total de 16 400 litres

= 20 reservoirs en 20 palettes = total de 20 000 litres.

It is possible to add some drums in addition to the colored containers. Maximum cargo weight per container: 26,000 kgs. AggreBind is manufactured with a unique and exclusive "tracer". This tracer allows an independent laboratory to validate the correct application of AggreBind in the installation. Specifically, it allows the amount of AggreBind per cubic meter to be determined and compared to the AggreBind protocol issued for the job or project in question. This test can be performed at any time as the tracer does not deteriorate over time. With this special post installation analysis capability, AggreBind is able to offer a 5-year product replacement warranty.

2.1.2. Specifications of AggreBind soil stabilizer based on cross-linked styrene-acrylic polymer

According to www.aggrebind.com, (accessed 28/02/2021),

- Properly applied stabilizer will meet the requirements of the AASHTO standards for soil stabilization.
- The stabilizer, in its undiluted liquid state, will withstand at least five (5) freeze-thaw tests and will retain its chemical properties.
- Once cured, the stabilizer has a temperature tolerance range of -57ºC to + 163ºC (-70ºF to + 325ºF)
- The stabilizer has an unconfined compressive strength approaching that of low-grade concrete of 1750 psi (123.07 kN/cm²) in common sandy loam soil as well as in low percentage (<15%) clay-based soil.
- The stabilizer is effective in both high and low PH soils and is "environmentally friendly".
- The stabilizer increases the load capacity of the site's basements.

- The stabilized base material can be opened to traffic within 2 hours of installation and can support full wheel loads of aircraft, helicopters and heavy equipment depending on depth. (A minimum of 30 cm (12 inches) is recommended for heavy load support requirements).
- The stabilizer repels water during and after the curing process, and resists water run-off during construction in case of rain.
- The stabilizer can be used on all soils. If desired, aggregates and/or fines can be added to optimize the reinforcement capabilities and reduce the polymer concentration.
- Stabilizer in unopened drums has a shelf life of 24 months; shaking is required before use.
- The stabilizer can be installed with standard agricultural or road construction machinery (depending on the project).
- The stabilizer has good resistance to UV damage and can be blended to contain additional UV protection, if required, to increase its uncoated life. (Uncoated means no wear surface).
- The stabilizer can be mixed with fresh or salt water. Using salt water for dilution will reduce the strength by about 10% but should not exceed 4% salts (total combined salt content of sea water).
- The stabilizer has the unique ability to "glue itself back together", giving it a permanent bond without the risk of delamination or separation.
- The stabilizer has the properties and strength to retain the polymer impregnated stone chips (2-4 mm) in the surface prior to final lamination and thus provide acceptable slip and skid resistance (PSV). (PSV Polished Stone Value is a standard test for skid resistance on a road surface).
- The stabilizer has the ability to seal and bind non-regular aggregate materials and to bond/seal them with the soil. These materials include (but are not limited to) crushed glass, rubber crumbs, construction waste, non-organic municipal waste (after extraction of green waste, metals and other recyclable materials).
- The stabilizer must have penetration capabilities from the surface spray application; it must bind and seal the surface to contain dust and prevent surface water penetration.

- The stabilizer must have the viscosity, penetration, sealing and encapsulation capacity to contain low level radiation and airborne heavy metals and can seal the surface to reduce/eliminate surface water percolation into the subsoil.
- Stabilizers are capable of sealing, rendering inert and realigning clay particles (so that they become inert) and can be used in soils with a high clay content and be compatible with polymers to bind and seal a stabilized soil layer.
- Stabilizers have the property that, once cured, they are irreversible and therefore the integrity of the product is maintained indefinitely.
- In the event of rain during installation, the stabilizers are able to retain their properties and can be reworked to bond and seal the floor without significant loss of strength or waterproofing properties.
- The stabilizer has soil lubricating properties which, when used with a properly graded soil mix, will give Proctor compaction results of 95-97. (Proctor is a standard compression test in the construction industry).
- Stabilizers must meet or exceed all standards set out in this document

2.1.3. Extract from the analysis of the tests and properties of the AggreBind polymer

According to www.aggrebind.com, (accessed 28/02/2021), the water-based styrene-acrylic polymer has the following properties:

- ✓ Adhesion: excellent on various stones; marble; cement; slate; tested using the crosshatch tape test. The coating is scratched with a sharp knife or special tool; tape is applied and removed. An estimate of the amount of coating remaining is made. This is a standard test for paints, polymers and lacquers.
- ✓ Durability: This is a polymer that does not degrade easily. The coatings have been exposed to air and light for years without any sign of deterioration.
- ✓ UV resistance: No deterioration has been observed. In addition, when used in construction, the underlying layers are protected by the surface minerals, which prevents UV damage.
- ✓ Ecological: the polymer content has a molecular weight well above 1000 and is therefore considered non-bioavailable. It is therefore considered to have minimal impact on the environment.
- ✓ Surface abrasion: Good resistance as a film; this will be enhanced by the mineral content in the construction.

- ✓ Surface spills: 2 layers of polymer, 48 hours drying time. 24-hours spot test
  Gasoline: slightly blunted film; no effect on film integrity Light mineral oil: no effect 15W/50 Engine oil: no effect Hydrochloric acid: dull and slightly swollen film; reduced adhesion to tiles Phosphoric acid: film destroyed The only chemicals that would destroy a dry AGB film are strong acids and bases (pH above 10), petrol and motor oil had no effect on a dry AGB film (note: the tests were carried out without tracer and carbon black, we are confident that the addition of tracer and carbon black does not have a negative impact on the chemical resistance of AGB)
- ✓ Temperature resistance: The dry AGB film starts to burn at temperatures above 300°C. Compatibility: This is an anionic dispersion and will therefore be coagulated by cationic surfactants, acids and high concentrations of ions, particularly trivalent metal salts. Various other water-miscible chemicals can be added without causing undue problems, especially if they are pre-diluted.
- ✓ Cured film recovery and memory characteristics: This is a styrene-acrylate polymer and not an elastomer. The film is flexible and has some recovery.
- ✓ Traceability: The polymer remains fully traceable for long periods of time after installation, thanks to a unique laboratory process that allows the polymer to be extracted from the treated soil to establish the dosage rate used during the stabilization process. This process is of considerable value as it provides the specifying authority and design engineer with accurate assessment procedures regarding the polymer content in any specific area of the stabilized soil layer

2.2. Using the AggreBind stabilizer

Soil stabilization with AggreBind involves using in-situ materials, subsoils, sands and even waste materials to make roads, brick blocks and pavers. Firstly, we increase the bearing capacity, the CBR (California bearing ratio) of in-situ soils by a factor of 4 to 6 (400% to 600%). Secondly, when the stabilized soil is surface sealed (above), AGB prevents water infiltration into the treated layer, as well as water penetration and heavy frosts, which are notorious for creating potholes, rapid deterioration and road failures

2.2.1.1. Areas of applications

AggreBind green solutions save customers time, money, and hassle in many applications around the world:

- Control of dust, sand migration and slope erosion
- Instant construction of runways and airfield aprons
- Rehabilitation and improvement of necessary local road condition
- Construction of new roads
- Road markings
- Pavement surfacing
- Airport and military applications
- Manufacture of lightweight roof tiles with local materials
- Agricultural solutions
- Solutions for golf courses and amusement parks,
- Solutions for eco-tourism
- Manufacture of water-resistant blocks, bricks and paving stones, built with almost all local materials
- Recycling of road surfaces: asphalting, gravelling and pothole repair
- Solutions for the mining industry
- Treatment and reuse of contaminated soil and mining waste
- Environmental solutions for the sustainable energy industry
- Hydro-cracking solution

AggreBind has many years of experience in the global road construction industry and provides the technique to support the growing demand that exists in today's road and transportation infrastructure market. AggreBind uses innovative techniques to facilitate the design and rehabilitation of the current road system at lower costs and reduced construction time compared to conventional construction methods and materials (see figure 2.2). The strength of a stabilized aggregate layer depends on the following:

The bearing capacity of the subgrade under the layer to be stabilized. If necessary, it should be recompacted before stabilizing the base layer.

- The 50 mm stabilized layers are reserved for access roads.
- The 150 mm stabilized layers are designed for vehicles up to 40 tones.
- The 250mm stabilized layers are intended for all other applications and should ideally, subject to available compaction equipment, be installed in 2 layers of 125mm.
- AggreBind has a back-bonding capability so there will be no loss of strength between the two treated layers.

- As a general rule, there should be +/-35% fines and no stones greater than 20% of the depth of the layer to be stabilized.
- Care should be taken to level the road surface for drainage.
- If required, any wear surface can be applied over a base coat treated with AggreBind.
- Any damage to a layer treated with AggreBind can be easily repaired with hand tools. The adhesion capacity of the polymers ensures that there is no loss of strength

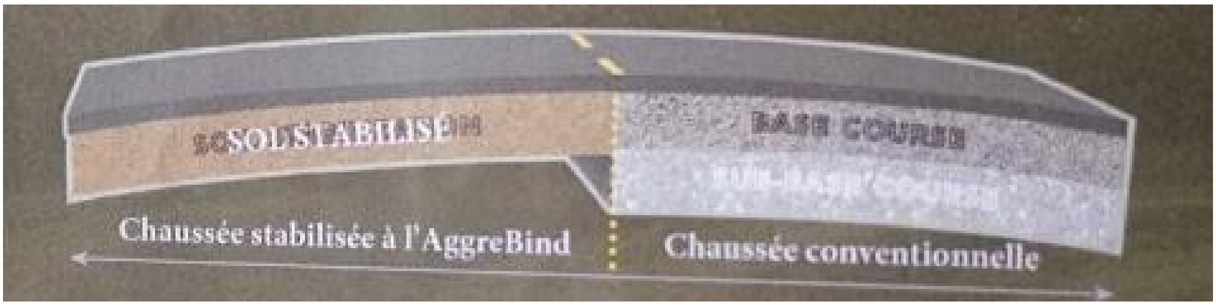


Figure 2. 2. Difference between an AggreBind stabilized pavement and a conventional pavement (www.Aggrebind.com)

2.2.2. Advantages of stabilization with AggreBind

2.2.2.1. On the technical side

The unique AggreBind cross-linked polymer formula has taken soil stabilization to a new level, with concrete-like performance and without the use of cement. Referred to by some as "disruptive technology", it offers strong, water-repellent, nature-friendly road structures, dust-resistant pavements, and in-situ construction materials (blocks, bricks and pavers) at remarkably low costs. The advantages of AggreBind include :

- Save more than 50% of the construction time
- Increase the CBR load capacity of all soils by 4 to 6 times, also improving the tensile strength.
- Ensuring strong, waterproof and durable pavement
- Controlling dust and preserving erosion
- Respect the environment: Non-toxic, Non-corrosive, Non-allergenic, Non-flammable
- Ensuring the safety of workers
- Provide low cost housing solutions with any type of soil, as well as non-cohesive materials such as desert sand, or crushed gravel.

- Produce blocks, bricks and paving stones from virtually any local material including earth, sand, gravel from building sites or mining where conventional methods are too expensive, or impractical.
- UV (ultraviolet) resistant for up to 12 years
- Guarantee a 5-year product replacement

Tableau 2. 1. Comparison of the AggreBind stabilizer with other stabilizers (www.aggrebind.com, accessed 28/02/2021)

MATERIAL	APPLICATION	PROBLEMS	SOLUTIONS
AggreBind	Roads and concrete block manufacture	Perception. Most engineers are comfortable with standard equipment and do not want to change conventional methods.	Make road tests and/or sample blocks. For roads, order AggreBind in black, as this will visually resemble asphalt.
Concrete	Roads	Several basic underlays.	Stabilize the site soil with AggreBind to improve its load-bearing capacity. This will reduce the depth of concrete required, resulting in significant cost and time savings
Cement	Roads and concrete block manufacture	Not environmentally friendly and requires strict specifications to be effective.	AggreBind can be diluted with virtually any type of water and will significantly improve the bearing capacity of any soil. It is environmentally safe and requires only basic skills and equipment to produce cost effective results.

The Bitumen	Roads Pothole repair	Not environmentally friendly and difficult to use. Cannot maintain the natural colour of the floor.	AggreBind can retain the natural colour of the floor and can be coloured to meet customer requirements if required.
The Asphalt	Roads Pothole repair		Can be used as a wear surface on any AggreBind stabilised floor layer if required
Contaminated waste/soil	Roads and concrete block manufacture	A serious environmental problem.	AggreBind can be coated in a flexible, impenetrable coating that retains contamination, making it soil and reusable waste.
Contaminated water	Roads and concrete block manufacture	A serious environmental problem	Can be used on site to dilute AggreBind.
Lime	Soil stabilization	Only effective in certain soil types. Difficult to apply in windy conditions.	AggreBind will stabilize and improve the bearing capacity of all soil

2.2.2.2. In economic terms

Soil stabilization with AggreBind allows:

- Save over 30% of costs compared to conventional methods
- Reduce maintenance costs by 50%.
- Save 100% of energy consumption

A comparison of the cost of building a road with different stabilizers over 1 km, 6 m wide and 150 mm deep was carried out by the company AggreBind (see Figure 2.3**).** The result is that in almost all countries where road construction is carried out, a concrete road of the same length costs 2.4 times the average cost of an AggreBind road; asphalt is 1.8 times and paving is 1.23 times the cost of an AggreBind road.

Figure 2. 3. Comparison of costs for 1 kilometer of road (www.aggrebind.com)

2.2.3. In-situ stabilization process with AggreBind: case of the development of a rural track

According to (www.aggrebind.com, accessed 28/02/2021), in-situ stabilization of a rural runway with the AggreBind product involves simple, cost-effective and less time-consuming steps:

(1) Take a sample of the road (soil) to be stabilized.

(2) Check the condition of the base layer under the area of soil to be stabilized and make improvements if necessary.

(3) Scrape the road surface to the required depth using an excavator or tractor with a disc harrow, ensuring that no stone exceeds 20% of the total depth of the layer to be stabilized.

(4) Spray the mixture of AggreBind and water solution on the surface of the dirt road. One part AggreBind (1/5) to four parts water (4/5), depending on the quantity and size of the stones.

(5) Mix the AggreBind and water solution into the dirt road to achieve uniformity, so that it is ready to be compacted

(6) Shape the road until it reaches the optimum level for compaction.

(7) Compact the treated soil using a smooth vibratory roller with a single compacting drum or similar equipment.

(8) Seal the road with a top spray of the aggregate and water solution and drive the road again without vibration.

(9) In general, the road can be used within two hours of completion. The surface should be dry to the touch. The AggreBind road will continue to cure for a further 28 days, but this will not prevent it from being used.

All these steps can be seen in Figure 2.4.

