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# THÈSE

Présentée pour l’obtention du diplôme de

## DOCTORAT EN SCIENCES

Spécialité**: Génie Civil**

Par
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Thème

# Comportement des édifices en matériaux locaux sous l'effet des actions accidentelles et climatiques : vers une réhabilitation des constructions

Soutenue le 16/02/2023 devant le jury composé de :

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## Abstract

**Title**: **Behavior of edifices in local materials under the influence of accidental and climatic actions: Towards rehabilitation, repair, and maintenance**

Many earthen buildings are in such a vulnerable situation that makes the permanent loss of this heritage only a matter of time. The lack of proper maintenance caused by economic and social changes, together with the fragility of the material itself, are the main threats of this heritage. Therefore, it is necessary to find new intervention techniques for earthen buildings. Preservation of earthen constructions is challenging because the durability capacity of this structural system is significantly instable in presence of water, as it has been demonstrated in previous floods worldwide. The objective of the present work is to investigate the possibility of stabilizing the soil with cheap, easily available and renewable local raw materials such as lime and cement. Human hair fibers, chicken feather fibers can be used to reinforce rammed earth leading to improved performances of the building material. It is also studied in this thesis, the valorization of the tuffs in the building construction as well as for use as a component in the foundation layers of road structures.

The experimental work includes two parts. The first one is carried out at the University of Houston Texas (USA) using Bentonite, kaolinite, Fly ash, Crushed Bricks, Sand and Cement. The second one is conducted at the University of Chlef using tuff, cement, lime and clay from Zebabdja quarry for brick making. After the characterization of the materials, the tests performed included compaction test, unconfined compression, liquid limit, and plastic limit by using different mixtures of kaolinite and sand, Bentonite and sand, and Bentonite, kaolinite and sand. The results found show that specimens stabilized by lime showed higher failure strain than those stabilized by cement. The inclusion of the chicken feather fibers into the treated soil (clay) has improved the compressive strength of the clay three times compared to that of the untreated soil and the best performance was obtained at 2% of fiber content. The compaction curves show strong improvements in the characteristics obtained by adding cement to the tuff than with the tuff alone.



**Keywords:** Earth, Construction material, Fibers reinforcement, Stabilization, Strength, human hair fibers, chicken feather fibers.

**خلاصة**

## العنوان: سلوك الصروح في المواد المحلية تحت تأثير الأحداث العرضية والمناخية: نحو إعادة التأهيل والإصلاح والصيانة

يعتبر العديد من المباني الترابية في وضع ضعيف يجعل الخسارة الدائمة لهذا التراث مسألة وقت فقط. إن الافتقار إلى الصيانة المناسبة بسبب التغيرات الاقتصادية والاجتماعية ، إلى جانب هشاشة المواد نفسها ، هي التهديدات الرئيسية لهذا التراث. لذلك ، من الضروري إيجاد تقنيات تدخل جديدة للمباني الترابية. يعد الحفاظ على الإنشاءات الترابية أمرًا صعبًا لأن قدرة التحمل لهذا النظام الهيكلي غير مستقرة بشكل كبير في وجود الماء ، كما ثبت في الفيضانات السابقة في جميع أنحاء العالم. الهدف من العمل الحالي هو التحقيق في إمكانية تثبيت التربة بمواد خام محلية رخيصة ومتوفرة بسهولة ومتجددة مثل الجير والإسمنت. يمكن استخدام ألياف شعر الإنسان ، وألياف ريش الدجاج لتقوية الأرض المحطمة مما يؤدي إلى تحسين أداء مواد البناء. كما تمت دراسته في هذه الأطروحة، تثمين الطبقات في تشييد المباني وكذلك لاستخدامها كعنصر في طبقات الأساس لهياكل الطرق.

يتكون العمل التجريبي من جزأين. تم إجراء أول تجربة في جامعة هيوستن تكساس (الولايات المتحدة الأمريكية) باستخدام البنتونيت والكاولين والرماد المتطاير C والطوب المكسر والرمل والإسمنت. أما الاختبار الثاني فقد تم إجراؤه في جامعة الشلف باستخدام الطوف والإسمنت والجير والطين من مقلع زبابجة لصناعة الطوب. بعد توصيف المواد ، تضمنت الاختبارات التي تم إجراؤها اختبار الضغط ، والضغط غير المحصور ، وحد السائل ، وحد اللدونة باستخدام خلائط مختلفة من الكاولينيت والرمل، البنتونيت والرمل، والبنتونيت والكاولين والرمل. أظهرت النتائج أن العينات المستقرة بواسطة الجير أظهرت إجهاد فشل أعلى من تلك المثبتة بواسطة الإسمنت. أدى إدراج ألياف ريش الدجاج في التربة المعالجة (الطين) إلى تحسين مقاومة الانضغاط للطين ثلاث مرات مقارنةً بالتربة غير المعالجة وتم الحصول على أفضل أداء عند 2% من محتوى الألياف. تُظهر منحنيات الضغط تحسينات قوية في الخصائص التي تم الحصول عليها عن طريق إضافة الإسمنت إلى الطف مقارنةً مع الطف وحده.



الكلمات المفتاحية: التراب، مواد البناء، تقوية الألياف، التثبيت، القوة، ألياف الشعر البشري، ألياف ريش الدجاج.

## Résumé

**Titre : Comportement des édifices en matériaux locaux sous l'influence des actions accidentelles et climatiques : vers la réhabilitation, la réparation et l'entretien**

De nombreux bâtiments en terre sont dans une situation si vulnérable que la perte permanente de ce patrimoine n'est qu'une question de temps. Le manque d'entretien adéquat causé par les changements économiques et sociaux, ainsi que la fragilité du matériau lui-même, sont les principales menaces de ce patrimoine. Il est donc nécessaire de trouver de nouvelles techniques d'intervention pour les constructions en terre. La préservation des constructions en terre est un défi car la capacité de durabilité de ce système structurel est considérablement instable en présence d'eau, comme cela a été démontré lors d'inondations précédentes dans le monde entier. L'objectif du présent travail est d'étudier la possibilité de stabiliser le sol avec des matières premières locales bon marché, facilement disponibles et renouvelables telles que la chaux et le ciment. Les fibres de cheveux humains, les fibres de plumes de poulet peuvent être utilisées pour renforcer le pisé, ce qui améliore les performances du matériau de construction. Il est également étudié dans cette thèse, la valorisation des tufs dans la construction de bâtiments ainsi que pour une utilisation comme composant dans les couches de fondation des ouvrages routiers.

Le travail expérimental comprend deux parties. Le premier est réalisé à l'Université de Houston au Texas (USA) en utilisant de la bentonite, de la kaolinite, des cendres volantes, des briques concassées, du sable et du ciment. La seconde est menée à l'Université de Chlef en utilisant du tuf, du ciment, de la chaux et de l'argile de la carrière de Zebabdja pour la fabrication de briques. Après la caractérisation des matériaux, les tests effectués comprenaient le test de compactage, la compression non confinée, la limite de liquidité et la limite plastique en utilisant différents mélanges de kaolinite et de sable, de bentonite et de sable, et de bentonite, de kaolinite et de sable. Les résultats trouvés montrent que les éprouvettes stabilisées à la chaux ont montré des déformations à la rupture plus élevées que celles stabilisées au ciment. L'inclusion des fibres de plumes de poulet dans le sol traité (argile) a amélioré la résistance à la compression de l'argile trois fois par rapport à celle du sol non traité et la meilleure performance a été obtenue à 2% de teneur en fibres. Les courbes de compactage montrent de fortes améliorations des caractéristiques obtenues en ajoutant du ciment au tuf par rapport au tuf seul.

**Mots-clés** : Terre, Matériau de construction, Renforcement des fibres, Stabilisation, Résistance, fibres de cheveux humains, fibres de plumes de poulet.

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| | |
|---|---|
| E | Modulus of Elasticity |
| LL | Liquid Limit |
| PL | Plastic Limit |
| PI | Plasticity Index |
| $I_p$ | Plasticity Index |
| MDD | Max Dry Density |
| UCS | Unconfined compressive strength |
| Cu | Coefficient Of Uniformity |
| BCD | Briaud Compaction Device |
| CS | Control Soil |
| UEO | Used Engine Oil |
| Wop | optimumWater Content |
| $\gamma_d$ | Dry Density Max |
| $CaCO_3$ | Calcium Carbonate Content |
| OMC | Optimum Moisture Content |
| UCS | Unconfined Compressive Strength |
| Wm | Manufacture water content |
| Wop | Optimum Proctor water content |
| WP | Water content at plastic limit |
| WL | Water content at liquid limit |

# Chapter 1: Introduction

# Chapter 1: Introduction

## 1.1 Background to the research

Heritage buildings have significant cultural value and correspond to a legacy that must be preserved for future generations. Worldwide, heritage buildings of most civilizations use earth as a structural material. Raw earth is one of the most ancient building materials and its related building techniques are spread worldwide. In fact, about between 20% and 33% of the global population is estimated to live in earthen constructions, while about 10% of UNESCO World Heritage is built with earth. Acknowledging the importance of earthen structures, the UNESCO approved a thematic program on earthen architecture and by 2007, launched the World Heritage Earthen Architecture Program (WHEAP) thanks to this many centennial earthen edifices in Algeria were included in the world heritage list in 2010 and others are on the waiting list. These are only a handful of the vast amount of earthen buildings that provide shelter to around a third of the world population. In south Algeria as well as Africa most historic structures were built using local materials nearby the construction site that is rocks and earth materials typical historic houses were built by either adobe or rammed earth (RE) masonry walls that support either a wooden floor or a heavy roof system. Rammed earth (or “tabia” in Algeria, “pisé” in France or “terra compressa” in Italy) is a building technique where a mixture of moistened earth is compacted within a temporary formworks. The result of this process is a large size masonry unit. Besides monuments, rammed earth technique was widely used also for affordable dwellings in response to the large housing demand, as for instance in South Algeria, where a considerable vernaculaire heritage is found.

From sustainability perspective, earthen structures provide several favorable characteristics for buildings construction when compared to conventional materials such as concrete, steel or wood:

- They provide effective thermal insulation and moisture regulation;
- Their construction does not require the use of scarce fuel;
- Their energy consumption during construction is minimum;
- They do not need skilled labor;
- Earth itself is a recyclable/sustainable source.

Therefore, the motivation to preserve existing structures goes beyond the historic conservation intention. Indeed, the built heritage and the various construction techniques around the world, such as the centuries-old 8-storey earthen buildings of Shebam/Yemen (Bahobail, 2012), show the full potential of this material. The major arguments for the reconsideration of this building material, after nearly a century of abandonment in developed countries in favor of cementitious materials, are its ecological and socio-economic advantages as well as its hygroscopic properties. Minke et al., (2009); Houben et al., (2006); Morton et al., (2008) detail all these qualities of raw earth. In fact, there are several countries worldwide that have already standardized either new construction or retrofitting existing earthen buildings. Some examples are Peru, Australia, New Zealand, USA (New Mexico), Germany, Spain and recently, Colombia.

Preservation of earthen constructions is challenging because the durability capacity of this structural system is significantly instable in presence of water, as it has been demonstrated in previous floods worldwide.

The instigator of this research work is the experience the author has had on the ground after a trip to the Wilaya (Province) of Bechar Algeria, where he visited the ksour of Taghit and Kenadsa. The walls of mud of the ksour made from earth are unable to withstand harsh rainy seasons even after rehabilitation. Figure 1.1 shows the kind of cracks that appear on the walls due to extreme shrinkage. Cracks appear because the soil particles are not held together with sufficient bonding strength. Given that moisture from rainfall is the main cause of cracking and other durability problems associated with handmade earth blocks or rammed walls, it was important to investigate the possibility of stabilizing the soil with cheap, easily available and renewable local raw materials.

Past researchers, as will be surveyed in chapter 2, have shown that use of traditional hydraulic stabilizers like cement or lime or waterproofing agents like bitumen do significantly improve the strength of rammed earth walls or rammed earth. These additives are, however, accompanied by increase in costs of material; this is not sustainable especially for the poor rural communities of the developing nations. It is the aim of the present investigation to show that these traditional binders can be replaced by environmentally friendly and sustainable alternatives i.e. earthen masonry walls and uncovering earthen masonry walls. Figure 1.2 depicts this stated idea.

*Figure 1. 1 - Pictorial illustration of the research background.*

(a)

(b)

*Figure 1. 2 - (a) Earthen masonry walls in compaction within formworks (b) Uncovering Earthen masonry walls.*

## 1.2 Hypotheses

• Lime and cement as stabilizing or reinforcing agent in preparation of rammed earth walls (see Figure 1.3 (a) and (b)).

• Indigenous raw materials, thus, soil, human hair or chicken feather fibers found in abundance in the developing nations can be used to develop a cost-effective building material composite for housing construction and rehabilitation purposes.

• Human hair fibers as well as chicken feather fibers, shown in Figure 1.3 (c) and (d), can be used to reinforce rammed earth leading to increased strength and reduced shrinkage consequently improving the durability.

• It is possible to develop a simple on -sight testing method -suitable for rural areas (without laboratory)-for the building materials strength and therefore durability based on a conversion factor (function).

(a) Cement

(b) Lime

(c) Human hair fibers

(d) Chicken feather fibers

*Figure 1. 3 - Proposed materials for research purposes*

**1.3 Motivation for the present study**

The subject of this study falls under what is now considered in many circles as appropriate technology. The term refers to application of techniques that best fit a particular people, community or society; this is, in part pegged to economic conditions, availability or raw materials, cultural orientation and geo-climatic environmental conditions. With respect to building materials, Mathey (1983) considers appropriate technology, as the application of techniques appropriate to the user, society and nature.

Appropriate construction reflects therefore to the concept of -Ecological Building- Other schools of thought put appropriate technology at par with -Alternative technology- A term used to describe some compromise situation between the very high technologies of the developed societies and the low technologies associated with the poor economies (Spence, 1982). Principal characteristics of intermediate technologies are that they are cheap, small in scale and use relatively simple production methods from locally available raw materials. Appropriate or alternative technologies are therefore seen to be in harmony with nature, and have as a prime orientation, to provide sustainable solutions to issues related to human development.

The need to provide more housing for the world`s poor societies cannot be over emphasized.

Shelter is, after all, a basic requirement of human being. As concerns the developing nations, it is already recognized that the huge housing requirement cannot be met with industrially produced building materials (Minke, 2000). Indeed, 25% of the world`s population does not have any fixed abode, while 50% of the urban population live in slums (Kerali, 2001). In spite of the many effort such as global strategy for housing by the year 2000.declaration by the UN, the shelter issue remains a major problem, and hence the need to look at possible solutions including scientific research.

It is most likely that the majority of the people in the developing world will, out of necessity, continue to live in mud (earth) houses, consequently, ways of improving on this traditionally built mud houses are a subject of concern to many researchers. Compressed earth block (CEB) construction is one of the most widely used technologies in building with earth and has been adopted as the Improvement to rammed mud houses. The key future of the technology is the compression of the soil in a mold with the help of a press at a compaction effort of 2-4 $MN/m^2$ (Mukeriji, 1994).

Although soil (earth) has been used as a building material for thousands of years, unprotected structures seldom withstand wet climates for long periods of time. Relatively new materials such as cement have meant that blocks can be made which will last for centuries, but they are too expensive for most people in developing countries. Traditionally built mud houses or ones constructed from compressed earth blocks made only of unfired earth have become a cheaper option. Attempts by past workers to improve strength of compressed earth wall are discussed in later chapter.

From the above discussion, it can be said that properties of soil as a building material should therefore be further studied. It is the intention of this work is to further contribute to the scientific knowledge of soil as a building material, and in particular strive to improve the strength and dimensional stability of rammed earth. This should be possible by introducing human hair or chicken feather fibers as well as lime powder or other additives to the soil structure and thus replace cement or other hydraulic binders stabilizing agents. An extra gain should be seen in terms of the low cost for the rehabilitation for the vanishing heritage for local population would benefit from plantation of these components.

## 1.4 State-of-the-Art

### 1.4.1 Stabilized rammed Earth walls

In accordance to (Compressed soil, standards, series technologies, Nr.11, CRATerre-EAG Basin,1998), compressed earth blocks (CEB) are masonry elements, which are small in size and have regular verified characteristics obtained by the static or dynamic compression of earth in a mold in a humid state followed by immediate demolding. Section 3.4 provides some insight on the use of earth presses. Compressed earth blocks are principally made of raw earth and owe their cohesion to the clay fraction within the earth. If any additive is added to the CEB in order to improve or enhance particular characteristics, then the CEB are referred to as stabilized compressed earth blocks. Additives may also be used to modify other characteristics such as color or shrinkage cracks. It should be noted that some literature refer to stabilized compressed earth blocks as stabilized soil blocks (SSB), Stabibloc, Terracrete, Soilcrete, pressed soil blocks (PSB) or Geocrete.

As discussed in the previous section, mud houses made only from earth face durability problems.

Several possible solutions have been forwarded by past researchers in bid to add strength and add durability to the earth raw material, even in less arid conditions, thus:

By using stabilized that improves certain characteristics of soil

- By appropriate architecture, i.e. earth building made with suitable design
- By using bonding mortar to improve the structure.
- By applying plaster and renders on the building surface.

The idea to use renders, paints or plasters on the external surface can protect the CEB or housing walls from external attacks, but these are expensive materials and hence not suitable for a developing society, additionally, expansion rates between soil blocks and renders/plasters mortars are different resulting in to peeling. The use of appropriate architecture is also hindered due to costs and skills required (Montgomery, 2002).

Application of stabilizers as a remedy to the soil instability problem or for improvement of the durability of compressed earth blocks appear, from literature survey, to be fairly widespread and most successful way of improving strength to soil. Many types of stabilizing agents are known (Stulz, 1988; Mukerji, 1994; Minke, 2000), although not much research appears to be available, the most tried ones are: cement, lime, gypsum and bitumen (mineral products), animal products, manufactured products and natural fibers (e.g. plant fibers). Earth blocks stabilized with 3.12% masse of cement seem to be the most common (Gooding, 1993). As Spence (1983) correctly points out, the potential of soil as a building material has been considerably underestimated, the reason being, that the enormous variety of naturally occurring soil has made specification for any particular set of properties difficult and that many soils in untreated state back strength and dimensional stability.

Indeed, past workers have given certain amount of light on the issue of earth construction. Fitzmaurice (1958) was first to point out that the population is more demanding of their building materials and that stabilization of soils normally with asphalt of cement is necessary to maintain the materials integrity when exposed to moisture. Most of the work has since then focused on the durability of the cement-stabilized compressed earth blocks (CEB) also referred to in some literature as compressed soil blocks (CSB). Durability of a soil block structure or element can be understood as it ability to withstand or resist weathering i.e. resistance to erosion of material by rain, wind or other environmental agents (Ngowi, 1997). The basics of soil stabilization are well covered by (Houben and Guillaud, 1994; Murkerji, 1994; Norton, 1997 and Minke, 2000) who describe the idea behind earth construction, soil stabilization, and characteristics of earth as a building material.

After Fitzmaurice forwarding the importance of CEB stabilization, most workers have tended to develop and examine parameters that provide information on the CEB durability. Compressive strength seems, from past research, to be the yardstick for measuring durability. According to (Heathcote, 1991) blocks with a minimum dry compressive strength of 2 MPa are acceptable by most codes (Australian code, New Mexico building code and UNESCO, CRATerre). Heathcote mentions soil type (clay quantity), cement content (generally in the range of 5. 10%) and density of the compacted soil as the main factors controlling strength. It is suggested that the stabilization mechanism lies in the cement forming a skeleton of hydrates throughout the voids.

A proposed correlation between density and cement content for estimating compressive strength can however, at best only be approximate and cannot substitute the physical testing of materials given the inherent variability in material. Although the author finds no sense in using the wet (saturated) compressive strength, he proposes in a later investigation in spite of the large data scatter, that the ratio of wet to dry strength of 0.33-0.55 to be a suitable criterion for durability evaluation of stabilized CEB (Heathcote, 1995). More contradictions occur as Walker (1998) finds blocks with a wet/dry strength ratio as low as 0.24 to provide adequate erosion resistance.

Earlier, Heathcote (1994) shows that minimum cement content exists (0.75%) below which strength is independent of cement quantity present; he tests samples with 0 -3.5% cement content. By establishing that suitable blocks may be manufactured from soil with cement content as low as 0.75%, the author the author contradicts other workers whose results show a value of between 5-12% to be best suitable; for instance, Walker (1995) reports that blocks made with less than 5% cement are often too friable to be handled. Later from survey of several works, Walker (1996) recognizes that the clay content of the soil should be between 5-20%, a cement content of 4-10% and soil plasticity index of 2.5-30%; see section 4.1.1 for definition of plasticity index.

Investigations by Kerali (2001, 2000) point out at the behavior of blocks in terms of compressive strength, water absorption, and microstructure with respect to composition, processing methods and exposure conditions; the variables being soil type, cement content, compacting pressure, curing conditions and water/(soil-cement) ratio. The source concludes that the CEB stability can be significantly raised if: inter-granular bonding between particles is improved, voids are reduced and block water absorption is lowered. It maintains that moisture (from rain, rising damp and vapor condensation) provides the most serious factor influencing the deterioration of CEB. Results of Kerali (2000) are in agreement with those of (Walker, 1997, 1998, 2001) and (Heathcote, 1995, 2000), both who perform erosion tests on earth blocks and find erosion resistance to improve with increase in cement content, block density, surface area to volume ratio and reduction in clay content. A shortcoming of the erosion tests is that a sample passing one type of erosion test may fail another, and some are open to operator bias; a unified approach is still none existent. Erosion is also dependent on the sample geometry. Attempts by the authors to simulate impact of falling rain (spray tests) provide only approximations as they fail to take care of the difference in wind and spray velocity, raindrop size and spray drop size as well as angle of attack by rain and effect of wetting and drying in the field. Wide ranging field data should be taken as attempt to close this gap.

In another similar study, Ozkan (1995) attempts to improve strength and water absorption of blocks stabilized not only by cement but also by lime, bitumen and gypsum, and observes that gypsum and bitumen blocks fail the erosion test; cement and lime addition increase strength and reduce water absorption. Related experiments are performed by Ngowi (1997). The source notes the low durability of earth walls in some villages in Botswana (Africa) and attempts to alleviate this problem by stabilizing the soils with cement, lime, and bitumen and cow dung separately. As in the case of Ozkan (1995), the bitumen as well as the cow dung stabilized blocks failed the water absorption test. Increase in lime content improved strength but, surprisingly unlike Ozkan (1995), increased the water absorption of the blocks.

Walker (1997) investigates the stability of mortars to the production of CEB, i.e. the effect of soil composition and cement content to the characteristics of CEB (compressive strength, draying shrinkage, wetting and drying durability, water absorption and mortar consistency). The source establishes that compressive strength, drying shrinkage and durability improve with increase in cement content but is inhibited by increase of clay content in the soil. Water absorption and retention rise with increase of clay.

The block compaction as a parameter influencing the durability of earth blocks is also documented. Moisture content and compaction delay as factors affecting quasi-static compression of cement stabilized soil blocks are examined by Gooding, (1993). The source attempts to establish a relationship between compaction pressure, cement content and compressive strength, and records better strength with increasing pressure, a fact that provides an improved water protective measure to the blocks. The same author (Gooding, 2000) looks at compressive strength as related to dynamic compaction. The following variables are considered: water content, compaction energy, mixing delay and compaction method. He underlines that this compaction method provides better block densification than static compaction at equivalent applied pressure. Montgomery (2002) investigates, in a PHD. Thesis, the process, production and performance of dynamically compacted cement-stabilized soil blocks as against those compacted by static means. Observing that moisture is the most critical variable, the author establishes that dynamic compaction provides the blocks with a 3-

5 MPa 7 days wet compressive strength, what is 40% higher than the compacted by quasi-statics method.

Another durability factor recorded in literature is the flexural bond strength. Walker (1995) investigates soil characteristics and cement content on dry density, compressive strength, flexural strength, durability and drying shrinkage. The source produces an empirical relationship equation 2.1 between flexural strength and compressive strength. A large scatter in the data is however, reported and hence eq. 2.2 may not be a substitute for direct testing.

$$\text{Compressive Strength} \times 0.61 = \text{flexural Strength} \qquad (2.1)$$

Rao (1996) looks at the effect of mortar composition, strength and moisture to the flexural bond strength of CEB. The source notes, as was the case with Walker, an increase in the flexural bond strength with rise in the CEB cement content and compressive strength; and establishes an optimum CEB moisture content above which the flexural bond strength falls off sharply. It asserts that flexural bond strength is a good measure of the blocks durability. Walker (1999) considers the flexural bond strength (using bond wrench method) as an indicator of CEB durability. Flexural bond strength (<0.1MPa) is noted to be a function of CEB compressive strength, clay and moisture content. The same author (Walker,2001) attempts to examine the durability of CEB by use of the pullout tests, i.e. asses bond of steel rebar's embedded in rammed earth. The pullout bond resistance is shown to be a function of compressive strength, bar type and bar length. Steel bar reinforcement is likely to be an expensive undertaking in poor economies, besides, steel may promote the corrosion phenomena.

The influence of steam curing is hardly available in literature. The effect of steam curing at 80 C as well as lime content on the wet strength (saturated strength) of lime (and fly ash) stabilized blocks is from Rreddy (2002) evaluated. The source observes increase of strength with increasing steam curing period (6-12 hours), lime content (6-14%mass) and lime and fly ash content (0-50% mass). Pozzolanic reactions between clay minerals and lime or fly ash are speculated to be responsible for strength gain.

### 1.4.2 Natural Fiber Reinforced Compressed Earth Walls

The use of the natural fibers as a building material poses a special challenge to science and technology. Their use can, whilst alleviating the housing problem, assist to save energy, conserve scarce resources and protect the environment (Swamy, 1990).

Although research data is not quite abundant, some workers have documented the issue of using natural fibers as stabilizing or reinforcing agent in earth construction. In discussion on kinds of stabilizers Stulz (1988) recognizes straw (wheat, rye, barley, etc.) and plant fibers (human hair, hemp, elephant grass, coir and bagasse) as an important category of stabilizers but provides no much scientific findings. Accordingly, such fibers check cracking in soils with high clay contents and increase insulating properties, adding however, that excessive use should be avoided due to possibility of increased water absorption. Rigassi (1995) observes that fibers create an omni-directional fibers network which improves tensile and shearing strength and reduce shrinkage.

The author stats further, without forwarding research data, that although fibers are commonly used to reinforce adobe, they are incompatible with REW compression process as they render the mix elastic. Mink (2000) agrees with Rigassi and notes that adding fibers such as animal or human hair, coir, agave, bamboo and straw may help to reduce shrinkage ratio; the reason being that the relative clay content is reduced and some of the water is absorbed by the fiber pores. Additionally, appearance of cracks is reduced as the mixture binding force is raised by the fibers. The author presents a study on linear shrinkage as a function of fiber (coir, flax straw and rye straw) type and amount but avails no further scientific results. Tests with human hair are also not available.

In work entitled seismic strength of CEB, Vergas (1986) observes increase in compression strength of CEB on addition of 0.5-8.0% by weight, 100 mm long straw and explains this by the sewing action of the CEB –mortar interface from straw fibers, i.e. controls micro-cracking produced by drying shrinkage (Filho,1990) reinforces adobe with human hair and coconut fibers; the investigation brings to surface the problem of high water absorption rates of the fibers-a phenomenon that may be detrimental to the blocks on frying. The author tries to circumvent this by application of water-repellent agents. However, addition of 4% human hair improves the brittle behavior of the adobe blocks.

Olivier (1995) performs so far the most comprehensive study of human hair reinforced earth blocks and claims that the weak point is the interface between earth mortar and earth blocks.

The source attempts to improve the interface by reinforcing the compressed earth blocks as well as the earth mortar with human hair fiber and describes, quantifies and evaluates the advantage of human hair use. An increase in cohesion (improved compressive and tensile strength) is observed. Plasticizer addition increase shear stress and reduces amount of water to be used. In a more recent related study, Eko et al. (2001) reinforce soils with a mixture of cement and sugarcane bagasse human hair fibers. The study uses 5 to 10% cement by weight and 5 to 15% bagasse fibers by volume. An improvement in the 28-day unconfined compressive strength with increasing cement content up to a maximum of about 5MPa is recorded. The increase in fibers volume is found to be detrimental to strength development.

### 1.5 Lime Stabilized rammed Earth walls

The possibility of using powder from lime (Manioc) as either a reinforcing agent or a stabilizer for earth blocks is not recorded in literature. Minke (2000) reports that the compressive and bending strength of earth can be improved by addition of starch and cellulose, and that, these additives reduce the binding force and increase the shrinkage level. The source does not specify the starch type neither does it provide any research support. Lime powder as stabilizing agent for soil (lime-soil mortar) is, however, already used by individuals in some villages in Kenya and Uganda.

### 1.6 Justification of the Present Study

Compaction with a suitable soil-stabilizer mixture can provide a relatively cheap raw building material. Stabilized rammed earth offer a wide range of advantages. They maximize use of local materials, low levels of energy required for production, simple production and construction methods and good thermal and acoustic properties. Their application is however, hindered by lack of test procedures and performance criteria. Requirement for, among others, compressive strength, tensile and flexural strength, durability, drying shrinkage, dimensional tolerance, dry density and water absorption may differ from region to region and should therefore be tested and documented appropriately.

Sections1 and 2 above show on one hand the need to improve the housing situation of the poor countries, and on the other hand, the role earth construction plays; they expose the inadequate research in this area. Several questions are as a consequence left open. Lack of standard performance criteria and adequate guidelines for CEB production are quite apparent from the above sections. Most of the estimations and correlations can only be approximate and may apply to a particular soil. Measurement should be taken in each study case to assign any specifications.

Rain patterns, intensity, drop angle and temperature changes-important for laboratory and field correlations-may for instance, not are the same for Australia and Kenya. Not much effort has been put in the direction of developing new building materials. CEB parameters considered seem to reoccur, one worker after the other, without much strives to create new ones or harmonize them. It is imperative that effort be put in both the direction of improving the existing materials as well as developing new ones; Griffin (1995) agrees with this view.

Literature in general supports this opinion as it recognizes that earth material forms a good case for a scientific study.

Natural fibers thus, human hair as well as lime is abundantly found in the developing nations.

They are cheap and could provide not only the required raw material for shelter, but also some income for the people. No research is recorded, documenting use of lime as a building component for soil although the very low income villagers are putting it in use; it was imperative to have a study carried out. This was the goal of the present research.

It is necessary to reconsider the way we build, and traditional architecture, built with local surrounding materials, sustainable by definition, integrated in the landscape, and with optimum climate behavior, stands out as an alternative. Traditional empirical processes of knowledge transmission, from one generation to another, have been improving this architecture for centuries, and it is the result of how the local population learnt to inhabit their territory according to the natural resources. Sustainability, such a trendy term nowadays, is complete and very ancient in this architecture.

There are many lessons to learn -or to re-learn- from traditional architecture to be applied in the construction of new buildings, but it is also important to understand the importance of preserving historic constructions. Heritage, in a wide sense of the word, cannot be related only to the architectonical, historical and cultural relevance of the monumental buildings, because they are exceptional. The importance of heritage also relies on the popular culture, since a wide part of the society belongs to it.

There are in Algeria as well as all over the world, of course, many examples of monuments built with earth, but they are an exception, and most of earthen constructions are -or were-, in fact, part of the popular architecture. Earthen materials are indeed considered as poor in western cultures, because they always belonged to poorness. This is the reason why traditional architecture, and especially earth as construction material, is still not well considered. However, this is starting to change, in part due to the sustainability of the material, but also because of the increasing need to respect architecture as a part of the historical identity of the society. And since society wants to move towards sustainability, it is necessary to reconsider not only the way we build, but also the way we manage our heritage.

The present dissertation is a result of this renewed interest, in many institutions of the Algerian ministry of high education and particularly of the University of Chlef, which in recent years is carrying out research in the Algerian traditional architecture. The interest of educational institutions is extremely important not only to guarantee a scientific approach to this topic, but mainly as a first step to increase the awareness about this heritage within the society.

## 1.7 Description of the problem

Many earthen buildings are in such a vulnerable situation that makes the permanent loss of this heritage only a matter of time. The lack of proper maintenance caused by economic and social changes, together with the fragility of the material itself, are the main threats of this heritage. However, even in those cases in which comprehensive interventions are possible, there is a lack of reliable techniques for earthen structures.

Therefore, it is necessary to find new intervention techniques for earthen buildings, or to adapt those already existing -and proved- to the specific characteristics of the material. The use of ties, geotextile meshes or the use of center-core rods have interesting possibilities when applied to earthen materials, and they are being tested for adobe structures within the research programs of several institutions such as CNERIB and the polytechnic school of architecture and urbanism of Algiers (EPAU). However, in the case of rammed earth structures, there is still an important lack of research that demands the development of new techniques and/or the adaptation of existing ones.

This is the context in which the present dissertation aims at contributing to the development of stabilization of rammed earth walls. This technique has been extensively used in ancient masonry and its effectiveness has been widely proved. However, the particular characteristics of the materials needs also of specific requirements that must be properly assessed.

## 1.8 Aims and objectives

The main purpose of this research study was to introduce some stabilizing products in a relatively low percentage like cement or lime as stabilizer of rammed earth through ingredients which are renewable resources in nature. A strength and therefore durability testing method, in the absence of laboratory facilities in the rural areas, was to be established; this was to be accomplished by determining a conversion function between standard laboratory tests and the proposed simple testing method i.e. loading strength was to be correlated with compressive strength; this is illustrated in Figure 1.4.

The prime objectives were to:

- Synthesize human hair fiber earth wall material for rehabilitation.
- Synthesize human hair stabilized earth wall material for rehabilitation.
- Prove the sufficient durability of the products.
- Prove the water transmission properties.
- Prove the mechanical strength.
- Develop an on –sight appropriate and easy –to-use testing criteria of strength.