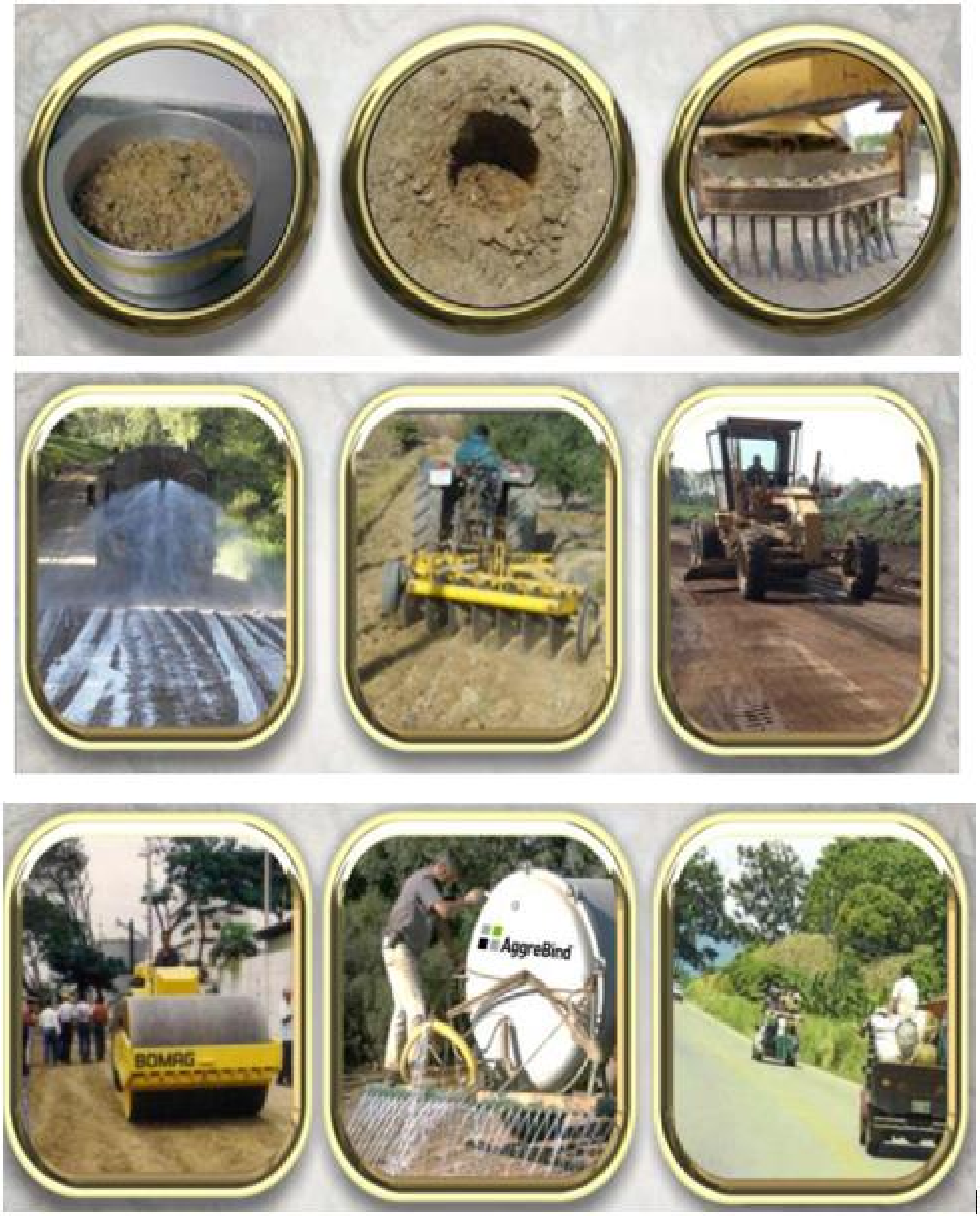


Figure 2. 4. In-situ stabilization process of rural tracks using the AggreBind product, (www.aggrebind.com., visited on 28/02/2021)

2.3. CONCLUSION

The objective of this chapter was to introduce the product AggreBind, its areas of application and benefits; and to show how in-situ soil stabilization with AggreBind is achieved. It was found that AggreBind is the only non-biodegradable, long-chain cross-linking polymer with tracers on the market that adheres to, and stabilizes, virtually any cohesive or non-cohesive surface, including desert sand. It improves soil bearing capacity (CBR) values ideally by 400-600% while also improving the tensile strength of the soil and prevents surface water infiltration into the treated layer, as water penetration and freezing are critical factors in road failure. AggreBind does not require any clay content in the layer to be treated unlike other soil stabilizing products. It is totally environmentally friendly, so it is safe for flora and fauna, nontoxic, non-flammable and does not degrade in the environment. It takes less time and labor to install and is less costly because the roadway can be built in a single layer of stabilized soil. Upon completion, AggreBind offers a full week's free training (following a minimum order), enough time to train a typical roadworks team, and efficient installation.

3 CHAPTER 3 : METHODOLOGY OF STUDY

INTRODUCTION

The methodology is the part that establishes the procedure of the research in order to achieve the set objectives. In other words, it describes the different components of our research. The recognition of the geotechnical characteristics of a soil involves a number of laboratory tests. The purpose of these tests is to identify the 3 essential parameters of a soil: nature, mechanical behavior and water status. The soil used in this research is a soil from the Yaounde-Obala road duplication project. In this chapter, we will therefore make a general reconnaissance of the project site, present the origin of the constituents (soil, AggreBind and water) of our stabilized material, present the soil identification tests (granulometric analysis, Atterberg limits) as well as the bearing capacity tests (modified Proctor, CBR after 4 days of immersion), and finally the soil treatment and characterization method.

3.1. GENERAL RECOGNITION OF THE SITE

General site investigation is a phase which consists of documentary research on the study site. However, it allows the knowledge of physical parameters such as geographical location, climate, relief, geology and hydrology on the one hand, and socio-economic parameters on the other hand.

3.2. ORIGIN AND PROCUREMENT OF MATERIALS

The objective of our study is to characterize the AggreBind product in a geotechnical manner with a view to its use in road construction, and we will therefore present the precise origin of our constituents, namely the soil and the AggreBind product.

3.2.1. The soils

The soil sample used for our experiments comes from the laboratory of the Ministry of Public Works delegation.

3.2.2. The AggreBind product

The AggreBind product used is AGB - WT - clear contained in a 4-liter white can and is manufactured by the US based company AggreBind Inc.

3.3. GEOTECHNICAL SOIL IDENTIFICATION TESTS

3.3.1. Particle size analysis by sieving (NF P 94-056)

3.3.1.1. Goal

The purpose of the test is to represent the respective size and percentages of the different families of grains constituting the material sample by means of a granulometric curve which is a representation of the percentages of the sieves or those of the cumulated refusals (percentages by weight of the total dry mass of the material after washing and drying) on the sieves as a function of the openings of the sieves.

3.3.1.2. Principle

The test consists of separating the agglomerated grains from a known mass of material by stirring under water, fractionating this soil, once dried, by means of a series of sieves and successively weighing the accumulated refusal on each sieve. The mass of accumulated rejects on each sieve is related to the total dry mass of the sample submitted for analysis.

3.3.1.3. Expression of results

a. Results table

It contains, according to the series of sieves used: the mass of accumulated rejects and the mass percentage of rejects on each sieve, as well as the percentage passing the same sieves (see table 3.1).

Tableau 3. 1. Results table of particle size analysis by sieving

Organisme :		Site :				N° dossier :		
		Échantillon n°		Profondeur =		Sondage n°		
		Date de prélèvement :				Date d'essai :		
		Tamis		Masse refus mesuré (g)		Masse refus R cumulé (g)	Pourcentage massique	
Matériau d_m = 63 mm	Masse m = 30 210 g	mm	µm	r_i	R		Refus cumulé r	Tamisat cumulé p
Partage au tamis d_c = 10 mm		100						
Masse sèche du refus au tamis d_c R_c = 9 040 g		80		—	—	—	—	
		63			0	0	0	100
		50			1 450	1 450	5	95
Masse passant au tamis d_c m_h = 20 675 g		40						
		31,5			3 150	3 150	11	89
Part (1) sur tamisat au tamis d_c	Masse humide m_{h1} = 2 820 g	25						
		20			5 338	5 338	19	81
	Masse sèche m_{s1} = 2 674 g	16						
		12,5						
Part (2) sur tamisat au tamis d_c	Masse humide m_{h2} = 3 525 g	10			9 040	9 040	32	68
		8						
	Masse sèche (80 µm, d_c) m_{s2} m_{s2} = 2 840 g	6,3						
		5		622		12 688	44	56
		4						
Masse sèche totale $m_s = R_c + m_h \times m_{s1}/m_{h1}$ = 28 645 g		3,15						
		2,5						
Coefficient multiplicateur sur refus au tamis de 80 µm $b = m_h/m_{h2}$ = 5,865		2,0		785		13 644	48	52
		1,6						
		1,25						
Refus cumulé $R = R_c + b.r_i$		1,0		1 050		15 198	53	47
Masse (80 µm, d_c) : m_{s4} = 2 828 g Prélèvement 2			800					
			630					
Masse passant à 80 µm de la fraction (80 µm, d_c) Sur part (2) m_{s3} = 8 g			500					
			400	1 330		16 840	59	41
			315					
Pourcentage	de refus : $r = 100\ R/m_s$		250					
			200	1 775		19 450	68	32
	de tamisat : $100\ (1 - R/m_s)$		160					
			125					
Vérification $(m_{s2} - m_{s4})/m_{s2} = 0{,}004 \leq 0{,}01$			100	2 650		24 582	86	14
			80	2 828		25 626	89	11
NB : Si $d_c = d_m$, $R_c = 0$, $b = 1$								

b. Graphical representation of the results of the particle size analysis

The particle size curve (see Figure 3.1) is made up of a succession of segments whose ends correspond to the mass percentage of rejects or sieves for each sieve opening with: On the x-axis, a logarithmic scale with base 10. On the ordinate, the vertical axis limiting the graph on the left-hand side is graduated with a linear scale increasing from bottom to top, with the weight percentage of the cumulative sieves. Optionally, the vertical axis bounding the right-hand graph may be graduated with a linear scale decreasing from top to bottom and show the mass percentage of accumulated refusals.

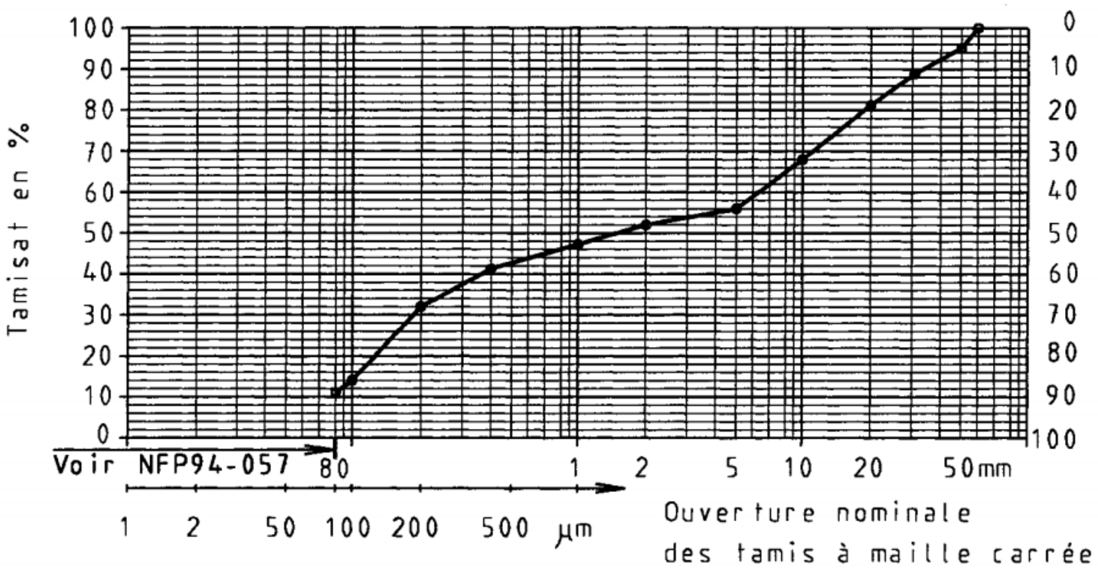


Figure 3. 1. Example of a grading curve

c. Calculation of curvature and uniformity factors

This calculation only needs to be made if the material passing the 63 mm sieve has more than 50% rejection on the 80 µm sieve.

The dimensions of the sieves corresponding to d_{10}, d_{30} *et* d_{60} are graphically interpolated on the curve. The curvature factor is calculated from:

$$C_c = \frac{(d_{30})^2}{(d_{10}*d_{60})} \quad \text{EQ 8}$$

And the uniformity factor from:

$$C_u = \frac{d_{60}}{d_{10}} \quad \text{EQ 9}$$

3.3.2. Particle size analysis by sedimentation (NF P 94-057)

3.3.2.1. Goal

The purpose of this standard is to determine the weight distribution of fine particles in soil.

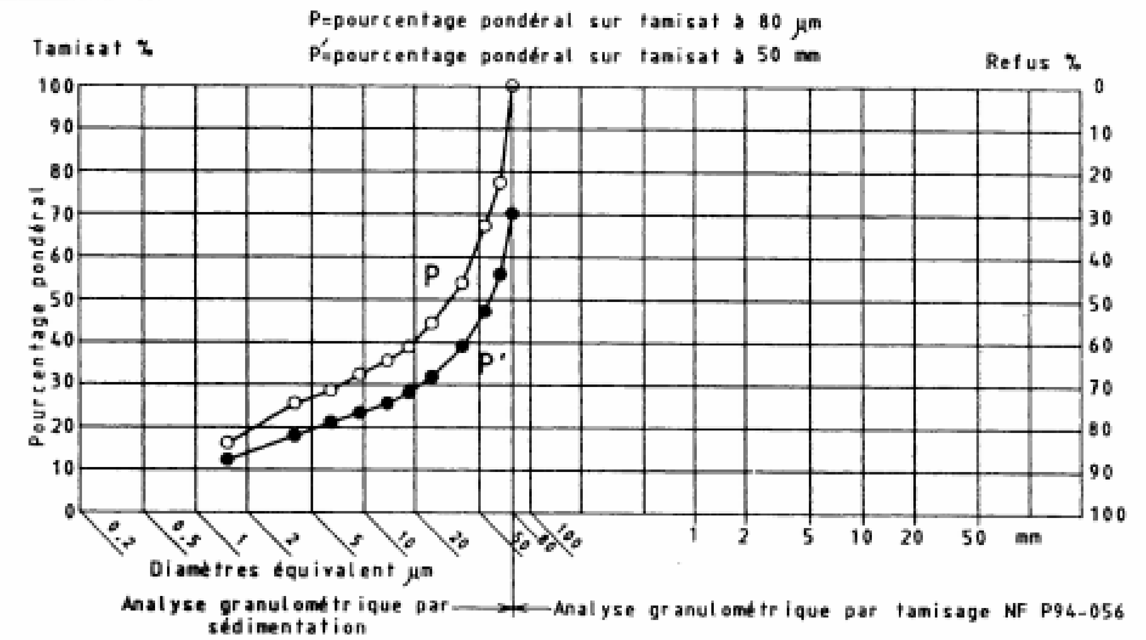
3.3.2.2. Principle

The sedimentation particle size analysis test uses the fact that in a liquid medium at rest, the settling speed of fine grains depends on their size. Stokes' law gives, in the case of spherical grains of the same density, the relationship between the diameter of the grains and their settling speed. By convention, this law is applied to soil elements to determine equivalent particle diameters.

3.3.2.3. Expression of results

The results are provided in the form of graphs on semi-logarithmic paper on which the particle size in millimeters will be increased on the X-axis (logarithmic scale) and their percentage weight in ordinate with increasing scale, possibly accompanied of the results table (see figure 3.2).