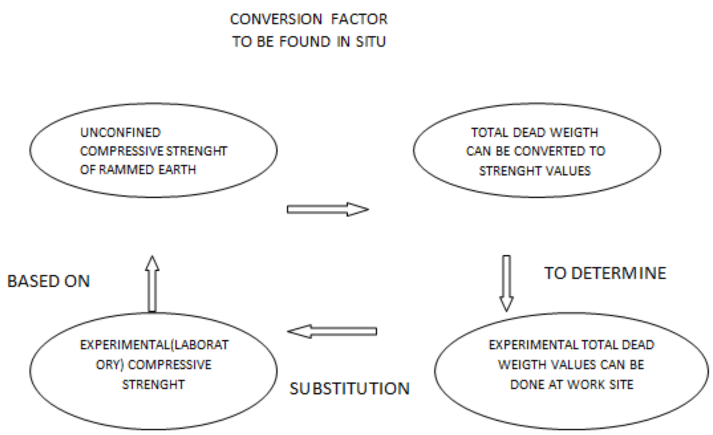



*Figure 1. 4 - Reproduction of laboratory work in situ*

This work aims at contributing to the understanding on the structural behavior of rammed earth architectural heritage, as well as to the development of stabilization as a feasible technique to repair structural failures caused by erosion and weathering.

To this aim, the second Chapter briefly presents a critical review of literature about the main topics related to rammed earth. These are mainly related to the description of the general properties of the unmodified soils, especially those of clays, and to point out the general behavior of rammed earth structures, as well as its vulnerable aspects.

Within the third Chapter, the methodology for the assessment of the suitability of soils for rammed earth is presented and discussed. In the same way, six rammed earth cylinders and wallets are tested under uniaxial compression and diagonal compression in order to evaluate the mechanical performance of the material before stabilization.

The fourth Chapter is focused on the requirements of the formulation of stabilized mixtures and of the compaction process.

In this Chapter, the mechanical behavior of the stabilized rammed earth wallets will be assessed by means of the compressive test, and the results will be compared with those previously obtained. The quality of the stabilization will also be assessed by means of non-destructive testing of the wallets before and after grouting.

Finally, the fifth Chapter presents the final conclusions and the suggested future lines of research.

The procedures followed for the assessment of soils, the formulation of the grouts, as well as the tested specimens before and after being stabilized are based on the study carried out in laboratory (2011 &2012 till 2022), in which the present dissertation is based.

# Chapter 2:
# Literature review

# Chapter 2: Literature review

## 2.1 Introduction

Since the Neolithic period, men have built dwellings to protect themselves from the hazards of their environment. Their first dwellings were caves dug in the mountains. However, far from the mountains and hills, later on man learned to build a shelter and he used a material that will cross the centuries: clay, that is to say the raw earth.

## 2.2 History of earthen construction

In Mesopotamia, the first cities were built in mud even before the invention of writing. Unfortunately, this material degrades more rapidly than stone. There are few architectural remains from this period of history. Thus the Middle East and central Asia have many exceptional sites such as Tchoga Zanbil (Iran), Mari (Syria), Shibam (Yemen) or Merv (Turkmenistan). From the stacking of hand-made loaves of earth, buildings began to be erected using earthen bricks. Later, fortification works followed by the appearance of domes will revolutionize the construction process. These later advances in construction gave rise to gigantic temples and temple cities about 5,000 years ago. The oldest traces of mud construction discovered in Europe seem to date from 6,000 B.C. They are primitive habitats located in Thessaly. Turkmenistan during difficult or economically troubled periods, the masons used earthen wattle and daub, while during more stable and richer periods; the buildings were constructed from bricks. Later on, timber-framed constructions appeared, thanks to the advances in carpentry. However, from the 18th century onwards, raw earth came back in force, probably under the influence of the more than 70 booklets written by François Cointeraux on the pisé process, combining stone and clay. From this time on, raw stone will become part of the construction landscape, until after the Second World War, when it will be left aside in favor of materials that are quicker to obtain in the emergency of reconstruction.

In Algeria, the historiographic data of recent research, offer several attestations of the use of earth for construction. The inventory of finds from the ancient period shows that earthen walls have been found in different chronological and architectural contexts in various Algerian regions as well as in the Maghreb and in the northern Mediterranean. The use of earth is attested throughout Antiquity; it was found in modest constructions, as is the case in the region of Oran (Andalouses and Mersa Medakh) for the pre-Roman period and in the countryside of Cherchell for the Roman period, as well as in the rich Punic53 and Roman urban dwellings. The annual excavation reports prove that the earthen walls were very rarely, if at all, identified during the first more or less extensive excavations carried out at the end of the 19th century on sites such as Timgad, Djemila Ortazoult (Lambèse, 1954).

From a technical point of view, several methods can be identified: adobe and pisé for the walls, cob for the roofs, roofing and plastering. The various examples show that the opus africanum also appears to be a mixed construction system whose fillings can be made of stones, adobes or earthenware.

### 2.2.1 Return of raw earth

A large part of the European heritage, and in particular the French, still remains a trace of the raw stone reign. Moreover, some European countries such as Germany, the Netherlands or Denmark are looking again at these traditional practices since the 1980s. Many techniques used in ancient times are still practiced in Europe by modern masons. This is for example the case for the cob, the bauge, the pisée, or the raw earth bricks.

In the construction industry, there has been a persistent need to turn to more sustainable construction solutions. Engineering professionals recognize that the construction industry accounts for about 40% of the world's energy use (Jenkins Swan et al. 2012). Not only the use of energy, but the amount of carbon dioxide ($CO_2$) emitted by building materials needs to be reduced. The construction industry accounts for 30% of $CO_2$ emissions. In addition, the construction industry throughout the world consumes more raw materials than any other industry. With an expected increase in the world population of more than 2 billion people by 2030, there will be a demand for buildings and other infrastructure to accommodate the increase in population (Pacheco-Torgal and Jalali, 2012). This would cause a further increase in the consumption of non-renewable materials and waste production. According to the Kyoto Agreement in 1997, countries have agreed to reduce the amount of production of cement until the year 2050 (Fahmy, 2007). As a result, many designers and engineers of the built environment are looking to locally resourced materials for construction in order to reduce energy consumption. Earthen materials have been suggested as one alternative to offer a sustainable construction material (Pacheco-Torgal and Jalali, 2012).

### 2.2.2 Various forms of earthen construction

There are various forms of earthen-building materials, such as: adobe bricks, compressed (pressed) earth blocks, rammed earth, cob, and wattle and daub. Adobe bricks are the most popular and oldest form of earthen construction. Adobes are made from a wet "mud" composed of 55-85% sand, 15-45% finer material (more silt than clay), and usually containing caliche. Caliche is formed in the soil calcium carbonate (Smith and Austin 1996). The wet "mud" is placed in wooden molding forms and allowed to dry (cure) for about one month in the sun (Wolfskill et al., 1980). Compressed earth blocks (CEBs) are formed one at a time using a hand-operated CINVA-Ram or a hydraulically operated, gasoline or diesel-powered machine. The first machine used to make CEB was the CINVA-Ram created by Raul Ramirez of the International American Housing Centre (CINVA) in Bogota, Columbia, in 1952 (PachecoTorgal and Jalali, 2012). CEBs are a mixture by weight of angular sand aggregate (40-70%), clayey soil (30-60%), and water (8-12%) (Allen, 2012). Stabilized compressed earth blocks (SCEBs) are CEBs with additives/binders such as, Type S hydrated lime or Type II Portland cement to protect the earth block from water intrusion. Rammed earth construction consists of continuous walls which are constructed by ramming moist soil between two wooden forms (Wolfskill et al., 1980).

The use of rammed earth walls are built in more humid climates than adobe blocks (Niroumand et al. 2013). The next earth building material, cob consists of molding stiff mud to create walls. The mud is stiffer than the adobe brick due to the high straw content. The mud is shaped on a trowel and placed directly on the structure and let to harden before more mud is applied on top (Wolfskill et al., 1980). This is the simplest of earthen building materials. Finally, the wattle and daub earthen structures consist of two parts. First, using materials such as, reeds, bamboo, branches and twigs to create the wattle, these materials are woven together to create a stiff frame. Daub or mud is then smeared on to the wattle by hand until the entire surface is covered and let to dry (Niroumand et al., 2013). Wattle and daub walls are thin and lack the thermal mass properties provided by all other earth building systems.

Despite this, wattle and daub construction are used in seismic zones throughout the world because the woven structure is earthquake resistant due to its ductility (Niroumand et al. 2013).

Earthen architecture is a vernacular architecture which is used throughout the world (Niromand et al., 2013). It is estimated that 30-40% of the world population currently live or work in earthen structures (Miccoli et al., 2014). The majority of earth construction is located in less developed countries (Pacheco-Torgal and Jalali, 2012). Yet, earthen construction is also used in the United States, Germany, France, the United Kingdom, Australia, and New Zealand. Earthen construction is dependent on adequate training for builders and homeowners but also on specific local regulations (Pacheco-Torgal and Jalali, 2012). Several countries already have earthen construction related standards, such as New Zealand, Australia, Germany, Ecuador, India, and Peru (ASTM E2392, 2010). The United States has no specific earthen building code, but New Mexico has a state regulation, the 2009 New Mexico Earthen Building Materials Code (NMAC, 2009). Within the United States, New Mexico is the largest producer and user of adobe bricks and compressed earth blocks (Smith and Austin, 1996). Earthen structures have a long architectural and cultural heritage in New Mexico. The traditional earthen construction method (adobe blocks) has been altered by using stabilizers such as hydrated lime or Portland cement to enhance the durability performance in order to make an improved construction material for low-cost, sustainable buildings (compressed earth blocks). However, there are advantages and disadvantages to using compressed earth blocks.

## 2.3 Earth as building material

### 2.3.1 Important notions

Given the environmental destruction and global warming caused by the excessive use of conventional industrial materials, a tendency of most of researchers is to recourse to the use of nonconventional materials. The notion of nonconventional materials in building is linked to local materials and is becoming worthy of interest again (Morel et al., 2001) due to the increasing demand for housing as populations increase, and to the need to reduce the energy consumption of the building industry. The concept of nonconventional building materials means materials manufactured using a simple, quick process with low embodied energy, using raw materials from the site or nearby. To translate this concept into action, many ideas have been developed, including the use of soil as a raw material. The term soil refers to the more or less argillaceous soil found between the rock substratum and the topsoil layer. We will refer here to unfired clay soil, exclusively called “soil”. This raw material thus does not have a standard composition. Consequently, each type of soil requires a specific manufacturing process to obtain a building material, and the process therefore cannot be industrialized. The soil must be taken from the construction site or nearby in order to limit transportation (Morel et al., 2001), and must contain clay particles to reduce or avoid the use of industrial binders like lime and cement.

Soils change significantly according to the climate, relief and nature of their bedrock, thus their properties vary considerably. Therefore, looking at a map of the soil suitable for building (Houben and Guillaud, 1994), one can observe a wide diversity of soils that can be used as a raw material to manufacture non-industrial building materials. Furthermore, the properties of a soil evolve according to the organization of its particles during the sedimentary process and the depth at which it was extracted (Vasseur et al., 1995).

Soil is a complex material composed essentially of clay minerals and sand with organic matter and associated minerals including anatase and hematite considered to be impurities. Each of these elements has different behaviors which influence soil properties. For example, the presence of organic matter increases plasticity (Malkawi et al., 1999). Furthermore, the proportions of clay and sand change, causing variations in soil structure, plasticity, cohesion and permeability. The nature of the clay minerals also influences soil properties.

The use of soil as a building material goes back thousands of years. Some examples include the oldest historical houses in the United States, the bam citadel in Kerman-Iran

(Manzano-Ramírez et al., 2007) and the Alhambra in Granada, Spain (Jaquin et al., 2007). Many techniques have been employed, some of which are still used, yet have been modernized. These techniques can be divided into three main categories: (i) monolithic load-bearing walls; (ii) load-bearing masonry; (iii) timber frame filler mud walls. The soil is mixed until one obtains a mixture as homogeneous as possible, which is then molded or compacted into formwork and sun-dried. This moulding or compaction (dynamic or static) reduces the quantity of voids between grains and thus gives a form to the mixture thanks to cohesion. Dry samples are directly used to build houses without any other treatment, i.e. these materials are neither fired nor stabilized. Clay is the only binder ensuring strength and stabilization. However, the building must be relatively well protected from water (by architectural design), since saturation of the soil reduces its mechanical performances. Like dry-stone masonry, soil results from a non-industrial technique, and they represent the only construction materials that can be so easily re-used and do not generate waste.

Scientific studies of earthen building materials have intensified over the last 20 years. Certain researchers focused on soil characterization and developed various techniques to identify clay minerals and classify soils (Lan, 1980; Lautrin, 1987; Ghosh and Bhattacharyya, 2002; Kaufhold et al., 2002; Sei et al., 2004). They showed that the soil for building materials must contain less than 20% clay minerals, and that kaolinite, is the best suited. Other studies dealt with manufacturing process optimization and the influence of compaction energy (Olivier and Mesbah, 1986, Venkatarama Reddy and Jagadish, 1995, Attom, 1997, Mesbah et al., 1999). In general, compaction increases dry density and compressive strength, but the water content must be optimum to achieve the highest strength. The optimum water content is determined by studying the relationship between water content and dry density. The Proctor test is used in the case of road design with non-argillaceous materials, to determine optimum water content. It is not recommended for earthen construction materials. Indeed, the compaction energy of the Proctor test does not usually correspond to that used for earthen construction (Mesbah et al., 1999). Other studies have focused on determining the hydraulic binder content (Portland cement and lime) to be added to the soil in order to improve its behavior with water (Kouakou, 2005, Jagadish et al., 2007).

Many new earthen architecture projects are built with compressed earth blocks (CEBs) and rammed earth. This is why several new articles have been published on these materials and structures, for example concerning the comfort of rammed earth houses (Hall and Allinson, 2008), their durability (Bui et al., 2009) and their mechanical behavior (Jayasinghe and Kamaladasa, 2007, Bui et al., 2008; Maniatidis and Walker, 2008). As for CEB masonry, the literature is older but there are some recent publications concerning the mechanical behavior of blocks and masonry (Morel et al., 2007, Gumaste et al., 2007, Reddy et al., 2007) and soil mortar (Azeredo et al., 2008, Reddy and Gupta, 2008).

All of these studies were focused on CEBs, and sometimes on rammed earth, which is made with soil containing 5% to 15% clay. A small number of studies have been made on soil containing 20% to 35% clay, focusing mainly on the incorporation of chemical stabilizers such as cement to improve strength and water resistance and to reduce shrinkage. Presumably, earthen building materials without cement (or with less cement) are eroded by water (Temimi et al., 1998) but old earthen construction methods using adobe without cement are still used today. Furthermore, the materials used in these studies (Ben Amor et al., 1997; Temimi et al., 1998) are not natural. They were made by adding sand and clay to reduce the complex variations of the natural earth's behavior. Thus the behavior of these recomposed soils may be different from that of natural soils containing associated minerals such as iron or calcium minerals, aluminum oxide, and others. These studies were limited to a given material, whereas we present a more general study here.

Our building heritage is proof that the use of soil as a building material was well-known all over the world. In Europe, the technique was abandoned after World War II, whereas in developing countries earthen construction is still widely used. But it was not popular until recently, when architects began again to encourage the use of compressed earth blocks (CEBs) in India and Africa, rammed earth in Australia and Europe, and adobes (mud bricks) in the USA. This rediscovery of earthen construction materials raises questions concerning soil characterization, the manufacturing process, and material testing. Until now empiricism was sufficient in order to build with soil, but today scientific data is necessary.

### 2.3.2 Advantages and drawbacks of earthen constructions

It is summarized in Table 2.1 the most advantages and drawbacks of earthen materials.

*Table 2. 1: Advantages and drawbacks of earthen constructions*

| **Advantages** | **Drawbacks** |
|---|---|
| Use of earth is economically | Inadequacy of local soil (Soil suitability). |
| promotes housing | Poor quality control. (Workmanship) (Crowley, 1997). |
| Earth can build extra secured and strong structures. | Long construction times. |
| Earth material is sustainable and eco-friendly; | Empiricism of design methods(lack of standards) |
| Naturally balance interior temperature and humidity (very low Carbon Footprint) | Sensitivity to moisture ingress. |
| Great for indoor Climate | Durability |
| Climatic control (a high mass material earth evens out temperature fluctuations) | Reliance on chemical stabilizers. |
| Moisture control (ability to absorb and release moisture from the indoor air) | Uncertainties about energy efficiency. |
| It is strong and durable (Rammed earth construction has been around for thousands of years all over the world) | |
| It creates employment opportunity. | |

| | |
|---|---|
| Earth is considered as sustainable building material | |
| Earth walls preserve organic materials, such as timber. | |
| Carbon emissions (earthen materials undergo less processing for construction) | |
| Pollutants are absorbed by earth wall (Detoxifying effect) because earth walls are completely breathable | |
| Designing with earth is easy and can produce building with high aesthetic value | |
| Earth wall possess a very low sound transmission levels high insulation property, therefore, excellent in controlling noise. | |
| Earth is local building material; therefore, it promotes heritage, tradition and cultural practice. | |
| It is available worldwide in abundance (100% Natural Local Resource) | |
| Fire resistance (earth doesn't burn) | |
| low lifetime cost (Low maintenance and heating) | |
| Recycling (Zero Waste) | |
| Beauty of Colors & Textures | |
| Warm, dry and healthy (it offers a healthy indoor environment) | |
| Beautifully unique (it can be can be customized to someone taste) | |
| pest protection (no cavities or gaps for insects and vermin to enter or hide) | |

## 2.4. Characteristics of the soil to use

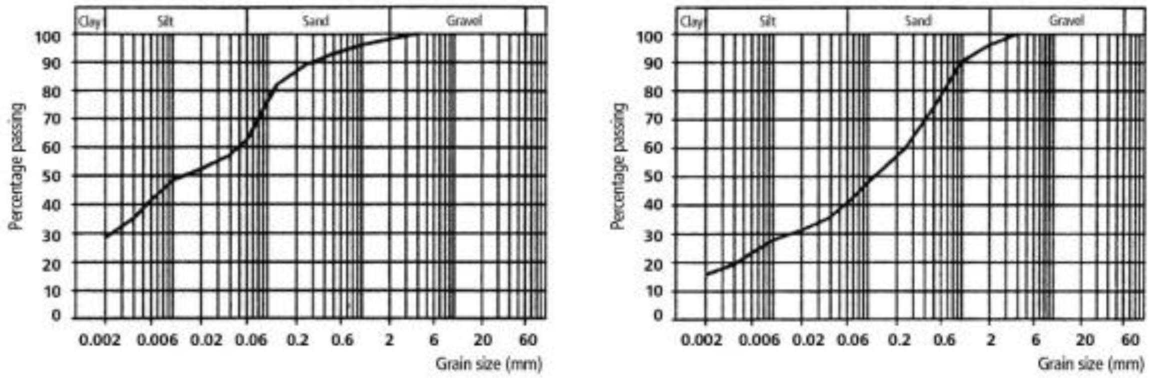
Earthen materials are in-situ materials which are directly available on site. They result from the alteration of the parent rock, which occurs through mechanical, physical, chemical and biological actions. The resulting material undergoes further transformations as it is continuously transported, deposited, compressed, and/or chemically modified (Houben & Guillaud, 1989). They are used by human beings from centuries as earth (rammed earth, adobe, cob,…). The construction techniques using in-situ materials are still widely used today in developing countries, this is due to their lower construction costs in comparing to conventional constructions (such as reinforced concrete or metal structures). The reason is that conventional materials are not always available in these countries and must be imported, that significantly increases the cost. In addition, the labor cost is not expensive, so the use of in-situ materials has a positive social aspect by providing jobs to local workers.

The mechanical properties of unsterilized soils (soils without additives or corrections) essentially depend upon the grain size of their constituents rather than to their chemical composition or the type of alteration (Torraca, 2009). For this reason, soils are mainly defined by the distribution of their particles, which are classified according to their size (Table 2.2).

*Table 2. 2: Range of particle sizes in soils (ISO, 2013).*

| **Fraction size** | **Type of soil** | **Particle diameter range (mm)** |
|---|---|---|
| Fine | Clay<br>Silt | ≤ 0.002<br>0.002-0.063 |
| Coarse | Sand<br>Gravel | 0.063-2<br>2-10 |
| Very coarse | Cobbes<br>Boulders | 10-200<br>> 200 |

The Particle Size Distribution (PSD) is plotted cumulatively, with each grain size including all the fine components (Figure 2.1).




(1) (2)

*Figure 2. 1- PSD of soils: (1) with high clay content (2) with high sand content (Minke, 2000).*

The classification of soils may vary depending on the country and the standard being considered, but fractions remain the same. In any case, earthen materials are referred to mineral soils with particular PSD depending on the technique (Figure 2.2), and consist of a binding agent -the clay minerals- and aggregates -the coarser fractions-, which in earth construction are generally sieved to less than 10 mm, (Jaquin, 2008) even if in historical rammed earth structures it is usual to find very coarse fractions.

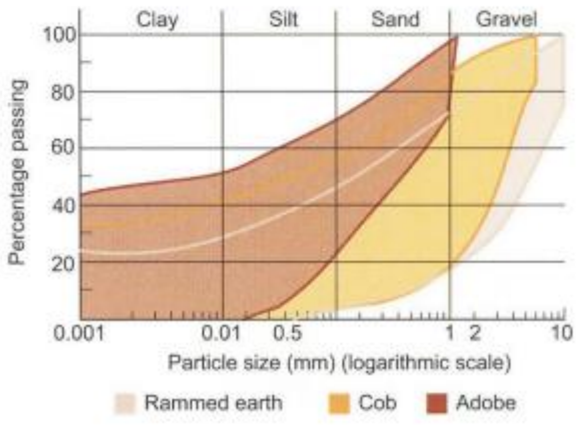



*Figure 2. 2 - PSD curves for different earth construction techniques (Jaquin & Augarde, 2012)*

Therefore, clays are a fundamental fraction in soils, and they are almost always present in different forms and with a wide variety of properties (Houben & Guillaud, 1989). Soils with high quantities of clays are known as rich mixtures or rich clayey soils, and have high binding characteristics. On the other hand, those that are not very cohesive are known as lean mixtures or lean clayey soils.

It is important to note that fine fractions -both clay and silt- are composed of cohesive and noncohesive minerals, which often can form 10%–20% of the fine particles (Velde, 2008). Therefore, the binding strength of an earth mixture may vary considerably depending on the type of clay minerals, e.g. kaolinite or illite, and the proportion of non-cohesive minerals, e.g. quartz, feldspars, and metal oxides (Röhlen & Ziegert, 2014). Fine non-binding fractions contribute to soil stability by increasing its internal friction, which is the key mechanical concept in soil strength. Nevertheless the main contributors to strength are coarse fractions, with higher friction between particles. They constitute the skeleton in the mixture, and their low sorption capacity limits swell and shrinkage (Houben & Guillaud, 1989).

Unstabilised soil strength depends on the binding forces of clays and on friction forces between coarse particles, but also on the free water in the voids between them, which acts as a bridge (Figure 2.3). These voids can be filled with air and water -unsaturated soil-, or completely with water -saturated soil. In the majority of geotechnical projects, soil is assumed to be saturated, since the numerical and analytical models are simpler, but it is clear that earthen materials are never neither completely dry nor saturated (Jaquin, 2008).

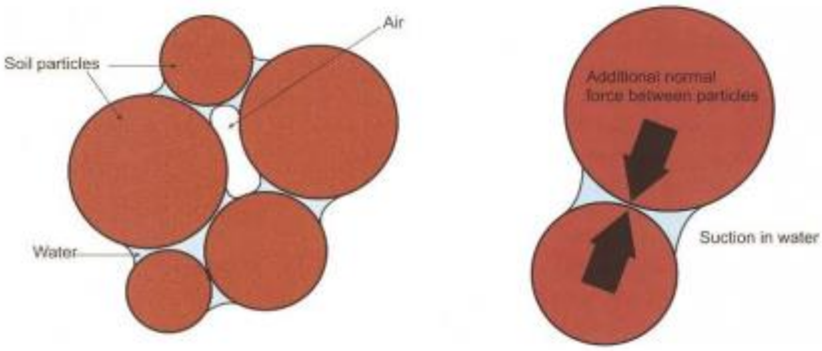



*Figure 2. 3 - Simple model of an unsaturated soil (Jaquin & Augarde, 2012)*

Therefore, it is necessary to precisely evaluate the contribution of water and air in the model of the earthen material and account it in the development of design rules for earthen construction. Nevertheless there is a lack of consensus about the constitutive modeling to be considered, which is an active area of research (Augarde, 2012). In qualitative terms, however, basic mechanical properties of earthen materials are characterized by low compressive and shear strength, and almost zero tensile strength (Miccoli et al. 2014).

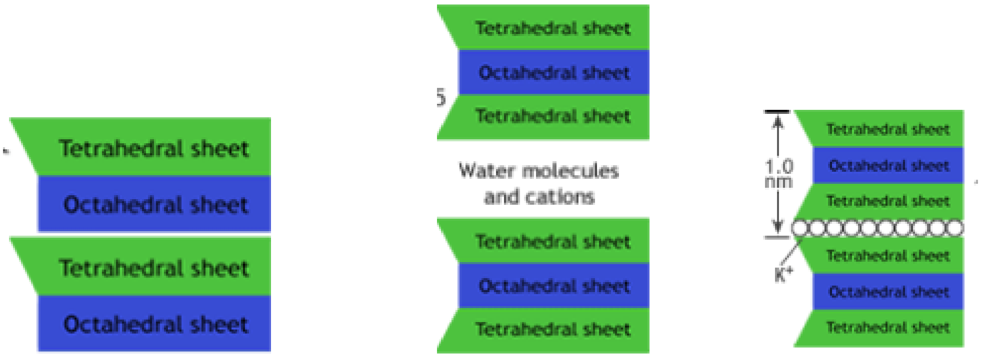
In short, properties of unsterilized earthen materials are determined by the properties of the binding agent and of the aggregates, as well as their relative proportions, i.e. texture, and the amount of water. Therefore, not all soils are adequate for earthen construction, and it is not common to find natural earth mixtures with ideal distribution of clays and aggregates.

However, it is not possible to state that a soil is unsuitable without testing its performance of the final earthen material (Röhlen & Ziegert, 2014).

## 2.5 Clay minerals as the binding agent

To understand the various unique engineering behavior of clay, it is most beneficial to study microstructures of clay particles first. There are three types of clay minerals as shown in Figure 2.4:

- Kaolinite clay
- Montomorillonite clay
- Illite clay




(a) (b) (c)

*Figure 2. 4 - Structure of clay minerals: (a) Kaolinite; (b) Montmorillonite (c) Illite; (Minke, 2000).*

All of these clay minerals have two basic atomic sheets

1. Silica tetrahedral sheet
2. Aluminum octahedron sheet

In silica tetrahedral sheet, silica (Si) occupies the Clay minerals belong to the phyllosilicates group of minerals and consist in a layer structure forming crystals, with sizes and chemical composition that depend on the type of parent rock and degree of weathering. The atomic structure of the clay minerals consists of two basic units, an octahedral sheet and a tetrahedral sheet. The octahedral sheet is comprised of closely packed oxygen's and hydroxyls in which aluminum, iron, and magnesium atoms are arranged in octahedral coordination. Each layer constitutes a unit cell, which is a two or three-layer structure formed by alumina octahedrons -less commonly magnesium or iron- and silica tetrahedrons (see Figure 2.5).

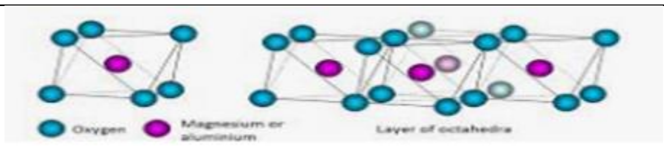
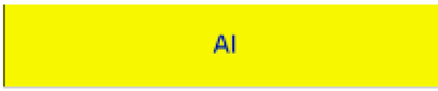
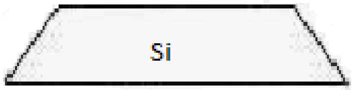
| | | |
|---|---|---|
| 1 |  |  alumina octahedral |
| 2 |  |  Silica tetrahedral |

*Figure 2. 5 - Structural units of clays: (1) Aluminium sheet; (2) Silica sheet (Reddi, et al., 2012).*

As presented in Figure 2.6, the aggregation of these basic units forming crystals depends on the type of structure. In the case of the two-layered unit cells, hydrogen bonds are formed between the oxygen atoms at the surface of the silica layer, and the hydroxyls at the surface of the alumina layer. These bonds strongly hold successive units, leaving a small space between them, so water is less able to penetrate (Reddi, et al., 2012).

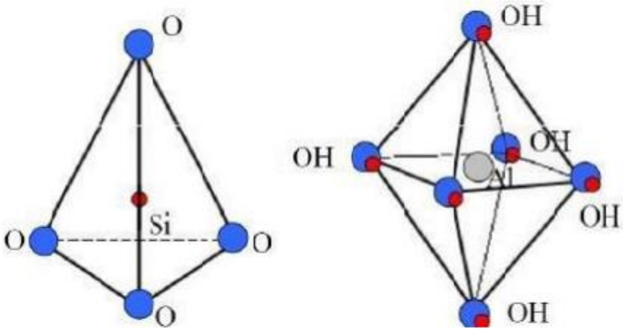



*Figure 2. 6 - Silica tetrahedral and aluminum octahedron*

In the case of the three-layered unit cells, bonding occurs when the aluminium cations are substituted with iron and magnesium -with smaller positive charge-, in addition to the exchange of silicon and aluminium atoms between layers. These structural changes are called isomorphous substitution (Reddi, et al., 2012), and result on a negative charge of the surfaces, which is compensated by the absorption on the unit surfaces of cations present in water, i.e. Na+ or K+.

The weakness of this bond allows the entrance of water between unit cells -absorbed water. If clay continues being moistened, the volume of absorbed water increases, expanding crystals. For this reason, three-layered clay minerals are termed expansive, while two layered clays, with some exceptions, are non-expansive (Reddi et al. 2012).

When the water content continues increasing, the binding force of clays is reduced. In this state, crystals easily swell but once water evaporates, coarse fractions hold their shape while clays shrinks. Cohesive effect continues reducing with a large excess of water, leading to a reduction of the internal cohesion of the particles of the soil and therefore, of the mechanical strength of the material (Figure 2.7) (Schroeder, 2011; Morel, et al., 2012).

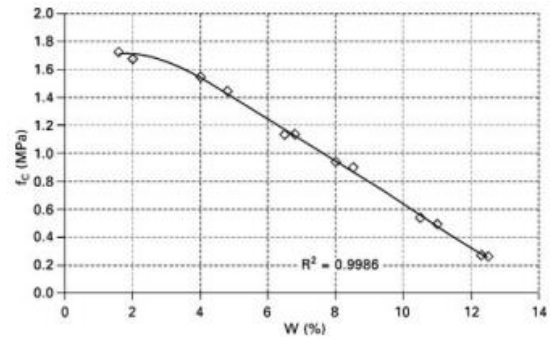



*Figure 2. 7 - Decrease in compressive strength with an increase in the water content of unstabilised rammed earth samples, 9% clay content (Morel, et al., 2012).*

Clay particles get in suspension in dispersed state, and when the content of free water is reduced, they get closer and electrostatic forces start acting again. The way these particles are arranged is determined by the surface properties at the sharpen edge of the crystals. At these edges, the primary bonds of the alumina octahedrons and silica tetrahedrons are broken, exposing aluminol (Al-OH) and silanol (Si-OH) groups, whose charge is determined by the pH of the suspension (Silva, 2013).

Therefore, particles join edge to face -negative to positive- in acid solutions -with pH lower than the point of zero charge of the edge-, while this process is harder to take place in alkaline solutions. Thus, a certain quantity of clay mixed in acid solutions may be plastic -flocculation occurs-, while in very alkaline solutions the mixture remains liquid (Anger & Fontane, 2009). This phenomena has a major influence on the rheological behavior of mud grouts (Silva, 2013).

In short, cohesion and flocculation of clays derive from physical phenomena -electrostatic forces-, which are related to their mineral structure. These effects do not only depend on the content of clays, but also on the type of mineral. There are about 15 types of clay minerals, classified in 4 main groups, with different bases, different structure configurations, and different interstratified materials. Three main groups define the most common clays: kaolinite, illite and montmorillonite (Reddi, et al., 2012).

Kaolinite is the most common mineral of the kaolin group, which is characterized by a structure with two linked layers (as shown previously in Figure 2.4 (a)). They are relatively stable -being non-expansive-, and water is less able to penetrate -meaning less swelling. The activity of kaolinites is small, which entails weakness as a binding agent compared with other clays. Nevertheless the lower swelling allows a lower degree of shrinkage, and their humidity regulating capacity is high (Röhlen & Ziegert, 2014).

On the other hand, montmorillonite and illite are characterized by a three-layer structure (Figure 2.4 (b) and (c)) with much larger surface area compared with two layer clays. This large area of unit cells exhibits large differences of charge, which facilitates the reaction processes in interlayer spaces. Illite structure is similar to montmorillonite, but is less expensive and more stable due to stronger bonding -with potassium cations- between units. This bond is weaker than the hydrogen bond of kaolinite, but stronger than the bond of montmorillonite (Reddi, et al., 2012). For earth construction, higher activity gives larger binding forces and increases humidity regulation. However, shrinkage is much higher, and in the case of mixtures with montmorillonite they have to be carefully compensated by the addition of mineral and organic additives (Röhlen & Ziegert, 2014).

## 2.6 Mix design

Several traditional techniques exist today to use soil as construction material: rammed earth, compressed earth blocks, adobes, cob. The main binder in those cases is clay. For new constructions, other hydraulic binders can be added (cement, lime or both) especially when the soil does contain enough clay or the clay type is not adapted for the earth construction technique chosen. The most difficult point in using of in-situ soil as construction material is the variability of soil characteristics on each construction site. So using of an unique construction technique (rammed earth, adobe,…) becomes difficult to satisfy several exigencies of the modern regulations because each soil type is adapted for a construction technique.

The strategy proposed is to create a “repertory” of several soil types and the corresponding adapted technique(s). The soils will be classed following their characteristics: size distribution, clay amount, clay type. And for each soil type, several techniques and several compositions were tried to find the most adapted techniques.

Field and mechanical tests in the laboratory are to be carried out for each composition; the results will be compared to current regulation demands as shown in Table 2.2.