Nom du laboratoire	ANALYSE GRANULOMÉTRIQUE PAR SÉDIMENTATION Essai effectué conformément à la norme NF P 94-057 Dossier : Date :



ORIGINE DE L'ÉCHANTILLON
Site :
Sondage : S1
Profondeur : 1,25 m

MASSE VOLUMIQUE DES PARTICULES SOLIDES
Mesuré : — conventionnel : 2 700 kg/m³
Pourcentage de passant au tamis de 80 µm = 71 %

Densimètre : H_0 = 13 cm H_1 = 3,8 cm h_1 = 18,4 cm V_d = 73 cm³

Facteurs correcteurs : C_m = 0,000 4 C_d = – 0,000 8 Éprouvette : A = 57 cm²

Temps de lecture h	min	s	R Lecture densimètre	Température (°C)	C_t Correction température	P % sur tamis à 80 µm	P' % sur tamis à 50 mm	D (µm)
—	—	30	1,018 0	22,8	0,001 1	76,5	54,3	73
—	1	—	1,015 4	22,8	0,001 1	65,9	46,8	53
—	2	—	1,012 6	22,8	0,001 1	54,4	38,6	39
—	9	—	1,010 1	22,8	0,001 1	44,2	31,4	25
—	10	—	1,008 7	22,8	0,001 1	38,5	27,3	18
—	20	—	1,007 6	23,0	0,001 4	35,2	25,0	13
—	40	—	1,007 0	23,0	0,001 4	32,7	23,2	9
—	80	—	1,006 0	23,5	0,001 5	29,1	20,7	6
4	—	—	1,005 1	23,8	0,001 5	25,4	18,0	3,9
24	—	—	1,003 1	22,8	0,001 1	17,6	12,5	1,5

Figure 3. 2. Example of sheet of analysis size by sedimentation

3.3.3. Atterberg limits (NF P 94-051

3.3.3.1. Goal

This standard for the determination of the two Atterberg limits (cup liquidity limit and roller plasticity limit) applies to soils whose elements pass through the nominal 400 µm mesh size sieve. The Atterberg limits are geotechnical parameters designed to identify a soil and characterize its condition by means of its consistency index.

3.3.3.2. Principle

The test is carried out in two phases:

Research into the water content at which a groove in soil placed in a cup of prescribed characteristics closes when the cup and its contents are subjected to repeated shocks;

Research into the water content at which a manually made soil roll of a fixed size cracks

3.3.3.3. Expression of results

a. Liquidity limit

The liquid limit W_L is the water content of the material which conventionally corresponds to a 1 cm closure of the groove lips after 25 impacts. It is the water content that separates the liquid state from the plastic state (see Figure 3.2). It is calculated from the equation of the mean line fitted to the pairs of experimental values $(logN, W)$.

This average line cannot be determined without a minimum of four points. The relationship is only acceptable if the difference in water content between the measured value and the calculated value for the same number of strokes does not exceed 3%. If this is not the case, repeat the measurement.

The limit w_L is obtained for a value N equal to 25. It is expressed as a percentage and rounded to the nearest whole number: the rounding interval is 1.

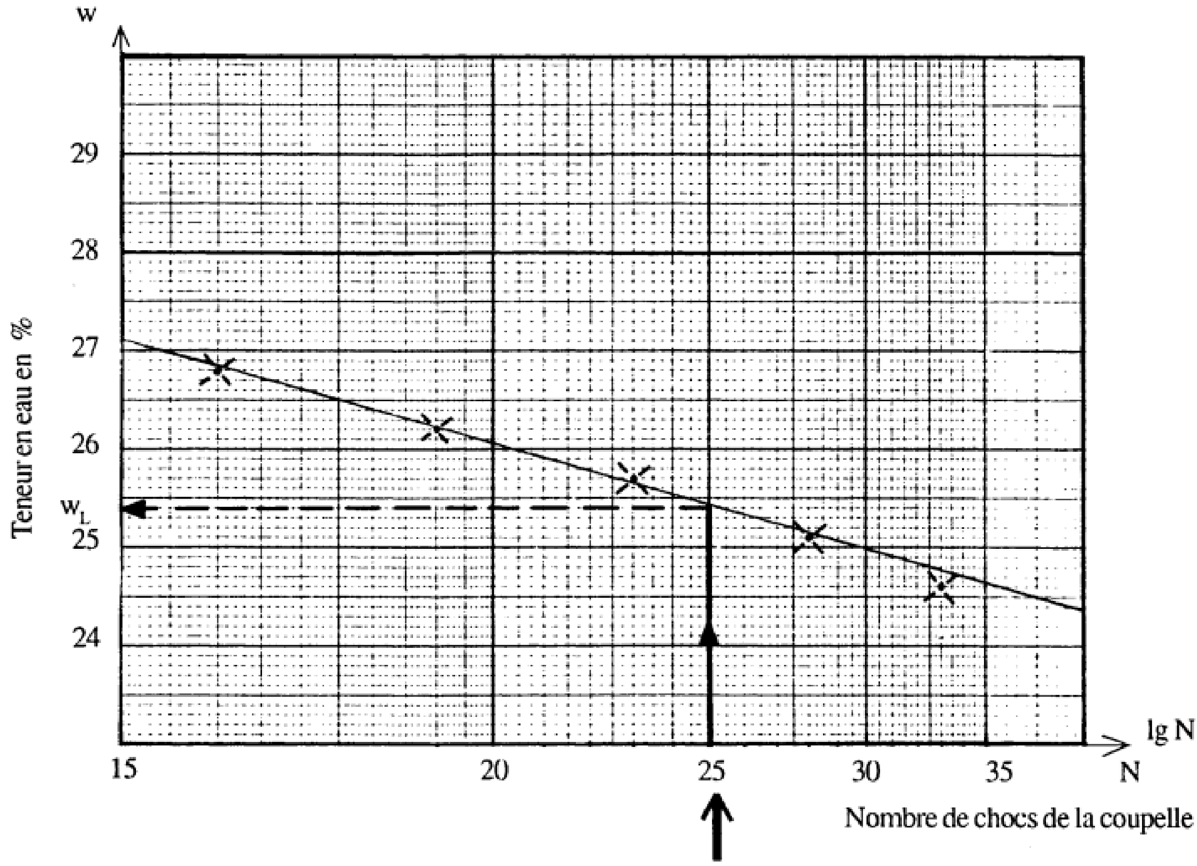


Figure 3. 3. Curve for determining the liquidity limit

b. Plasticity limit

The plastic limit W_p is the conventional water content of a soil roll that cracks at the point where its diameter reaches 3.0 mm ± 0.5 mm. It is defined as the water content of a soil that has lost its plasticity and cracks by deforming when subjected to low loads. This limit separates the plastic state from the semi-solid state. w_p is the arithmetic mean of the water contents obtained from two tests. The value of the plasticity limit is expressed as a percentage and the rounding interval is 1. If the values deviate by more than 2% from the average value, a new test must be carried out.

c. Plasticity index

I_p is the difference between the values of the liquidity and plasticity limits. It is used to establish the plasticity of a given soil, i.e. to determine a zone in which the soil is considered to be in a plastic state.

$$I_p = W_L - W_P$$

3.4. SOIL BEARING CAPACITY TEST

3.4.1. Modified Proctor test (NF P 94-093

3.4.1.1. Goal

This standard concerns the test to determine the compaction characteristics of a material. These characteristics are the optimum moisture content and the maximum dry density. Depending on the compaction energy applied to the specimen, a distinction is made between the normal Proctor test and the modified Proctor test, which lead to different value pairs. This standard applies to materials defined in the NF P 11-300 classification, whose largest elements (D_{max}) does not exceed 20 mm, whether they are natural or treated with lime and/or hydraulic binders.

3.4.1.2. Principle

The Proctor compaction characteristics of a material are determined from the so-called Normal Proctor Test or Modified Proctor Test. Both tests are identical in principle, only the values of the parameters that define the applied compaction energy differ. The principle of these tests is to moisten a material with several water contents and to compact it, for each of the water contents, according to a conventional process and energy. For each of the water content values considered, the dry density of the material is determined and the curve of the variations of this density as a function of the water content is drawn. In general, this curve, called the Proctor curve, shows a maximum value of the dry density of the material that is obtained for a particular value of the water content. These two values are referred to as the optimal compaction characteristics of the normal or modified Proctor curve, depending on the test performed.

3.4.1.3. Expression of results

For each compacted specimen, the following should be calculated:

- Water content;
- The mass of dry material contained in the mould;
- The unit weight of dry material taking into account the actual volume of the mould used, determined

from geometrical measurements made to the nearest 0.1 mm.

The values of the dry material densities and the corresponding water contents are plotted on a graph ($\rho_d = f(w\%)$) as shown in Figure 3.3. The scale ratio is 2% water content to 0.1 t/m^3 of unit weight.

The fitted curve is then plotted on the experimental points. Except in the case of very permeable materials, this curve has a maximum whose coordinates are called optimum dry density and optimum water content respectively. This result is expressed to the nearest 0.01 t/m^3 This result is expressed to the nearest 0.01 for the density and to the nearest 0.1 point for the water content (expressed as a percentage). The graph should also show $\rho_d = f(w\%)$ the equation curves:

$$\rho_d = \frac{S_r * \rho_s}{S_r + w * \frac{\rho_s}{\rho_w}} \qquad \text{EQ 10}$$

With $\rho_w = 1\ t/m^3$

Prepared for :

$$S_r = 100\ et\ 80\%\ /m^3$$

And for :

$$\rho_s = 2{,}70\ t/m^3$$

If the measured value of ρ_s of the material in question is available, it will be used to establish these two curves.

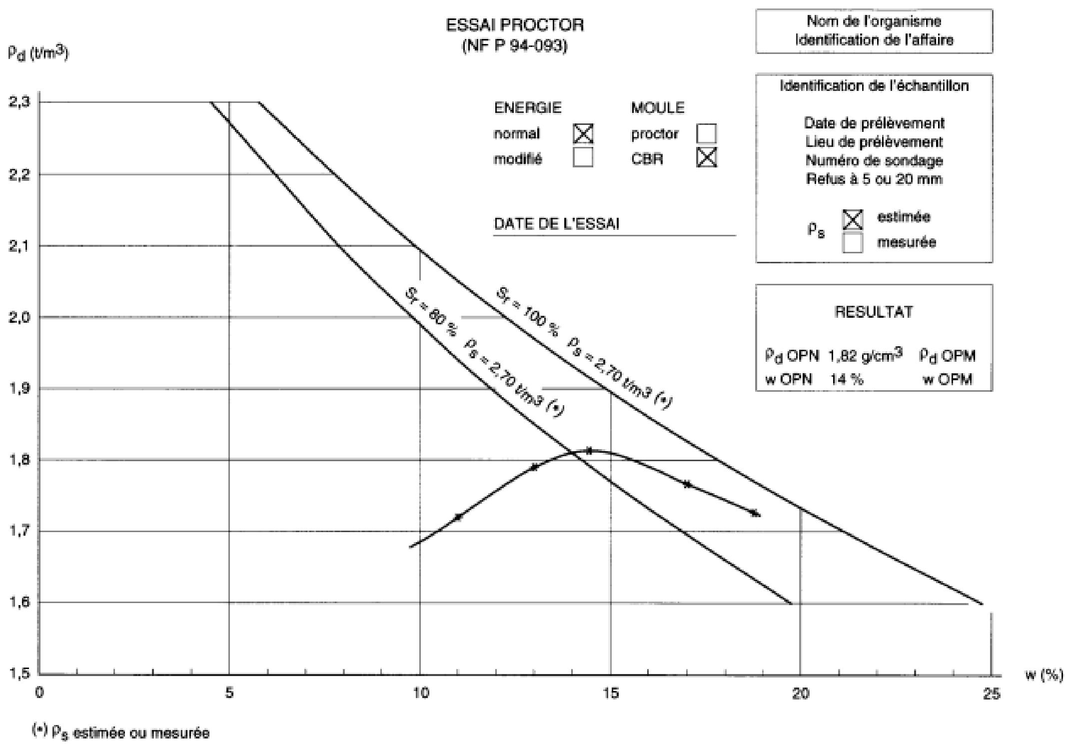


Figure 3. 4. Proctor test curve

3.4.2. CBR test (NF P 94-078)

3.4.2.1. Goal

This test allows the determination of:

- From the immediate bearing index (IBI);
- From the immediate CBR index;
- From the CBR index after immersion;

A soil or granular material used in the construction of earthworks or road bases. It applies to soils, rocky materials, industrial by-products defined in standard NF P 11-300 and provided that the proportion of elements whose D_{max} exceeds 20 mm does not exceed 30%. It also applies to these same materials when they are mixed with different products such as air lime, hydraulic or pozzolanic binders, fibers, etc.

3.4.2.2. Principle

The general principle of the test is to measure the forces to be applied on a cylindrical punch to make it penetrate at constant speed into a material specimen. The particular values of the two forces which caused two conventional indentations are respectively related to the values of the forces observed on a reference material for the same indentations. The index sought is conventionally defined as the greater value, expressed as a percentage, of the two ratios thus calculated. The values of the parameters (punch section, driving speed, conventional driving, forces observed on the material) are standardized and specified in Articles 6 and 7. The CBR test after 4 days of immersion measures the resistance to punching of a soil compacted with different water contents and then immersed for 4 days. It characterizes the evolution of the bearing capacity of a compacted soil and/or one subjected to variations in the water regime.

3.4.2.3. Expression of results

The following values are calculated:

$$\frac{effort\ de\ pénétration\ à\ 2{,}5\ mm\ d'enfoncement (en\ KN)}{13{,}35} * 100 \qquad \text{EQ 11}$$

$$\frac{effort\ de\ pénétration\ à\ 5\ mm\ d'enfoncement (en\ KN)}{19{,}93} * 100 \qquad \text{EQ 12}$$

The index sought is by convention the greater of these two values;

If necessary, make an original correction.

3.5. SOIL TREATMENT WITH AggreBind

The soil sample used will be stabilized with AggreBind AGB-WT which will be diluted with water.

3.5.1. Binder formulation

The binder is the AGB-WT + water mixture. Figure 3.2 shows the dosage rate of the AggreBind polymer per cubic meter of treated soil as a function of the percentage of fines in the soil sample. Thus, the volume of binder should correspond to the optimum water content of the soil as determined by the Proctor test. And from the ratio of X liters of AggreBind per m^3 of soil, the volume of AGB-WT required for a soil sample of mass (m) is determined, knowing the density of the soil sample. Finally, the volume of water required will be the difference between the volume of liquid corresponding to the optimal water content of the soil and the volume of AGB-WT calculated above.

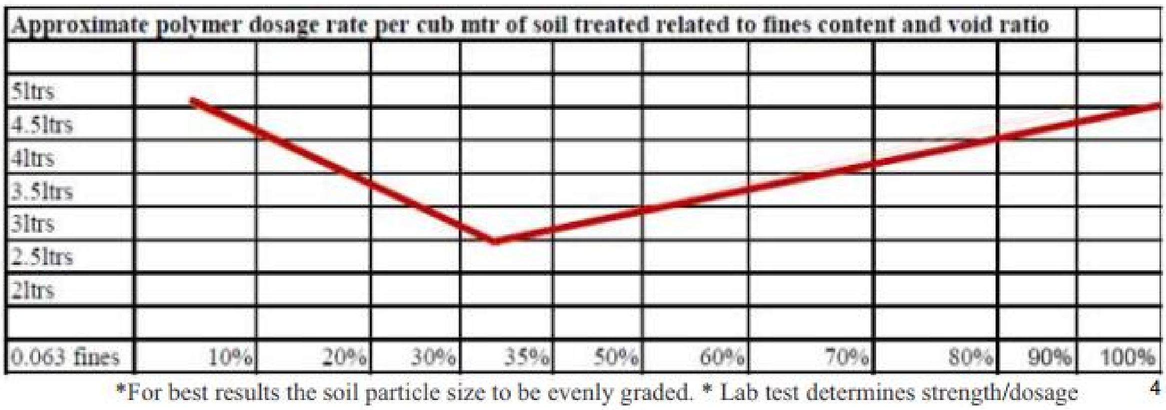


Figure 3. 5. Polymer dosage rate per cubic meter of soil as a function of the percentage of fines
in the soil

3.5.2. Characterization of the mixture

The OPM 95% CBR test will be used to characterize the AggreBind treated soil. The only difference is that the saturation and swelling phase of the CBR test does not apply when using AggreBind. Therefore, the specimens should not be immersed in water and should be stored in a ventilated area without direct exposure to sunlight and on a flat surface to allow for curing. This characterization will involve determining the immediate CBR, the CBR after immersion and the CBR after air drying for 3 days, 7 days, 14 days, 21 days and 28 days.

3.6. CONCLUSION

At the end of this chapter, where it was a question of developing a characterization procedure of the soil-AGB mixture. It emerges that an identification study (particle analysis, Atterberg limits) of soil sample used will first have to be carried out in order to know its natural properties, then proceed to a formulation of the mixture and a treatment with AggreBind product. And finally, the results of the CBR tests at different ages we will allow to study the behavior of the soil with addition of the product AGB-WT. The results of these tests and their interpretations will be presented in Chapter 4.

4 CHAPTER 4: PRESENTATION AND INTERPRETATION OF RESULTS

INTRODUCTION

There are several techniques for soil improvement as described in Chapter 2. Most of these techniques are aimed at increasing the bearing capacity of soils to allow their use in road construction. In this chapter, the results of the treatment of a soil with the innovative product AggreBind will be presented and interpreted. First of all, it will be necessary to present in a general way the constituents of our study, then the results resulting from the complete identification of our soil sample, i.e. the granulometric analysis tests by sieving and by sedimentation, the Atterberg limits, the Proctor test and the CBR test. And finally, to present and interpret the results of the bearing capacity tests carried out on our soil treated with AggreBind.

4.1. GENERAL PRESENTATION OF THE COMMUNE OF SOA

4.1.1. Physical characteristics

The commune of Soa is physically presented by its geographical location, soil, climate, relief, hydrology and vegetation.

4.1.1.1. Geographic location

Located in the Centre Region, Mefou and Afamba Department, the commune of Soa covers an area of 326 km2 and is divided into 40 villages with an urban area. It is circumscribed as follows:

- In the North by the Commune of Edzendouan ;
- In the South by the Communes of Nkolafamba and Yaoundé V;
- To the East by the communes of Esse and Awae;

In 1979, the locality became an Arrondissement by presidential decree N° 79-469 of 14 November of the same year. The commune of Soa is located at an altitude of 675 m and has the following geographical coordinates: 3°58'41"N and 11°35'45"E in DMS (degrees-minutes-seconds).

The sampling point for our soil sample is in the Ebang 2 district near a lateritic borrow area.

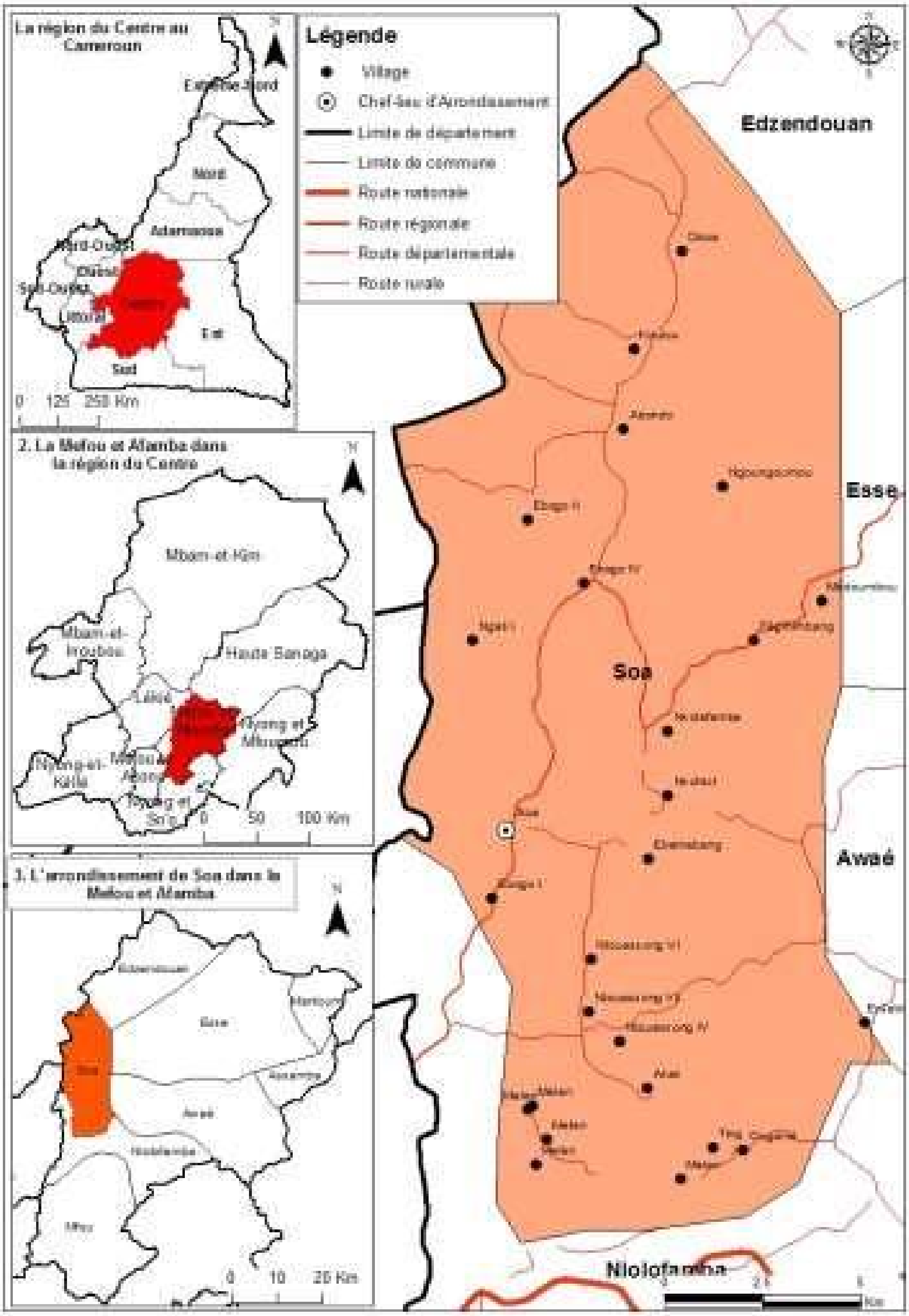


Figure 4. 1. Description of the biophysical environment of the commune of Soa (Soa communal development plan, June 2015)

4.1.1.2. The soils

The soils identified in Soa are ferralitic soils where the hydrolysis of rock minerals by heavy and hot rainfall is complete. These are poor soils characterized by a low nutrient content (PH between 4 and 6). They are deep due to the presence of organic matter, red clayey, loose and permeable. The quality of the soil and the presence of rocks offer possibilities for the creation of quarries like the AKAK quarry and the RAZEL quarry.

4.1.1.3. The climate

The climate of the locality of Soa is of the humid equatorial type. It is a four-season climate of the Cameroonian plateau. It rains all year round with two maxima, one in October (main rainy season) and the other in March-April (short rainy season). The drought maxima are in December-January (long dry season) and July-August (short dry season).

4.1.1.4. The relief

The relief is that of a dissected plateau that slopes from the centre to the north, from 740m to 800m in the small Ndogo massif, in the extreme centre-east from 580m to 600m in altitude at the northern tip of the district, following a gentle slope of 0.66%. The average altitude is 675m. The relief of the district of Soa is uneven with its many deep valleys, which are ideal for fish farming. There are also steep areas in Ebogo III, Nkolbewa, Nkolzie by Mbansan II, Mbansan I, Otonton, Ndi, Nso'o by Ntouessong VI and the main hills of Ndeedzala, Minsole, Bomena and Nkonda. The areas at risk are present in the commune of Soa, namely the ravines of Akak II, Ovangul, Ting Melen and Mbansan II. The soil consists largely of granitic stones. The soils are generally poor, exhausted and not very fertile. Erosion is easy. Some plantations grow well, however, such as oil palms.

4.1.1.5. Hydrology

The hydrographic network is organised around the Afamba River and its main tributaries, the Mbende and the Foulou. Several rivers water the Commune, and these rivers collect the water from streams and drain it towards the Sanaga in the North.

4.1.1.6. Vegetation

The forest is semi-deciduous with sterculiaceae and ulmaceae. It comprises large trees with straight shafts and grey bark. Indeed, there are some primary forests in Ntouessong V and secondary forests in Ntouessong V, Ebang I, Koulou, Mebougou and Ngoungoumou. However, woody species such as Abissia, Fraqué, Ilomba, Ficus, Antiaris and Dabema can still be found. There are also many valuable species, including Bibolo, Padouk, Fraque, Canarium, Osmoso, Hévea, Ilomba, Sapeli and Iroko.

4.1.2. Socio-economic characteristics

4.1.2.1. Demographics

According to the Soa communal development plan released in June 2015, the commune of Soa had 69084 inhabitants of which 31942 were men and 37142 were women.

4.1.2.2. Ethnic groups

The Commune of Soa is made up of four clusters, namely Ebang, Mbendé, Ntouessong and Ngali. The ethnic groups found there are mainly the Baaba, Etoudi, Ndong, Etenga, Mvog Belo, Tsinga, Yeminkol, Elendé, Emombo, Endongo, Ebanda, NangaEboko.

4.1.2.3. Economic activities

The Commune of Soa is the seat of several economic activities. In order of importance,
These include:

- Agriculture, the main activity of the local population;
- Small-scale livestock farming, practised by a minority;
- Trade in agricultural products;
- Office automation, electro-computer services around the university campus;
- Industry: metallurgy, agro-industries including SOFAMAC, FAFINSA, HYSACAM, SOCIA, etc.
- Leisure activities: games rooms, bars and refreshment areas.

4.2. DATA COLLECTION

4.2.1. The natural soil

The soil used for the geotechnical characterization of the AggreBind product is a reddish clay soil (see Figure 4.2) from the area of the Yaoundé-Obala road duplication project corresponding to KP 5+000 (Ebang 2 district in the commune of Soa). The Yaoundé-Obala road duplication project (40 km) starts after the end of the Olembé median strip where KP 0+000 is located (781573 m; 437972 m; 683 m) and ends before the Obala crossroads (KP 40+000) where the construction of an interchange is underway. The soil studied was taken using traditional drilling tools such as pickaxes and shovels over an area of one meter square to a depth of 15 cm below the vegetation layer.

Figure 4. 2. Soil sampling

4.2.2. The AggreBind Product (AGB-WT)

The AGB-WT product used (see Figure 4.3) was provided to the National School of Public Works (ENSTP) by Mr Conrad Dieudonné Bébé NDI, S/C Ministry of Housing and Urban Development. The objective was to characterise this product for use in rural road stabilisation and communal housing projects.

Figure 4. 3. AggreBind AGB-WT product

AGB-WT is a white, non-biodegradable liquid, characterized by its particular odor, slow evaporation rate, non-oxidizable, miscible in water because it is non-viscous and has an evaporation temperature equal to that of water (100°C). Its relative density at 20°C is 1.05 and its pH varies between 7.7-8.3

4.3. Results of soil identification tests

The results of the various geotechnical identification tests carried out on the natural soil are presented here. The soil identification is carried out according to the AASHTO standard (see paragraph 1.6.3) in accordance with the AggreBind soil stabilization protocol in the laboratory and covers: particle size assessed by particle size analysis; The liquidity limit and the plasticity index through Atterberg limits; Compaction characteristics (optimum moisture content and maximum dry density) as assessed by the modified Proctor test; The load-bearing capacity assessed by the CBR test after 4 days of immersion.

4.3.1. Summary of identification results

These tests, whose records are presented in (**Appendix 1),** give the results listed in Table 4.1.

Tableau 4. 1. Summary of soil identification test results

Nature du sol	Limites d'atterberg LL (%)	Limites d'atterberg LP (%)	Limites d'atterberg IP (%)	Proctor modifié: densité sèche (KG/m3)	Proctor modifié: Teneur en eau optimale (%)	CBR à 95% de l'OPM: CBR immédiat	CBR à 95% de l'OPM: CBR après 4 jours d'immersion	Classification AASHTO
silt argileux	23	14	9	1890	15	30	23	A-4 (2)

Analyse granulométrique par tamisage (ouverture des tamis en mm)

	20	16	12,5	10	6,3	4	3,15	2,5	0,8	0,63	0,4	0,2	0,16	0,08
Pourcentage des passants (%)	100	99,8	99,6	99,3	98,7	98,5	98,4	98,3	95,2	91,6	80,2	67,9	59,9	51,2

Analyse granulométrique par sédimentation (diamètre équivalent des particules en mm)

	0,0297	0,0211	0,0149	0,0122	0,0094	0,0067	0,0039	0,0027	0,0019	0,0016	0,0012	0,0006
Pourcentage des passants (%)	49,4	48,2	46,5	46,1	45,7	45,7	43,2	41,6	39,9	39,1	38,1	37

4.3.2. Results of the particle size analysis

The results of the sieve and sedimentation particle size analysis are presented in the curve shown in Figure 4.4 and the tables in Appendix 1.