*Table 2.2 List of equivalent field test to regular laboratory test*

| **Field tests** | **Laboratory tests** |
|---|---|
| Visual And Touch Tests (ASTM D 2488 - Standard Practice for Description and Identification of Soils (Visual-Manual Procedure)) | Particle Size |
| Bite or Grit Test | Sedimentometry |
| Odor Test | Optimal Grading (Granulométrie optimal) |
| The Wash Test | Methylene Blue |
| The Pen Test | Atterberg Limits |
| The Stick Test (Test Du Cigare) | Proctor |
| Feel Test | Compression |
| The Shine Test | Flexural Strength |
| Test Tube Particle Gradation | Shear |
| The Jar Test | Indirect Tensile Test |
| Acid Test | Absorption Test |
| Pad Test | Erosion Test |
| Shrinkage Test | Wetting-Drying Test |
| The 8 Test | |
| Carazas Test | |

## 2.7 Characteristics values

These laboratory tests allow us to know the characteristics of the available soil with more precision than with the tests carried out on site. At present, there is very little standardization for the use of soil as a construction material. There are only a few standards for adobe and stabilized rammed earth that specify the minimum strength and durability of the earth material. Experimental tests carried out by different organizations in industrialized countries give an idea of the technical performance of earth materials in general. These characteristics can be compared with the results obtained from the tests previously mentioned to ensure their reliability. Doat et al. (1979) recommend the following characteristics for single-story construction:

- Compressive strength: 2 kg/cm².
- Wet compressive strength is about half of dry strength.
- Tensile strength: 0
- Shear strength: 0.3 kg/cm².
- Young's modulus: 7000 to 70 000 kg/cm².
- Permeability: 1x10-6 cm/sec
- Thermal expansion: 0.012 mm/m per °C
- Thermal conduction coefficient: 0.44 to 0.57 Kcal/h.m.°C
- Specific heat: 0.2 Kcal/kg
- Hourly phase shift for a 40 cm wall: 8 to 12 hours
- Sound damping for a 40cm wall and a frequency of 500 Hz: 56 dB

## 2.8 Soil stabilization

### 2.8.1 Interest

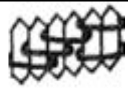
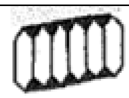
In order to improve these different properties, a stabilizer can be added to the soil. However, it is important to choose one that is appropriate for the type of soil used. There are more than a hundred products that can be used as stabilizers in earth construction, whether they are added to the mass or to the rendering. Although stabilization has been studied since the 1920s, there is still no "miracle recipe" that can meet all needs. The most common methods used are: densification by compression, adding fibers to the mix, adding cement or lime to the soil or mixing the soil with bitumen. However, stabilization should not be practiced automatically because it is relatively expensive and complicates the production of the material by adding preliminary studies. Soil already has many interesting properties in its natural state. Stabilizers are therefore not always useful. They must be used in a thoughtful way in order to meet needs that are lacking.

Thus, for a project, there are three ways to proceed: either one builds with the soil present on site by adapting the project to this soil, or one imports soil in order to meet the requirements of the project, or one modifies the soil present on site so that it can match the desired project (Guillaud & Houben, 1995). When deciding to stabilize soil, i.e., to "modify the properties of a soil-water-air system to achieve permanent properties compatible with a particular application" (Guillaud & Houben, 1995), one must first consider:« the properties of the soil to be stabilized ;

- the improvements envisaged;
- the economy of the project, i.e. the costs and time of realization;
- the techniques of implementation of the soil chosen for the project and the construction systems;
- The maintenance of the completed project, i.e. the cost of maintenance" (Guillaud & Houben, 1995).

Stabilization will act on the texture and structure of the soil, the only parameters that can be modified. It can proceed in three different ways. The first one is to play on the porosity of the soil material by reducing the volume of voids present between the particles. The second is to modify the permeability of the soil by blocking the voids that cannot be removed. The last possibility is to modify the mechanical resistance by reinforcing the links between particles. These modifications can be done according to three different processes: the first is the mechanical stabilization. This method corresponds to the compression of the soil, which modifies its density, mechanical resistance, compressibility, permeability and porosity. The second process is the physical stabilization. It acts on the texture of the soil by controlling the granulometry, by making it undergo a thermal treatment or an electrical treatment. The last system is the chemical stabilization. It corresponds to the modification of the properties of the soil by the addition of other materials or chemical products. It is important to specify that "each stabilizer does not necessarily act according to an exclusive process but can also combine several processes: physical and chemical" (Guillaud & Houben, 1995). Six stabilization mechanisms are mainly present in earth construction (Table 2.3).

*Table 2. 3- Stabilization mechanisms (Guillaud & Houben, 1995)*

| Means for stabilizing reworked soil | | | | | | |
|---|---|---|---|---|---|---|
| Stabilizer | | Nature | Process | Means | Principle | symbol |
| No stabilizer added | | | mechanical | Densify | Create a dense medium that blocks pores and cappilar channels |  |
| With the addition of stabilizer | Inert stabilizers | Mineraux | physical | | | |
| | Stabilizers phisico-chemical | Fibers | | Reinforce | Create an omni-directional frame that reduces movement |  |
| | | Binders | chemical | Enchain | Create an inert skeleton that opposes any movement |  |
| | | | | Link(bind) | Form stable chemical bonds between the clay crystals |  |
| | | Hydrophobic | | waterproofing | Surround the soil grains with an impregnable film and plug the pores and channels |  |
| | | | | hydrophobicize | Eliminate water absorption and adsorption as much as possible |  |

## 2.8.2 Main techniques

These mechanisms are possible thanks to stabilization techniques that have been developed and improved over the years as a result of extensive research on the subject. The main techniques are listed and detailed below (Guillaud & Houben, 1995).

### *2.8.2.1 Densification by compression*

Densification by compression acts on the porosity of the material by distributing the pores homogeneously in the soil and by modifying their size in order to make the material more compact and thus more resistant to compression. Four methods of compression have been developed: "static compression, dynamic compression by vibration, dynamic compression by impact and compression by kneading" (Guillaud & Houben, 1995). Each has its own optimum moisture content (O.M.C.) to which an optimum dry density corresponds. Several parameters are taken into account in order to obtain the best possible compactness. For example, it is important to use the right compaction energy for the type of soil. The higher the compaction energy, the lower the O.E.T. and the higher the dry density, but too high an energy will cause the blocks to roll. Therefore, it is necessary to find the right energy to be deployed to be efficient. It is also necessary to pay attention to the grading curve of the soil used. Indeed, a tight granularity will not allow to reach a good compactness while a spread granularity will allow to reach a maximum compaction. If the compaction of the soil is carried out in good conditions, a lower permeability, a lower compressibility and a lower water absorption and swelling will be obtained. The mechanical strengths will be increased, both initially and in the long term (Guillaud & Houben, 1995**).**

### *2.8.2.2 Mineral additions*

If the soil is too rich in clay, the first materials to be added are sand and gravel. Indeed, they make it possible to obtain a better distributed particle size curve. Thus, shrinkage and swelling will be controlled while a better distribution of porosity will be obtained. The density will also be higher thanks to a better cohesion between the soil particles. However, care must be taken to ensure that the materials are mixed in an optimal manner to avoid the presence of clay lumps (mottes d'argile).

Pozzolans, such as certain volcanic ashes, can also be added to soils with excessive clay content. Fly ash containing calcium carbonate can be used as a stabilizer in proportions varying from 5 to 10%. These improve the compressive strength and reduce shrinkage and swelling. They also keep termites away. However, they have no effect on water resistance. They can be combined with lime stabilization to obtain better results (Ruskulis, 1991).

From an ecological perspective, sugar cane bagasse ashes can be added for the production of cement-stabilized BTC. Indeed, in countries such as Brazil, this waste is produced by thousands of tons every day. Introducing them to the production of BTC could thus find an interest in them. For proportions of 6% to 12% of cement, up to 8% of ash can be added. The compressive strength and water absorption of BTC are not affected (Lima, Neto, Sales & Varum, 2012).

### *2.8.2.3 Addition of fibers*

The addition of fibers in the soil as a stabilizer is a technique widely used in the world. Straw, which reinforces the structure, is the most used because it adapts to the different modes of implementation of the earth, i.e. plastic, viscous or in the case of compression. The fibers play several roles: they allow:

- to prevent cracking during drying by distributing the tensions due to the shrinkage of the clay throughout the mass of the material;
- Accelerate the drying process by draining the humidity towards the outside through the channels of the fibers. Conversely, the presence of fibers increases the absorption in the presence of water;
- to lighten the material: the volume of straw is often very important, lightening the density of the material and improving its insulation properties;

- To increase the tensile strength (Guillaud & Houben, 1995).

Soil stabilized with fibers therefore has very good resistance to cracking and crack propagation because they resist cleavage when the stress increases. Depending on the tensile strength of the fibers used, the shear strength will be increased to some degree. Depending on the amount of fiber used and its tensile strength, and depending on the compressive strength of the soil and the internal friction between the fiber and the soil, good compressive strength can be achieved with the fiber reinforcement in place. If we compare the strength of a material reinforced with fibers to the original material without fibers, we observe a strength superior of about 15% for the material containing the fibers except in the case of a material too sandy where the fibers can have a negative effect. If we take the example of adding sheep wool fibers to the soil, we observe an increase in compressive strength of about 37%. In the case of deformations, there is also a greater capacity to absorb energy in the case of fiber-reinforced earth, which will be very interesting in earthquake-resistant regions. This is due to the fact that the fibers modify the behavior of the earth beyond the point of failure (Guillaud & Houben, 1995; Galán-Marín, Petric & Rivera-Gómez, 2010).

There is an optimum amount of fiber to add beyond which there is a loss of strength. Indeed, if an exaggerated quantity of fibers is added, the density will be too much reduced and there will be insufficient contact points between the fibers and the soil. This implies that the deformations will not be transmitted correctly, which will decrease the resistance of the earth. Good results are already obtained with a dosage of 4% by volume. The fibers are preferentially placed in all directions in order to obtain better results. To further improve the results, the fibers can be combined with a second stabilizer such as cement, lime or bitumen. The fibers can be of vegetable, animal or synthetic origin. Straw of all species, cereal husks, hemp, coconut fibers, palm fibers, etc. are generally used for plant fibers; cattle hair and mane for animal fibers; steel, glass fibers and cellophane for synthetic fibers (Guillaud & Houben, 1995).

#### *2.8.2.4 Cement stabilization*

The use of cement for soil stabilization dates back to 1915 in the road sector. Since then, the technique has largely evolved and is used in both public works and construction. When mixed with soil, hydrated cement reacts in two ways. The first is a self-reaction which gives rise to a pure hydrated cement mortar and a reaction with the sandy skeleton. The second is a three-stage reaction of the cement with the clay. These phases are as follows: first, cement gels are formed on the surface of the clays following the hydration of the cement which releases lime. This one is quickly consumed by the clays which enter then in deterioration. Secondly, we are facing a dissociation of the clay aggregates following the evolution of the hydration. The cement gels formed in the previous stage can then penetrate inside the clays.

The third phase is that of the "intimate interpenetration of cement gels and clay agglomerates. The hydration persists, but more slowly" (Guillaud & Houben, 1995). This entanglement of structures gives rise to three intertwined matrices: "an inert sandy matrix bound to cement; a matrix of stabilized clay; a matrix of unstabilized earth" (Guillaud & Houben, 1995). This leaves a portion of sand and clay aggregates that is not stabilized and is surrounded by the stabilized matrix (Guillaud & Houben, 1995).

Cement stabilization has several effects. It changes the dry density of the soil (decreasing for well-compacting soils and increasing for poorly compacting soils); it increases its compressive strength in the dry and wet state as well as its tensile strength; it decreases dimensional variations (less shrinkage on drying and swelling on wetting); and it improves its resistance to erosion. In order to obtain effective stabilization and satisfactory results, a cement dosage of 6 to 12% is recommended for most soils. Results are also improved when the soil is sandy. However, the organic matter content of the soil should be less than 2% to avoid slowing the setting of the cement. When organic matter is present in the soil, lime (2%) or calcium chloride (0.3 to 2%) can be added in small quantities to accelerate the setting of the cement. The sulfate content should also be less than 2 to 3% because sulfates destroy the hardened cement in the earth-cement matrix and increase the moisture sensitivity of the clays. Ordinary cements are used for stabilization. Portland type cements are largely sufficient. The properties are not significantly better with high strength cement stabilization. Therefore, mainly artificial Portland cements (APC) of class 250 or 325 (APC 250 - APC 350), i.e. CEM I, composed of 95 to 100% clinker are used. Slag cements (CPAL), fly ash cements (CPAC) and pozzolans (CPAZ) can also be used. Portland iron cements (PIF), blast furnace cements (BF), mixed metallurgical cements (MMC) and clinker slag cements (CLK) should be rejected because their curing is too delicate. In order to improve certain properties, some additives can be added in small quantities to the mix such as bitumen (2 to 4%) which will improve the waterproofing of the soil, organic or mineral products to reduce the sensitivity to water, lime (2%) to modify the plasticity of the soil or sodium additives to increase the reactivity of the soil (Guillaud & Houben, 1995).

In order to implement quality cement stabilization, several steps must be followed. The first is pulverization. This requires a good mixture of the constituents and fine modules not exceeding 10mm with a maximum of 50% of modules larger than 5mm in order to guarantee a good compressive strength. The second step is mixing. The soil must be dry in order to obtain a homogeneous mixture and a good distribution of the cement. After this dry mixing, the necessary amount of water will be introduced to the mixture. This quantity of water is close to the O.E.T. (wet side for clay soils and dry side for sandy soils). The third step is the molding or shaping of the stabilized soil. The latter is compacted directly after mixing before the cement can set. The last step is the drying of the material. This step is very important because it is during this drying time that the strength of the earth cement material develops: the longer the cure, the better the strength. The latter will be subjected to a minimum drying cure of 14 days (28 days being preferable) during which it will be kept in a humid environment (relative humidity close to 100%), sheltered from the sun and protected from the wind in order to avoid any "risk of drying out too quickly on the surface that could cause the formation of shrinkage cracks" (Guillaud & Houben, 1995).

#### *2.8.2.5 Lime stabilization*

Lime stabilization appeared in the USA in 1920 for pavements. Today, it meets an increasing interest in the field of construction and mainly in the case of compression molding. Lime is added to the soil in the same proportions as for cement stabilization, i.e. a dosage of 6 to 12%. However, in contrast to cement stabilization, there is an optimal quantity for each type of soil. Different types of lime can be used, but mainly air lime is used, which is obtained by firing very pure limestone. Quicklime (CaO) is less used than slaked lime ($Ca(OH)_2$) even if it is more efficient than the latter for the same weight, because it requires special storage and transport conditions. Natural hydraulic lime (XHN) and artificial hydraulic lime (XHA) are only used in spite of another available lime. Lime stabilization can be broken down into five mechanisms. The first is the absorption of water from the wet soil by the lime. This hydration is accompanied by a significant release of heat. The second is the cationic exchange of calcium ions from the wet soil: these are substituted for the exchangeable cations in the soil. The third is the flocculation and agglomeration of soil particles due to the increased number of electrolytes in the pore water caused by the preceding cation exchange, resulting in a change in texture and structure. The fourth mechanism is carbonation: "lime added to soil reacts with carbon dioxide from the air to form poor carbonate cements" (Guillaud & Houben, 1995).

The last mechanism is the pozzolanic reaction. This one is very important because it is the one that influences the performance of lime stabilization the most. The latter produces an alkaline environment with a high pH in which the clay minerals dissolve. The silica and alumina of the clays then recombine with the calcium, forming aluminum and calcium silicates that will cement the grains together. Lime stabilization therefore requires a clay soil containing mainly alumina silicates, silica or iron hydroxides. The presence of organic matter in the soil is less problematic than in the case of cement stabilization: here, soils containing up to 20% organic matter can be used. However, sulphates are harmful in the wet state (Guillaud & Houben, 1995).

Lime stabilization influences the dry density of the soil following flocculation. It also increases its compressive strength. When the dosage is optimal, resistances ranging from 2 to 5 MPa or even 20 to 40 MPa in the case of industrial processes can be obtained. The tensile strength varies according to the quality and quantity of the clays that will react with the lime. Dimensional variations are also influenced by the addition of lime to the clay: an addition of 1 to 2% of lime can decrease shrinkage of 10% to 1% and eliminate any swelling. In order to further improve certain properties such as the reactivity of the soil or the compressive strength, the addition of additives (such as Portland cement or sodium sulfate) in small quantities can be considered (Guillaud & Houben, 1995).

There are five important steps in the implementation of lime stabilization. The first is spraying. A finely ground clay will allow the lime to react quickly with it. The second is the mixing, which allows to obtain a homogeneous mixture of the soil and the lime. The third is the holding time, which allows the earth and lime to react and thus obtain better resistances. The resting time will be longer for plastic processes (several weeks) than for wet processes (a few hours). The fourth step is compression, which takes place at almost optimal water content. The last step is the drying cure, which is done in a warm and humid environment. The longer this stage, the higher the compressive strength will be (Guillaud & Houben, 1995).

#### *2.8.2.6 Bitumen or asphalt stabilization*

Finally, the use of bitumen stabilization in construction, although limited, dates back to the $5^{th}$ century BC. It was redeveloped in 1940 in the USA but is again gradually being forgotten in view of the cost of oil. It is "a product composed of at least 40% heavy hydrocarbons and filler" (Guillaud & Houben, 1995). In order to be used in stabilization, bitumen must be either "mixed with volatile solvents" such as diesel, kerosene or naphtha, or "dispersed in water in an anionic or cationic emulsion" (Guillaud & Houben, 1995).

Once mixed with the soil, the water or solvent evaporates and the bitumen globules stretch into very thin solid films that adhere to the soil particles and coat them (Guillaud & Houben, 1995). The role of bitumen is multiple: it allows to decrease the density of the soil and to increase the optimal water and bitumen content. The compressive strength is also improved by the addition of bitumen. In the dry state, however, the quantity of bitumen added should be limited because after a certain threshold, it acts as a lubricant and the compressive strength drops sharply. Bitumen reduces water absorption, which becomes very low and stationary over time after a few days of drying. Swelling is also reduced, especially when mixing in a liquid state. Bitumen is added to the soil in a proportion varying from 2 to 3% and in some cases up to 8% depending on the granularity of the soil. Bitumen stabilization is effective for sandy or silty soils. They must not contain too much organic matter because this prevents the bitumen from adhering to the soil particles. Similarly, mineral salts should not be used for this stabilization: they should be neutralized by adding 1% cement to the mixture. Additives (such as cement, lime, quaternary amines, waxes or phosphoric anhydride) can be considered to obtain additional improvements. There are four steps in the process: first, mixing. For plastic or liquid soils, this is done without special precautions. If the soil is to be compressed, it must be mixed with water content close to optimum. The second step is the holding time between mixing and demolding for slow or semi-rapid breaking stabilizers. For fast breaking stabilizers, the retention time will be shorter. The third step is compaction, which ensures the evaporation of volatile solvents and a good dry density of the soil. The last step is the drying cure which is done in dry air. It is the duration of this one which will determine the compressive strength of the material according to the quantity of bitumen added (Guillaud & Houben, 1995).

#### *2.8.2.7 Characteristic values after stabilizing the soil*

Previously, compressive strength values have been cited. When the soil is stabilized, Doat et al. (1979) recommend the following values:

- Stabilization with cement: 50 to 100 kg/cm².
- Stabilization with lime: 30 to 80 kg/cm².
- Stabilization with bitumen: 15 to 60 kg/cm².
- Stabilization with fibers: 5 to 20 kg/cm².
- Stabilization with chemical products: 20 to 40 kg/cm².
- Stabilization with strong chemicals: 150 to 400 kg/cm².

It can be seen that the values obtained for stabilized soil are much higher than the compressive strength of 2 kg/cm² of unstabilized soil. However, when we talk about earth construction, the mechanical resistance of the material is often the first element we worry about. In the imagination, earth is a heavy and not very resistant material. It is true that traditional constructions are often not very resistant to compression because they are built without care and previous study. But the results stated above prove that contrary to preconceived ideas, earth can be a very resistant material when it has been stabilized in a factory for example. Before anything else, it will be necessary to make sure of the nature of the soil that will be used for the construction as well as to choose the appropriate application technique and see if it requires any stabilization. With a little care, earthen constructions can easily reach several floors safely. But in order to achieve a weather-resistant building, it must be protected from water runoff, erosion, and rising water by providing "good boots and a good hat" (Frey, 2013). This means that the building's footing will need to be large enough and of a material that prevents water from seeping into the walls, and the building's roof will need to overhang enough to protect the building from storm water by draining it away from the walls. This will ensure that the building is resistant to all stresses.

## 2.9 Earth construction techniques

If we look at the different edifices erected around the world, we can see that there is panoply of constructive typologies. Indeed, there are different ways of using raw earth. Each of these techniques is born from different geographical contexts, particular ways of life, different customs, and different climates or even according to the available materials.

In reality according to surveys around the globe, there are about a hundred practiced constructive techniques to build shelters. Among those, Guillaud and Houben (1995) have schematically listed the most practiced techniques in a "wheel" of earthen construction methods. Then, soils can be processed into twelve different states of hydration varying from solid to liquid: rocky concretion, friable concretion, solid concretion, friable aggregation, dry soil moist soil, solid paste, semi-solid paste, semi-soft paste, soft paste, mud, and slurry. In each specific state of hydration the soil can be workable as a monolithic, unit base or mixed structure. These three main construction classification systems are subdivided in twelve different construction techniques (Figure 2.8): dugout, earth-sheltered space, fill-in, cut-blocks, compressed earth, direct shaping, stacked earth, molded earth, extruded earth, poured earth, straw clay, and daubed earth. These construction techniques, as mentioned before, have likely evolved through time and are still in use in many countries around the world. Among those techniques, five are most widespread: adobe, rammed earth, cob, wattle and daub and compressed earth bricks (CEB).

The suitability of a soil for a particular application and its associated construction technique is determined by the combination of its:

- texture, mostly linked to particle size distribution;
- hydration state, driven by the amount and the type of reaction to water at the molecular level;
- Its stabilization, which determines its resistance to erosion, compression, flexural stress, and other chemical and mechanical properties.

In this section, a brief review will be given on the five more common technics with a special emphasize on rammed earth.

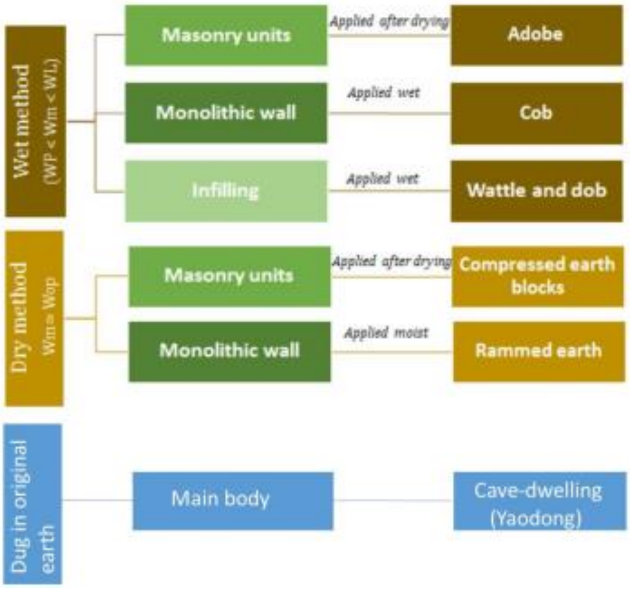



*Figure 2. 8 - Classification for the earth construction techniques (Wm =manufacture water content, Wop = optimum Proctor water content; WP = water content at plastic limit; WL = water content at liquid limit)*

### 2.9.1 Wattle and daub

Wattle and daub is perhaps the oldest earth-building technologies in the world. This technique consists of two parts, wattle and daub: a wattle is a woven structure of small plant elements held together in a stiff frame; common materials used to create wattle are reeds, bamboo, branches and twigs. Daub or mud adheres to the irregularities and overhangs of the organic matrix. The daub is then smeared on to the wattle by hand until the entire surface is covered. After drying, either the finish surface can be a smooth final coat of daub, or it can be whitewashed with lime. This technique is for the construction of non–loading bearing walls, either partition walls or external walls, with widths between 8 cm and 20 cm. It is the wattle who holds the bearing capacity rather than the earth, and the wattle (woven structure) is highly earthquake resistant because it is extremely flexible. This is the reason why wattle and daub is often used in seismic zones throughout the world such as South America and Indonesia (Niroumand et al. 2013).

### 2.9.2 Compressed earth bricks

CEB or compressed earth block is a natural building material. The process of making and using bricks made of earth is part of sustainable development and regenerative design, Compressed Earth Block (CEB) is a building material that is habitually used to raise walls using conventional construction techniques. It can come it different sizes, but the most common one is 15x15x30 centimeters. The most unusual aspect of the CEB is its composition: it is made of compacted earth. The earth used to manufacture compressed earth blocks contains a certain degree of moisture, and once it is poured into a formwork of the size of the final piece, it is submitted to a compression strength that renders it compact, generating a solid block with a sufficient degree of cohesion and resistance to be comfortably manipulated. By applying compression strength the mechanical resistance of earth is improved and at the same time the porous structure of the material is altered, the volume of the pores is reduced and the apparent density is increased.

### 2.9.3 Adobe

Adobe mud blocks are one of the oldest and most widely used building materials. Use of these sun-dried blocks dates back to 8000 B.C. The use of adobe is very common in some of the world’s most hazard-prone regions, such as Latin America, Africa, the Indian subcontinent and other parts of Asia, the Middle East and Southern Europe.

Adobe is a material used for building that is made of organic materials such as earth, clay, straw, and so on. In Spanish, ‘adobe’ translates as ‘mud brick’, and buildings that are constructed from adobe have a similar appearance to cob or rammed earth buildings.

Adobe bricks are traditionally made in open cast molds and left to sun-dry rather than being kiln-fired. They are laid using an earth mortar and smoothed down when the wall is finished before a clay render is usually applied as a surface coating. This production process, as well as the nature of clay, means that adobe bricks have advantageous water resistance. However, buildings that are exposed to a lot of wet conditions should be provided with eaves to protect the walls. Adobe bricks have similar properties to other forms of earth construction– fire-resistant, flexible, durable, provide sufficient thermal mass to ensure good energy efficiency, and good sound insulation.

### 2.9.4 Cob

The word Cob or Cobb comes from an old English root meaning a lump or rounded mass. Cob is a natural building material where the basic ingredients are made from a mixture of sandy-sub soil, water, clay and fibrous organic material (typically straw),and sometimes lime. Cob building uses hands and feet to form lumps of earth mixed with sand and straw. Cob is easy to learn and inexpensive to build. Because there are no forms, ramming, cement or rectilinear bricks, cob lends itself to organic shapes: curved walls, arches and niches. Earth homes are cool in summer, warm in winter. Cob is also fireproof, resistant to seismic activity Pullen and Scholz (2011) use low-cost materials, although it is very labor intensive. It can be used to create artistic and sculptural forms, and its use has been revived in recent years by the natural building and sustainability movements.

In technical building and engineering documents, such as the Uniform Building Code of the western USA, cob may be referred to as an "unburned clay masonry" when used in a structural context. It may also be referred to as an "aggregate" in non-structural contexts, such as a "clay and sand aggregate" or more simply an "organic aggregate," such as where the cob is a filler between post and beam construction.

### 2.9.5. Rammed earth (Technique of the compressed earth)

#### *2.9.5.1 General overview of rammed earth construction techniques.*

The technique of the compressed earth, more generally called technique of the pisé, appeared for the first time in Carthage in Tunisia. It then spread around the Mediterranean basin and the Maghreb before reaching Europe in the 7$^{th}$ century. It "consists of building massive walls by compacting wet and powdered earth in forms" (Anger & Fontaine, 2009). The soil used is generally extracted directly from the construction site. It will be necessary to verify that it does not contain too much clay, causing cracks during drying. The rammed earth soil can contain pebbles and gravel as well as finer particles. Because of the use of forms and the granulometry of the earth used, this construction technique is the one that most closely resembles the concrete technique.

"Clay concrete" or "earth concrete" is widely used names for rammed earth. The moisture content of the soil in the spring and fall is perfect for this construction technique. The extracted earth is placed in forms, also called "banches". One side of the form is made of dry wood planks reinforced with rafters and is less than a meter high. The two long sides are placed parallel to each other with the desired wall thickness as the spacing. For the first stage, two other sides measuring this desired thickness are attached to the ends of the long sides. In the following steps, only one small side will be kept, the soil from the previous step being used to close the last side. For the last step closing the perimeter of the construction, the two small sides will be removed, the bank being closed by earth at both ends. The two long sides are held at a distance by crosspieces, called the "keys" of the formwork. These are very strong in order to resist the horizontal thrust of the earth.

The forms are filled with soil in thin layers of about 15 cm. Once the layer of soil is spread in the formwork, the soil is compacted. This is what will give it the necessary cohesion. Therefore, it must be done carefully with the "pisoir". This instrument, used to compact the soil by shocks, consists of a solid handle to the end of which is fixed a large mass that can be made of wood or metal.

With the evolution of the concrete industry, the techniques of the rammed earth knew an important modification. The insertion of the pneumatic rammer, inherited from the foundry industry, in the implementation of the rammed earth allowed to increase the production output as well as the resistance of the wall. The replacement of wooden keys by threaded rods or concrete irons, leaving holes of much smaller dimensions in the adobe, was also known. The formwork systems have also undergone a beautiful evolution with the arrival of the "climbing formwork" which allows a faster construction than with the classic horizontal formwork as well as with the curved formwork allowing obtaining a greater richness in the shape of the buildings. Motorized machines, the "bucket mixers", have also appeared, that allow to sieve the earth and to mix it while adjusting its water content and then to pour it into the formwork. All these modernizations make it possible to obtain more regular and more stable walls more quickly.

#### *2.9.5.2 Compaction of the earth*

An important parameter determining the compressive strength of rammed earth is the dry density of the soil, i.e. the bulk density, which depends on the type of soil, the moisture content during the compaction process, and the energy of compaction. This process consists of mechanically densifying a soil to consolidate the space occupied by the soil particles into a close state of contact so that the entrapped excess air and water can be expelled from the soil mass. The idea of compacting earth is to improve the quality and performance of molded earth walls (walker et al. 2005). Compacting of earth walls is usually referred to as tamping. Compaction is accomplished by applying a force or vibration to the soil mass. The efficiency and success of any compaction effort will be dependent on the type of soil being worked, the moisture content present in the soil mass, and the technique used to compact the soil.

Traditional tamping used wooden tamper to manually press the earth in a wooden mould to form the walls. In earthen wall design, properly compacted soils help to strengthen the internal strength of the soil mass by aligning the soil particles together and increasing the coefficient of friction when a load is applied to the soil, and reducing undesirable settlement.

Compaction is measured using an industry standard proctor test. The level of compaction in a soil mass is determined by comparing the density of the soil as measured at the site with the density of that soil type as defined in the Standard Proctor tests. For example, specifications often require compaction to be 95 percent of Standard Proctor. This means the on-site soil density must be equal to 95% of the maximum achievable compaction. Compaction is achieved by applying three basic types of force to the soil mass.

#### *2.9.5.3 Dynamic compaction*

Traditional tampers are made of a heavy wooden block with a handle extending upward through its center. A more compact version can be made from 10 cm square steel plate welded to a section of 2.5 cm pipe. A 10-15 cm layer of moistened soil is placed inside the form, and a worker drops the tamper from a height of 30-46 cm. In fact, most of the work is now done quickly with pneumatic tampers, and manual devices are used only in tight spaces around electrical boxes or plumbing pipes. After many repetitions with the tamper over the entire surface of the layer, the noise made by the impacting tampers changes from a dull thud to a ringing sound. This happens when the soil has been compacted to about half of its original volume. At this point, another layer of prepared soil is added, and the tamping process is repeated. When the tamping is finished, the wood forms are removed.

#### *2.9.5.4 Static compaction*

By simply using the weight of the machine being passed over the desired area, compaction can occur. Generally this will only yield compaction of a thin top layer where the load is applied. A heavy, walk-behind roller can develop good results when used in 20.3 cm lifts. Don't count on obtaining proper compaction by driving your construction equipment back and forth over soil. Heavy equipment cannot be driven within 0.3 m of the back of the wall.

#### *2.9.5.5 Vibro-compression*

Vibratory machines send waves of motion through the soil to reposition and consolidate the soil particles. Forces of this type do a good job of forcing out excess air within the uncompacted mass. Vibratory machines work well in noncohesive soils; soils comprised of at least 50 percent sand or gravel.

#### *2.9.5.6 Mechanical behavior of rammed earth structures*

A key element to establishing a base level of standardization of rammed earth is having a regulated, uniform compaction to each lift of earth during construction. Regulated compaction would ensure a compressive strength that, although variable depending on the soil used, would establish a framework for measurement of the strength of the wall. Further testing would yield site-specific a standard to which the rammed earth wall must meet for code. Regulated, uniform compaction during earth construction can only reasonably be achieved using mechanized techniques. The proposed compaction method is based on two well-known geotechnical principles:

1) The stress applied on a saturated soil volume coincides with the effective stress acting on the solid skeleton only if the excess pore water pressures generated during loading are dissipated. In turn, excess water pressures are dissipated only if the soil is allowed to consolidate, i.e. if pore water is allowed to drain under constant load.
2) The dry density of a soil volume increases as compaction energy increases. Therefore higher compaction pressures generally correspond to improved mechanical properties.

By exploiting the above two simple principles, we have produced compressed earth blocks with excellent mechanical properties. This can help to overcome some of the historical drawbacks that have hindered the dissemination of this construction technique across current practice.

### *2.9.5.7 Damage and vulnerability of rammed earth structures*

As previously pointed out, the general behavior of earthen structures is mainly determined by the low mechanical performance of the material and its nature, especially in the case of rammed earth. Likewise, these properties also define its vulnerability, which are mainly related to the presence of water, erosion, and cracking under low compressive and tensile stresses, as well as low resistance to dynamic actions, which are worsened by the high dead-load of the structure (Miccoli et al., 2014).

Nevertheless, it is important to note that structural vulnerability is not only related to the specific characteristics of the material itself, but also to the constructive system. In this way, and considering that earth construction techniques are often linked to vernacular architecture, their poor performance can be also related to the low quality of constructions, which is often conditioned by the use of local materials and the application of different crafts within the construction site. In this regard, local materials may present lower performance, while crafts are based on principles of broad application, adapted to different environmental and economic conditions and with a quality control relied upon the skill of the craftsmen (Tavares et al., 2014). Thus, aiming at retrofitting the structural performance of any building -and more specifically of those with earthen materials -means to improve the quality of construction and the quality of the materials, leading both to the good connectivity between elements. This is generally considered a critical aspect for the mechanical properties of the building. These concepts are all related to the principles of good construction, which guarantee a good structural performance.

Durability is strongly bound to Vulnerability. Monjo (2007) defines it as proportionally inverse to vulnerability. Therefore, the more vulnerable a wall is, the less durability it shows. In order to assess the damages and vulnerability, it is essential to thoroughly know how rammed earth functions and also its pathological response in order to obtain a better base for decision-making. If solely current damages are considered, only corrective measures can be applied. Nevertheless, the management of a heritage object requires greater understanding for medium and long-term behavior. To this end, a study of vulnerability and damages has been introduced, as claimed by several international organizations (Iscarsah, 2000). The objective is to achieve the greatest Durability. First of all, three types of vulnerabilities should be studied and characterized, corresponding to those stated weak aspects of rammed earth: vulnerability to water, physical vulnerability (erosion) and structural vulnerability (structural instability). Each type of vulnerability depends on several risk factors that must be determined and classified in order to identify any weaknesses of the rammed earth wall.

➢ **Vulnerability against water**

The water sensitivity of the rammed-earth material and the earth material is a negative point in the public and engineering eye. Several researchers have shown, however, that there was a range of water content in which the mechanical characteristics of rammed-earth material were constant. As described previously, clay minerals are hydrophilic, therefore the durability of earthen structures is mainly related to the action of water on the walls. All damages with the exception of specific kind of cracks can be directly or indirectly linked to the effects of water, which may be present from various sources, mainly rainwater (Röhlen & Ziegert, 2014). The penetration of rainwater leads to the washing of the wall due to the saturation of the material, which progressively washes the surface. When this process occurs over a long period, coarse particles loss their support and they are removed either by abrasion or fall, causing a loss of strength and stiffness and of the bearing capacity.

Considering materials with a low pore radius, water will take 1 hour to penetrate 13 mm into a wall and 2 weeks to penetrate 23 cm (Jaquin, 2008). Therefore, an important function in earthen buildings is performed by renders, which protect the structure when exposed to rainwater. Traditional renders are made of rich mixtures mixed with fibers in order to avoid shrinkage, and they should be periodically substituted when the surface has been washed out and the fibers are visible. Other water-repelling agents such as lime, cement or oils are also used as additives. In these cases, compatibility and permeability should be taken into account (Houben & Guillaud, 1989).

As a hygroscopic material, condensation also occurs within the pore structure in response to ambient humidity, but earthen materials are not in danger of losing stability, even if material strength is lowered. However, the hygroscopic behavior may have an important influence due to the wetting-drying cycles, which may lead to cracking in rich clayey materials that may destabilize them structurally (Velde, 2008). High hygroscopicity also makes earthen constructions vulnerable to rising damp, which affects to the base of the walls, especially at the evaporation zone near the surface. In this area, decay is caused not only by water, but also by the presence of salts, which crystallization and hydration process breaks the material due to the increase of volume.

➢ **Vulnerability against biological actions**

Soil is a vulnerable material against biological actions, which may induce severe structural damage. The high content of water allows the growth of vegetation on the material, which roots may cause cracking on the walls. Larger quantities of water can also cause the decomposition of the straw, leading to a loss of strength and the increase of acidity. This acidity may cause changes in the clay minerals and to the degradation of the hardened lime, if present (Röhlen & Ziegert, 2014). Furthermore, the softness of the material when moistened facilitates the action of small animals such as rodents or rats. They excavate nests at the foot of the walls that may affect to the structure if extensive (Jaquin, 2008). Termite infestation, however, can lead to the collapse of the structure. Insects do not attack mud, but straw and/or embedded organic additives traditionally used in the mixture (Langenbach, 2005). This causes the complete loss of internal cohesion, which may be worsened by the drilling of tunnels to reach the timber elements of the roof (Figure 2.9).

*Figure 2. 9 - Termite damage in an adobe structure (Langenbach, 2005)*

- **Vulnerabilty against mechanical damages**

As previously pointed out, fundamental mechanical properties of earthen structures are related to the low mechanical performance of the material, and this performance determines the mechanical vulnerability. For instance, rammed earth is characterized by higher dry density and thickness, which means higher compressive strength but also higher dead loads. For this reason, rammed earth structures are more vulnerable than other earthen structures to the damage caused by differential settlements (Jaquin, 2008). Cracks may also appear due the concentration of stresses. Brittle behavior and low tensile strength may easily lead to the initiation and propagation of cracks, for instance when trusses or beams are directly supported by walls and not by an intermediate element such as ring beams or wall plates.

Specific damage pattern in rammed earth structures is related to the compaction process. The layered configuration of the lifts and the lifted structure itself present weak points at the interface between layers and lifts. Nevertheless layering does not have an influence on crack mechanisms, while shrinkage may lead to the propagation of cracks at the vertical and horizontal joints between lifts (Miccoli, et al., 2014). All these considerations are qualitative, since knowledge on static and dynamic structural behavior of rammed earth structures is very limited within literature, for instance with regard to their non-linear behavior (Miccoli, et al., 2014). This fact is related not only to the lack of research, but also to the complexity of the problem, which entails many difficulties that have still not been overcome.

## 2.10 Index properties and strength of artificial soil using the Harvard miniature method

Compaction characteristics of soil are usually determined by conducting Standard Procter tests in the laboratory over the soil and the test results are utilized in the field for different construction and also for ensuring the quality of construction. However, the test is quite costly and time consuming. Further when extent of construction is very large for example making sub-grade of roads of large length, generally existing materials along the length widely varies due to depositional reasons, and in such cases, number of compaction tests to be performed, becomes very large, extremely time consuming and costly. In such cases if the estimation of the moisture-density relationship could be developed on the basis of some test which are quick to perform, less time consuming and cheap, then the process will help the constructors enormously. In the present study moisture-density relationship from Harvard Miniature compaction method with the help of index properties and compressive strength of the soil was studied. Throughout this research project, the relationship between index properties (liquid limit, plasticity index), maximum dry unit weight and strength of artificial soil was observed. The tests performed included the unconfined compression test using the Harvard Miniature apparatus, liquid limit, and plastic limit tests.

## 2.11 Assessment of cementitious materials impacts on clayey soils properties

Good sites for construction are becoming limited these days and the growing need for construction platforms for civil engineering activities has made imperative the use of existing soils with low load-bearing capacity and has gradually become essential over the last decades. Buildings of earth dated 6000 years back from the civilizations of Mesopotamia (Deboucha and Hashim, 2011) and even 12,000 BC (PachecoTorgal and Jalali, 2012). The use of earth as a building material is very obvious and, often sought after for economic reasons.

Housing is not only the building of sustainable communities, but Similar tendencies concerns also the rehabilitation of endangered heritage, earth dams to meet water needs and the extension of road networks, especially in areas where local sources of suitable aggregate deposits are deficient or scarce, has created conditions that constrain the use of in-situ transient or cohesive soils thus facilitating community renewal and creating places where people would settle down and work for the present and future generations (Kabir and Bustani, 2012). Soft clays are associated with low compressive strength and excessive settlement. Many others have a potential to shrink and swell in response to varying moisture content in these types of soils. Several factors like amount and type of clay minerals, soil structure, dry density, confining pressure, moisture content and climate changes influence the amount of swell and shrinkage (Firoozi et al. 2016). Soil compaction is one of the most important processes of mechanically densifying a soil.

The principal soil properties affected by compaction involve consolidation and settlement, shearing resistance, movement of water and volume change (shrinkage and swelling) very decisive when soils are used as subgrades for roads and airfield pavements. Using dry density and the compaction process to characterize the stabilized soils is inadequate to improve the soil properties particularly in arid and semi-arid regions where the compacted soils are unsaturated, and as a consequence the engineering properties are influenced by the matrix suction during winter time affecting then the strength and density. Considerable research has been undertaken in the modern times to make soils of poor quality as a sustainable construction material. Increase in soil strength, durability stiffness, and reduction in soil plasticity and swelling/shrinkage potential are the benefit of soil stabilization. Various stabilization methods have been used to overcome this shrink/swell hazard and thus prevent the potential damage. Two well-known of these methods that have proven themselves treating problematic soils involve lime and cement have been successfully used for decades to stabilize shrink/swell soils by lowering their plasticity index (PI). Such stabilization processes improve the various engineering properties of the stabilized soil and generate an improved construction material.

Hence, durability aspects of cement stabilized earth specimen could be indirectly satisfied through the specification of unconfined compressive strength.

Over the last few decades lime and cement have been used for soil stabilization. When lime is added to clayey soils, two pozzolanic chemical reactions occur: cation exchange and flocculation–agglomeration. In the cation exchange, the cations can be arranged in a series based on their affinity for exchange:

$A^{+3} > Ca^{+2} > Mg^{+2} > NH4^{+} > K^{+} > Na^{+} > Li^{+}$

For example, calcium ions can replace potassium and sodium ions from clay. In Flocculation–agglomeration, the clay particles tend to clump together to form larger particles, thus reducing both the liquid limit and plasticity index, and improving both of the plastic and shrinkage limits, as well as the workability. Likewise cement helps decrease the liquid limit and increase the plasticity index and workability of clayey soils. Cement stabilization is effective for clayey soils when the liquid limit is less than 45 to 50 and the plasticity index is less than about 24. Both lime and cement help increase the strength and deformation properties of soil strength of soils, and strength increases with curing time. Granular soils and clayey soils with low plasticity obviously are most suitable for cement stabilization. Calcium clays are more easily stabilized by the addition of cement, whereas sodium and hydrogen clays, which are expansive in nature, respond better to lime stabilization Das BM (2015).

These issues had also been discussed at length by the authors (Saussaye L et al. (2015), (Abu-Farsakh et al. (2015), (Chittoori BCS (2008), (Al-Kiki et al. (2011),( Pacheco-Torgal et al. (2012),Mitchell and Basma (1981), Nagih et al. (1991), Arabani and Karami (2005), Boardman et al. (2001), clough et al. (1981), Dallas (1995), Diamond and Kinter (1965), Dallas (1996), Consoli et al. (2007), Healthcote (1991), Shrinivas (1993), Venkartarama (1995), Walker and Stace (1997) indicated the effectiveness of lime and cement for soil stabilization. These studies were mainly limited to one type of soil and there is no clear trend in the effectiveness of the stabilizing materials on the wide spectrum of soils. This study therefore quantifies the influence of lime and cement on the strength of a variety of mixtures involving sand and CH clay (Bentonite).This study used the Harvard miniature method to compact the soils and prepare specimens for the strength test.

## 2.12 Role of optimum moisture content and Bentonite clay on the compacted soil material properties

Renewal interest in earthen construction material raises questions concerning soil characterization, the manufacturing process and material testing to enhance the popularity of such product of soil made of mixture of sand, clay, water and in some cases some stabilizers are added to improve the bearing capacity and reduce the settlements which are the two main problems in design and construction of soil-supported projects such as dwellings in developing countries. This study aims to investigate soil optimization by combining the amounts of the different ingredients and see the influence of such changes on the properties of the soil material such as compressive strength, tensile strength, elastic modulus, and optimum dry density.

Dry density and water content have been used almost exclusively for compaction control. Using the dry density or the modulus as an alternative tool to assess and compare the material performance is well known for the first parameter (dry density) while few attempts were done to promote the second as a key parameter. The influence of the water content on the dry density is well covered by many researchers. Little has been done concerning the influence of the water content on the modulus, compressive strength and strain energy Turnbull and McRae 1950; Turnbull and Foster 1956; Seed and Chan1959; Lenke et al. 2003. Considering the three parameters – dry density, modulus, and water content - it appears that one must have two of the three parameters to determine whether a soil is well compacted or not. A soil modulus is influenced by soil state factors such as soil structure, moisture content, soil history, the loading used and the cementation. One of the problems associated with using the modulus as a compaction-control parameter instead of the dry density is that there is no established link to obtain the expected modulus value in the laboratory.

Elastic Modulus of a soil also known as Young’s Modulus or soil Modulus E is a soil characteristics that measures how much it can be stretched or squeezed and must be taken into account particularly in construction. It’s a key parameter for the soil as much as strength which is measured by the stress needed to break a material while the soil modulus expresses the ability of the material to regain its original shape after unloading. The lower value E can get the more Elastic the soil type is. It is influenced by many factors such as water content, soil particle or organization, stress history. glue effect (cementation) between particle developed at contact due to lower water content or chemical cementation can increase E specially for clayey soils.

Several methods are available for estimating the stress-strain Modulus value. Unconfined compression test, The Briaud Compaction Device (BCD), CBR test, unconfined cyclic triaxial test, plate bearing test where E is correlated to modulus of deformation.

The estimation of the modulus from UCT test is lower than the estimation from the CBR test. The gap between the two values is probably explained by the confinement of the sample inside CBR mold (Karimi et al., (2010)).

Grammatikopoulos et al. (2000) worked on the determination of the modulus of elasticity in saturated clay-silty sand mixtures using the consolidation apparatus (oedometer) and the unconfined compression tests. It was found that Es resulting from the first test is different from the value given by the second one. It can be explained by the prevention of horizontal deformation of the sample leading to the emergence of the horizontal stresses.

Arabani and Veis Karami, (2012) found the correlation between CBR, Compressive strength and tensile strength. It was found practical values for E can be reduced 20-30% less than the values given by the parabolic model of stress strain curve.

Raper and Erbach (1990) investigated the effect of the elastic parameters, Poisson’s ratio and Young’s modulus on soil compaction using an ax symmetric finite element program by analyzing soil compaction when a compressive load was applied. The results were compared with Boussinesq linear elastic theory. It was found that Young’s modulus correlated poorly with laboratory experiments.

In the absence of direct experimental data, empiricism was a way to correlate modulus of elasticity to compressive strength as in the New Zealand Standard (NZS 4297:1998, 1998) where the modulus of elasticity for earth wall construction is taken as three hundred times the value of the characteristic compressive strength value (E = 300 fc). While for the Australian earth building handbook E for rammed earth is 500 N/mm$^2$ (Standards Australia, 2002). Permissible stress approach used in USA recommends taking the modulus of elasticity as 750 times the rammed earth compressive strength (Easton, 1996; King, 1996).

Unconfined compressive strength is one of the most important properties taken into consideration when compressed soils are evaluated for engineering purposes. Correlating unconfined compressive strength of compressed soils with their engineering index properties such as water content, specific gravity, density, degree of saturation, absorption, porosity, and pore size distribution Colback and Wiid, (1965); Broch, (1974); Michalopoulos and Triandafilidis, (1976); Venkatappa Rao et al., (1985); Shakoor and Bonelli, (1991); Hawkins and McConnell, (1992); Haney and Shakoor, (1994); Ulusay et al., (1994). Attempting to correlate unconfined compressive strength with other properties of soil is that Reduction of unconfined compressive strength due to saturation has been observed in a number of studies (Colback and Wiid, 1965).

The amount of dissipated strain energy per unit volume of soils, which is also known as the energy density or unit energy, has been introduced as a useful index to study the cyclic behavior of sands. Dissipated strain energy density is the cumulative enclosed area of the shear stress–strain loops, which are commonly formed in the geological materials subjected to cyclic loading.

The concept of strain energy and its application in the geotechnical earthquake engineering problems has been described in several references (e.g., Grammatikopoulos, et al. (2000), Pantelidis (2008)), Raper and Erbach (1990), use of strain energy density for the evaluation of excess pore pressure is rational since this parameter accounts for both cyclically induced shear stress and strain. Minimization of the strain energy density is of considerable relevance when stiff structures (or materials with structure) must be achieved for given loadings, whereas its maximization is remarkable feature when a large amount of energy absorption under impact loading is demanded.

## 2.13 Used oil as chemical admixture for earthen construction

Used engine oil is a waste not readily avoidable byproduct for which there is no economical demand and it requires disposal. Less than 50% of this product is collected. 1 liter of spilled oil can pollute 1 million liters of clean fresh water.

**Applications for used engine oil (UEO)**

- Air entraining of concrete
- Road construction
- Earthen construction, which is the aim of our study.
  - To improve $\gamma_{dry}$
  - Stress-strain behavior
  - Swelling
  - Several series of tests have been done to answer some of these issues

## 2.14 Performance evaluation of human hair fiber reinforcement on lime and cement stabilized clayey- sand

There is a widespread shortage of permanent housing in developing countries all over the world. This shortage is increasing because of the relatively high cost of traditional building materials (cement). Along with the unaffordable cost, as well as adverse effects, cement industry is listed as one of the major contributor in global warming and climate change causing a tremendous harm to ecology and human well-being. For these reasons and more, even in developed countries the go green revolution heartened the resurface of building materials based on natural resources. One such material that has captured the interest of many researchers in the recent decades is earth. Since soil has been used as a construction material from the dawn of time, it`s unsuitable mechanical properties has been putting impediments to construction engineers to enhance its properties depending upon the required standards. Among these factors we can cite the morphological (texture and structure) and mineralogical composition of the material.

Soil texture describes the proportion, size and type of particles that make up the soil (gravel, coarse and fine sand, silt, and clay). The percentage of each component may be known in the lab in one of two ways (jar test or sieve analysis). It determines soil characteristics which are water-holding capacity, permeability, and soil workability.

Soil structure is the arrangement of the soil particles into aggregates of various sizes and shapes. These larger particles, or clusters, are often referred to as aggregates.

Minerals are natural inorganic compounds with definite physical, chemical, and crystalline properties. They are classified as primary (sand and coarse fraction of silt) or secondary (clay and fine fraction of silt), silicates or non-silicates, and crystalline or non-crystalline minerals.

Soil minerals play also a significant role in setting the suitability and behavior of the soil for various uses. They contribute to soil structural alteration and can act as depolluting agents for several environmental problems.

Keeping in view how texture, structure and minerals if combined properly can form a suitable material that can be used in housing, paving, dams, and embankments, researchers around the world studied the influential factors that rejuvenate attraction to this material soil by mastering the art of shaping up a good combination using these key parameters (texture, structure, and mineral activity) of soil to meet up the ideal building conditions in mind (resistance, durability, cost and sustainability), that has driven researchers for decades to multiply their attempts to find the optimum structure to overcome the reversibility of soil properties.

Soil material characteristics vary from one sight to another and are mostly unfit for builders, however they can be amended until ideal composition is reached.

Compaction is the process of mechanically densifying a soil, a key parameter when soils are used as rammed earth for load-bearing walls, compressed blocks, cob or even pavement design. Many researchers based their work on improving density mechanically (static or dynamic) (Bahar.et al. 2004, Kenai et al. 2006) by increasing sand content, tests results confirmed that the weight loss and water absorption reduces, while increasing the compacting stress (Guettala et al. 2002). In studying cob mixture found that sand content appeared to influence the compressive strength (Kenai et al. 2006).Poured mud blocks and compacted mud blocks were compared and found that compaction is very important to achieve a mud block with required strength (Somarathna et al. 2012).

Using only dry density to characterize the soils is not enough to improve the soil properties particularly in arid and semi-arid regions where the compacted soils are unsaturated. A joint treatment by stabilizing a soil mechanically and chemically, or mechanically and fiber reinforcement or the three means at once is recommended depending on the type of the soil to be treated.

Chemical admixture is a way of improving both the structure and the texture by cementing artificially the parent soil. The influence of cement content was quantified beside compaction and found that by increasing cement dosage and reducing porosity of artificially cemented sand increased the tensile and compressive strength (Consoli, et al. 2010). In the same trend stabilizing the parent soil by increasing the compacting stress from 5 to 20 MPa and the lime content from 5 to 12% improved the strength in dry as well as wet state and the water strength coefficient which leads to lower weight loss and water absorption (Guettala et al. 2002). The influence of lime (10 to 20%) on a slurry stabilized clay bed and a column stabilized bed, confirmed that for both soils considerable increase in strength was noticed, while plasticity indexes and liquid limits reduced (Merina, et al. 2012). The joint effect of mechanical and chemical stabilization (8% cement) of clay sandy soil had optimal improvement in mechanical properties in wet and dry states (Bahar.et al. 2004, Kenai et al. 2006). Cement was used (7.5%) to stabilize lateritic soils unfit by itself to produce compressed earth blocks. Results showed that the blocks gained significant characteristics that made them suitable to be used for construction (Waziri, et al. 2013). Residual soil was stabilized using cement and rice husk ash. Tests results revealed that cement and /or RHA improved the soil properties, induced reduction in plasticity index, maximum dry density and increased steeply the optimum moisture content (Basha, et al. 2005). For silty soils using fiber reinforcement up to 1% beside compaction enhanced the load carrying capacity and reduced significantly the immediate settlement (Singh, et al. 2013). Cohesive soil and sand mixture was reinforced with wheat straw, barley straw, wood shavings, sisal, New Zealand flax, and coir. Compressive strength as well as the strain at failure increased with fiber content [Pullen, et al. 2011, Cheah, et al. 2012, Ashour, et al. 2010, Singh and Bagra, 2013, Kabiraj and Mandal 2012, Sreekumar, et al. 2013, Singh, 2013). When compaction along with chemical and reinforcement were used to improve expansive soil (lime 5%) and (jute 0.65%) (Neeraja, et al. 2010 ) or cement and straw with compacted or poured mud blocks (Somarathna et al. 2012) Fly ash as soil with human hair (Kaushik, et al. 2014) all improved the engineering properties of the concerned soils.

## 2.15 Improving properties of modified clay with cement containing random chicken feather fibers

Construction world is now faced with a need to change its practices and methods in order to respond to the challenges of sustainable development, which can be summed up in the preservation of natural resources, the reduction of energy consumption and greenhouse gas emissions. This development involves the use of materials with a low environmental impact and (Ziegert, 2013). In civil engineering, earthen construction materials (soil), whose use is ancestral, meet the environmental requirements and a renewed interest related to their insulation properties and their low environmental impact (use of local materials, non-use of conventional binders, easy recycling at the end of life) (Foucault, 2004).

Inadequate mechanical characteristics, such as low strength and brittle behavior, are probably the main problems related to the structural use of materials, especially for buildings and civil works likely to be subjected to natural hazards that have a decisive impact on their lifespan. For these reasons, these soils can be improved by chemical and / or cement additives and by the inclusion of fibers. The effectiveness of these additives and their content depend on the nature of the soil to be treated and the characteristics of the addition materials. In old earthen constructions, commonly used additives are lime and more recently cement and other by-products considered as artificial pozzolana. Numerous experimental studies have been carried out on the stabilization potential of the mineral additions and their effect on the physical and mechanical properties of the clay soils. These properties depend on the type of soil, the combination of the amount of stabilizers and even the curing time.

The addition of cement to coherent soils has widened the stabilization zone. Many studies on the effect of cement on Atterberg boundaries conducted by Osula (1991) and others, agree that a soil treated with cement showed a significant decrease in the plasticity index. Sasanian (2010) also noted that the shear characteristics, internal friction angle and cohesion of unstable soils to which cement was added, improved remarkably during different curing times. This is attributed to the calcium ions present in the cement which causes a decrease in the plasticity, thus making the soil more friable and easier to handle. Even for swelling clays, Afès and

Didier (1999) deduced the same conclusion. Bozbey and Garaisayev (2010) examined the efficiency of adding cement on improving the compaction characteristics of problematic soils. They found a decrease in the maximum dry density and an increase in the optimum moisture content. In the same trend, other investigators, Mellal and Lamri (2009) used cement to improve shear strength. The test results revealed an increase in shear strength compared to control soils. Mahantesh and Keshavaraj (2017) conducted an experimental study to evaluate the compressive and shear strength of cement stabilized rammed Earth material in both dry and wet state. They show that the wet compressive strength of the rammed earth specimen is less than that of the dry one.

To create from a soil an innovative construction material, the addition of fibers plays a key role in the reinforcement of earthen matrix, giving them not only a greater tensile strength, but also the ductility essential for their structural use. Currently, the use of natural fibers as reinforcements continues to spread over the world because of the strengthening of environmental legislation and the growing pressure on high-performance materials. The development of composite materials based on natural fibers or eco-friendly composites with high specific properties is a very promising research area. The improvement of problematic soil resistance with the addition of randomly distributed fibers has been reported by many researchers (Aymerichal et al. 2012, Kumar and Singh, 2017).

Chicken feathers are among all natural keratin-rich reinforcing fibers. Millions of metric tons of waste feathers are generated each year by commercial poultry processing plants creating a tremendous volume of solid waste problem all over the world (Parkinson1998, McGovern, 2000). These by-products generated in large quantities by the poultry processing industry and considered as the least studied and unexploited protein waste. They are in abundance, with good properties, durability and resistance to degradation. In Algeria, poultry droppings are the only waste that is really valued. Feather chicken waste is not valued; they are incinerated or thrown into the public landfill (Nouad, 2011). Many researchers use them either alone or sometimes in combination with other materials to make profitable commercial applications such as to manufacture composites for construction or textile products (yarns and fabric) (Tesfaye et al., 2017). It was observed that the incorporation of feather fibers into the cement plaster resulted in crack-free mortar surfaces, reduced acoustic echo and contributed to increased roughness, porosity, compressive strength and durability (Cao et al., 2013). It also improves the thermal conductivity and the adhesion to the surface of the hardened mortar coating. In geotechnical engineering, several researchers have randomly incorporated lime-stabilized ground feathers to improve their resistance. They concluded that this is an interesting alternative for the stabilization of an expansive soil (Zarazúa et al. 2015).

## 2.16 Physical and mechanical behavior of the tuffs for their valorization in the building construction. Application to the Chlef Extra Quarry (Algeria)

In a move towards environmental construction, the valorization of compacted geo-materials in a form such as tuff and its use in building constructions is a way increasingly prospected by researchers these last decades. For a long time tuff has been the principal component of pavement layers for a significant number of roads in Algeria and throughout the world. This paper treats the exploitation of tuff of the Extra quarry of tuff (Chlef-Algeria) and their valorization in rammed walls. Physico-chemical, mineralogical and mechanical analyses were investigated to determine their level of influence on the mechanical behavior. In this work, a first experimental phase was carried out to determine the optimal composition of a mixture of tuff-limestone or cement in terms of compressive strength and Thereafter, humid and instant CBR tests on the optimized mixture in a compacted state were carried out. The second part concerns the study of the influence of cement contents as well as human hair fibers on the mechanical characteristics of the optimized mixture. It is inferred from the experimental results of these tests the importance of the treatment process with cement, which is necessary in order to mitigate the problems of nonstability in wet medium, and showed the possibility of the use of local materials such as tuff and human hair fiber waste (lime sand) for the design of rammed walls.

These analyses showed that a treatment by human hair fibers, lime and cement proved to be necessary. Various mixtures were worked out in this direction and a synthesis of the mechanical characteristics was elaborated in accordance with the standards and the classification of materials used in rammed earth walls.

Since 1999, the Algerian economy has been marked mainly by a boom, which has enabled the country to mobilize all means to implement an ambitious development policy by launching major economic projects, thus creating an increased momentum in the economy. Construction activity, through the construction of infrastructure, especially that of the East-West Highway and a program of construction of two million homes creating a rush to cheap commodities such as sand and gravels.

Exploitations have turned massively towards rivers and beaches, to the detriment of the balance of ecosystems. To remedy this, the current policy of public authorities in environmental protection revolves around the main axis of its strategy, namely the protection of the sand bed resources of the beds along the plain of the river around the city of Chlef and the neighboring municipalities.

To this end, we have set ourselves the objective of replacing this material with other locally present products, which represent a major stake, thus making it possible to reduce to a minimum the excessive exploitation of sands whose impact on the environment is very direct.

It is in this context that the use of abundant material tuff in the Chlef wilaya is a valuable substitute for the realization of road projects.

In Algeria, tuffs cover an area of approximately 300,000 km$^2$ (Durand, 1959). To do this, more than 50 tuff production quarries are active throughout Algeria and spread across 17 Wilaya in the country. The Wilaya of Chlef contains a significant mining potential generating an intense activity in this sector. There are currently at least five active quarries, one of which is the main source of limestone supply, namely the Oued Sly-Chlef cement plant). Other new quarries have come into production since the time of the realization of road projects, following the excessive over-exploitation of all the surpluses observed in previous decades and the environmental problems that it has created. The use of tuff as a substitute material for the construction of the roads whose part of the highway is along the Chlef and Relizane wilayate and the ongoing road projects linking the towns of Tenes and Mostaganem to the east-west highway. Millions of m$^3$ of tuff are needed annually for Algeria's future projects and require adequate treatment to meet the standards prevailing in road techniques.

Their use in road construction, particularly in medium- and low-traffic basement (base and subbase layers), has greatly increased (Fumet 1959, Fenzy 1966, Inal 1980, Boularek 1989).

Indeed, several studies have shown that the tuffs acquire after wet compaction and desiccation, a cohesion which is prolonged in time. This has been confirmed by studying their mechanical behavior under static and dynamic loading (Alloul 1981, Ben Dhia 1983, Ben-Dhia et al., 1984, Boukezzi 1997, Gidel 2001, CTTP 2001, Morsli et al. 2007, Morsli & Bali, 2009).

This cohesion disappears almost completely after total saturation by affecting the mechanical behavior of the tuffs (Alloul 1981, Ben-Dhia 1983, Ben-Dhia et al., 1984, Struillou & Alloul 1984, Colombier 1988, Hachichi et al. 2000, Améraoui, 2002, Goual et al., 2005, Morsli et al., 2007).

Several techniques have been elaborated and developed for more than 30 years in order to remedy these problems and to extend the use of these materials to high traffic pavements, it is a question of associating them with other materials (eg, gravel or sand) or treat them with hydraulic binders (cement, lime) (Ben Dhia, 1983, Ben-Dhia et al., 1984, Colombier, 1988, Boukezzi, 1997, Dupas & Pecker, 1979, Porbaha et al., 1998, Hachichi et al., 2001, Morsli et al., 2005; Thomé et al., 2005, Goual et al., 2008).

Our study is limited to the tuff quarries of the wilaya of Chlef (Figure 2.10) where the use of this material has become today an inevitable option for their cost, as well as to protect the environment by the preservation (tout venant) of all rivers along the plain of the city of Chlef (Figure 2.11).

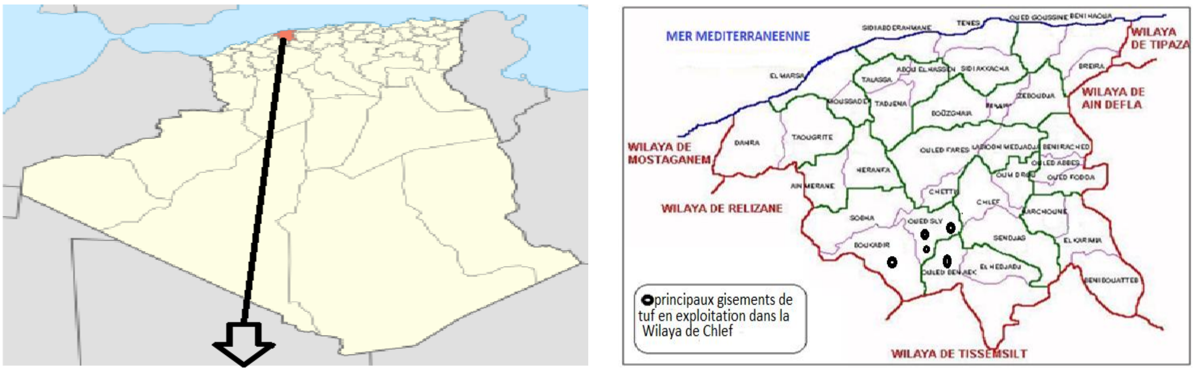



*Figure 2. 10 - Location of tuff quarries already in operation in the Wilaya of Chlef*

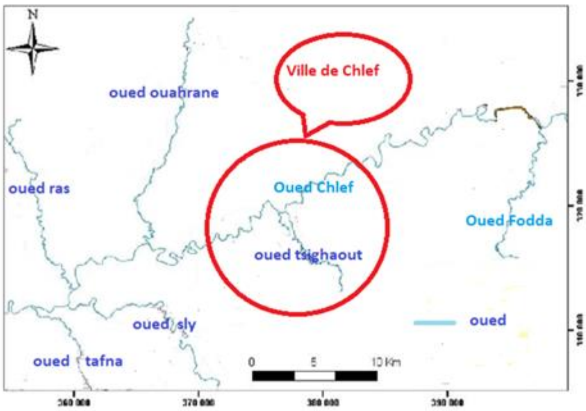



*Figure 2. 11 - Location of streams crossing the surrounding plain of the city of Chlef*

## 2.17 Conclusions

Since an exhaustive literature review is out of the objectives of the present work, this Chapter aimed at describing the state-of-the-art in those topics that are related to the objectives of the dissertation. In this sense, only a brief outline of the problem has been presented due to the complexity of the topic. However, it is important to stress, on the one hand, the necessity of fixing some basic concepts, and on the other, the necessity of further research. It is, in short, the necessity of an essential understanding of earthen materials.

The characterization of soils is a key procedure for the understanding of the characteristics and properties of earth as a building material. However, guidelines and standards differ one from each other when evaluating results and ranging suitable values to define the most relevant properties to be assessed. This is due to the different criteria adopted in each guideline, which in some cases may entail significant differences in the correlation between soil properties and structural behavior.

It is also necessary to state the absence of reliable guidelines when assessing the earthen materials of an existing building, which may present a granulometry that does not fulfil any standard. Therefore, any value given by guidelines should be taken into account only as indicative, especially with regard to historic earthen materials but also in the case of new constructions. This situation reflects the lack of consensus with regard to the properties of the material, as it was also stated within the literature review. There is not enough research neither determining the properties of earthen materials, nor evaluating their performance in architectural applications, and therefore, there are very few standards and reliable guidelines and the existing ones are mostly not correlated between them.