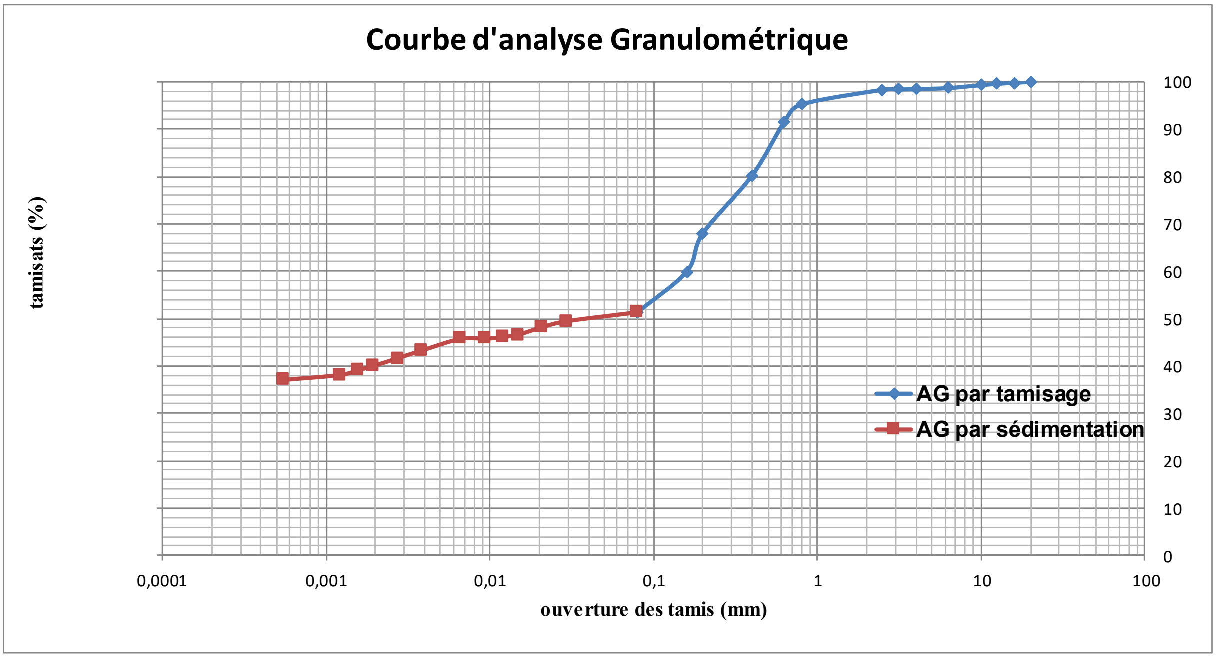


Figure 4. 4. Curve of the particle size analysis

The calculation of the curvature and uniformity factors is not necessary because our soil sample contains more than 50% of sieves with an 80 µm sieve, i.e. 51.2%. This soil therefore contains **51.2% of fine particles** qualified as silty and **39.9% of clay** (particles smaller than 2 µm), it is therefore a class A-4, A-5, A-6 or A-7 soil.

4.3.3. Results of the Atterberg Limits

The liquid limit and the plasticity index necessary for the identification of the soil according to the AASHTO classification are given by the Atterberg limit test.

4.3.3.1. Liquidity Limit (LL)

The liquidity limit is given by a point on the curve of water content (y-axis) versus the logarithm of the number of strokes (x-axis) shown in Figure 4.5. This point corresponds to a number of strokes equal to 25.

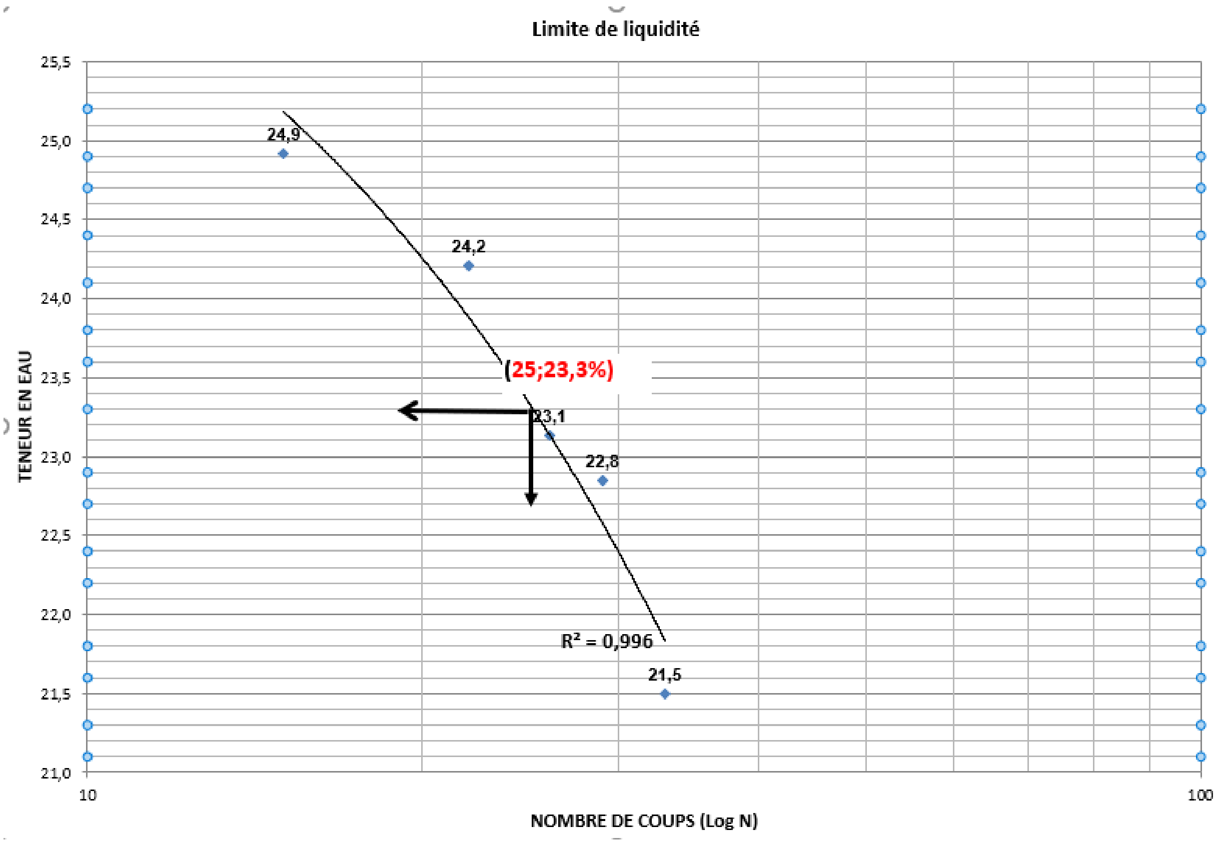


Figure 4. 5. Determination of the liquidity limit at the cup

This curve indicates that the water content corresponding to 25 shots is 23.3%, i.e. a liquidity limit of **23%.**

4.3.3.2. Plasticity limit

The results of the plasticity limit are shown **in** Table 4.2.

Tableau 4. 2. Plasticity limit results

	Teneur en eau	
N° de la tare	3	4B
Poids total humide (g)	15,92	16,250
Poid total sec (g)	15,560	15,85
Poids de la tare (g)	12,87	13,070
Poids d'eau (g)	0,360	0,4
Poids du matériau sec (g)	2,69	2,780
Teneur en eau (%)	13,38	14,39
Limite de plasticité (%)	**14**	

4.3.3.3. The plasticity index

It is calculated by the difference between the liquidity limit and the plasticity limit. With a **liquidity limit of 23** and a **plasticity limit of 14,** we obtain a **plasticity index of 9** (lower than 11). Knowing the percentage of passing on the 80 µm sieve given by the granulometric analysis, the AASHTO classification system (**paragraph 1.6.3**) concludes that this soil is a low plasticity clayey silt of class A-4 (2). As the group index (**equal to 2)** is closer to 0 than to 20, the potential performance of this soil as a road subgrade could be qualified as good compared to a material of the same group.

4.4. Results of soil bearing tests

4.4.1. Modified Proctor test

The compaction curve shown in Figure 4.6 allows the identification of references to the modified Proctor optimum such as optimum moisture content and dry density.

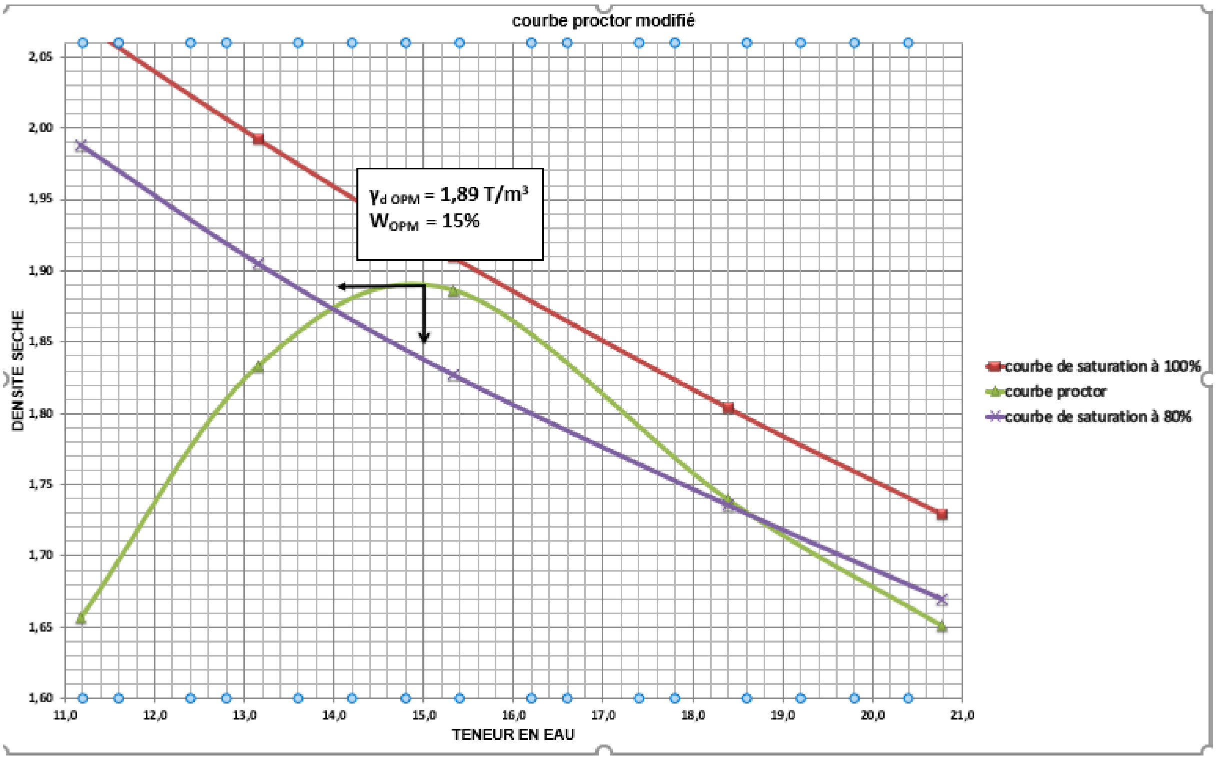


Figure 4. 6. Modified Proctor curve

At optimum, the moisture content and dry density are **15%** and **1.89 T/m^3**.. This corresponds to a saturation state of more than 80%.

4.4.2. CBR test

The CBR test was carried out at 95% of the Modified Proctor Optimum (MPO), i.e. compaction in 5 passes at a rate of 25 passes per layer in a CBR mould.

4.4.2.1. Immediate CBR

It characterises the evolution of the bearing capacity of a compacted subgrade (or pavement component) at the optimum water content. Punching takes place immediately after compaction and the data collected (see **Appendix 1**) allows the effort-penetration curve to be plotted as shown in **Figure 4.7**.

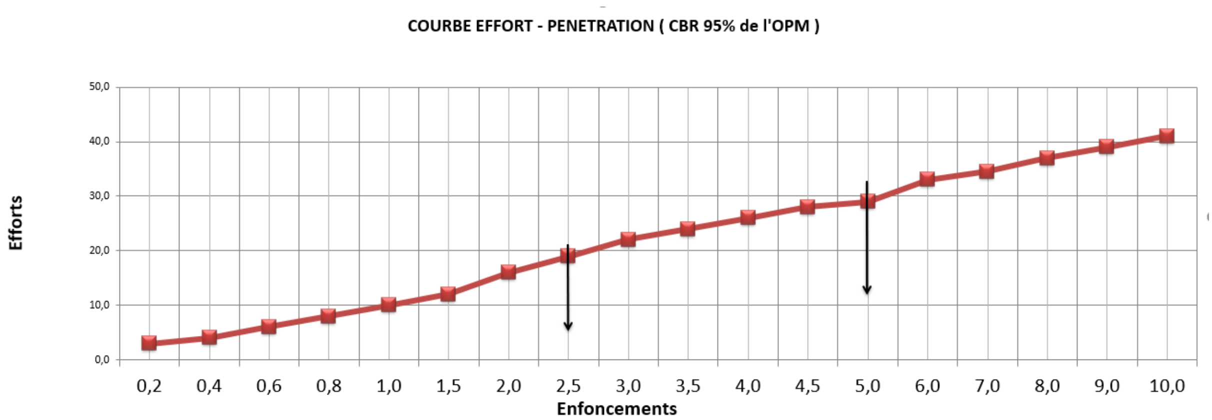


Figure 4. 7. Effort-penetration curve

This curve is used to determine the forces required at a 2.5 mm and 5 mm indentation to determine the immediate CBR. Its value and the dry density achieved are listed in Table 4.3**.**

Tableau 4. 3. Results of the immediate 25-shot CBR

Calcul de l'indice CBR à 25 coups		
Enfoncement (mm)	2,5	5
Effort (KN)	4	6
CBR calculés	29	30
Indice CBR	30	
Densité sèche (kg/m3)	1827	

4.4.2.2. CBR after immersion during 4 days

It characterizes the evolution of the bearing capacity of a support soil (or pavement component) compacted to the optimum water content and subjected to variations in the water regime. After 4 days of immersion, the specimen is removed from the water, drained and punched. The data collected from the punching allows the effort-penetration curve shown in Figure 4.8 to be plotted.

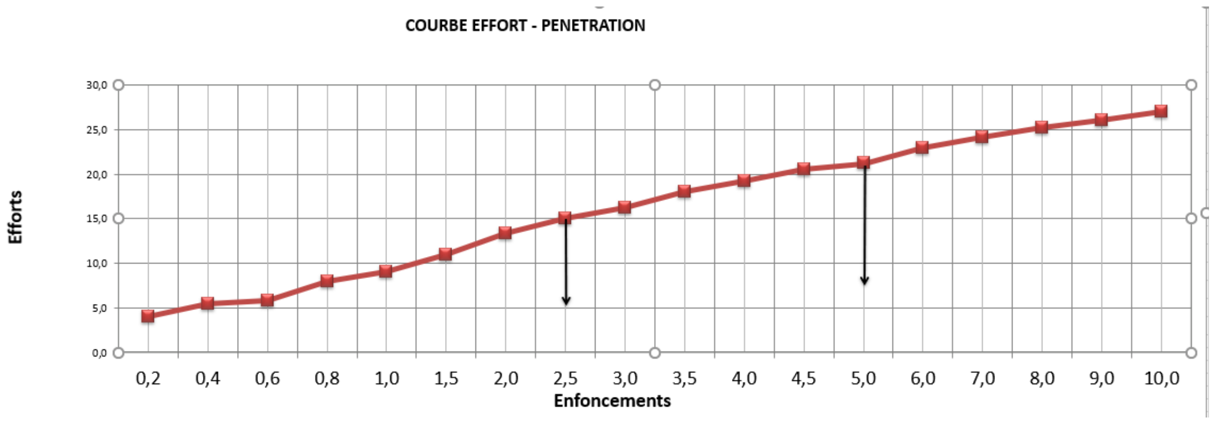


Figure 4. 8. Effort-penetration curve after immersion

This curve is used to determine the forces required at 2.5 mm and 5 mm embedment to determine the CBR after immersion. Its value, as well as that of the dry density and swelling, are listed in Table 4.4.

Tableau 4. 4. Résultats de l'essai CBR après immersion

Calcul de l'indice CBR à 25 coups		
Enfoncement (mm)	2,5	5
Effort (KN)	3	4
CBR calculés	23	22
Indice CBR	23	
densité sèche (kg/m3)	1877	
Gonflement G (%)	0,18	

The CBR index at 25 strokes after immersion is equal to **23** (between 15 and 30), which makes this soil an **S4 class**. The dry density obtained is **1877 kg/** i.e. a compactness rate equal to 99% in relation to the dry density at the OPM.