# Chapter 3: Materials and testing methods

# Chapter 3: Materials and testing methods

## 3.1 Index properties and strength of artificial soil using the Harvard miniature method

### 3.1.1. Objectives

The overall objective of this research project was to investigate the relationships between the maximum dry unit weight ($\gamma_{dry}$), the index properties (LL, PI) and strength of artificial soil prepared using the Harvard Miniature Method.

### 3.1.2. Materials and methods

A compilation of artificial soil mixtures were used in varying proportions in order to better observe the characteristics. These mixtures consisted of:

#### 3.1.2.1 Binders

**a) Cement**

Ordinary Portland cement Type 1 (ASTM C150) was used. The D50 for cement is about 100µm and the particle distribution is much higher than the Bentonite clay.

**b) Lime**

Calcium oxide (CaO), commonly known as quicklime was also used as a binder. Quicklime produces heat energy by the formation of the hydrate, calcium hydroxide,

$CaO\ (s) + H_2O\ (l) \rightleftharpoons Ca\ (OH)_2\ (aq)\ (\Delta H_r = -63.7\ kJ/mol\ of\ CaO)$

**c) Bentonite (B)**

Bentonite clay, also known as the montmorillonite, is common part of the smectite group of clays, which are groups of clays with three layer structure (Figure 3.1).

*Figure 3. 1 - Bentonite clay*

Numerous types of Bentonite clay exist, and while each type has properties that serve to set each clay apart from the other, the clay types all share the common characteristic of being able to absorb water at a significantly higher rate than other forms of clay. Sodium Bentonite which is also known as "Swelling Clay," is capable of holding many times its weight in water. This capability makes it usable as a sealant for older, unused oil wells and toxic waste storage areas, as it bonds with the natural surrounding soil to create a barrier where oil and toxins cannot penetrate. The Bentonite containing a specific gravity of 2.89 and its properties are summarized in Table 3.1. In this study, Bentonite with the chemical composition as shown in Figure 3.2 was selected to represent the clay fraction of the soil. The D50 for the clay was about 1 µm. Hydrometer tests (ASTM D 422-63) were applied for Bentonite.

*Table 3. 1: Properties of Bentonite*

| Type of sample | LL% | PL% | Gs | γdry | O.M.C% |
|---|---|---|---|---|---|
| Remodeled | 324 | 43 | 2.66 | 11.45 | 38.1 |

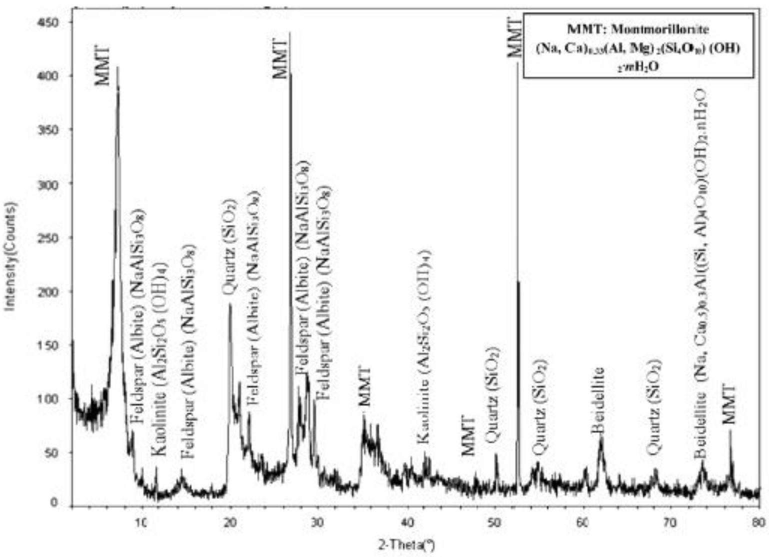



*Figure 3. 2 - XRD Analysis of Bentonite Soil*

**d) Kaolinite**

Kaolinite particles are traditionally known as hydrated aluminium silicate, which are present in nature under the form of the layered mineral (Figure 3.3). This raw kaolinite particle underwent a vigorous process such as blunging, centrifuging, chemically treating, classifying, concentrating, drying, grinding, hydro cloning, magnetically treating, slurring, and sieving for it to achieve a specific level of brightness, grade, impurity, particle size, and residue. This procedure is better known as water washed kaolinite which converts crude kaolinite into refined kaolinite particles. Kaolinite particles with various sizes have been used extensively in many areas of applications such as ceramics, paints, and construction materials. Kaolinite has specific gravity of 2.623. Hydrometer tests (ASTM D 422-63) were applied for kaolinite also.

*Figure 3. 3 - Kaolinite clay.*

### 3.1.2.2 Sand (S)

The grain size distribution of the sand used in this study is shown in Figure 3.4. Poorly graded sand with a specific gravity of 2.65 and a coefficient of uniformity (Cu) for the sand was 2.6. The D50 for the sand was 0.6 mm. For the sand, coefficient of uniformity (Cu) and coefficient of curvature (Cc) are 3.15 and 1.15 respectively for the sand. The Cu and Cc values indicate that the ASTM C-33 sand is poorly graded and classified as SP.

Grain size distribution of soil samples was determined using sieve analysis are as shown in Figures 3.4 and 3.5.

The tests performed included compaction test, unconfined compression, liquid limit, and plastic limit by using different mixtures of kaolinite and sand, Bentonite and sand and Bentonite, kaolinite and sand.

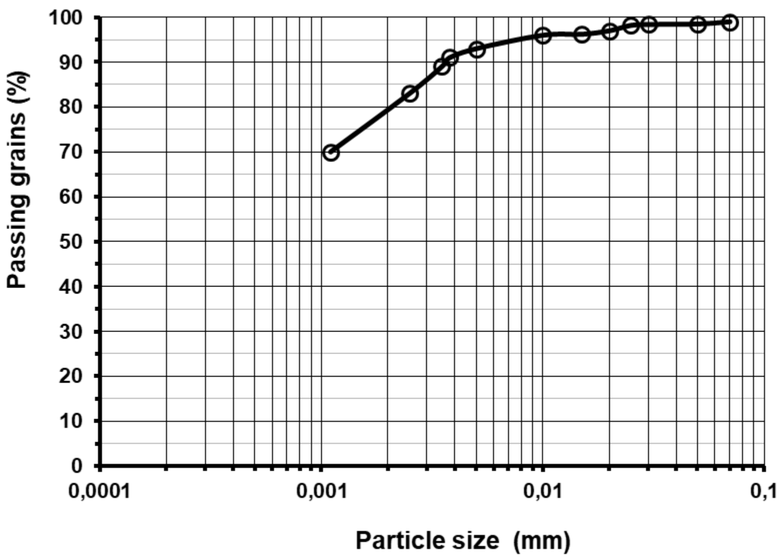



*Figure 3. 4- Grain Size distribution of kaolinite*

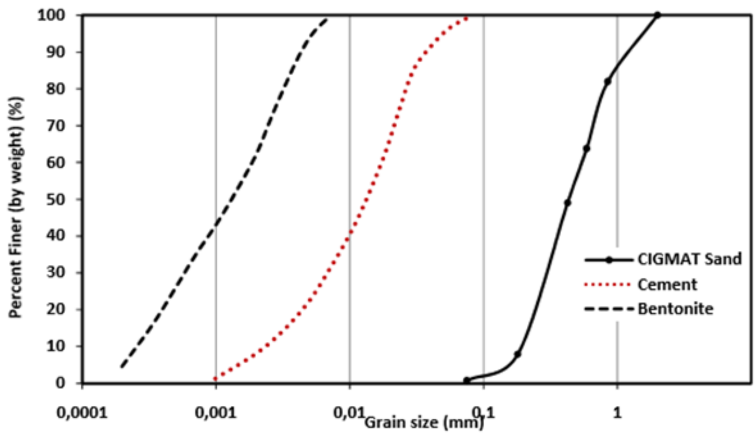



*Figure 3. 5- Grain size distributions for sand, cement and Bentonite*

### ***3.1.2.1*** *Compaction test*

Compaction is a process by which the soil particles are artificially rearranged and packed together into a closer state of contact by mechanical means in order to decrease the porosity of the soil and increase its dry density. The compaction process may be accomplished by rolling, tamping or vibration. The compaction characteristics are determined in the laboratory by various compaction tests. These tests are based on any one of the following methods are types of compaction: dynamic or impact, kneading, static and vibration. Some of the usual compaction tests in the laboratory are: Standard and Modified Proctor tests, Harvard Miniature compaction test, Abbot compaction test etc.

### ***3.1.2.2 Harvard miniature compaction***

Harvard Miniature compaction (Figure 3.6) was developed by Wilson (1950). The intent was to duplicate more closely field compaction using a sheep-foot roller. In this test soil is compacted by kneading action of a cylindrical tamping foot 0.5 in. in diameter. The apparatus consists of a mold 1 5/16 in. in diameter x 2.816 in. long having a volume of 1/454 ft3. The tamping foot operates through a pre-set compression spring so that the tamping force does not exceed appreciably a predetermined value. Commonly three layers at 25 tamps per layer may be used. The principal test advantages are:

1) Only small amounts of soil are required (but must pass through No. 4 sieve)

2) One can obtain samples of dimensions suitable for testing unconfined or triaxial compression. These samples also may be suitable for falling-head permeability tests using triaxial apparatus.


*Figure 3. 6 - Harvard Miniature compaction apparatus.*

### *3.1.2.3 Unconfined compressive test*

The unconfined compressive test is a special case of triaxial compression test in which $\sigma_2$=$\sigma_3$=0. Due to the absence of confining pressure the uniaxial test is called the unconfined compression test. The cylindrical specimen of soil is subjected to major principal stress σ1 till the specimen fails due to shearing along critical plane of failure. Samples prepared from Harvard miniature mold were cured for 28 days in the laboratory, and subjected to a series of unconfined compressive strength tests in a Geotac machine (Figures 3.7 and 3.8) to determine index and engineering properties.

*Figure 3. 7 - Geotac Compressing Apparatus*

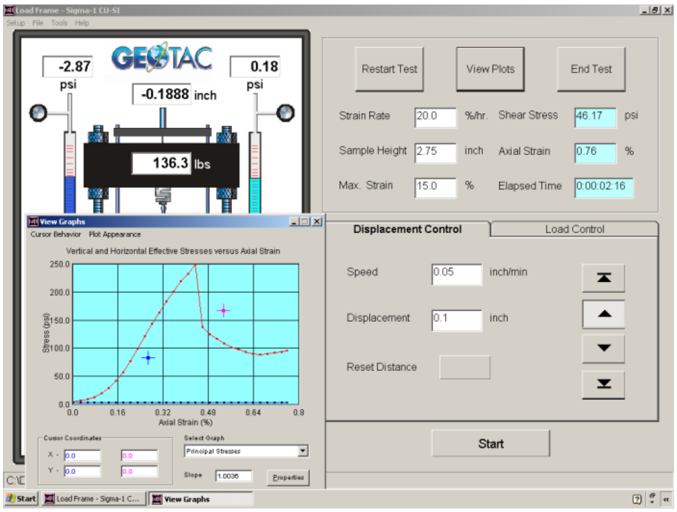



*Figure 3. 8 - Geotac Compressing Apparatus (Testing Setup)*

## 3.2 Assessment of cementitious materials impacts on clayey soils properties

### 3.2.1. Objectives

Investigate the effectiveness of 3% lime and cement treatment on the behavior of soils with varying Bentonite content. The behavior of the stabilized soils was investigated after 14 days of curing.

### 3.2.2. Materials and methods

- All Binders characteristics are shown in Figures 3.2 and 3.3 and defined earlier (see paragraphs 3.1.2.1and 3.1.2.2).

- Bentonite Soils.

The sand-Bentonite mixtures were prepared with Bentonite contents of 10, 50 and 90% by weight. For the first mixture of soil sand content was 10% with 90% of Bentonite. The soil was stabilized with 3% of lime and cement.

#### 3.2.3. Sample preparation

The sand-Bentonite mixtures were prepared with Bentonite contents of 10, 50 and 90% by weight. For the first mixture of soil sand content was 10% with 90% of Bentonite. The soil was stabilized with 3% of lime and cement.

At least three samples were prepared by dry mixing sand with Bentonite and cement or lime with varying amount of water for each mixture. As shown in Figure 3.6, the Harvard Miniature compaction mold was used to compact the soils and prepare specimens for the strength test. The samples were cured for 28 days in the laboratory, and subjected to a series of tests in a Geotac machine (Figures 3.7 and 3.8) to determine index and engineering properties.

The samples were prepared by dry mixing sand with Bentonite and cement or lime with varying amount of water. The Harvard Miniature compaction mold was used to prepare the specimens.

## 3.3 Role of optimum moisture content and Bentonite clay on the compacted soil material properties

### 3.3.1. Objectives

The overall objective of this study was to investigate the variation of optimum moisture contents based on strength, modulus and strain energy of the Bentonite soils. The specific objectives were as follows:

(1) Effect of Bentonite content on compacted soil properties

(2) Influence of optimum moisture content on the compacted soil properties.

Total of 90 specimens were compacted and tested in this study.

### 3.3.2. Materials and methods

All used materials were presented and defined earlier in previous paragraphs 3.1.2.1 and 3.1.2.2. The Harvard Miniature compaction method was used to compact the soil. The spring pressure may by 89 N or 178 N. The number of layers of soil in the mold and the number of tamps can be varied, thus varying the energy of compaction per unit volume of soil. The Harvard miniature compaction is applied through a tamper rod of 12.7 mm in diameter over the surface of the soil compared to standard compaction with 60.45 kg.mm/cm$^3$ for standard proctor`s test and 272.60 kg.mm/cm$^3$ for modified proctor`s test. Bentonite, sand and water were used in different proportions to determine the optimum water content.

- sand-Bentonite Soil

The sand-Bentonite mixtures were prepared with Bentonite contents of 20, 50 and 80% by weight. For the first mixture of soil sand content was 20% with 80% of Bentonite. The plasticity index as function of the liquid limit of the sand bentonite mixtures is presented in Figure 3.9.

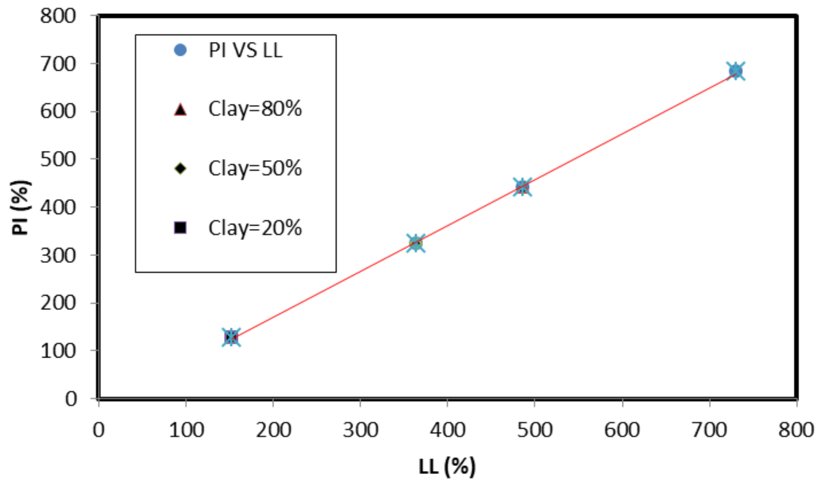



*Figure 3. 9 - Plasticity Index vs. Liquid Limit of Bentonite Soil Mixtures*

- Sample preparation

The samples were prepared by dry mixing sand with Bentonite with varying amount of water. The Harvard Miniature compaction mold was used to prepare the specimens.

## 3.4 Used oil as chemical admixture for earthen construction

### 3.4.1 Objective of the study

The main objective of this investigation is to study the effect of used engine oil on the performance of compacted soils and compressive strength of RE and to compare the performance with that of conventional rammed earth. The chemical composition of waste engine oil is shown in Table 3.2.

*Table 3. 2: Chemical Composition of Waste Engine Oil*

| Chemical composition | Used engine oil (%) |
|---|---|
| $Fe_2O_3$ | 0.43 |
| CaO | 15.9 |
| $SO_3$ | 37.0 |
| $P_2O_5$ | 8.95 |
| ZnO | 17.7 |
| $Cl^-$ | 15.9 |

All used materials were presented and defined earlier in previous paragraphs 3.1.2.1 and 3.1.2.2.

### 3.4.2 Design mix

- ➢ First series of test
- ✖ Bent./Sand - [ 10/90 ] → mixed with water
- ✖ Bent.+ Cement /Sand - [ (5+5)/90 ] → mixed with water
- ✖ Cement/Sand - [ 10/90 ] → mixed with water
- ✖ Bent./Sand - [ 10/90 ] → mixed with (UEO + water)
- ➢ Second series of test
  - ✖ Bent+ Fly Ash/Sand - [(5+5)/90] → mixed with (UEO + water)
- ➢ Third series of test
  - ✖ Bent. + Fly Ash/Sand - [(10+10)/80] → mixed with (UEO + water)
- ➢ Fourth series of test
  - ✖ B + FA+C/Sand - [(10+5+5)/80] → mixed with (UEO + water)
- ➢ Fifth series of test
  - ✖ Kaolinite/Sand - [20/80] → mixed with (UEO + water)
- ➢ Sixth series of test
  - ✖ Bent./Cr.Brick - 10+10/80] → mixed with (UEO + water

## 3.5. Performance evaluation of human hair fiber reinforcement on lime and cement stabilized clayey- sand

### 3.5.1. Objectives

The principal objective of the present investigation focuses on the individual and mutual impact of lime or cement stabilization and randomly distributed short human hair fiber on the strength and mechanical behavior of a variety of mixtures involving sand and high plasticity clay (Bentonite). A series of unconfined compression (UCS) tests were undertaken on soil samples with different percentages of fiber and cementing agents included to select a suitable soil mixture that can be used for varying range of applications such as rammed earth walls construction.

### 3.5.2. Materials and methods

As mentioned in earlier paragraphs, all used materials were presented and defined earlier in the previous paragraphs 3.1.2.1 and 3.1.2.2. The Harvard Miniature compaction method was used to compact the soil.

#### 3.5.3. Reinforcement fibers

The lightweight, strength and deformation properties of fibers make them effective materials in various construction engineering applications. Human hair fibers (hair can elongates and often breaks only after its length has almost doubled) were used throughout this study to reinforce the soil mixture. Hair is readily available and considered valueless solid waste that is being dumped in waste landfills. As seen in Figure 1.3(c), these fibers are considered as wastes that create ecological problems because of being non-biodegradable in nature. The length of these fibers varies from 5 to 50 millimeters generally. The elongation ranges from 290 to 500. Hair exhibits a high tensile strength, 150–270 MPa, which is significantly dependent on strain rate and humidity. These fibers are available everywhere in the world with very little cost.

The properties of the fibers used in this study are summarized in Table 3.3.

*Table 3. 3: Mechanical properties of human hair fiber*

| | | | | |
|---|---|---|---|---|
| Elastic modulus (GPa) | 3.5 | | Linear Density (g/cm) | 1.32 |
| Yield Strength (MPa) | 74.34 | | Fiber Length (mm) | 4-15 |
| Breaking Strength (MPa) | 119 | | Fiber Diameter (µm) | 40-111 |
| Strain at Break (%) | 29 | | Tensile Strength (MPa) | 384.79 |

### 3.5.4. Sample preparation

The sand-Bentonite mixture was prepared by weight contents of 50% of Bentonite and 50% of sand. The soil was stabilized with 3% then 6% of lime or cement (weight percentage of dry soil mixture). At least three samples were prepared by dry mixing sand with Bentonite and cement or lime with varying amount of water for each mixture. The Harvard Miniature compaction mold was used (Figure 3.4) to compact the soils and prepare specimens for the strength test. The samples were cured for 28 days in the laboratory, and subjected to a series of tests in a Geotac machine (Figures 3.7 and 3.8) to determine index and engineering properties. The reinforcing content of fibers (0.5%, 1.0% and 2.0% by weight of soil) was added to the soil ingredients before mixing. Addition of a larger amount of fibers can lead to their tangling and uneven distribution resulting in non-homogeneous mixture and consequently hampering strength gain.

## 3.6. Improving properties of modified clay with cement containing random chicken feather fibers

### 3.6.1. Objectives

This study is an additional contribution in the field of soil stabilization to enrich the range of soil improvement methods that has continued to expand. The main objective of this work is to assess the viability and impact of including chicken feathers on the consistent soil reinforcement used as an earth building material and to study its relevance as a replacement for commercial materials a bit expensive. It will also contribute to find a solution for the disposal of such waste in bulk which is a global environmental problem responsible for the pollution of soils and groundwater sources. The mechanical properties of the clayey soil including unconfined compressive and direct shear tests are studied to show the influence of the main variables considered in this investigation, which were the amount of cement and the percentage of the chicken feather fibers.

### 3.6.2 Materials

The soil samples used in this study comes from the clay quarry of the brickyard located in Chlef (western Algeria). In the laboratory, the crushing and grinding of soil samples were carried out using a disk mill to obtain a 0/5 mm grind (see Figure 3.10).

The grading and the particles fractions for the clayey soil from natural source are illustrated on the Figure 3.11. The Engineering properties of the collected clay soil used as well as its classification were determined according to American ASTM D2487-98 standards (1998) and showed in Table 3.4.

*Figure 3. 10 - Zebabdja clay after crushing and grinding*

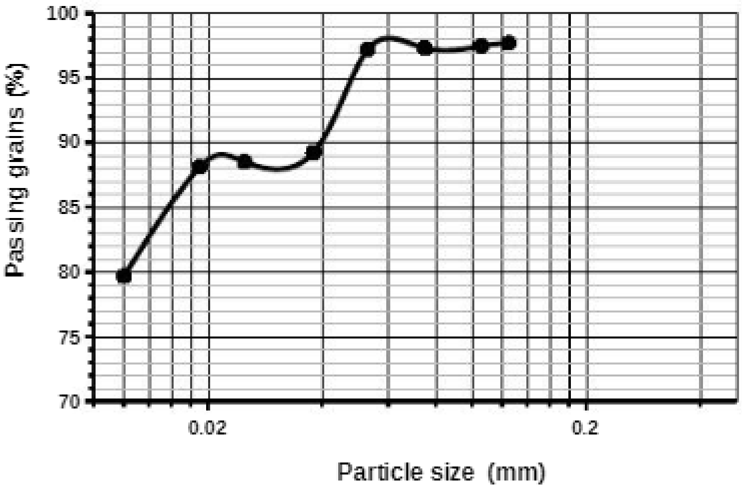



*Figure 3. 11 - Grain size distribution of the clayey soil (Zebabdja clay)*

*Table 3. 4: Chemical and geotechnical characteristics of the treated soil*

| Basic Characteristics | |
|---|---|
| CaO | 12.04 |
| MgO | 1.53 |
| $Fe_2O_3$ | 6.40 |
| $Al_2O_3$ | 14.48 |
| $SiO_2$ | 29.10 |
| $SO_3$ | 0.03 |
| Color | Dark Grey |
| Depth (m) | Quarry |
| Natural water content (%) | 21.92 |
| Specific Density | 2.6 |
| Fineness ($cm^2/g$) | 803900 |
| Elements passing by sieve 80 µm (g) | 318.73 (79.68%) |
| Liquid Limit (%) | 39.48 < 50 |
| Plastic Limit (%) | 20.86 >20 |
| Plasticity Index (%) | 18.62 > 7 |
| Optimum water content (%) | 20 |
| Maximum dry density ($kg/m^3$) | 1550 |
| Cohesion (kPa) | 18.07 |
| Friction angle ($^o$) | 21.29 |

### *3.6.2.1 Cement*

The cement used in this study was supplied by the cement factory of Chlef located in west of Algeria. The physical and chemical properties of the product are presented in Table 3.5.

*Table 3. 5: Physical and chemical properties of cement*

| Name | Cement CEM II/A 42.5 |
|---|---|
| Physical appearance | Grey powder |
| CaO | 64.76 |
| MgO | 0.47 |
| $Fe_2O_3$ | 3.78 |
| $Al_2O_3$ | 5.13 |
| $SiO_2$ | 21.34 |
| $SO_3$ | 2.28 |
| $Na_2O$ | 0.04 |
| LOI | 1.00 |
| $K_2O$ | 1.18 |
| Specific Density | 3.14 |
| Fineness ($cm^2/g$) | 2950 |
| $C_3S$ | 66 |
| $C_2S$ | 14 |
| $C_3A$ | 7 |
| $C_4AF$ | 12 |

#### *3.6.2.2 Chicken feather fibers*

As shown in Figure 1.3(d), chicken feather fiber used in this investigation was provided by a slaughtering facility. Chicken feathers contain crude lipid (0.83%), crude fiber (2.15%), crude protein (82.36%), ash (1.49%), nitrogen-free extracts (1.02%) and moisture content (12.33%) whereas the ultimate analyses showed: carbon (64.47%), nitrogen (10.41%), oxygen (22.34%), and sulphur (2.64%) (Tesfaye et al., 2017). The mean density of whole chicken feathers is 0.97 $g/cm^3$ (Tesfaye et al., 2017). Before mixing the chicken feather, they we cut to reduce their length.

### 3.6.3 Experimental procedure

In this experimental program, the clay used herein was mixed with cement (C) as stabilizer and reinforced with solid inclusions of chicken feather fibers (CFF). The obtained soil sample with varying content of additives will be subjected to unconfined compressive test and direct shear test. After finding the optimum moisture content for the control soil (CS), cement is added by different percentages to the control soil, then after, chicken feather fibers are introduced.

#### *3.6.3.1 Sample preparation*

The dry components of the samples were hand mixed, thoroughly in a tray before water was added. A determined percentage of water should be added and then the soil can be mixed thoroughly again. The percentage of cement used as clay replacement was 6, 8, 10 and 12%, while the chicken feather content was 1, 2 and 3%. The mix compositions of the different mixtures and the applied tests were selected as shown in Table 3.6. All the samples were compacted at the optimum water content deduced from the compaction test according to the standard ASTM-D698-91 (1991).

### *3.6.3.2 Testing procedure*

For compression test, the mixtures were cast in cylinder specimens of 70 mm diameter and 140 mm height. After demolding, the samples were stored in a plastic bag for different periods before testing (7, 14 and 28 days). The unconfined compression was performed according to ASTMD 2166-06 standards (2006). A minimum of three samples are used to determine the compression strength.

For direct shear test, the specimens were cast in square with the size 60×60 ×25 $mm^3$. Normal stresses applied were 100 $kN/m^2$, 200 $kN/m^2$, and 300 $kN/m^2$. The speed of the movement of the half-box was fixed at 1 mm/min. The test was carried out according to ASTM D 3080-04 (2004).

*Table 3. 6: Mix design of the different mixtures and the different tests applied*

| Designation test | Mixture of CS with different % cement | Mixture of CS with different % of chicken feather | Mixture of CS+10%C with different % of CFF | Water added |
|---|---|---|---|---|
| Unconfined compressive strength | CS+ 0%C<br>CS+ 6%C<br>CS+ 8%C<br>CS+ 10%C<br>CS+ 12%C | CS+0% CFF<br>CS+1%CFF<br>CS+2%CFF<br>CS+3%CFF | CS+10%C+<br>CS+10%C+1%CFF<br>CS+10%C+2%CFF<br>CS+10%C+3%CFF | 20% of each mixture |
| | Normal stress applied on the different mixtures | | | |
| | 100 kPa | 200 kPa | 300 kPa | |
| Direct shear strength | CS<br>CS+10%C<br>CS+10%C+1%CFF<br>CS+10%C+2%CFF<br>CS+10%C+3%CFF | CS<br>CS+10%C<br>CS+10%C+1%CFF<br>CS+10%C+2%CFF<br>CS+10%C+3%CFF | CS<br>CS+10%C<br>CS+10%C+1%CFF<br>CS+10%C+2%CFF<br>CS+10%C+3%CFF | 20% of each mixture |
| CS :Control Soil | C: Cement | | CFF: Chicken Feather Fibers | |

## 3.7 Physical and mechanical behavior of the tuffs for their valorization in the building construction. Application to the Chlef Extra Quarry (Algeria)

### 3.7.1 Objectives

This one studies the treatment of tuffs for use as a component in the foundation layers of road structures. After Physico-chemical characterization of tuffs of different quarries already in operation or an evaluation of characteristics and properties are analyzed to define the best choice.

The proposed treatment for valorization in building shelters as well as road technology in accordance with the recommendations of the technical guide GTR (LCPC-SETRA, 2000), is based on formulations of mixtures at different percentages of tuff, granular materials and binders in accordance with the technical guide GTS (LCPC -SETRA, 2000). The objective being to propose a material treated economically competitive and easy to implement in situ.

## 3.7.2 Materials Identification

### *3.7.2.1 Human hair fibers*

As were presented and defined earlier in previous paragraph 3.5.3

### *3.7.2.2 Tuff*

Tuff is a rock formed by the accumulation of volcanic projections of millimeter-sized fragments that may contain rocks and consolidated by the action of water. When the granulometry of the ashes is lower than two millimeters, the tuff is called cinerite. Not to be confused with calcareous tuff, more generally called travertine, which is a sedimentary rock resulting from the deposition of limestone layers. Reputedly very resistant, tuff has been widely used as a building material in the region of Chlef, which has several quarries. We often find a form of tuff scoriaceous light and porous called pozzolan. The latter is used for road construction or in the industry for the manufacture of cement.

The exploitation of the Chlef tuff quarries (Figure 3.12) dates back to the colonial period when this material was the main material used for sports fields. The actual exploitation began with the entry of the Chlef cement plant in production in the 70 s with 2 million tons. With the completion of the new unit the production capacity will have to increase to 4 million tons.

Cement with limestone source of lime in the form of carbonates represents 80% of the raw material of the finished product.

In the laboratory, the basic materials used for the physico-mechanical characterization tests are taken from the four quarries listed in Table 3.7.

*Figure 3. 12 - Overall view of the limestone supply quarry for the Chlef cement plant.*

### 3.7.3 Materials analysis (TUF) of the four quarries in Chlef

This study is conducted on the characterization of deposits of the quarries of Sonelgaz, Meknassa, Boukadir and Extra in the region of Chlef for their use in road technology, and value as local materials if necessary. The experimental work has allowed to obtain the best characteristics of physical and mechanical properties of the optimal Proctor, Atterberg limits, sand equivalent as well as the carbonate rate.

*Table 3. 7: Summary of materials characteristics*

| Tuff source quarry | | Extra | | Sonelgaz | | Meknassa | | Boukadir | |
|---|---|---|---|---|---|---|---|---|---|
| Granulometry | | Sieve size | (%) passing | Sieve size | (%) passing | Sieve size | (%) passing | Sieve size | (%) passing |
| | | 50 | 95.62 | 50 | 93.95 | 50 | 95.38 | | |
| | | 31.5 | 86.96 | 31.5 | 81.25 | 31.5 | 85.00 | 31.5 | 80.41 |
| | | 5 | 46.79 | 20 | 68.63 | 20 | 77 | 20 | 70.18 |
| | | 1 | 38.31 | 5 | 32.61 | 5 | 62.06 | 5 | 50.43 |
| | | 0.2 | 28.65 | 0.2 | 24.87 | 0.2 | 16.75 | 0.2 | 20.75 |
| | | 0.08 | 19.11 | 0.08 | 10.74 | 0.08 | 13.55 | 0.08 | 16.85 |
| Atterberg limits | $W_L$% | 24.91 | | / | | 32.95 | | 29.17 | |
| | Wp% | 19.64 | | / | | 22.29 | | / | |
| | $I_p$ | 5.27 | | 5.45 | | 10.66 | | / | |
| References OPM Proctor test | $\gamma_d$ (t/m$^3$) | 1.89 | | 1.87 | | 1.83 | | 1.82 | |
| | Wopm (%) | 11.46 | | 10.44 | | 7.5 | | 11.73 | |
| Equivalent to sand at 10% fines | | 32.98 | | 49 | | 28.60 | | 74.00 | |
| Carbonate rate (%) | | $CaCO_3$ | 71.67 | / | | 54.17 | | 70.00 | |
| | | $CO_2$ | 31.53 | / | | / | | 33 | |

$\gamma_d$ : dry density Max $I_p$: plasticity index; w: Water content Max

Substrate materials must meet the following conditions:

- $w_L < 40$
- $I_p < 15$
- $CaCo_3 \geq 45\%$

#### *3.7.3.1 Determination of Calcium Carbonate Content*

The determination of the $CaCO_3$ content is carried out with the Dietrich-Früling calcimeter. The test consists in measuring with a gas burette the volume of $CO_2$ released by the reaction of the HCI on the calcium carbonate contained in the sample. The dilute hydrochloric acid decomposes the calcium carbonate according to the reaction:

$$CaCO_3 + 2\ HCl^- + CaCl_2 + H_2O + CO_{2\uparrow}$$

The $CaCO_3$ content of a fine soil is a good indicator of its mechanical strength and its sensitivity to water. Depending on the value of this grade, soil behavior changes from clay to rock, with the transition value being around 60-70% (Table 3.8).

*Table 3. 8: Physical parameters of the tuff of the various exploited tuff quarries in Chlef*

| $CaCO_3$ content (%) | geotechnical designation | |
|---|---|---|
| 0 -10 | Clay | soil |
| 10-30 | Marly Clay | soil |
| 30-70 | Marl | soil |
| 70-90 | Marly Limestone | rock |
| 90-100 | Limestone | rock |

### *3.7.3.2 Determination of granulometry*

Table 3.9 summarizes the results of granulometric analyzes of EXTRA tuff in the natural state. The results are presented in the Table 3.9 and on the curve of Figure 3.13.

*Table 3. 9: Granulometric analysis results of tuff*

| Sieve size (mm) | Sieve residue (g) | Cumulative grams retained | Cumulative retained (%) | (%) passing |
|---|---|---|---|---|
| 4 | 160 | 160 | 16 | 84 |
| 2 | 132.7 | 292.7 | 29.27 | 70.73 |
| 1 | 110.3 | 403 | 40.3 | 59.7 |
| 0.63 | 90.9 | 493.9 | 49.39 | 50.61 |
| 0.25 | 249.4 | 743.3 | 74.33 | 25.67 |
| 0.125 | 146.7 | 890 | 89 | 11 |
| 0.08 | 58.2 | 948.2 | 94.82 | 5.18 |
| 0 | 50.5 | 998.7 | 99.87 | 0.13 |

The results of particle size analyzes showed that the quantity of particles smaller than 80 µm is less than 5%. The granulometric test of the tuff was carried out in the central laboratory of public works (LCTP), according to standard NF P 94-056.