4.5. SOIL TREATMENT WITH AGGREBIND (AGB-WT-CLEAR)

The specimens were made according to the standards for bearing capacity tests (modified Proctor and CBR). The only difference is that the saturation and swelling phase of the soil according to the CBR standard does not apply when using the AggreBind product. Therefore, the specimens should not be immersed in water and should be stored in a ventilated area, but not in direct sunlight, on a flat surface to allow curing.

4.5.1. Results Characteristics

4.5.1.1. Emulsion formulation

The emulsion is the mixture AGB-WT-clear + water (see **figure 4.9**). Thus, the volume of emulsion should correspond to the optimum soil moisture content (OMC) determined by the modified Proctor test. And from the ratio **4 litres of AggreBind per m^3** of soil, the volume of AGB-WT-clair required for a 6000 g dry soil sample will be determined, knowing its optimum dry density. Finally, the volume of water required will be the difference between the volume of emulsion corresponding to the optimum water content of the soil (OMC) and the volume of AGB-WT-clear calculated previously. The results are listed in Table 4.5.

Figure 4. 9. AGB + water mixture (emulsion)

Tableau 4. 5. Emulsion formulation

Masse de l'échantillon de sol sec (g)	Volume de l'émulsion (ml)	Volume de AGB-WT (ml)	Volume d'eau (ml)
6000	900	13	887

4.5.1.2. Preparation of test specimens

After diluting the AGB product in water to the optimum water content to obtain the emulsion, mix it with the soil sample by kneading carefully to homogenise the whole. Finally, apply compaction at 95% of the OPM in a CBR mould in 5 layers at a rate of 25 strokes per layer (according to NF P 94-053). Figure 4.10 shows the specimens obtained at the end of compaction. Thus, 7 CBR specimens will be produced, distributed as follows:

- A specimen of material treated for punching after immersion for 4 days;
- A specimen of material treated for immediate punching;
- A specimen of material treated for punching after air drying for 3 days;
- A specimen of material treated for punching after air drying for 7 days;
- A specimen of material treated for punching after air drying for 14 days;
- A specimen of material treated for punching after air drying for 21 days;
- A specimen of material treated for punching after 28 days air drying.

Figure 4. 10. CBR samples of AggreBind treated soil

4.5.1.3. Results of CBR tests at 95% OPM

The data collected during the punching of all 7 specimens is presented in **Appendix 2**. The summary of the results obtained are given in **Table 4.5** and **Table 4.6.**

Tableau 4. 6. Summary of CBR test results for specimens

Résultats essais CBR à 95% de l'OPM						
Nombre de coups	25	25	25	25	25	25

Nombre de jours	0	3	7	14	21	28
Indice CBR	29	30	62	121	146	156
Densité sèche (kg/m3)	1814	1855	1881	1886	1888	1893
Taux de compacité (%)	96	98	100	100	100	100
Teneur en eau (%)	14,7	13,4	10,6	9,8	8,4	7,4

Tableau 4. 7. CBR test results after immersion for 4 days

Nombre de coups	Indice CBR après immersion	Densité sèche (kg/m3)	Gonflement G (%)
25	25	1843	0,22

4.5.2. Interpretation of results

4.5.2.1. Stress-strain curve as a function of time

Punching of the CBR test specimens allows the stress-strain curves to be plotted (see Figure 4.11) and the evolution of the stresses applied to the material to be observed over the curing time.

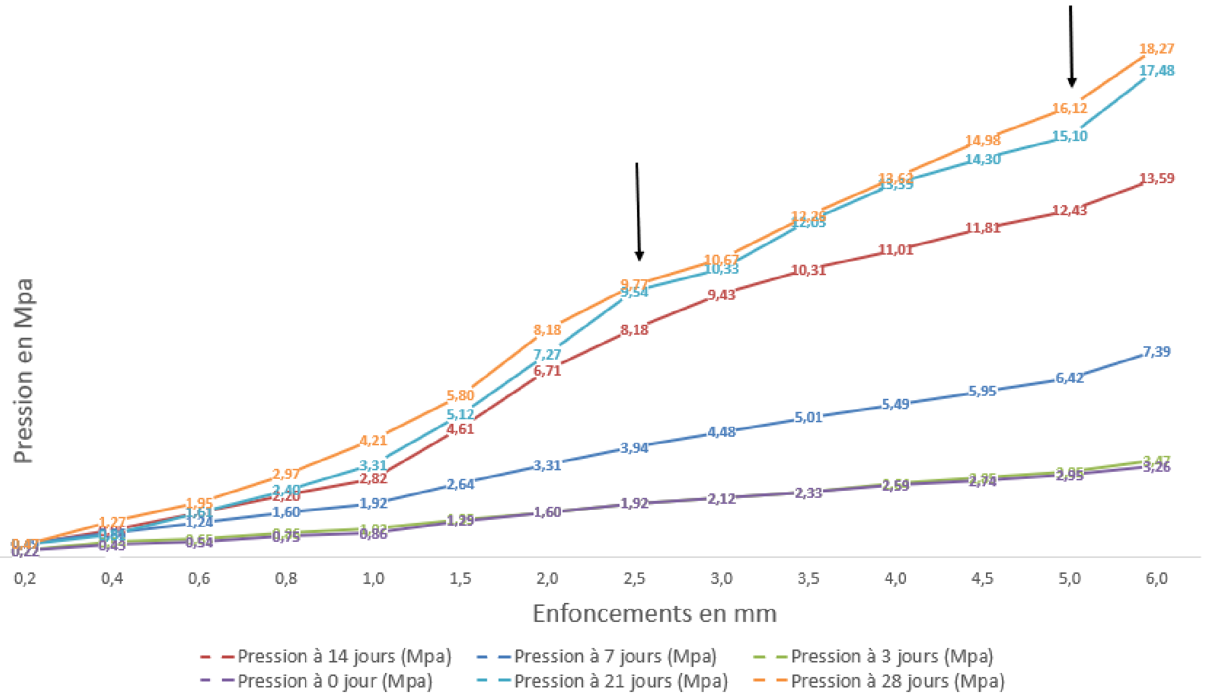


Figure 4. 11. Pressure-strain curves

Figure 4.11 generally shows an increasing evolution of the stresses applied to the treated material from day 1 to day 28, ranging from 2.95 Mpa to 16.12 Mpa at a 2.5mm embedment. Although no stress evolution is observed during the first 3 days, this is due to the fact that the nature of the material remained unchanged but starts to change after the 3rd day causing an abrupt and rapid evolution of the applied stresses for the same deformation.

4.5.2.2. Curve of CBR evolution over time

The evolution of the CBR of the AggreBind treated material over the dry air cure time is shown in Figure 4.12.

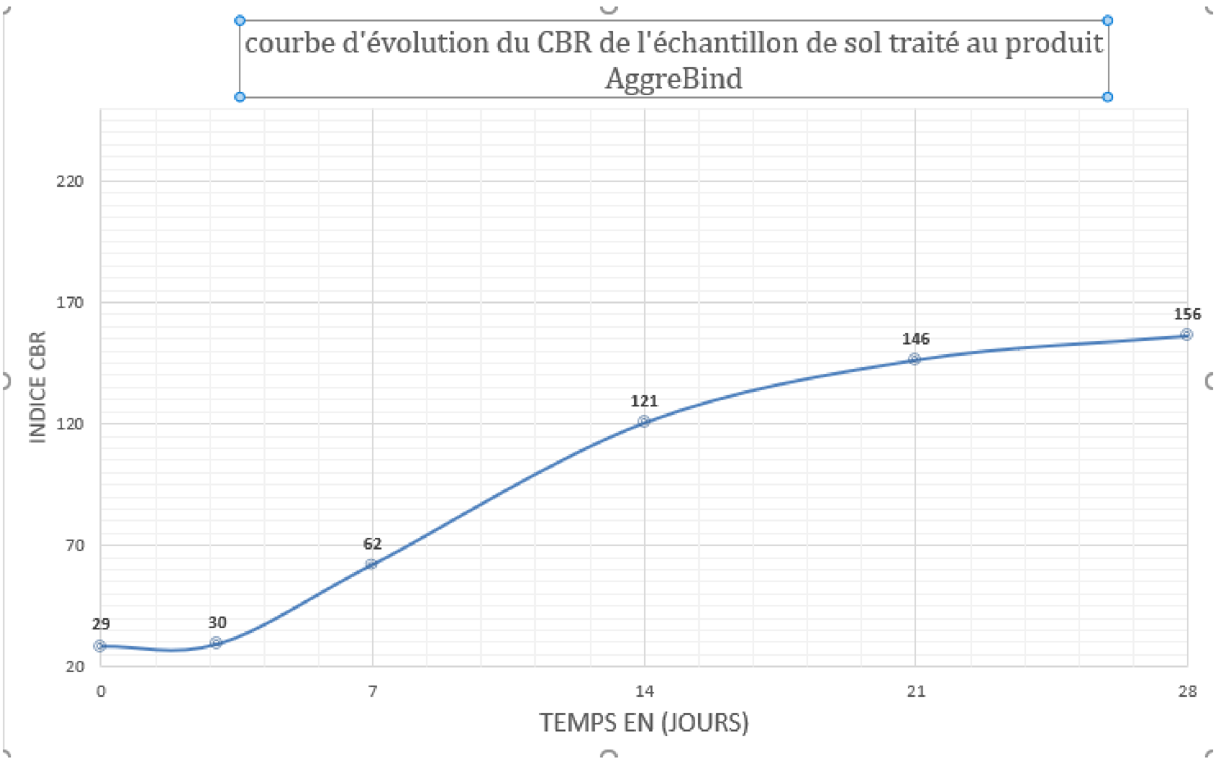


Figure 4. 12. Curve of CBR evolution versus time

After 3 days of curing in dry air, the CBR of the treated material has hardly changed, it remains close to its immediate CBR. From the 7th day of curing there is a sudden and exponential increase of the CBR from 30 to 156 until the 28th day, which shows that the cross-linking of AGB (molecular action) does not start immediately after compaction but about 3 days later and causes the CBR of the material to increase very quickly from 107% to 438%.

4.5.2.3. Dry density evolution curve over time

Figure 4.13 describes the evolution of the dry density of the treated material over the curing time in dry air.

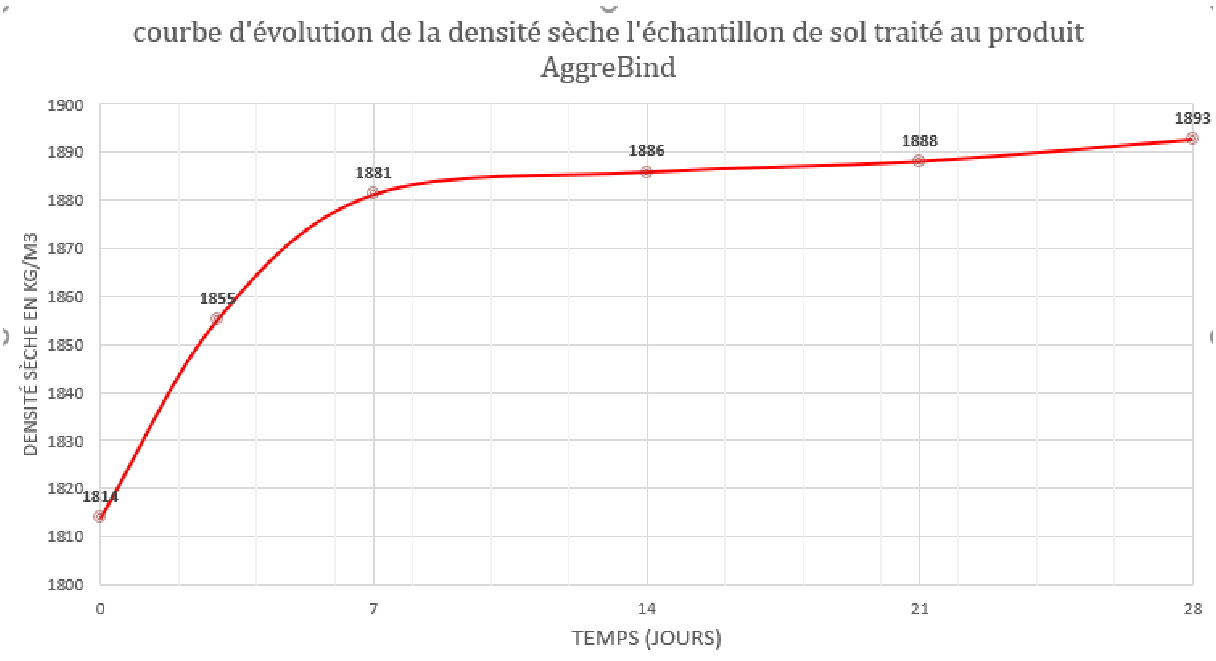


Figure 4. 13. Dry density versus time curve

Figure 4.13 shows an increasing evolution of the dry density of the treated material until day 7 and a slowing down of the growth between day 7 and day 28. This slowing down of growth proves that the treated material is approaching its optimal dry density after treatment of the natural soil, reaching a value well above the maximum dry density of the natural soil. Thus on day 28 the dry density reached is **1893 kg/m3, which** corresponds to a compaction rate of 100.2% for a CBR test performed at 95% of the compaction energy around the modified Proctor optimum.

4.5.2.4. Water content versus time curve

As the water content is variable since the treated material is dried in dry air and at constant temperature, it will be necessary to study its behaviour over time through Figure 4.14**.**

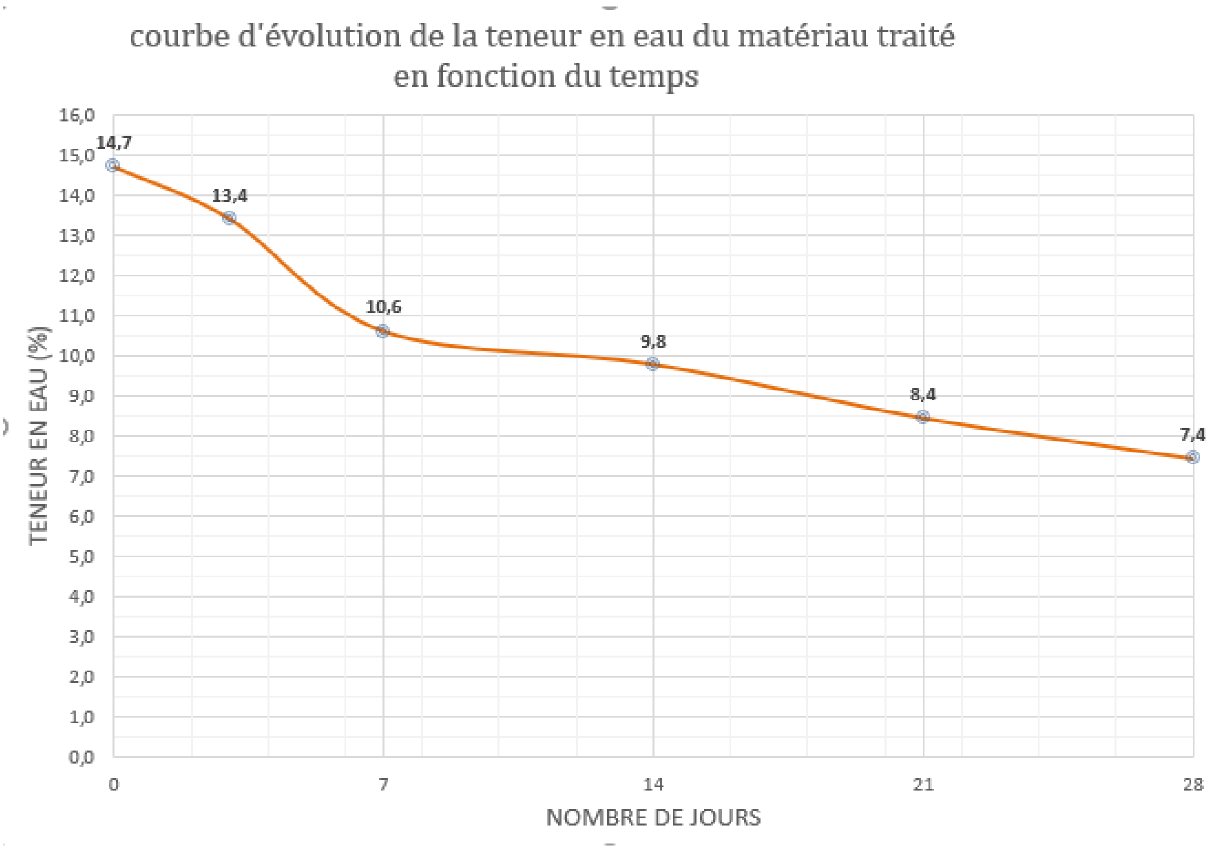


Figure 4. 14. Evolution of the water content of the treated material as a function of time

Figure 4.14 shows a small decrease in water content (1.3%) within 3 days after compaction and then a rapid decrease in water content (2.8%) between days 3 and 7 after compaction. It can be assumed that the cross-linking of AGB, which started on the 3rd day, caused dehydration of the material, which accelerated the decrease of the water content of the material. The decrease in water content becomes gradual again between days 7 and 21, which shows that the molecular reactions of the AGB product with the soil gradually fade away and give way to a natural dehydration of the material by the air.

4.5.3. Summary of results

The results of the soil identification tests identified the soil as an A-4 (2) Low Plastic Clay Silt with an optimum moisture content, maximum dry density, immediate CBR and CBR after immersion of 15%, 1890 Kg/m3, 30 and 23 respectively. The CBR test at 95% OPM (25 strokes) was used to characterize the AggreBind treated material in terms of its bearing capacity. The AggreBind treatment increased the immediate CBR of the natural material from 29 to 156 after 28 days of dry curing. As a result, the dry density of the treated material was also increased to 1893 Kg/m3, giving a final compactness of 100.2% compared to the maximum dry density of the natural material obtained by the Modified Proctor test at 56 strokes.

The CBR index after immersion of the natural material and the treated material being respectively 23 and 25, it follows that the AggreBind product is inactive in the presence of water (wet environment) thus the treated material behaves like the natural material in a wet environment. This conclusion is further proven by the measurement of the swelling of the natural material which is 0.18% and the treated material which is 0.22% as the difference is very small.

In summary, the cross-linking of AGB (molecular action) is initiated as the volume of water in the soil decreases, resulting in a rapid increase in the CBR of the soil. Thus, an increase in CBR of 107% in 7 days, 317% in 14 days, 403% in 21 days and 438% in 28 days is observed as the water content in the treated material rapidly decreases, followed by an increase in its dry density to a compactness of 100.2%.

Thus, the treatment of the soil with AggreBind increased the CBR of our material from 29 to 156 in 28 days, taking it from road soil class **S4** to class **S5.** The use of our treated material on the pavement can be seen in Table 4.8**.**

Tableau 4. 8. Minimum quality requirements for the characteristics of the layers making up the pavement

Couches de chaussées	Granularité	Indice de plasticitéP	Limite de Liquidité	CBR	Gonflement linéaire	Pourcentage de fines	Spécifications
Plateforme		< 40	< 70	> 2	< 2%		dépend de la nature du sol et ne dépend pas du trafic. Et pour les sols devant être traités à la chaux, ciment ou au bitume
Couche de forme	< 150 mm	< 30		> 5 ou >= 10	< 2%	<35 % ou 45%	
Couche de fondations	<= 60 mm	< 30		>= 30 ou 25 pour le trafic T1	<= 2,5 %	< 50%	
Couche de base	<= 50 mm	< 30		>= 80 ou 60 pour le trafic T1	< 2%	< 40%	

This table shows that the granular distribution of the soil, the plasticity index, the linear swelling and the CBR index of the soil obtained after treatment with AGB meets the minimum quality requirements for use in all pavement layers and for all types of traffic. Only the percentage of fines in the material can restrict its use.

4.6. CONCLUSION

In this chapter it was necessary to identify the material used in order to stabilize it with AggreBind and thus increase its mechanical characteristics. As a result, the soil sample used is a class A-4(2) clayey silt with low plasticity, whose 95% OPM modified Proctor characteristics are 15% for optimum water content, 1890 Kg/m3 for maximum dry density and its immediate and after immersion CBR index are 30 and 23 respectively. As the present research was limited to the improvement of the CBR bearing capacity of the soil as it represents a sine qua non condition for the use of the soil in the different pavement layers, it results that the treatment with AggreBind increases the bearing capacity of the soil by more than 438% in 28 days, thus allowing the use of the clayey silt in all the pavement layers and for all types of traffic according to the CCTP related to the project. However, the treatment of the soil with AggreBind can only be done in dry conditions as it does not react in the presence of water (saturated environment) as shown by the results of the CBR test after immersion for 4 days.

5 GENERAL CONCLUSION AND OUTLOOK

Throughout this thesis, the geotechnical properties of a soil stabilized with AggreBind for use in road construction were investigated. The literature review provided information on the soil (generally and geotechnically), all stabilization techniques currently used in road construction and a description of the AggreBind product. The laboratory tests, namely the soil identification tests (particle size analysis, Atterberg limits) identified the soil as a class A-4(2) clayey silt with low plasticity, and the bearing capacity tests (modified Proctor test and CBR) also provided information on the optimal water content of the material (15%), the maximum dry density (1890Kg/m3), the immediate CBR index (30) and the CBR index after immersion for 4 days (23). Only the CBR test at 95% of the OPM was carried out on the soil-AGB-WT mixture in order to characterize the effects of the product on the soil. The results obtained allow us to conclude that there was a progressive increase in the CBR index over time, from 29 on the 1st day to 156 on the 28th day, i.e. an increase of 438% compared to its initial value. The study showed that the treatment of clayey silt subject to our study for use in pavement layers is possible because our treated material at 28 days has the required bearing capacity for use in base courses and can thus replace crushed gravel on certain road sites. But it would be important to respect certain conditions, namely

- For AggreBind treatment, the average dosage is 4 liters of AGB-WT per cubic meter of soil, but this dosage can be more precise as it depends on the percentage of fines in the soil.
- The AggreBind protocol states that the emulsion content (AGB-WT + water mixture) during treatment must correspond to the optimum water content of the natural soil as determined by the Proctor test.
- When carrying out CBR tests in the laboratory, the samples should not be immersed in water as specified in NF P 94-078. This is because the saturation and swelling phase does not apply when using AggreBind.

The ecological and economic benefits of soil treatment are significant, namely: limiting truck movements (removal of spoil) limitation of truck movements (evacuation of excavated material), limitation of the need for materials or the reuse of excavated materials for the creation of an efficient construction site track The technique is simple and effective and can be applied by all types of road construction companies, as AggreBind Inc. offers a free week's training (following a minimum order), which gives enough time to train a road construction team. To follow up on these findings, it can be seen that AggreBind treatment is an effective means of improving infrastructure soils by avoiding costly relocation and environmental pollution. Cameroon would benefit from developing expertise and establishing its own design methods to democratize understanding and application. Future research should address structural design and its integration with current design methods. Considerations of *in-situ* heterogeneity and performance through durability must be placed at the heart of this design. In addition, it would be interesting to explore construction methods and their optimization. It is only with a combination of all these stages, from preliminary design to construction, to commissioning and service life, that the application of this technology has its greatest potential. In order to ensure the objective continuity of this study, we formulate the following perspectives and choices:

- Extend research on other stabilization techniques in road geotechnics and experiment with different dosages;
- An economic study is needed to complete the laboratory study which will allow a comparison between prices and thus a technical and this will allow a comparison between prices and thus a technically and economically justified choice economically justified choice;
- Extend the research to several types of soil and put the results in the form of a database this will make it easier to use the results obtained. A study can be carried out on other materials available in certain regions of Cameroon, such as Cameroon, such as: Karal (in the North and Far North), pozzolan and slag (in the West, Littoral and South-West), rice fiber (in the Far North) or cotton derivatives (grains, shells, powder in the Far North), sugarcane derivatives (in the Central region);
- It is necessary to check the bearing capacity of stabilized materials in the long term because some materials lose their strength gradually over time;
- The modified Proctor and CBR tests may be supplemented by other tests such as simple compression, diametral compression, shear and Atterberg limits after treatment and compaction, etc.
- Conducting a preliminary test board is an excellent way to see the effects of the treatment in real conditions.

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APPENDIX

Appendix 1. Soil sample identification tests data sheets.

ANALYSE GRANULOMETRIQUE PAR TAMISAGE				
Poids initial sec :		**3003,0**	**g**	
Ouverture des tamis en mm	**Masse des refus en (g)**	**POIDS DES REFUS CUMULES (g)**	**POURCENTAGE DES**	
			REFUS CUMULES	**TAMISATS**
20	0	0	0,0	100,0
16	5	5	0,2	99,8
12,5	7	12	0,4	99,6
10	8	20	0,7	99,3
6,3	19	39	1,3	98,7
4	7	46	1,5	98,5
3,15	2	48	1,6	98,4
2,5	2	50	1,7	98,3
0,8	93	143	4,8	95,2
0,63	108	251	8,4	91,6
0,4	343	594	19,8	80,2
0,2	369	963	32,1	67,9
0,160	241	1204	40,1	59,9
0,080	260	1464	48,8	51,2

Analyse granulométrique par sédimentation										
volume de la suspension (cm3)		masse de la prise d'essai m (g)		masse volumique des particules		Pourcentage de passant au tamis de 80 µm				
1000		20		2,7		51,20%				
Données du densimètre										
H0 (cm)	d (cm)	Cm	Ce (cm)		G					
26,8	0,25	0,5	3,2		2,7					
t (secondes)	Temps	lectures		température (°c)	R= A-B	p (%)	Ht (cm)	η (poise)	Dy (mm)	Pourcentage total de passant (%)
		A	B							
						100			0,08	51,2
30	30 sec	10,50	-1,50	21	12,00	96,4	24,1	0,00099	0,0297	49,3
60	1 min	10,20	-1,50	21	11,70	94,0	24,1	0,00099	0,0211	48,1
120	2 min	9,80	-1,50	21	11,30	90,7	24,2	0,00099	0,0149	46,5
180	3 min	9,70	-1,50	21	11,20	89,9	24,3	0,00099	0,0122	46,0
300	5 min	9,60	-1,50	21	11,10	89,1	24,3	0,00099	0,0094	45,6
600	10 min	9,50	-1,60	21	11,10	89,1	24,3	0,00099	0,0067	45,6
1800	30 min	8,90	-1,60	21	10,50	84,3	24,5	0,00099	0,0039	43,2
3600	1 h	8,50	-1,60	21	10,10	81,1	24,6	0,00099	0,0027	41,5
7200	2 h	8,10	-1,60	21	9,70	77,9	24,7	0,00099	0,0019	39,9
10800	3 h	7,90	-1,60	21	9,50	76,3	24,7	0,00099	0,0016	39,1
18000	5 h	7,50	-1,75	21	9,25	74,3	24,8	0,00099	0,0012	38,0
86400	24 h	7,0000	-2,0000	22	9,00	72,3	24,9	0,00097	0,0006	37,0

Limite de liquidité à la coupelle					
poids sec initiale (g)					
200					
Nombre de coups	15	22	26	29	33
N° de la tare	**D4**	**D7**	**K7**	**A5**	**4**
Poids total humide (g)	20,4	14,99	15,900	16,590	16,520
Poids total sec (g)	18,8	14,38	15,31	15,82	15,89
Poids de la tare (g)	12,38	11,86	12,76	12,45	12,96
Poids d'eau (g)	1,6	0,61	0,59	0,770	0,630
Poids de matériau sec (g)	6,42	2,52	2,55	3,370	2,930
Teneur en eau (%)	24,9	24,2	23,1	22,8	21,5

ESSAI DE PROCTOR MODIFIE										
pds matériau initial sec	6000	g								
volume du moule	2758	cm3								
N° tare	A12	N13	N7	C2	N15	Z5	ZA	N10	E2	3I
Pds total humide (g)	51,0	53,3	48,6	57,5	63,7	65,7	65,4	64,94	72,6	73,2
Pds total sec (g)	47,8	50,4	45,4	53,5	58,4	60,1	58,9	58,0	64,18	64,1
Pds de la tare (g)	19,6	23,6	20,8	23,8	23,8	23,8	23,8	20,34	23,6	20,97
Pds d'eau (g)	3,2	2,95	3,22	3,94	5,3	5,58	6,48	6,92	8,37	9,03
Pds mat. Sec (g)	28,26	26,71	24,63	29,76	34,63	36,32	35,18	37,68	40,57	43,15
Teneur en eau (%)	11,3	11,0	13,1	13,2	15,3	15,4	18,4	18,4	20,6	20,9
Moyenne(%)	**11,2**		**13,2**		**15,3**		**18,4**		**20,8**	
Pds Mat. + Moule (g)	13340		13980		14260		13940		13760	
Pds du Moule (g)	8260		8260		8260		8260		8260	
Pds du mat. (g)	5080		5720		6000		5680		5500	
Densité Hum. (T/m3)	1,84		2,07		2,18		2,06		1,99	
Densité Sèche (T/m3)	**1,66**		**1,83**		**1,89**		**1,74**		**1,65**	
Poids Spécifique (T/m^3)	**2,70**									

CBR immédiat à 95% de l'OPM						
Compactage		**25 Coups**				
N° Moules				**TENEUR EN EAU**		
GONFLEMENT	**L 0**				**immédiat**	
	L 1			**N° Tare**	**3I**	**A12**
	L 1-L0			**Pds Humide (g)**	34,9	33,3
	G (1/100)			**Pds Sec (g)**	33,3	31,6
ENFONCEMENT (1/100 mm)		**Lectures sur l'anneau**	**Effort (KN)**	**Pds Tare (g)**	21,0	19,6
				Pds Eau (g)	1,7	1,6
	0,2	3,0	0,6	***P.mat.sec (g)***	12,3	12,1
	0,4	4,0	0,8	***Teneur en eau (%)***	13,5	13,6
	0,6	6,0	1,3	***Moy.***	13,5	
	0,8	8,0	1,7			
	1,0	10,0	2,1	**N° Moule**		**ZAMBA**
	1,5	12,0	2,5	**Mode de Compactage**		**25coups**
	2,0	16,0	3,3	**Pds Humide (g)**		13980
	2,5	19,0	3,9	**Poids moule (g)**		8260
	3,0	22,0	4,5	***Poids mat.(g)***		5720
	3,5	24,0	4,9	**Volume Moule (g)**		2758
	4,0	26,0	5,3	***γh(T/m³)***		2,07
	4,5	28,0	5,7	**γd(T/m³)**		1,83
	5,0	29,0	5,9	***Compacité(%)***		**97%**
	6,0	33,0	6,7	**Pds moulage après im.**		
	7,0	34,5		***Pds d'eau absorbé***		
	8,0	37		***Taux d'imbibition (%)***		
	9,0	39				
	10,0	41		**Densité Proctor (opm) (KG/m3)**		**1827**
				Teneur en eau à l'OPM (%)		**13,5%**