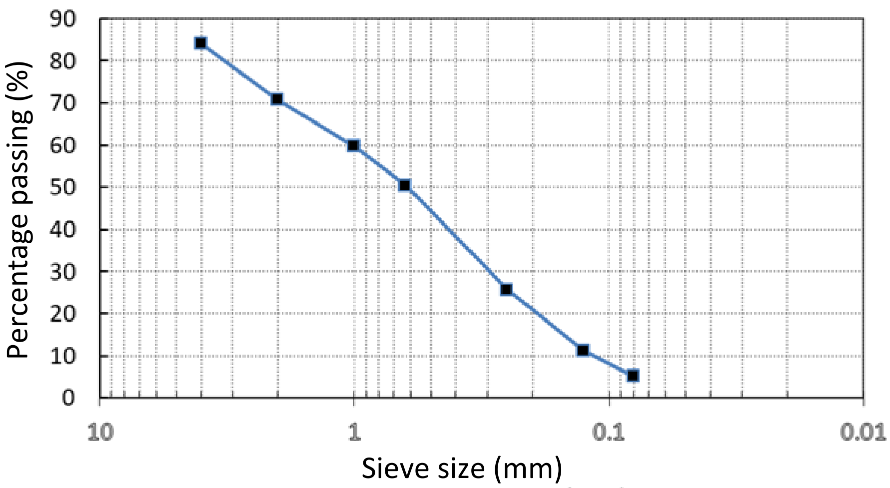



*Figure 3. 13 - Granulometric curves: Tuff EXTRA*

### *3.7.3.3 Determination of Equivalent of sand*

The purpose of the sand equivalent test, designated by the symbol ES, is to evaluate the relative proportion of fine elements contained in the soil, the presence of which in significant quantities may modify the mechanical behavior. The results on our soil are in the Table 3.10.

*Table 3. 10: Results of the TUFF EXTRA equivalent test.*

| | First Sample | Second Sample |
|---|---|---|
| $h_2$ (cm) | 4.6 | 4.9 |
| $h_1$ (cm) | 14.19 | 14.6 |
| $100\times(h_2/h_1)$ | 32.41 | 33.56 |
| | ES Average | 32.98 |

As part of the valorization in road technology, the classification of GTR materials according to standard NF-P11-300 (LCPC-SETRA, 2000), based on geotechnical data values ($D_{max} \leq$ 50mm and 80 µm sieve ≤ 35%), the material is repositioned in class B, that of sandy and gravelly soils with fines.

The subclass determined by the particle size analyzes, the blue value (VBS) and the Atterberg limits ($I_p$) direct this material towards the class B, more precisely the subclass B1 corresponding to natural materials containing soils sand silty materials generally insensitive to water and can still be split into 2 subgroups B11 if FS ≤ 60 or B12 if FS >60 (Figure 3.14).

Based on these analyzes, the use of this tuff in road structures requires prior treatment in order to meet the requested requirements in terms of bearing and deformation.

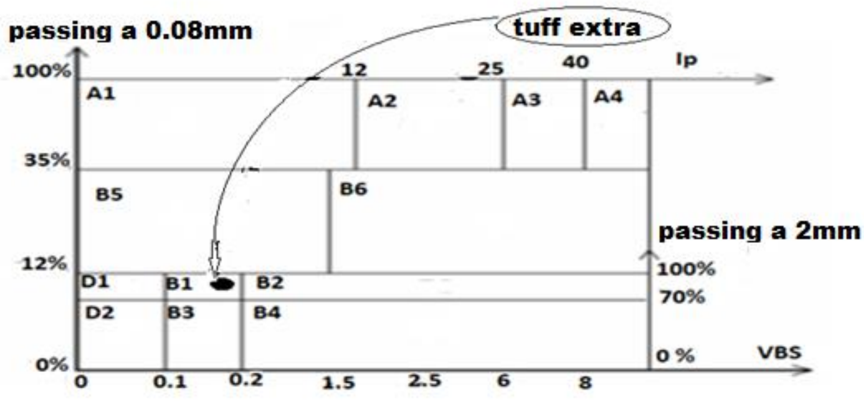



*Figure 3. 14 - Classification of tuff quarry Extra Oued Sly (LCPC-SETRA, 2000).*

### *3.7.3.4 Treatment of tuff for valorization in rammed earth walling*

Particle size and organic matter content are the key factors in choosing tuff valorization in road techniques. After treatment, it is necessary to obtain a material that fulfills the following conditions:

- Meet the classification and sizing standards in vigor GTR (LCPC-SETRA, 2000);
- Maintain its mechanical and structural properties over time to meet sustainability standards;
- Master the costs of processing and implementation in situ to obtain an economically competitive material.

The treatment methodology consists of two steps:

- Improvement of the mechanical characteristics by treatment with binders, in particular cement.
- Correction (vetting) of the ductility curve of the treated tuff or natural tuff by adding a fraction of natural fibers. The choice of the respective dosages of these various components will also make it possible to reduce the water content by the hydration and dry matter supply phenomena (Abriak 2007, Sfar Felfoul et al., 2003).
- A decrease in the water content at OPM ($W_{opm}$) clearly observed for the mixture compared to natural tuff;
- An average increase of the density at the OPM ($\gamma d_{OPM}$) of the material of the order of 26%; In addition, there is a drop in the immediate bearing index (IPI) with a drop in the optimal water content in the case of the mixture compared to the natural sediment. This is probably due to the entrapment of occluded air bubbles generating a reversible compressibility of the interstitial fluid, and thus appearance of the so-called "quilting" phenomenon.

### 3.7.4 Laboratory Study of the treatment of the materials used

The preparation of the mixtures is made according to the French standard (P-94.093). The method that is used for the preparation of the mixtures is simple and requires the following laboratory means:

- tubs;
- Small shovels;
- An oven;
- Electric balance;

Each time a quantity of tuff is sieved at 20 mm and then quantities of percentage of cement are added. Compaction of Tuff + 3%, 5%, 7%, 9% and 11% cement mixtures. Same principle of the Proctor test is done with the soil at natural state. For each value of the water content the value of the dry density $\gamma_d$ is determined, and the density values as a function of the water content found during the test are plotted on a graph. From this relationship, one can determine the optimum water content and the maximum dry density of each mixture.

### 3.7.5 Determination of the compressive strength

Tuff was dried prior to use in the blends. Initially the amounts of Tuf and reinforcing material were mixed together in the dry state. All tested specimens (tuff + fiber) were compacted to the dry density of the pure soil and to the maximum moisture content derived from the compaction tests.

All test specimens (Soil + Cement + Fiber) were compacted to the dry density of the cement-mixed soil and its maximum moisture content derived from the compaction tests of the mixtures (Soil + Cement).

#### *3.7.5.1 Preparation of samples*

The preparation of the mixtures is a very important step for the smooth running of a laboratory test program.

The samples are, at first, tuff mixed with different percentages of human hair. In a second step, the soil is mixed with percentages of cement (9%) before mixing it with the percentages of fiber, to see the effect of these fibers on the tuff with the cement.

All samples were prepared with different percentages of fiber.0.5%, 1%, and 1.5% of the weight of the soil. The fibers were mixed with dry soil. The addition of the fibers has been done very carefully and the percentage is calculated by weight.

#### *3.7.5.2 Manufacture of specimen.*

The test specimens used in our study are specimens made from a cylindrical mold (D = 10.2 cm, h = 10.4 cm) with the optimal water content and the maximum dry density deduced from compaction tests. The numbers of the samples are three test pieces for each test.

#### *3.7.5.3 Mixing*

The mixing is performed manually; the mixing steps are combinations:

- soil-hair
- Soil-cement with hair.

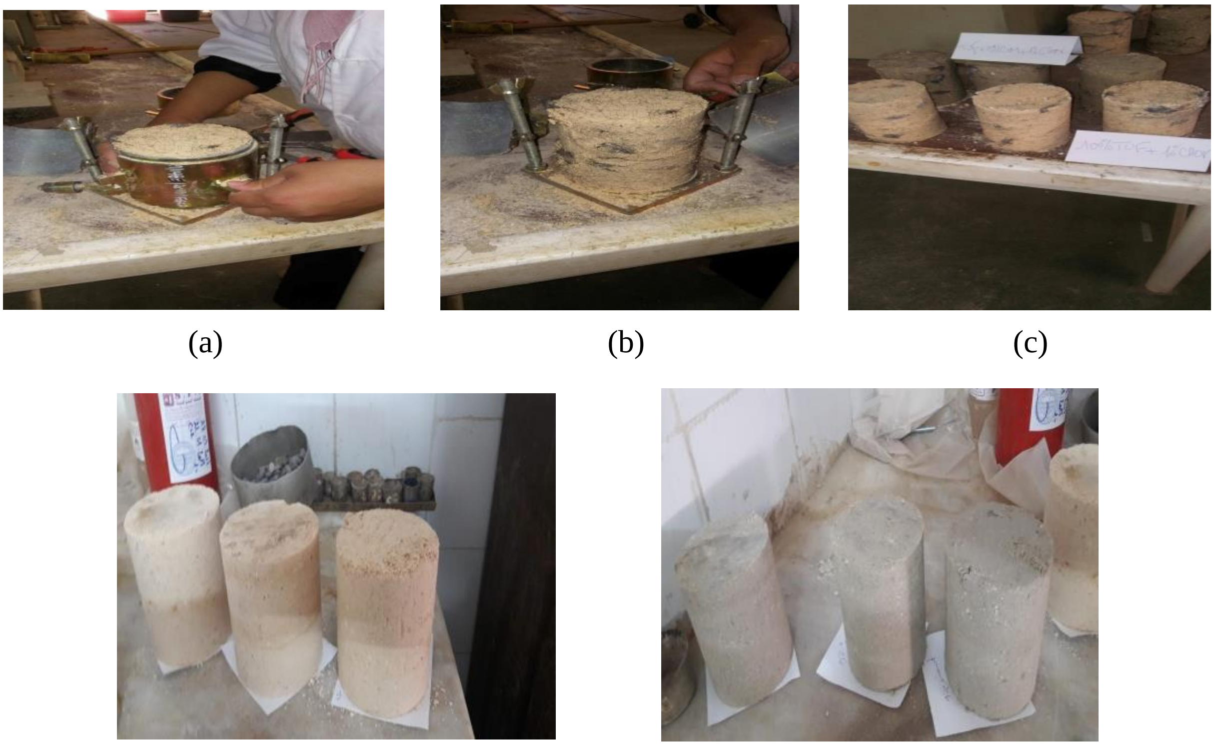
The procedure was done according to the following steps:

- Weigh the necessary quantities of the constituents for a mixture.
- Introduce the aggregates into the mixing container.
- Add the optimum moisture content and mix manually.

#### *3.7.5.4 Molding and demolding*

After mixing, the combinations of samples are ready for use. The sample is introduced from a mold already greased with an oil to facilitate demolding after compaction. The filling of the mold is carried out in several layers each time a layer is poured and compacted manually until the filling of the mold and after these steps the sample is placed under the making machine to compact it well.

The test pieces should be sharpened (screeded) with a ruler (Figure 3.15 (a) and (b)). The upper face of the test piece should be smooth and well finished (Figure 3.15 (c)). After demolding, each sample is stored in a plastic bag to preserve moisture. The samples are made for different periods: 7, 14 and 28 days (Figure 3.15 (d) and (e)).



(a) (b) (c)

(d) (e)

*Figure 3. 15- Mold, preparation of samples and storage of test pieces for different periods of cure.*

The tests were examined in the compression testing machine (Figures 3.16 and 3.17) at 7 days, 14 days and 28 days. The corresponding charges were measured during the test.

*Figure 3. 16 - Compression testing machine*

*Figure 3. 17 - Specimen under testing machine*

# Chapter 4:
# Results and discussion

# Chapter 4: Results and discussion

## 4.1 Index properties and strength of artificial soil using the Harvard miniature method

### 4.1.1 Liquid limit and Plastic limit ASTM D 4318-00

The mechanical properties of a fine grained soil are altered by changing the water content. Liquid limit and plastic limit tests were performed on different mixtures of artificial soil in order to find the relationship between mechanical properties and index properties. The results of liquid limit, plastic limit and plasticity index on different soil mixes are summarized in Table 4.1. The classification of soil based on USCS soil classification has been found from the plasticity chart Figure 4.1.

*Table 4 1: Summary of liquid limit and plastic limit for different mixes*

| Artificial mixture | Liquid limit (%) | Plastic limit | Plasticity Index (%) | USCS Classification |
|---|---|---|---|---|
| 30K70S | 7 | NP | 7 | CL-ML |
| 50K50S | 22 | 15 | 78.21 | CL-ML |
| 70K30S | 31.709 | 16 | 15.92 | CH |
| B10K40S50 | 68.25 | 12 | 56.25 | CH |
| B15K35S50 | 80.816 | 10 | 7.085 | CH |
| B20K70S50 | 106.7 | 14 | 93.1 | CH |
| 30B70S | 142.19 | 17 | 124.08 | CH |
| 50B50S | 213.006 | 27 | 185.81 | CH |
| 70B30S | 342.45 | 36 | 306.4 | CH |

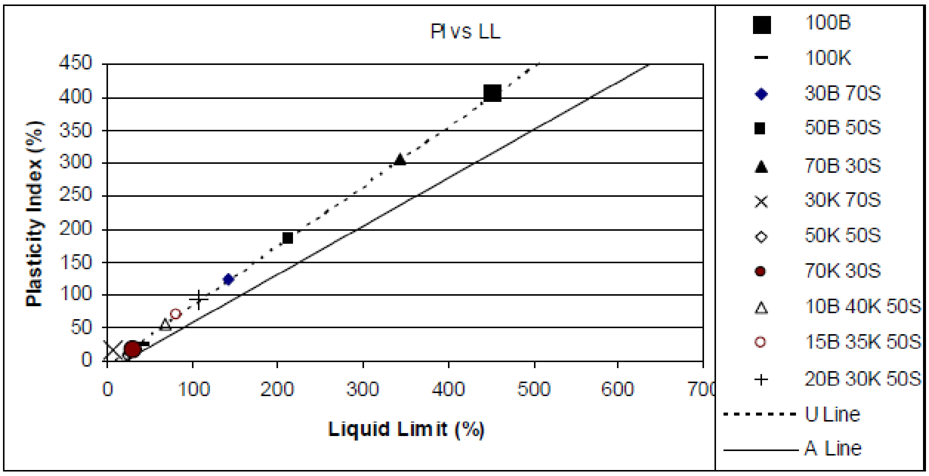



*Figure 4. 1- Plasticity Chart*

The liquid limit of Bentonite and kaolinite was 450 and 42 respectively. Plastic limit for Bentonite and kaolinite was 43 and 25 respectively. The liquid limit and plasticity index of soil increases with increase in clay content. The increase is more pronounced in the case of Bentonite mixtures.

### 4.1.2 Compaction characteristics

Figures 4.2, 4.3 and 4.4 show the moisture density relationship for the Bentonite, sand, and kaolinite, sand mixtures. The maximum dry density varies from 311–261 pcf and optimum moisture content (OMC) varies from 16.6-21.5% for increase in Bentonite content whereas maximum dry density for kaolinite varies from 338-273 pcf and OMC varies from 11-23 for the similar sand ratios. It has been found that maximum dry density decreases and OMC increases with the increase in Bentonite and kaolinite content.

The ratio of Bentonite and kaolinite was varied keeping the sand as constant. OMC increases with increase in Bentonite and decreases with the increase in kaolinite.

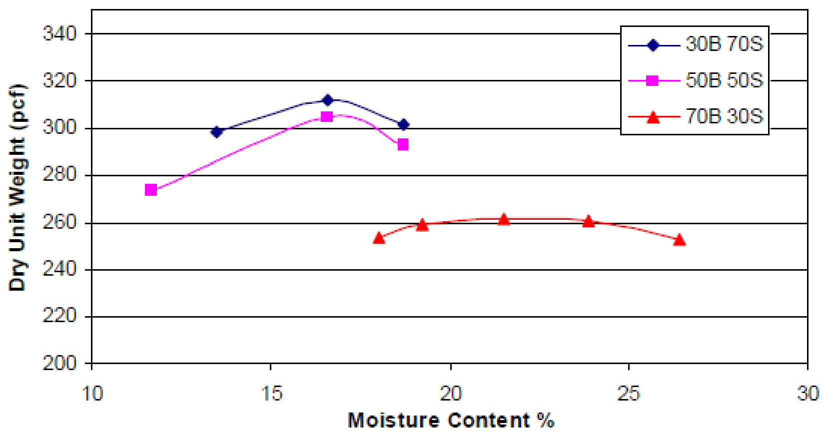



*Figure 4. 2- Moisture density relationship for Bentonite and sand mixture*

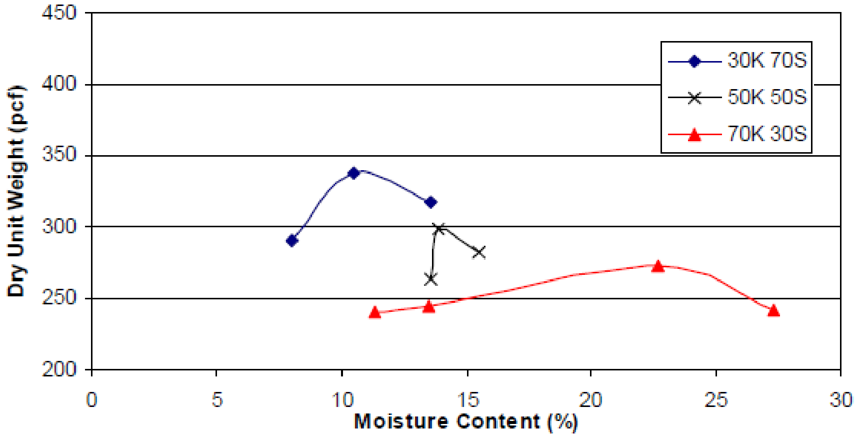



*Figure 4. 3- Moisture density relationship for kaolinite and sand mixture*

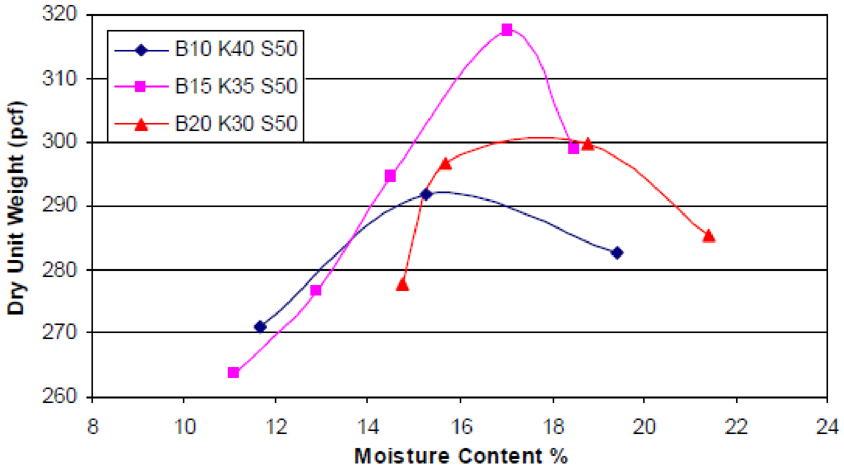



*Figure 4. 4- Moisture density relationship for Bentonite, kaolinite and sand mixture*

Figure 4.5 shows the variation of optimum moisture content with maximum dry density for different mixtures. The variation is linear in the case of kaolinite, sand and Bentonite, sand mixtures. The Bentonite, kaolinite and sand mixtures shows a parabolic variation which shows that ratio of Bentonite and kaolinite plays an important role in the moisture density relation irrespective of the increase in the Bentonite content.

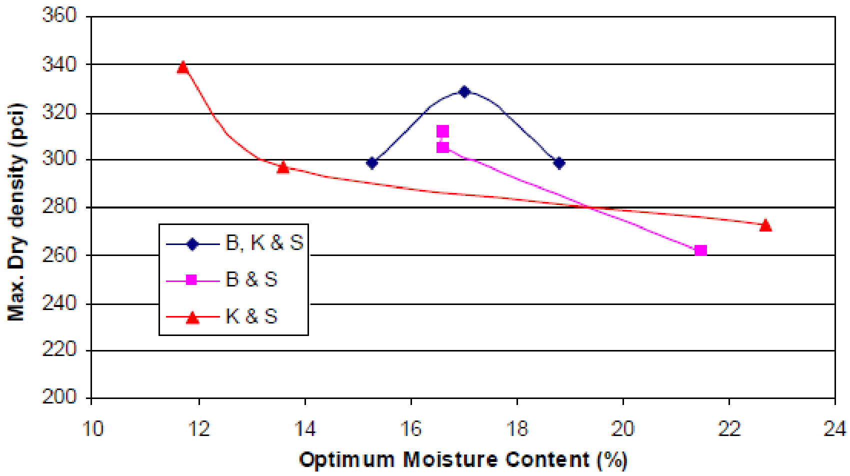



*Figure 4. 5- Maximum dry unit weight Vs. OMC*

### 4.1.3 Strength characteristics

Unconfined compressive strength was performed on the samples prepared from the Harvard miniature mold for different moisture contents. Figures 4.6, 4.7 and 4.8 show the unconfined compressive strength values for Bentonite, kaolinite and sand mixtures with variation in moisture content. Unconfined compressive strength increases with increase in moisture content and after reaching optimum moisture value the strength decreases. The strength values shows similar trend for all the mixtures of soil. The peak strength value increases with increase in clay content except for the kaolinite and sand mixture which shows more strength. In the Bentonite, kaolinite and sand mixture B10K40S50 shows more strength.

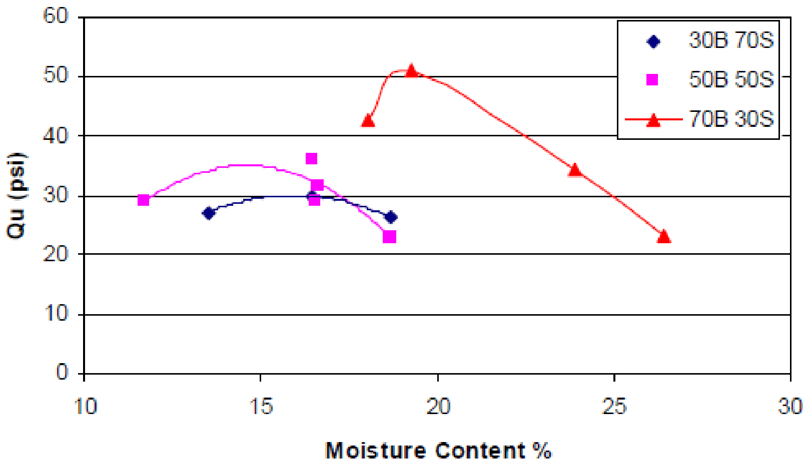



*Figure 4. 6- Variation in Qu for Bentonite and sand*

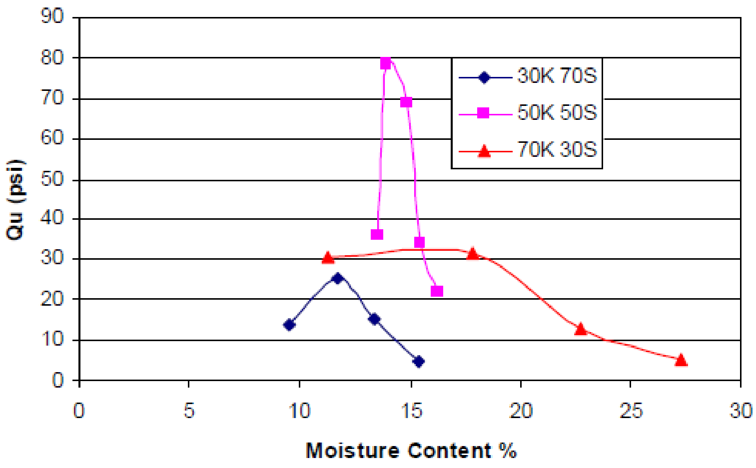



*Figure 4. 7- Variation in Qu for Kaolinite and sand*

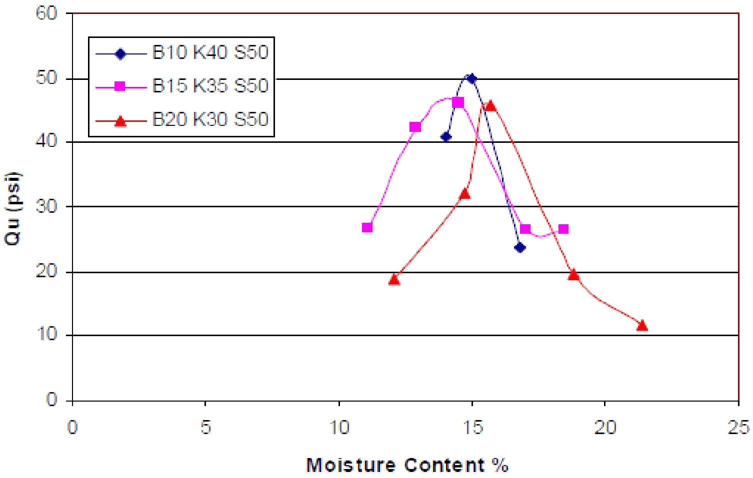



*Figure 4. 8- Variation in Qu for Bentonite, kaolinite and sand*

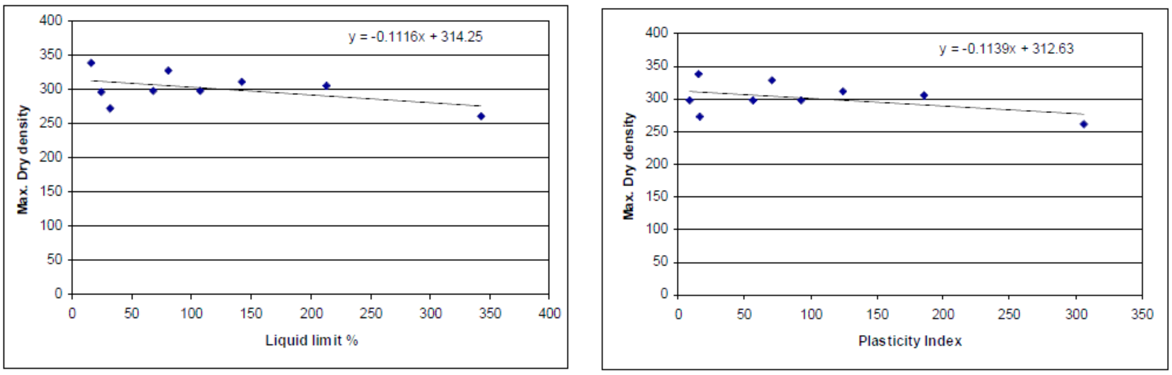
### 4.1.4 Relationship between index properties and strength properties

Based on the various tests performed on artificial soil of different mixes relationship has been brought out for the index properties (LL and PI) and the strength properties (unconfined compressive strength Qu, maximum dry density γdry and optimum moisture content OMC.

Relationship between maximum dry density and Index properties (Figures 4.9(a) and 4.9(b)).

$$\gamma_{dry} = -\ 0.116\ LL + 314.25 \qquad (4.1)$$

$$\gamma_{dry} = -\ 0.1139\ PI + 312.63 \qquad (4.2)$$



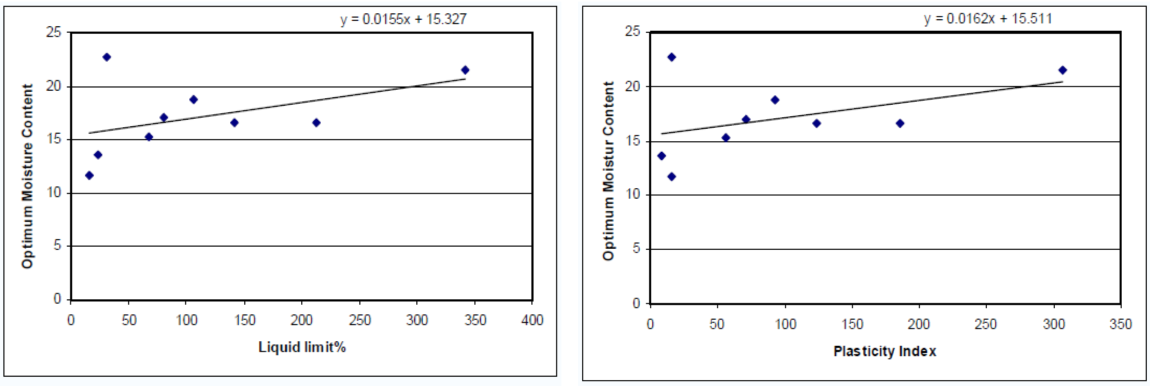

(a) (b)

*Figure 4. 9- Relationship between maximum dry density and Index properties*

Relationship between optimum moisture content and index properties (Figures 4.10(a) and 4.10(b)).

$$OMC = 0.0155\ LL + 15.327 \qquad (4.3)$$

$$OMC = 0.0162\ PI + 15.511 \qquad (4.4)$$



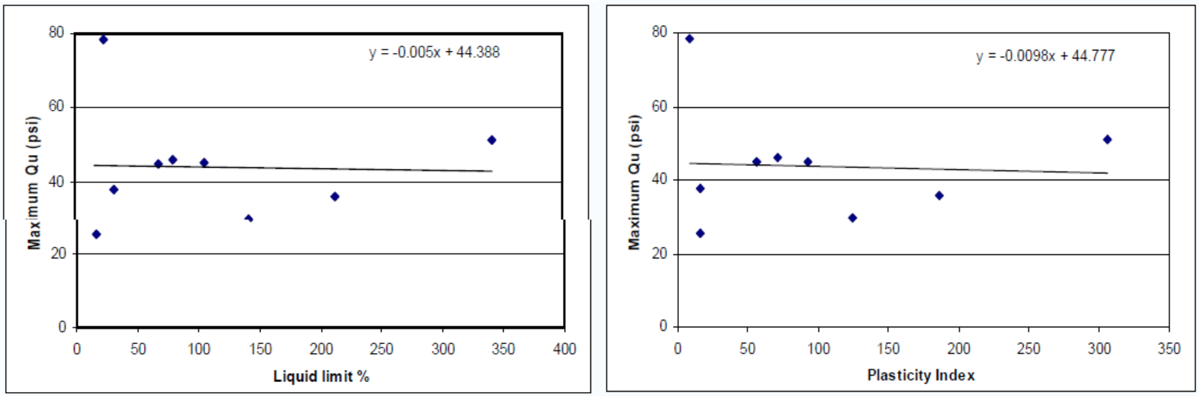

(a) (b)

*Figure 4. 10- Relationship between optimum moisture content and Index properties*

Relationship between shear strength and index properties (Figures 4.11(a) and 4.11(b)).

$$Q_u = -0.005\ LL + 44.388 \tag{4.5}$$

$$Q_u = -0.0098\ LL + 44.779. \tag{4.6}$$




(a) (b)

*Figure 4. 11- Relationship between shear strength and Index properties*

### 4.1.5 Conclusions

Relationships between the index properties and strength of artificial soil were investigated in this research project and the following conclusion has been brought out.

1. The liquid limit and plasticity index of the artificial soil increases with increase in clay content and the increase is more pronounced in Bentonite and sand mixtures and Bentonite, kaolinite and sand mixtures.

2. Maximum dry density decreases and OMC increases with increase in Bentonite, sand and kaolinite, sand mixtures.

3. OMC increases with increase in Bentonite and decreases with the increase in kaolinite in Bentonite, kaolinite and sand mixtures for the same sand content.

4. Peak shear strength increases with increase in the clay content except for 50K50S mix which shows high strength.

5. In the Bentonite, kaolinite and sand mix B10K40S50 shows high strength.

6. Relationship between strength and index properties has been brought out based on the test.

## 4.2. Assessment of cementitious materials impacts on clayey soils properties

### 4.2.1 Introduction

Observations from Harvard Miniature compaction test and unconfined compaction tests have been analyzed to study the effect of lime and cement on compaction characteristics and stress-strain behavior of the different mixtures of soil. The results are summarized in Table 4.2.

*Table 4. 2 - Summary of test results*

| Mixture | Sand % | Clay % | Lime % | Cement % | OMC % | γdry (g/cm³) | $q_s$ (kpa) | $\varepsilon_u$ | Curing Days |
|---|---|---|---|---|---|---|---|---|---|
| I | 10 | 90 | 0 | 0 | 28.9 | 1.54 | 820,476 | 1.76 | 14 |
| | 10 | 90 | 3 | 0 | 30.6 | 1.63 | 3212,96 | 3.15 | 14 |
| | 10 | 90 | 0 | 3 | 27.5 | 1.72 | 2240,8 | 2.2 | 14 |
| II | 50 | 50 | 0 | 0 | 18.5 | 1.97 | 985,95 | 2.21 | 14 |
| | 50 | 50 | 3 | 0 | 19.2 | 1.96 | 1254,85 | 2.31 | 14 |
| | 50 | 50 | 0 | 3 | 20.1 | 1.97 | 1999,48 | 2.54 | 14 |
| III | 90 | 10 | 0 | 0 | 12.7 | 2.08 | 586,054 | 1.16 | 14 |
| | 90 | 10 | 3 | 0 | 10 | 1.93 | 1185,9 | 1.70 | 14 |
| | 90 | 10 | 0 | 3 | 9.8 | 1.87 | 537,791 | 0.4 | 14 |

## 4.2.2 Compaction characteristics

### *4.2.2.1 Bentonite Clay (90/10)*

As shown in Figure 4.12 for the untreated soil (B90%; S10%) the optimum moisture content was 28.9% while the dry density was 1.54g/cm$^3$.The treatment of this type of soil gave the following results:

1. Addition of 3% of lime to this mixture increased the OMC by 6% while the dry density was increased by 5.5% compared to the untreated soil.

2. Addition of 3% of cement increased the dry density by 11%compared to the untreated soil while the OMC was not changed compared to the untreated soil. Hence the addition of cement was more effective in modifying compaction properties (density and optimum moisture content) of the Bentonite clay soil.

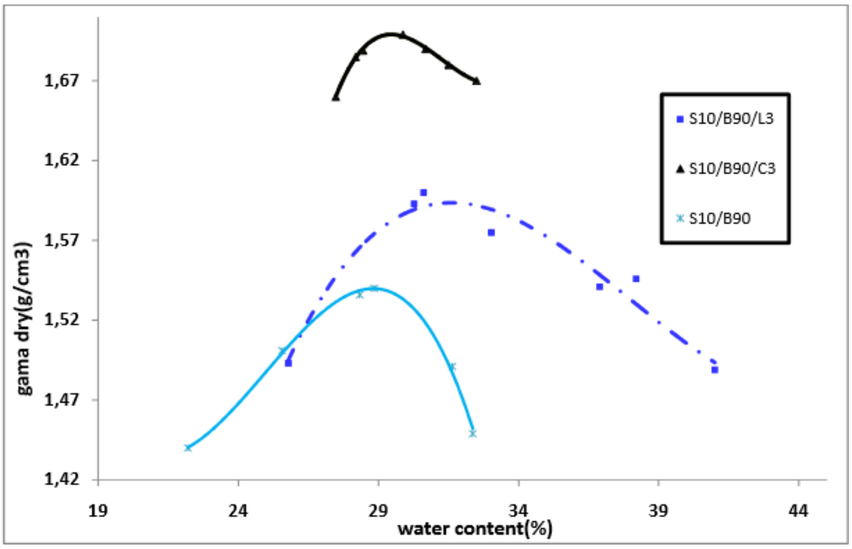



*Figure 4. 12- Dry Density vs. Water Content for the Clayey Sand*

### *4.2.2.2 Bentonite Clayey Sand (50/50)*

As shown in figure 4.13, the maximum dry density and optimum moisture content for the soils were 1.97 g/cm$^3$ and 18.5% respectively.

1. Addition of 3% of lime decreased the maximum dry density by 0.4% while the OMC increased by 4%.
2. The treatment of the soil with 3% cement decreased the dry density slightly. While the optimum moisture content increased by 9%. Hence the addition of 3% lime and cement had minimal effect on the compaction properties (dry density and optimum moisture content)

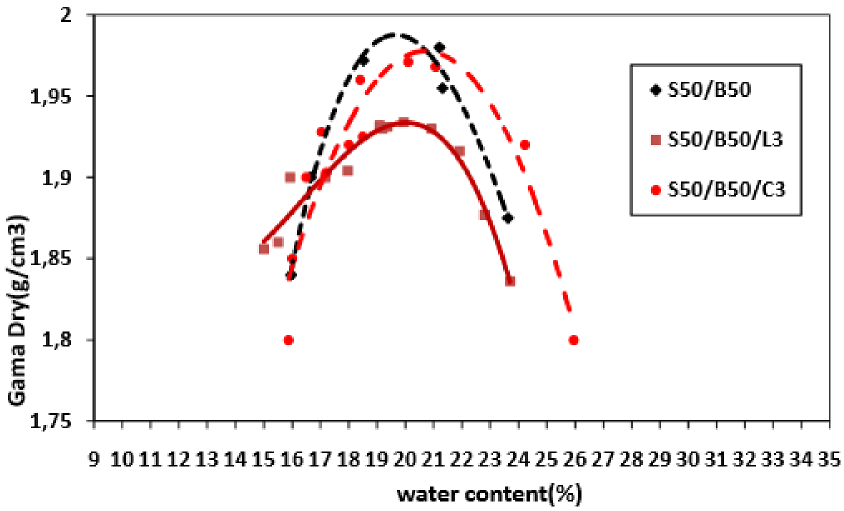



*Figure 4. 13- Dry density vs. Water Content for the Clayey Sand*

### *4.2.2.3 Bentonite Sandy-Clay (10/90)*

The maximum dry density and optimum moisture content for the untreated soil were 2.08 g/cm3 and 12.7% respectively (Figure 4.14).

1. Addition of 3% of lime caused a decrease of 21% in optimum moisture content and 7% in dry density.
2. Addition of 3% of cement caused a decrease on both dry density and optimum water content by 10% and 23% respectively.

Hence, the addition of 3% of cement and lime reduced the maximum dry density and optimum content of the sand clay.

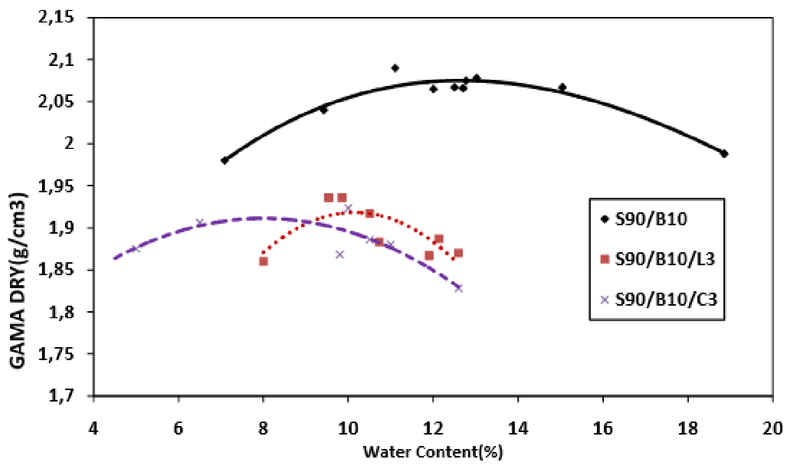



*Figure 4. 14- Dry density vs. Water content for the sandy clay*

### 4.2.3 Compressive strength

Specimens were tested at a deformation rate of 0.05 in/mn. After a curing period of 14 days for each combination of Bentonite clay and sand, the results were as follow for:

#### *4.2.3.1 Bentonite Clay (90/10)*

The unconfined compressive strength of the untreated soil near optimum moisture content was 119 psi as shown in Figure 4.15.

1. Addition of 3% lime increased the UCS by 292% compared to the untreated soil
2. Soil stabilized with 3% of cement show an increase of 173% compared to the control soil.
3. Based on these tests, it was noticed that specimens stabilized by lime ($\varepsilon_u$ = 3.15%) were less brittle than those stabilized using cement ($\varepsilon_u$ = 2.2%).

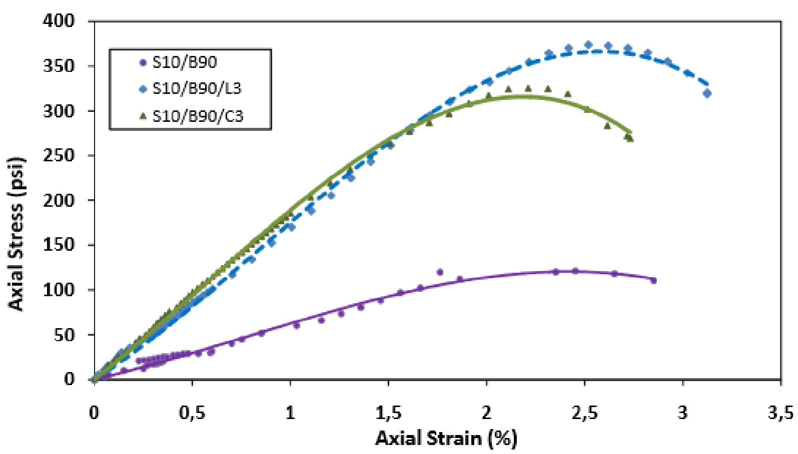



*Figure 4. 15- Compressive stress-strain relationship for clay soil*

### *4.2.3.2 Bentonite Clayey Sand (50/50)*

Figure 4.16 showed axial stress-strain relationship for the control soil near the optimum control a value of 985,95 kPa.

1. By comparing UCS of the different mixtures, it was observed that lime stabilized specimens had 28% higher strength than the untreated soil (S50B50) 2. Soil treated with 3% cement showed an improvement of 102% in UCS compared to the control soil.

3. The specimens stabilized with lime ($\varepsilon_u$ = 2.3%) and cement ($\varepsilon_u$ = 2.5%) had comparable failure strains.

4. In this case, as shown in Figure 4. 1 the specimens stabilized by cement exhibited better performance.

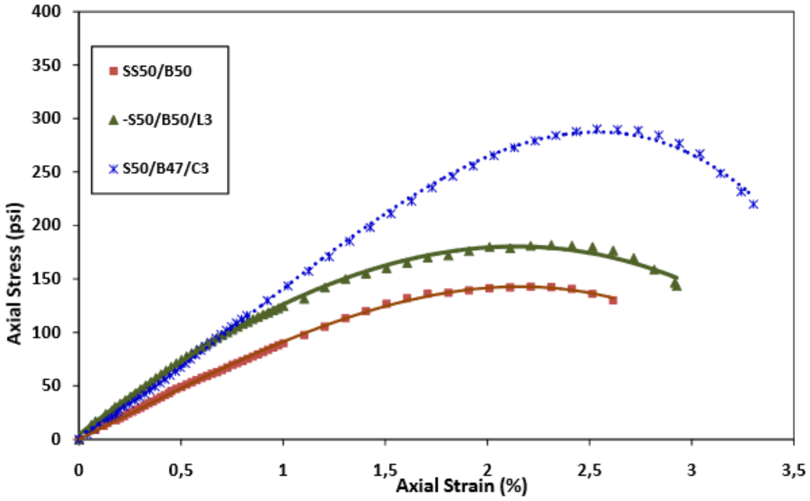



*Figure 4. 16- Compressive stress-strain relationship for clayey sand*

### *4.2.3.3 Bentonite Sandy-Clay (90/10)*

As seen in Figure 4.17 for these combinations, the USC for the control soil is 586,054 kPa.

1. The soil treated with 3% of lime gave a UCS 102% higher than the value of the untreated soil with an improvement in failure strain of 48%.

2. Addition of 3% cement had no effect on the strength but the failure strain was 0.4%. The failure strain of the control soil ($\varepsilon_u$ = 1.16%) was substantially reduced by the addition of 3% cement.

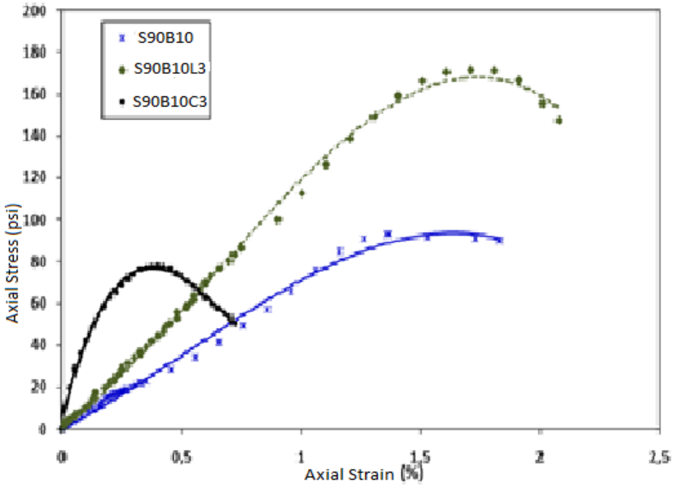



*Figure 4. 17- Compressive stress-strain relationship for clay–soil*

### 4.2.4. Conclusion

Addition of cement and lime had varying effects on the soils studied and the properties of interest such as the unconfined compressive strength, failure strain, dry density and optimum water content. Based on the experimental study the following observations are advanced:

1. For the sandy-clay (10% sand 90% Bentonite) addition of 3% lime increased the UCS by 292% and the treated soil with cement had an increase in UCS of 173% compared to the control soil. Based on these tests, it was noticed that specimens stabilized by lime showed higher failure strain than those stabilized by cement
2. Addition of 3% of cement and lime increased the maximum dry density. The optimum water content of the sand clay showed an increase (6%) for the treated soil with lime while a decrease (5%) was noticed in treating the soil with cement.
3. For the clayey sand (S50%B50%) by comparing UCS of the different mixtures, it was seen that lime stabilized soils (3%) are 28% higher than the untreated soil. The addition of 3% cement showed an improvement of 102% in UCS compared to the control soil. Soils stabilized with cement had a higher failure strain (10%) compared to the soil treated with lime. Lime or cement had slight effect on the compaction properties (dry density and moisture content).
4. For the sandy clay soil (S90%B10%) addition of 3% lime to the soil improved the UCS by 102% compared to the untreated soil, while the failure strain increased by 47% also.
5. For this group of combination, soil treated with 3% cement had no effect on the control soil.
6. The addition of 3% of cement and lime reduced the maximum dry density by 10% and 7% respectively, while the optimum water content decreased by 23% and 21% respectively for the sand clay.

## 4.3 Role of optimum moisture content and Bentonite clay on the compacted soil material properties

This study aims to provide a thorough evaluation for the changes in the Opt dry density, Modulus, Ei, Energy, and evolution of strength of highly expansive clay. Three series of testing were carried out on specimens with 80%, 50% and 20% of bentonite content that were mixed with 20%, 50%, 80% respectively of sand over a period of curing time as a function of the mixing moisture content. Table 4.3 summarized the test results.

*Table 4. 3 - Summary of test results*

| Parameter | | Series 1 | | Series 2 | | Series 3 | |
|---|---|---|---|---|---|---|---|
| | | S80B20 | WC | S50B50 | WC | S20B80 | WC |
| Opt dry density, $\gamma_{dry}$ | $g/cm^3$ | 1.92 | 11 | 1.729 | 21.9 | 1.437 | 29.3 |
| Modulus, $E_i$ | (kPa) | 2378,69 | 10 | 1213.5 | 21.4 | 244.07 | 29.3 |
| Energy | $Kg.m^2 s^{-2}$ | 2629.59 | 13.6 | 13286.4 | 21.7 | 3515.35 | 30.1 |
| Strength | (kPa) | 1151,42 | 12 | 2344.22 | 24.8 | 854.95 | 30.2 |
| Mean | | | 11.65 | | 22.45 | | **29.73** |
| Standard deviation | | | 1.75 | | 1.58 | | 0.49 |
| Covariance | | | 0.15 | | 0.07 | | 0.016 |

### 4.3.1 Stress-Strain Relationship

The stress-strain relationship at the optimum moisture content for the three types of soils are shown in Figure 4.18.

a) clayey sand (S20B80)

The liquid limit and plasticity index of the soil was 486.4 and 440.5 respectively. The unit weight was 1.437 $g/cm^3$, the lowest of all the soil mixtures studied. The unconfined compressive strength and modulus were **854.95** and **3515.347** respectively. These properties were the lowest for the three types of soils studied at their optimum moisture contents.the failure strain of the soil was 2%.

b) sand-clay mix(S50B50)

The liquid limit and plasticity index of the soil was 363.5 and 324.9 respectively. The unit weight was 1.729 $g/cm^3$, the lowest of all the soil mixtures studied.The unconfined compressive strength and modulus were **2344.22** and **1213.5** respectively. These properties were the lowest for the three types of soils studied at their optimum moisture contents.the failure strain of the soil was 2.5%.

c) Sandy-clay (S80B20)

The liquid limit and plasticity index of the soil was 152.16 and 127.76 respectively. The unit weight was 1.92 g/cm$^3$, the lowest of all the soil mixtures studied.The unconfined compressive strength and modulus were **1075.56** and **2378.7** respectively. These properties were the lowest for the three types of soils studied at their optimum moisture contents.the failure strain of the soil was 1%.

Increasing the sand content to 80% reduced the failure strain and strength by more than 50% compared to the sand clay mix.

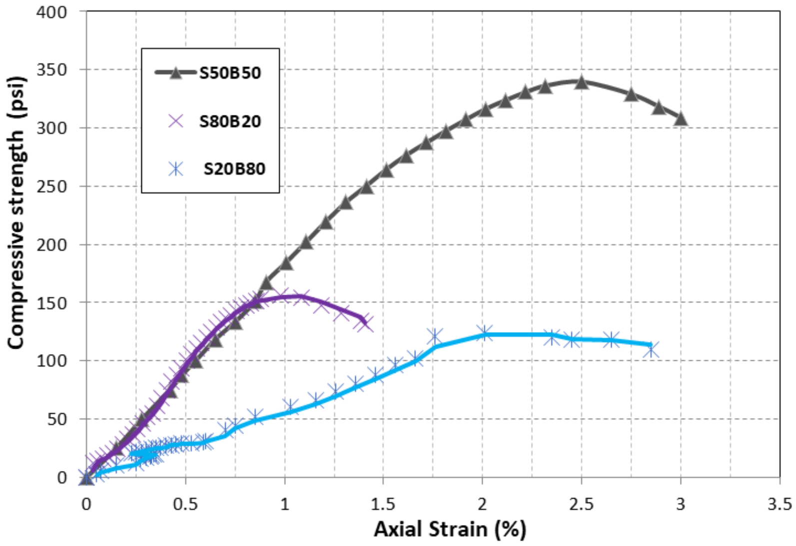



*Figure 4. 18- Compressive strength vs Axial Strain*

### 4.3.2 Strength-moisture content relationship.

The strength- moisture content relationship at the optimum moisture content for the three types of soils are shown in figure 4.19.

#### *4.3.2.1 Clayey sand (S20B80)*

The optimum moisture was 30% and the maximum strength was 854.95 kPa. This soil had the highest optimum moisture contents and the lowest strength. At 95% of the maximum strength the moisture content range was 29.4% to 30.4%. This moisture range is important to ensure quality control during construction.

#### *4.3.2.2 Sand-clay mix(S50B50)*

The optimum moisture was 22.45% and the maximum strength was 2344.22 kPa. This soil had the medium optimum moisture contents and the highest strength. At 95% of the maximum strength the moisture content range was 21.4% to 24.8%. This moisture range is important to ensure quality control during construction.

### *4.3.2.3 Sandy-clay (S80B20)*

The optimum moisture was 11.65% and the maximum strength was 1075.58 kPa. This soil had the lowest optimum moisture contents and the lowest strength. At 95% of the maximum strength the moisture content range was 10% to 13.6%. This moisture range is important to ensure quality control during construction.

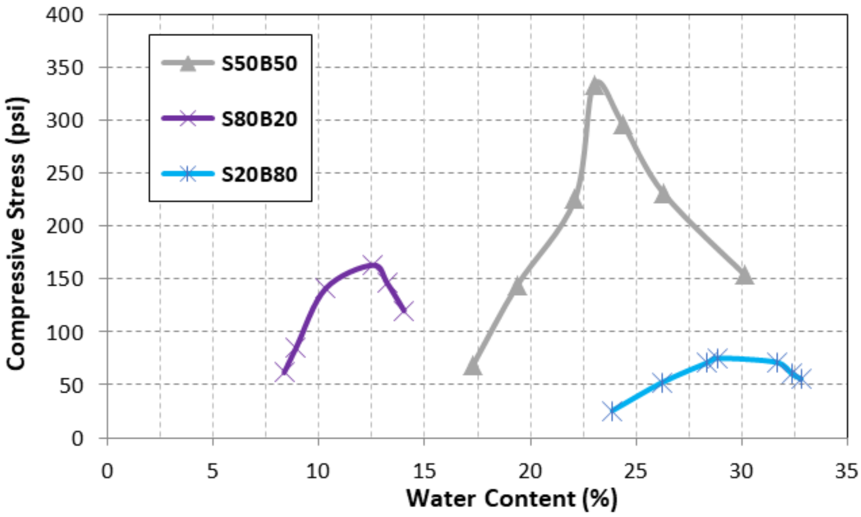



*Figure 4. 19- Compresive stress vs Water Content*

## 4.3.3 Strain energy-optimum water content relationship

The strain energy- moisture content relationship at the optimum moisture content for the three types of soils are shown in Figure 4.20.

### *4.3.3.1 Clayey sand (S20B80)*

The optimum moisture was 22.45% and the maximum strain energy was 3515.347 kPa. This soil had the medium value of the optimum moisture contents was 22.45% and the lowest strength. At 95% of the maximum strength the moisture content range was 21.4% to 24.8%. This moisture range is important to ensure quality control during construction.

### *4.3.3.2 Sand-clay mix (S50B50)*

The optimum moisture was 30% and the maximum strain energy was 13286.35 kPa. This soil had the highest optimum moisture contents and the lowest strength. At 95% of the maximum strength the moisture content range was 29.5% to 30.4%. This moisture range is important to ensure quality control during construction.

### *4.3.3.3 Sandy-clay (S80B20)*

The optimum moisture was 11.65% and the strain energy was 2629.59 kPa. This soil had the lowest optimum moisture contents and the lowest strength. At 95% of the maximum strength the moisture content range was 10% to 13.6%. This moisture range is important to ensure quality control during construction.

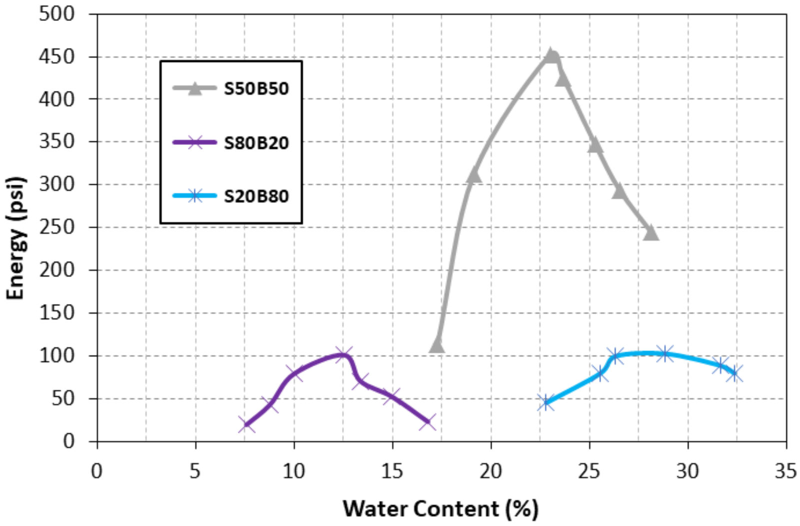



*Figure 4. 20- Strain Energy vs Water Content*

### 4.3.4 Dry Density -Optimum Water Content Relationship

The dry density-moisture content relationship at the optimum moisture content for the three types of soils are shown in Figure 4.21.

#### *4.3.4.1 Clayey sand (S20B80)*

The optimum moisture was 22.45% and the dry density was 1.437 g/cm$^3$. This soil had the highest optimum moisture contents and the lowest strength. At 95% of the maximum strength the moisture content range was 21.4% to 24.8%. This moisture range is important to ensure quality control during construction.

#### *4.3.4.2 Sand-clay mix (S50B50)*

The optimum moisture was 30% and the dry density was 1.729 g /cm$^3$. This soil had the highest optimum moisture contents and the highest strength. At 95% of the maximum strength the moisture content range was 29.5% to 30.4%. This moisture range is important to ensure quality control during construction.

#### *4.3.4.3 Sandy-clay (S80B20)*

The optimum moisture was 11.65% and the dry density was 1.92 g /cm$^3$. This soil had the lowest optimum moisture contents and the highest dry density. At 95% of the maximum strength the moisture content range was 10% to 13.6%. This moisture range is important to ensure quality control during construction.

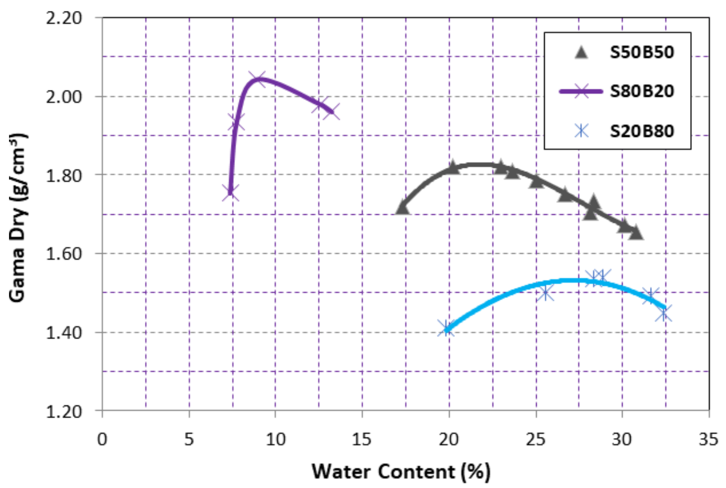



*Figure 4. 21- Maximum Dry Density vs Water Content*

### 4.3.5 Modulus -optimum water content relationship

The modulus-moisture content relationship at the optimum moisture content for the three types of soils are shown in Figure 4.22.

a) clayey sand (S20B80)

The modulus were **3515.347**. These properties were the lowest for the three types of soils studied at their optimum moisture contents.the failure strain of the soil was 2%.

b) sand-clay mix(S50B50)

The modulus was **1213.5**. These properties were the lowest for the three types of soils studied at their optimum moisture contents.the failure strain of the soil was 2.5%.

c) Sandy-clay (S80B20).

The modulus were **2378.7**. These properties were the lowest for the three types of soils studied at their optimum moisture contents.the failure strain of the soil was 1%.

Increasing the sand content to 80% reduced the failure strain and strength by more than 50% compared to the sand clay mix.

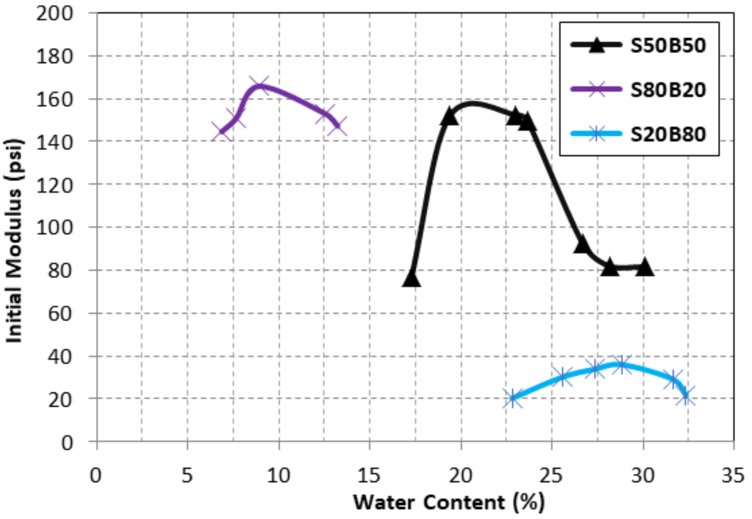



*Figure 4. 22- Initial Modulus vs Water Content*

### 4.3.6 Conclusions:

In this experimental study the influence of Bentonite clay and optimum moisture content on the compacted soil properties were investigated. Total of 90 compacted soil specimens were tested. Based on this study the following conclusions are advanced:

1 The material dry density was obtained for the first mixture S80%B20% (which comprises 80% of sand and 20% of Bentonite). It decreases with the increase of the amount of Bentonite

2 Compressive strength is maximum for the mixture S50% B50%

3 The lowest modulus of elasticity is obtained with the use of optimum amount of Bentonite

4 Energy is optimum for the mix S50%B50%.

## 4.4 Used engine oil as chemical admixture for earthen construction

### 4.4.1 Effect of used engine oil on dry density

Stability of cohesive swelling soil near large-scale rainfall for rammed earth is all too frequently compromised due to water ingress. In this research, a multilevel research approach was adopted by conducting a comparative study by the admixture of variety of pozzolanic materials to investigate the maximum absorbance correlation along with mechanical investigations such as the compressive strength. The native high plastic soil sample (CH) was blended with varying percentages of used engine oil independently at 0%, 4%, 8%, and 12%. A comparison of results in the case of used engine oil is summarized in Table 4.4.

*Table 4 4 - Summary of test results for the six series of mixtures*

| Series | Sand % | Bent % | Kaolinite | Crushed Bricks | FA % | Cement | Water % | UEO | $\gamma_{dry}$ |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 90 | 10 | | | - | - | 12 | / | 1.99 |
| | 90 | 5 | | | | 5 | 12 | / | 2.10 |
| | 90 | 10 | | | - | - | 0 | 12 | 2.36 |
| | | | | | | | 3 | 9 | 2.18 |
| | | | | | | | 6 | 6 | 2.20 |
| | | | | | | | 9 | 3 | 2.35 |
| | | | | | | | 0 | 8 | 2.34 |
| 2 | 80 | 10 | - | - | 10 | - | 6 | 6 | 2.37 |
| 3 | 80 | 10 | - | - | 10 | | 12 | - | 2.29 |
| | | | | | | | 0 | 6 | 2.44 |
| | | | | | | | 4 | 5 | 2.46 |
| 4 | 80 | 10 | - | - | 5 | 5 | 12 | 0 | 2.19 |
| | | | | | | | 5 | 4 | 2.47 |
| 5 | 80 | - | 20 | - | - | - | 8 | - | 2.45 |
| | | | | | | | 5 | 3 | 2.55 |
| | | | | | | | 0 | 8 | 2.52 |
| 6 | - | 20 | - | 80 | - | - | 16 | - | 1.89 |
| | | | | | | | 4 | 12 | 2.28 |

## 4.4.2 Effect of soaking on unconfined Compression strength

Table 4.5 describes the comparative overall performed testing on the soil specimen (S70B30, S80B20 and S75B25) soaked and unsoaked in used engine oil (UEO). Tests such as the unconfined compressive strength were investigated on oven-dried soil sample in order to check the effect of temperature on soil reversibility.

*Table 4. 5 - Summary of test results for the strength of soaked specimen (S70B30, S80B20 and S75B25)*

| Sand | Bentonite | Water Content | Soaked in UEO | Non-soaked in UEO | Failure Load | Loss of Strength (%) |
|---|---|---|---|---|---|---|
| 70 | 30 | 16 | | × | 182 | 34 |
| | | | × | | 120 | |
| 80 | 20 | 12 | | × | 156 | 41 |
| | | | × | | 91 | |
| 75 | 25 | 15 | | × | 162 | 31 |
| | | | × | | 111 | |

In light of the Figures 4.23, 4.24 and 4.25, the unconfined compressive strength performance of three lot soil mixtures samples respectively S80B20, S70B30, and S75B25 molded each at its optimum moisture content to its Proctor density and tested for its soaked and unsoaked in used engine oil. It is revealed that for the S80B20 mixture the loss of strength was the highest value 41%, while for S70B30 the loss is 34%. For preliminary design purposes the S75B25 gave the less loss value that is 31% might be used.

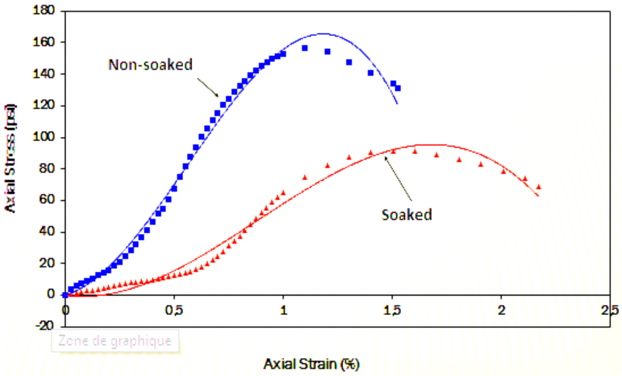



*Figure 4. 23- Unconfined Compressive Strength (S80-B20 W.C 12%)*

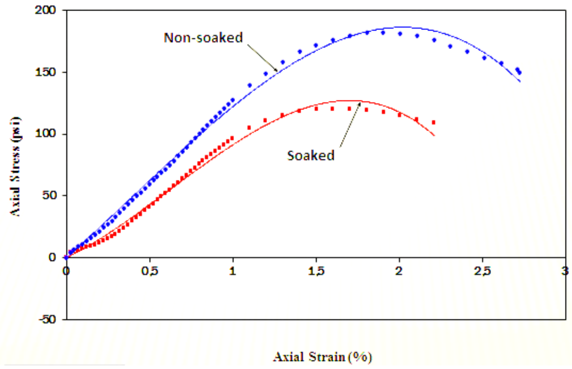



*Figure 4. 24- Unconfined Compressive Strength (S70-B30, W.C 15%)*

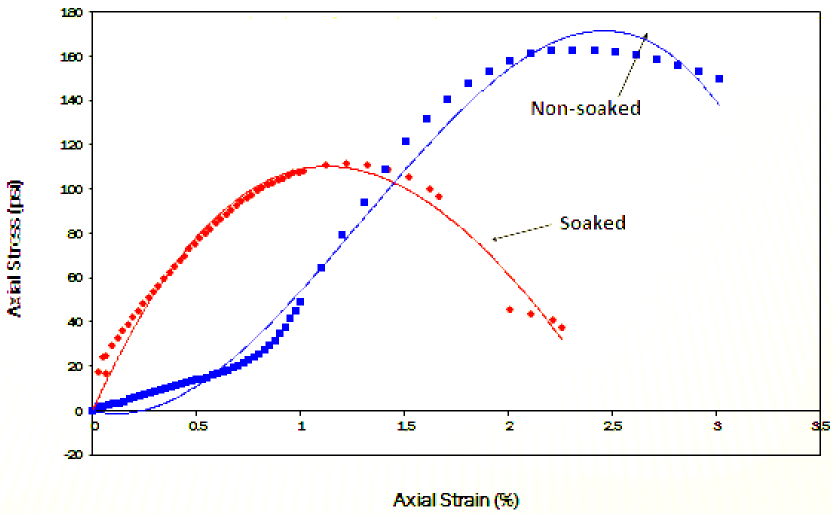



*Figure 4. 25- Unconfined Compressive Strength (S75-B25 W.C 15%)*

Figure 4.26 and 4.27 show bentonite soil (S80B20) totally soaked and partially soaked in water, respectively. Both samples showed an interaction between the volumetric strain and soil-water characteristics, the swelling potential of reactive clay soil according to the aspect of the volume of water. Therefore these soils require modification, which demands an engineering solution to satisfy the design criteria.

As a first remedy, Figure 4.28 Show bentonite sand mixture (S80B20), where the water content was replaced by a mixture of used engine oil and water. Then, the prepared sample was partially soaked in water. It can be noticed an improvement in the response of the sample. The swelling potential diminished compared to Figure 4.26 and 4.27.

In Figure 4.29 the soil mixture (S80B20), the water content was totally replaced by used engine oil. It is noticed that sample didn't stand as shown in the figure. As a result used engine oil can be used to solve the heaving problem of swelling soil if used properly.