CBR à 95% de l'OPM après immersion								
Compactage		25 Coups		TENEUR EN EAU				
N° Moules								
GONFLEMENT	L 0	0		Avant immersion			Après immersion	
	L 1	22					25cps	
	L 1-L0	0,22		N° Tare	C	N5	N15	N5
	G (1/100)	0,18%		Pds Humide (g)	50,0	46,0	40,3	36,3
		Lecture sur le comparateur	Effort (KN)	Pds Sec (g)	46,6	42,7	38,2	34,1
				Pds Tare (g)	23,7	20,0	23,73	19,96
ENFONCEMENT (1/100 mm)	**0,2**	4,0	0,8	*Pds Eau (g)*	3,4	3,4	2,2	2,2
	0,4	5,5	1,1	*P.mat.sec (g)*	22,9	22,7	14,4	14,2
	0,6	5,8	1,2	*Teneur en eau (%)*	14,7	14,8	15,0	15,3
	0,8	8,0	1,7	*Moyenne*	14,8		15,1	
	1,0	9,0	1,9					
	1,5	11,0	2,3	N° Moule			**ZAMBA**	
	2,0	13,3	2,8	Mode de Compactage			**25coups**	
	2,5	15,0	3,1	Pds Humide après im. (g)			14400	
	3,0	16,2	3,3	Poids moule (g)			9500	
	3,5	18,0	3,7	*Poids mat. (g)*			4900	
	4,0	19,2	3,9	Volume Moule (g)			2268	
	4,5	20,5	4,2	*γh(T/m ^{3})*			2,16	
	5,0	21,2	4,3	γd(T/m^3)			1,88	
	6,0	22,9	4,7	*Compacité(%)*			**99%**	
	7,0	24,1		Pds moulage avant im. (g)			14340	
	8,0	25,2		*Pds d'eau absorbé (g)*			60	
	9,0	26		*Taux d'imbibition (%)*			1,2	
	10,0	27		Densité Proctor (opm) (KG/m3)			**1877**	
				Teneur en eau à l'OPM (%)			**14,8%**	

Appendix 2. Data sheet of the CBR tests carried out on the soil sample treated with AggreBind product.

CBR à 95% du matériau traité après immersion								
Compactage		25 Coups						
N° Moules				TENEUR EN EAU				
GONFLEMENT	L 0	0		Avant immersion			Après immersion	
	L 1	28			25cps		25cps	
	L 1-L0	0,28		N° Tare	Z	3l	3l	Z2
	G (1/100)	0,22%		Pds Humide (g)	51,5	46,6	42,3	38,5
		Lectures sur le comparateur	Effort (KN)	Pds Sec (g)	47,5	43,3	39,2	36,5
				Pds Tare (g)	19,9	21,0	21,0	23,7
ENFONCEMENT (1/100 mm)	0,2	4,5	0,9	*Pds Eau (g)*	4,1	3,3	3,1	2,0
	0,4	7,2	1,5	*P.mat.sec (g)*	27,6	22,3	18,3	12,8
	0,6	8,5	1,8	*Teneur ene eau (%)*	14,7	14,7	16,9	15,6
	0,8	9,8	2,0	*Moyenne.*	14,7		16,3	
	1,0	11,0	2,3					
	1,5	13,1	2,7	N° Moule			Zamba	
	2,0	15,0	3,1	Mode de Compactage			25coups	
	2,5	16,5	3,4	Pds Humide après immersion (g)			14500	
	3,0	17,9	3,7	Poids moule (g)			9640	
	3,5	19,0	3,9	*Poids mat. (g)*			4860	
	4,0	19,8	4,1	Volume Moule (cm3)			2268	
	4,5	20,5	4,2	*γh(T/m ^{3})*			2,14	
	5,0	21,3	4,4	γd(T/m^3)			1,84	
	6,0	22,5	4,6	*Compacité(%)*			**95%**	
	7,0	24		Pds moulage avant im. (g)			14460	
	8,0	24,9		*Pds d'eau absorbé (g)*			40	
	9,0	25,1		*Taux d'imbibition (%)*			0,8	
	10,0	26,2						
				Densité Proctor (opm) (Kg/m3)			**1843**	
				Teneur en eau à l'OPM (%)			**14,7%**	

CBR immédiat à 95% de l'OPM du matériau traité						
Compactage		**25 Coups**				
N° Moules				**TENEUR EN EAU**		
GONFLEMENT	**L 0**			**Immédiat**		
	L 1					
	L 1-L0			**N° Tare**	**N7**	**ZA**
	G (1/100)			**Pds Humide**	51,5	46,6
		Lecture sur le comparateur	**Effort (KN)**	**Pds Sec**	47,5	43,3
				Pds Tare	19,9	21,0
ENFONCEMENT (1/100 mm)	**0,2**	2,0	0,4	***Pds Eau***	4,1	3,3
	0,4	4,0	0,8	***P.mat.sec***	27,6	22,3
	0,6	5,0	1,0	***Teneur en eau (%)***	14,7	14,7
	0,8	7,0	1,5	***Moyenne***	14,7	
	1,0	8,0	1,7			
	1,5	12,0	2,5	**N° Moule**	**JSUS**	
	2,0	15,0	3,1	**Mode de Compactage**	**25coups**	
	2,5	18,0	3,7	**Pds Humide**	14120	
	3,0	20,0	4,1	**Poids moule**	8380	
	3,5	22,0	4,5	***Poids mat.***	5740	
	4,0	24,5	5,0	**Volume Moule**	2758	
	4,5	26,0	5,3	*γh(T/m³)*	2,08	
	5,0	28,0	5,7	**γd(T/m³)**	1,81	
	6,0	31,0	6,3	***Compacité(%)***	**96%**	
	7,0	33,5		**Pds moulage après im.**		
	8,0	**35,5**		***Pds d'eau absorbé***		
	9,0	**36**		***Taux d'imbibition (%)***		
	10,0	**39**				
				Densité Proctor (opm) (Kg/m3)	**1814**	
				Teneur en eau à l'OPM (%)	**14,7%**	

CBR à 95% après 3 jours						
Compactage		**25 Coups**				
N° Moules				**TENEUR EN EAU**		
GONFLEMENT	**L 0**			**Après 3 jours**		
	L 1					
	L 1-L0			**N° Tare**	**C2**	**E1**
	G (1/100)			**Pds Humide (g)**	47,8	37,5
		Lecture sur l'anneau	**Effort (KN)**	**Pds Sec (g)**	45,0	35,6
				Pds Tare (g)	23,8	20,9
ENFONCEMENT (1/100 mm)	**0,2**	2,0	0,4	***Pds Eau (g)***	2,8	2,0
	0,4	5,0	1,0	***P.mat.sec (g)***	21,2	14,7
	0,6	6,0	1,3	***Teneur en eau (%)***	13,4	13,3
	0,8	8,0	1,7	***Moyenne***	13,4	
	1,0	9,5	2,0			
	1,5	12,5	2,6	**N° Moule**	**ZAMBA**	
	2,0	15,0	3,1	**Mode de Compactage**	**25coups**	
	2,5	18,0	3,7	**Pds Humide (g)**	14180	
	3,0	20,0	4,1	**Poids moule (g)**	8380	
	3,5	22,0	4,5	***Poids mat. (g)***	5800	
	4,0	25,0	5,1	**Volume Moule (cm3)**	2758	
	4,5	27,0	5,5	**γh(T/m^3)**	2,10	
	5,0	29,0	5,9	**γd(T/m^3)**	1,86	
	6,0	33,0	6,7	***Compacité(%)***	**98%**	
	7,0	36		**Pds moulage après im. (g)**		
	8,0	**39,5**		***Pds d'eau absorbé (g)***		
	9,0	**42**		***Taux d'imbibition (%)***		
	10,0	**44,5**		**Densité Proctor (opm) (Kg/m3)**	**1855**	
				Teneur en eau à l'OPM (%)	**13,4%**	

CBR à 95% de l'OPM après 7 jours						
Compactage		**25 Coups**				
N° Moules				**TENEUR EN EAU**		
GONFLEMENT	**L 0**			**Après 7 jours**		
	L 1					
	L 1-L0			**N° Tare**	**C2**	**C**
	G (1/100)			**Pds Humide (g)**	29,6	33,3
		Lecture sur le comparateur	**Effort (KN)**	**Pds Sec (g)**	29,1	32,4
				Pds Tare (g)	23,8	23,7
ENFONCEMENT (1/100 mm)	**0,2**	4,5	0,9	***Pds Eau (g)***	0,6	0,9
	0,4	8,0	1,7	***P.mat.sec (g)***	5,3	8,7
	0,6	11,5	2,4	***Teneur en eau (%)***	10,8	10,4
	0,8	15,0	3,1	***Moyenne***	10,6	
	1,0	18,0	3,7			
	1,5	25,0	5,1	**N° Moule**	**ZAMBA**	
	2,0	31,5	6,4	**Mode de Compactage**	**25coups**	
	2,5	37,5	7,6	**Pds Humide (g)**	8820	
	3,0	42,5	8,6	**Poids moule (g)**	4440	
	3,5	47,5	9,7	***Poids mat. (g)***	4380	
	4,0	52,0	10,6	**Volume Moule (cm3)**	2105	
	4,5	56,5	11,5	*$\gamma h(T/m^3)$*	2,08	
	5,0	61,0	12,4	$\gamma d(T/m^3)$	1,88	
	6,0	70,0	14,3	***Compacité(%)***	**100%**	
	7,0	77		**Pds moulage après im. (g)**		
	8,0	83,5		***Pds d'eau absorbé (g)***		
	9,0	89,2		***Taux d'imbibition (%)***		
	10,0	94		**Densité Proctor (opm) (Kg/m3)**	**1881**	
				Teneur en eau à l'OPM (%)	**10,6%**	

CBR à 95% de l'OPM après 14 jours						
Compactage		**25 Coups**				
N° Moules				**TENEUR EN EAU**		
GONFLEMENT	**L 0**			**Après 14 jours**		
	L 1			**N° Tare**	**Z**	**B1**
	L 1-L0			**Pds Humide (g)**	54,0	65,8
	G (1/100)			**Pds Sec (g)**	51,0	61,7
ENFONCEMENT (1/100 mm)		**Lectures sur l'anneau**	**Effort (KN)**	**Pds Tare (g)**	19,9	20,3
				Pds Eau (g)	3,0	4,1
	0,2	5,0	0,9	***P.mat.sec (g)***	31,1	41,4
	0,4	9,3	1,8	***Teneur en eau (%)***	9,8	9,8
	0,6	15,0	3,1	***Moyenne***	9,8	
	0,8	20,3	4,3			
	1,0	25,8	5,5	**N° Moule**		**ZAMBA**
	1,5	41,5	8,9	**Mode de Compactage**		**25coups**
	2,0	60,0	13,0	**Pds Humide (g)**		13970
	2,5	73,0	15,8	**Poids moule (g)**		8260
	3,0	84,0	18,2	***Poids mat. (g)***		5710
	3,5	91,8	19,9	**Volume Moule (cm3)**		2758
	4,0	98,0	21,3	*γh(T/m ^{3})*		2,07
	4,5	105,0	22,8	γd(T/m ^{3})		1,89
	5,0	110,5	24,0	***Compacité(%)***		**100%**
	6,0	120,8	26,3	**Pds moulage après im. (g)**		
	7,0			***Pds d'eau absorbé (g)***		
	8,0			***Taux d'imbibition (%)***		
	9,0			**Densité Proctor (opm) (KG/m3)**		**1886**
	10,0			**Teneur en eau à l'OPM (%)**		**9,8%**

CBR à 95% de l'OPM après 21 jours						
Compactage		**25 Coups**				
N° Moules				**TENEUR EN EAU**		
GONFLEMENT	**L 0**			**Après 21 jours**		
	L 1			**N° Tare**	**2A**	**6**
	L 1-L0			**Pds Humide (g)**	79,1	69,6
	G (1/100)			**Pds Sec (g)**	75,1	65,8
ENFONCEMENT (1/100 mm)		**Lectures sur l'anneau**	**Effort (KN)**	**Pds Tare (g)**	26,7	21,6
				Pds Eau (g)	4,0	3,8
	0,2	5,0	0,9	***P.mat.sec (g)***	48,4	44,2
	0,4	8,0	1,6	***Teneur en eau (%)***	8,3	8,5
	0,6	15,0	3,1	***Moyenne***	8,4	
	0,8	22,0	4,6			
	1,0	30,0	6,4	**N° Moule**		**ZAMBA**
	1,5	46,0	9,9	**Mode de Compactage**		**25coups**
	2,0	65,0	14,1	**Pds Humide (g)**		8750
	2,5	85,0	18,4	**Poids moule (g)**		4440
	3,0	92,0	20,0	***Poids mat. (g)***		4310
	3,5	107,0	23,3	**Volume Moule (cm3)**		2105
	4,0	119,0	25,9	***γh(T/m ^{3})***		2,05
	4,5	127,0	27,6	**γd(T/m^3)**		1,89
	5,0	134,0	29,2	***Compacité(%)***		**100%**
	6,0	155,0	33,8	**Pds moulage après im. (g)**		
	7,0			***Pds d'eau absorbé (g)***		
	8,0			***Taux d'imbibition (%)***		
	9,0			**Densité Proctor (opm) (KG/m3)**		**1888**
	10,0			**Teneur en eau à l'OPM (%)**		**8,4%**

CBR à 95% de l'OPM après 28 jours						
Compactage		25 Coups				
N° Moules				TENEUR EN EAU		
GONFLEMENT	L 0			Après 28 jours		
	L 1			N° Tare	2A	6B
	L 1-L0			Pds Humide (g)	81,2	66,7
	G (1/100)			Pds Sec (g)	77,5	63,6
ENFONCEMENT (1/100 mm)		Lectures sur l'anneau	Effort (KN)	Pds Tare (g)	26,7	21,5
				Pds Eau (g)	3,8	3,1
	0,2	5,0	0,9	*P.mat.sec (g)*	50,8	42,1
	0,4	12,0	2,4	*Teneur en eau (%)*	7,4	7,4
	0,6	18,0	3,8	*Moyenne*	7,4	
	0,8	27,0	5,7			
	1,0	38,0	8,1	N° Moule		ZAMBA
	1,5	52,0	11,2	Mode de Compactage		25coups
	2,0	73,0	15,8	Pds Humide (g)		8700
	2,5	87,0	18,9	Poids moule (g)		4420
	3,0	95,0	20,6	*Poids mat. (g)*		4280
	3,5	109,0	23,7	Volume Moule (cm3)		2105
	4,0	121,0	26,3	*γh(T/m ^{3})*		2,03
	4,5	133,0	28,9	γd(T/m^3)		1,89
	5,0	143,0	31,1	*Compacité(%)*		100%
	6,0	162,0	35,3	Pds moulage après im. (g)		
	7,0			*Pds d'eau absorbé (g)*		
	8,0			*Taux d'imbibition (%)*		
	9,0			Densité Proctor (opm) (KG/m3)		1893
	10,0			Teneur en eau à l'OPM (%)		7,4%