In Figure 4.30 the sand was replaced by the crushed brick instead (CB80 B 20). Brick is a pozzolanic product that can play a stabilizing role like cement or lime. Moreover the sample was exposed to higher temperature than the room temperature (between 50 to 60°c). This joint effect had a positive reaction in decreasing the volumetric strain and limited the water ingress capability.

*Figure 4. 26 - (S80 B 20) totally soaked in Water*

*Figure 4. 27- (S80 B 20) Partially Soaked in Water*

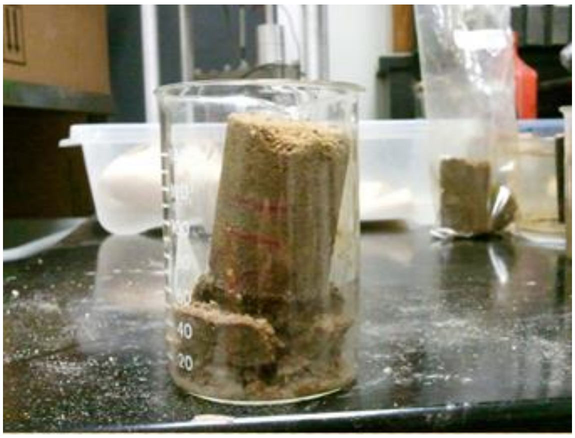


*Figure 4. 28 - (S80 B 20) Partially Soaked in Water*

*Figure 4. 29- (S80 B 20) Contaminated by 16% of UEO*

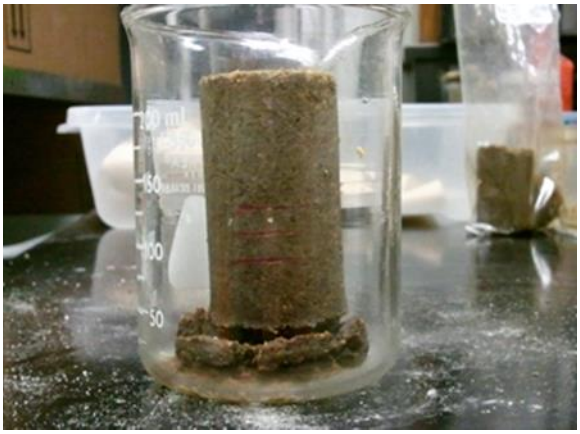


*Figure 4. 30- (CB80 B 20) Partially Soaked in water exposed to high temperature*

### 4.4.3 Conclusions

The use of engine oil:

- Improved $\gamma_{dry}$
- Decreased the strength
- Decreased cohesion of high plasticity clay
- The replacement of Bentonite by cement or fly ash improved $\gamma_{dry}$

## 4.5. Performance evaluation of human hair fiber reinforcement on lime and cement stabilized clayey-sand

### 4.5.1 Introduction

Observations from Harvard Miniature compaction and unconfined compressive tests have been analyzed to examine the joint effect of lime or cement and fiber reinforcement on compaction characteristics and stress-strain behavior of the different mixtures of soil. The findings are summarized in Table 4.6.

The unconfined compressive strength (UCS) of soil showed considerable increment in strength when human hair fiber was added to cement or lime. The fiber soil composite exhibits also improvement in the ductility behavior up to 3.25 fold compared to the parent soil and the strength has more than doubled (2.09 times). The OMC decreased as the amount of hair increased. With the inclusion of fiber and cement or lime, the peak strain at failure is increased. Table 4.6 shows the variation of U.C.S with the inclusion of fiber in the control soil. Figures 4.31 to 4.38 illustrate the influence of the used stabilizing agents on the stress-strain curves for the soil mixture with and without reinforcement.

*Table 4. 6 - Unconfined compression strength, maximum dry density, strain, and optimum moisture content values*

| Stabilization | Human Hair Fiber (%) | Maximum Dry Density ($g/cm^3$) | Maximum Strength (MPa) | Maximum Strain (%) | Optimum Moisture Content (%) |
|---|---|---|---|---|---|
| Control Soil (S50B50) | 0 | 1.972 | **0.902** | **2.211** | 21.31 |
| No Stabilization | 0.5 | 2.048 | 1.705 | 5.285 | 19.15 |
| | 1 | 2.048 | 1.867 | 6.156 | 18.69 |
| | 2 | 2.046 | **2.056** | **7.200** | 17.42 |
| 3% Cement | 0 | 1.994 | 1.480 | 4.143 | 22.63 |
| | 1 | 1.972 | 2.164 | 7.576 | 18.38 |
| | 2 | 1.949 | **2.734** | **9.832** | 17.44 |
| 6% Cement | 0 | 2.057 | 1.613 | 3.360 | 21.42 |
| | 1 | 2.040 | 2.606 | 4.655 | 20.36 |
| | 2 | 1.934 | **3.448** | **5.306** | 18.42 |
| 3% Lime | 0 | 1.952 | 0.983 | 3.480 | 20.13 |
| | 1 | 1.972 | 1.945 | 6.285 | 19.30 |
| | 2 | 1.996 | **2.163** | **7.567** | 18.38 |
| 6% Lime | 0 | 1.982 | 2.299 | 2.227 | 18.46 |
| | 1 | 1.971 | 2.851 | 4.030 | 17.70 |
| | 2 | 1.933 | **3.810** | **5.517** | 16.44 |

Results indicated that stabilized soil samples fails at higher strains when compared to control soil. Human hair fibers provided more ductility to the samples compared to the parent soil and the stabilized one. Moreover, fiber reinforced soil with cement or lime shows the improvement in peak stress at failure and failure strain. For the inclusion of 6% of cement or lime and 2% of fibers, the value of UCS is increased significantly to more than fourfold of the control soil. By addition of cement or lime without reinforcement the UCS of the fiberless mixture reached only half of the value of the mutual effect where cementing agent and fiber reinforcement are combined.

### 4.5.2 Compressive strength test

It is revealed from Figure 4.31 that the addition of the reinforcement up to 2% was connected to the decrease in the moisture content and an increase in dry density. However, the enhancement of the compressive strength and the strain reached 2.28 and 3.25 times respectively compared to the control soil.

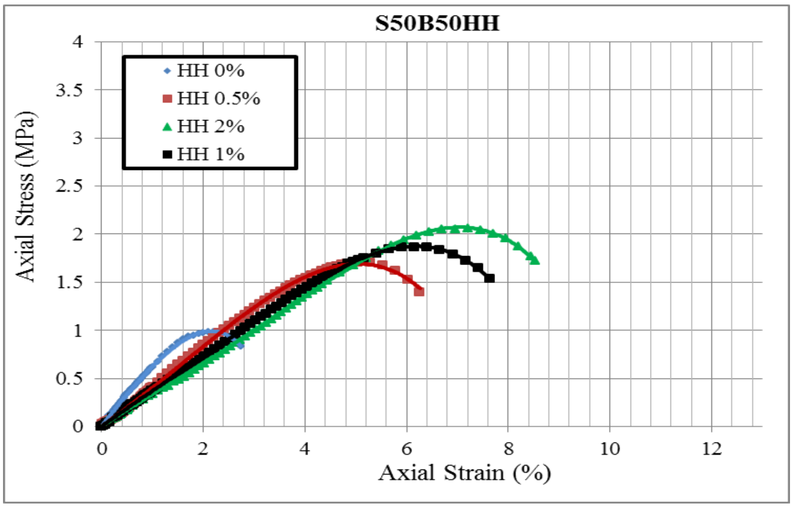



*Figure 4. 31- Stress strain curve for fiber reinforced non stabilized soil.*

Figure 4.32 shows decrease in the dry density and moisture content when the control specimen was mixed with 3% cement, and human hair up to 2%. The addition of 2% of human hair to the mixture enhanced both compressive strength and ductility by 3.02 and 2.38 fold respectively compared to the unreinforced specimen.

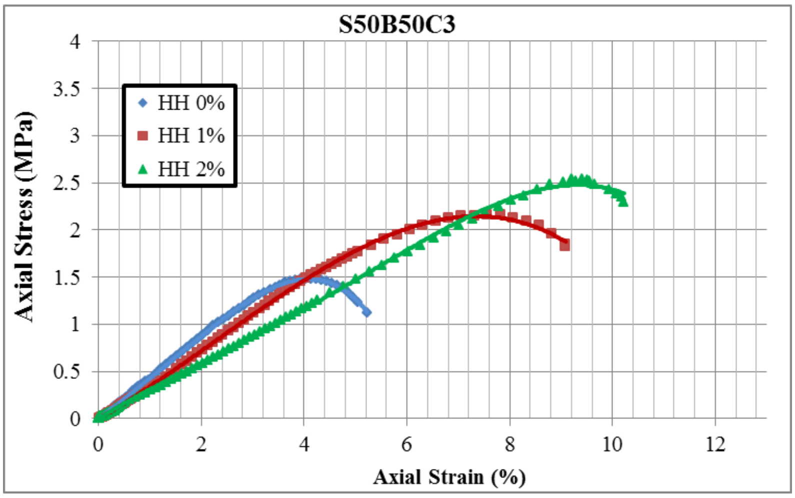



*Figure 4. 32- Stress strain curve for fiber reinforced soil with 3% of cement.*

Figure 4.33 shows a decrease in the moisture content and an improvement in the strength up to 2.137 times with the addition of 6% of cement with hair reinforcement up to 2% yielded, whilst the strain increased by 1.6 times compared to the unreinforced stabilized soil.

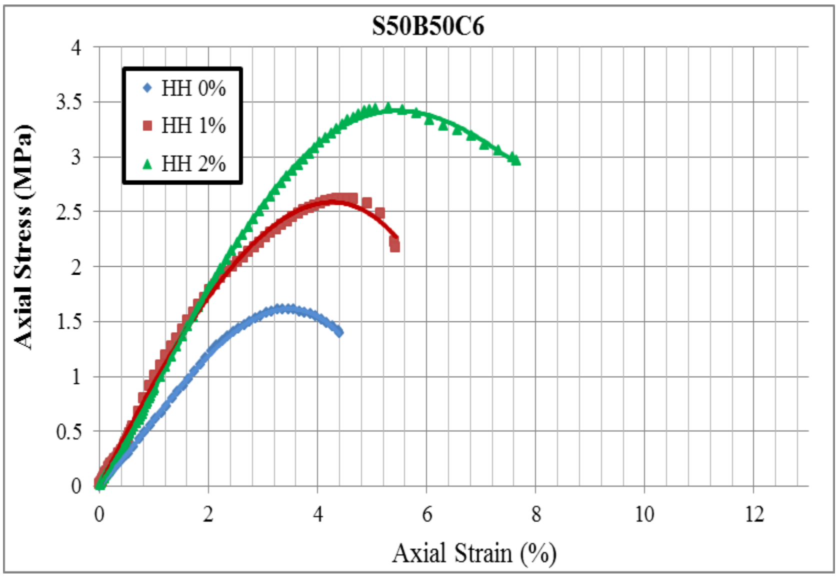



*Figure 4. 33- Stress strain curve for fiber reinforced soil with 6% of cement*

Figure 4.34 shows an enhancement in the dry density, moisture content and ductility when the parent soil was stabilized with 3% of lime, and reinforced with human hair up to 2%. Moreover the inclusion of 2% of human hair improved also the compressive strength and strain by 2.15 and 1.80 fold respectively compared to the unreinforced specimen.

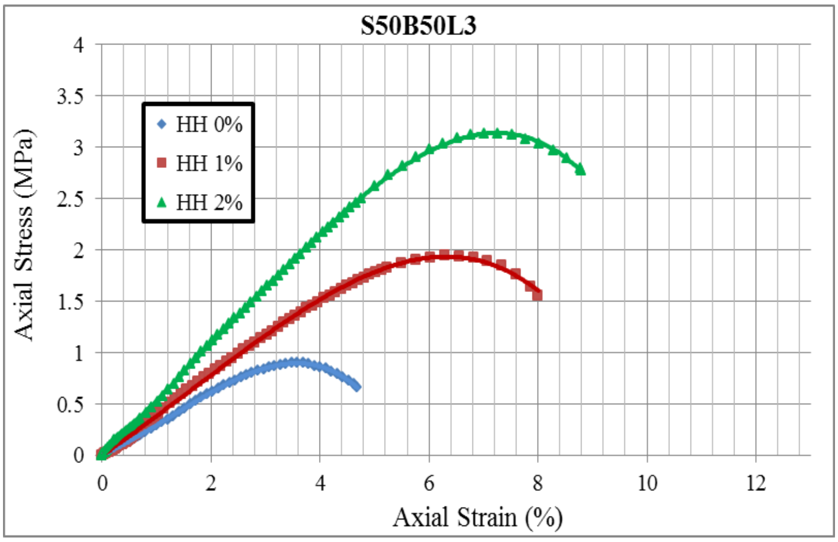



*Figure 4. 34- Stress strain curve for fiber reinforced soil with 3% lime and different fiber content*

From figure 4.35, it can be shown as the dosage of lime passed from 3 to 6% it generated an additional increase in the dry density and a minor change in moisture content.

The strength and strain improved by 1.66 and 2.47 fold respectively compared to the control specimen.

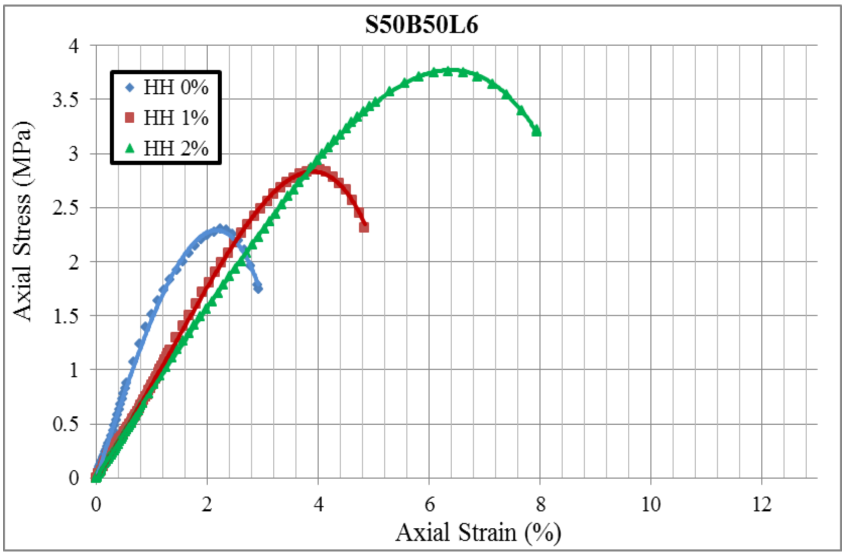



*Figure 4. 35- Stress strain curve for fiber reinforced soil with 6% lime.*

Figure 4.36 shows the plot of the comparative effect of performance of cement when the amount passed from 3 to 6% as stabilizer alone without reinforcement led to an increase in the dry density and a slight change in moisture content. The strength and the strain improved by 1.79 and 1.87 times respectively compared to the control specimen. The peak of the strain was observed at 3% after that a decrease in the ductile behavior of the soil was noticed by 1.52 times at 6%.

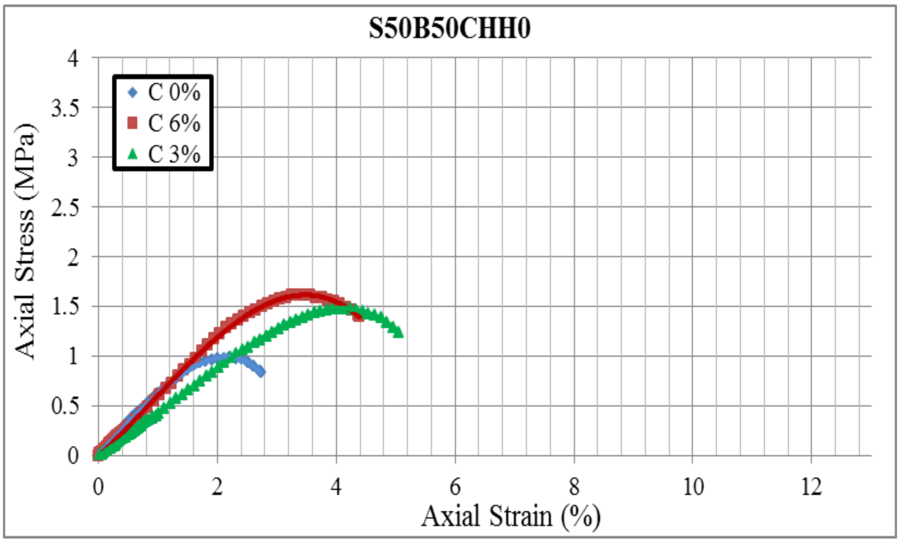



*Figure 4. 36- Stress strain curve for unreinforced soil with varying cement content*

Figure 4.37 shows the plot when doubling the content of lime 3 to 6% as stabilizer alone without reinforcement was accompanied by an increase in the dry density with a slight change in moisture content. The strength and the strain improved by 2.55 and 1.57 times respectively compared to the control specimen. The peak of the strain was observed at 3%, after that a decrease in the ductile behavior of the soil was noticed up to 1.007 times at 6%.

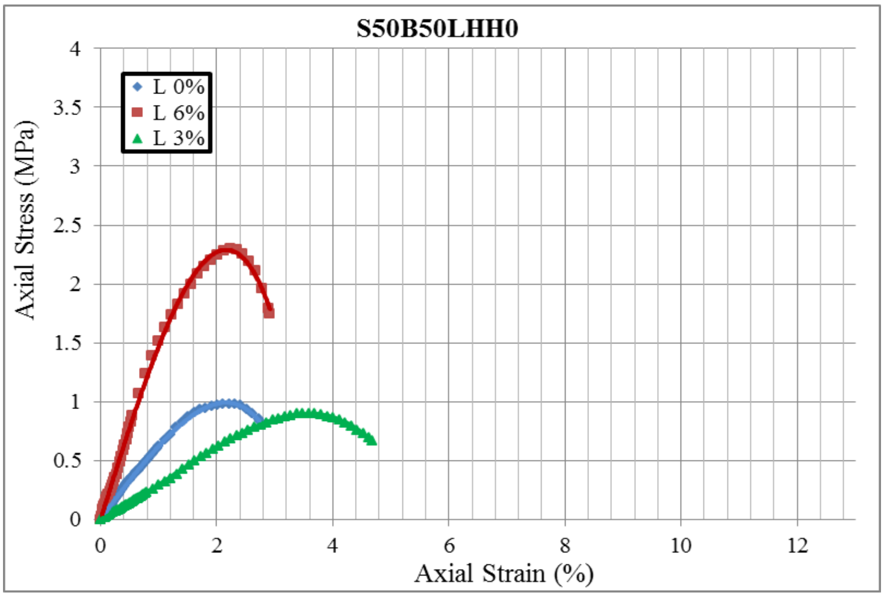



*Figure 4. 37- Stress strain curve for unreinforced soil with varying lime content*

Figure 4.38 shows the plot of the Comparative performances of 6% of either cement or lime. The axial strength of the soil increased with the increase in the dry density with a minor change in moisture content. The strength improved by 1.64 and 2.34 times by the addition of cement and lime respectively compared to the control specimen. Whilst the strain increased by 1.5% when cement was added and no change happened in case of lime.

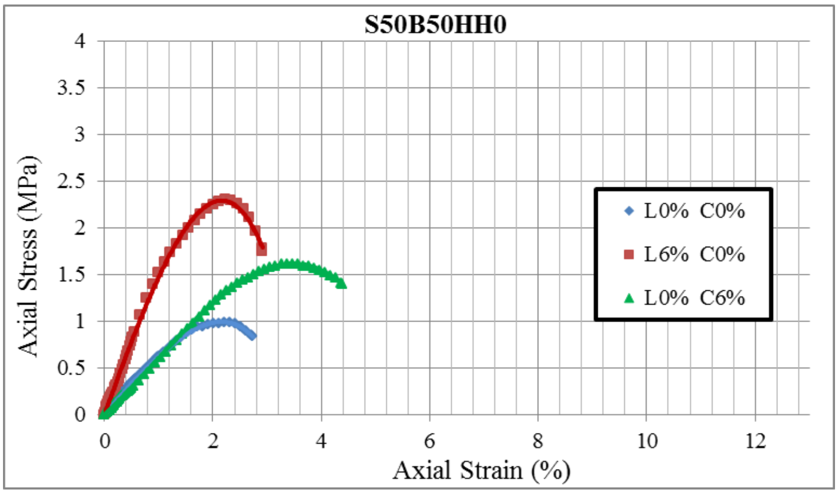



*Figure 4. 38- Stress strain curve for unreinforced soil with 6% of lime or cement content*

### 4.5.3 Conclusions

The following conclusions are drawn on the basis of test results obtained and discussion made in this study:

- From Harvard miniature compaction test, it is observed that inclusion of human hair fibers marginally affects the dry density-moisture content relationships of sandy-Bentonite soil.
- MDD initially reduces lightly due to addition of light weight hair fiber and then practically remains same. However, OMC increases marginally due to moisture absorption of hair fibers.
- The UCS strength of unreinforced and reinforced soils is substantially different; reinforced soil with fibers shows higher strength than unreinforced soil. With addition of 2.0% fibers by weight, the unconfined compressive strength increased up to 2 fold compared to the unreinforced stabilized soil.
- From the stress-strain curve it is clear that the ductility of the composite is also improved. This clearly indicates that the human hair fiber could be used in the improvement of cohesive soils.
- The inclusion of fiber reinforcement within soil and cement or lime soil mix caused an increase in the axial strain at failure.
- The inclusion of 2% of fiber reinforcement caused an increase of 2.09 times in the UCS and an increase of 3.25 times in the peak axial strain.
- The inclusion of 2% fiber reinforcement to the mix with 3% cement or lime stabilized soil mix gave more ductility than the 6% cement or lime stabilized soil mix.
- The inclusion of 2% fiber reinforcement within 6% lime stabilized soil mix gave slightly more strength than the 6% cement stabilized soil mix.
- Lime is more suitable stabilizing agent than cement for CH clayey-sand soils

It could be concluded from this study that the combination of discrete fiber and cementing agents to the control soil can be more efficient method for ground improvement and may cause a higher increase in strength than stabilizing agents by themselves.

## 4.6 Improving properties of modified clay with cement containing random chicken feather fibers

### 4.6.1 Proctor results

The Proctor curve results for Zebabdja clay mixed with and without the cement are presented in Figure 4.39. An increase in the optimum water content value from approximately 20% to 22.5% is observed when adding cement to the control soil from 6% to 12%, which corresponds to an enhancement in the maximum dry density ranged from 1550 to 1750 kg/m$^3$ respectively. As expected, the soil with cement needs more water than the soil without cement. This resulted in an increase of the dry density of the soil of 13%. It is deduced that the introduction of 10% of cement in the clayey soil, improves the physical characteristics of the soil. This performance may be due to the fine particles of the cement added to the clayey soil which has minimized the voids in the combined soil (Sinha, et al., 2021).

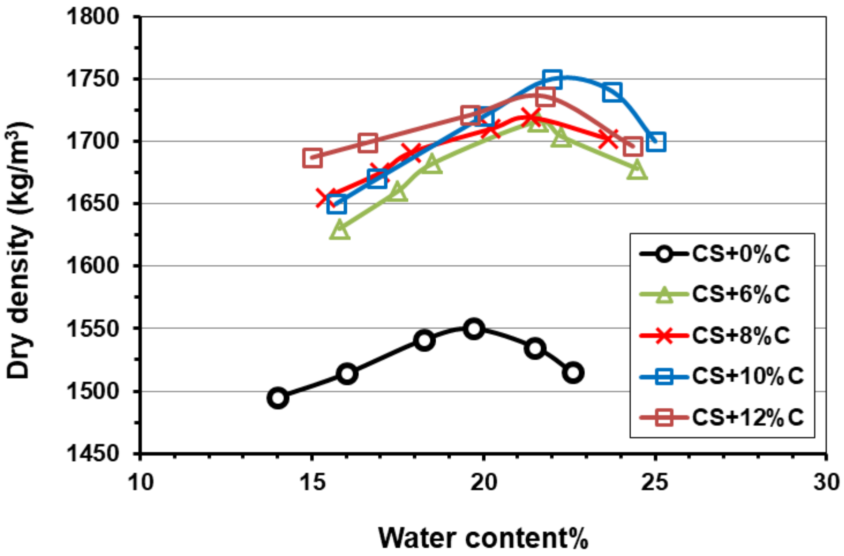



*Figure 4. 39- Proctor curves for the clayey and stabilized soil with different amounts of cement*

### 4.6.2 Unconfined compression strength results

The results of unconfined compressive strength of the clayey soil with different cement contents (6%, 8%, 10%, and 12%) are presented in Figure 4.40 at different curing times. A clear improvement of the unconfined compression strength is seen on the samples incorporating amounts of cement. The increase in unconfined compressive strength is attributed to the soil-cement reaction. When the pore water of the soil reacts with cement in the specimens, it bonds the components together; thus it creates a strong mixed soil resulting in high unconfined compressive strength (Victor, et al., 2014). The tendency of the strength curves of the soil cement indicates a continuous increase of the strength even over the 28 days age. The enhancement of the compression strength caused by the introduction of the cement reached its maximum for the 10% cement content (see Figure 4.40). The 12% cement content does not show the same level of strength in the soil samples as for those of the 10%. The latter is maybe the optimum content of cement needed for stabilizing the clayey soil of Zebabdja region.

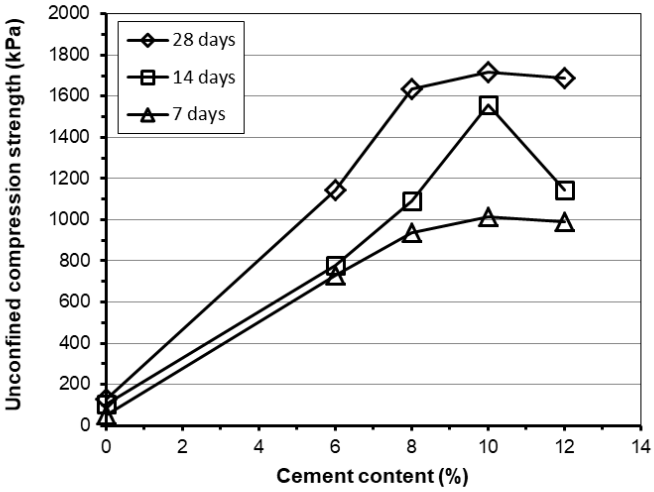



*Figure 4. 40- Unconfined compression strength of the soil as function of the cement content at different ages*

### 4.6.3 Effect of the feather fiber contents on the unconfined compression strength of the clayey soil

The evolution of the unconfined compressive strength of the clay samples with curing time for the different chicken feather fiber contents is shown in Figure 4.41. The soil samples develop strength gradually with the curing time, particularly before 14 days. It is observed that there is not a significant increase of the compressive strength of the soil with feather fibers after 14 days, except for the soil without feather fibers. The inclusion of the feather fibers into the clayey soil has probably affected the evolution of the compression strength with time as seen in the figure after the fourteen days age. Furthermore, it is clear that the inclusion of CFF has enhanced the compressive strength of the control soil according to the CFF contents. It is noted that the best performance was obtained at 2%. The increase in the compressive strength almost tripled compared to that of the control soil. The increase of the strength was also observed by other researchers (Marína et al., 2010).

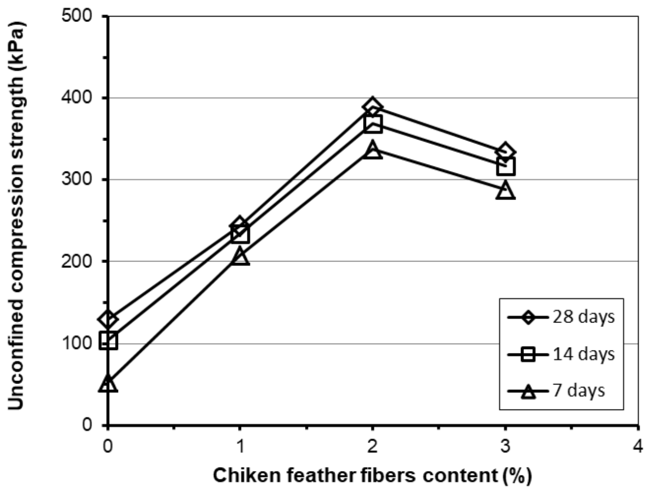



*Figure 4. 41- Unconfined compression strength of the clayey soil as function of curing time for control soil with different contents of CFF*

#### *4.6.3.1 Influence of chicken feather fiber contents on the characteristics of the clayey soil incorporating 10% of cement*

The mechanical behavior of the soil treated with 10% of cement as a function of the chicken feather fiber percentages for different ages is plotted in Figure 4.42. The obtained results show an enhancement of unconfined compressive strength with increasing feather fibers percentage up to 2%. It is observed that this improvement becomes more important with the increase of the curing time. The observed increase in the unconfined compressive strength of the reinforced soil may be attributed to fibers intersecting any developing failure zone through the interlocking and interweaving of fibers with the soil particles (Patel et al., 2017).

It is noted that over this rate (10%), the reinforced soil strength begins to decrease indicating the inverse effect of incorporating feather fibers. The maximum compressive strength value of the soil treated with 10% of cement was obtained for 2% of CFF inclusion at 28 days. This indicates that there is an optimum fiber content at which reinforcement benefit is the maximum in terms of bond strength and friction between soil particles and fiber. Patel and Singh (Patel et al., 2017) found that the unconfined compressive strength of the cohesive soil reinforced with glass fibers reaches its maximum value at 0.75% fiber content. The value of the strength corresponding for the studied soil is approximately 1900 kPa, which is equivalent to 13 times the value of the strength of the untreated control soil. The process to combine cement with chicken feather fibers may constitute a very interesting engineering solution in stabilizing the clayey soil.

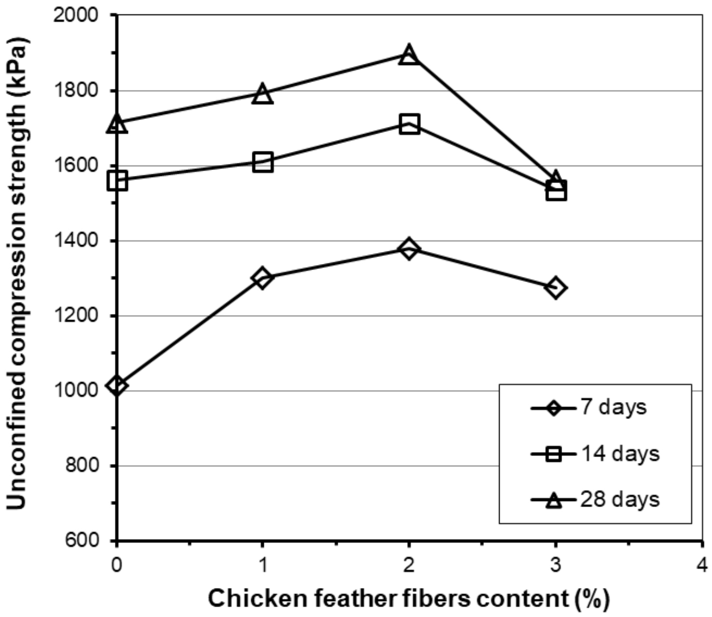



*Figure 4. 42- Unconfined compression strength of the stabilized soil with 10% cement as function of the chicken feather fibers content for different ages*

### *4.6.3.2 Influence of the mix composition on the unconfined compression strength of the clayey soil*

In the Figure 4.43, it is plotted the evolution of the unconfined compression strength of the clay soil including both cement and chicken feather fibers with the curing time in the aim to show the effect of each parameter. The rate of enhancement of compressive strength of the control soil reinforced with 2% of chicken feather fibers inclusion, control soil containing 10% of cement content and soil with 2% of chicken feather fibers plus 10% of cement content are equivalent to two times, 12 times and 13 and half times respectively. The addition of the cement to the control soil is the most important change observed on the mechanical behavior of the soil sample. The effect of incorporating the animal fibers in the clayey soil was less with regard to the cement effect. Many research works demonstrated the great effect to add cement to the clayey soil (Victor et al., 2014).

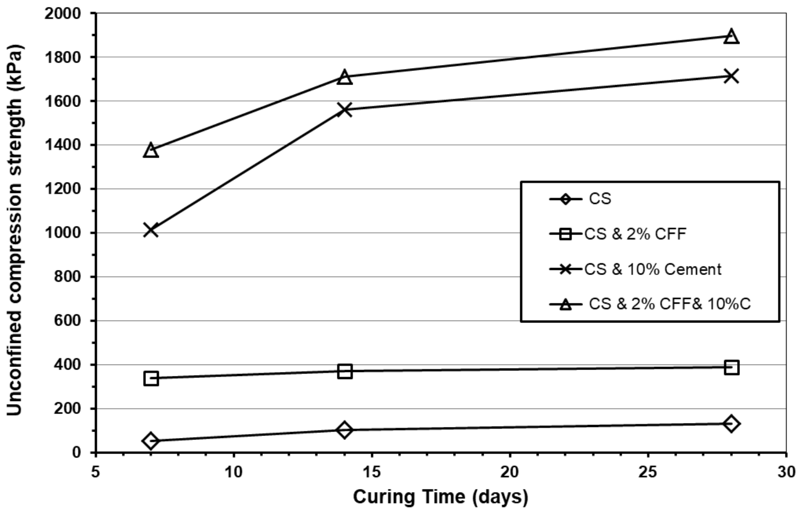



*Figure 4. 43- Comparative curves for stabilized soil with 10% cement & 2% inclusion of CFF*

### *4.6.3.3 Shear strength results*

The influence of feather fiber inclusion in Zebabdja clay stabilized with 10% cement at optimum water content and respective maximum dry density on the variation of the shear strength parameters was studied. For each clay mixture, three direct shear tests were conducted for axial stresses of 100, 200 and 300 kPa. The tests were conducted until the rupture of the soil specimens.

### *4.6.3.4 Shear strength of the control soil*

The relation between shear stresses and horizontal displacements of the control soil subjected to the aforementioned axial stresses is illustrated in Figure 4.44. For all normal stresses, the shear stresses of the control soil increase with the increase of the horizontal displacement and reach the peak value and do not show any clear reduction. It can be seen also that increasing in normal stress ($\sigma_n$) leads to the increase of the peak strength of the clayey soil. It is thought that the increase in peak stress is highly dependent on the normal stress.

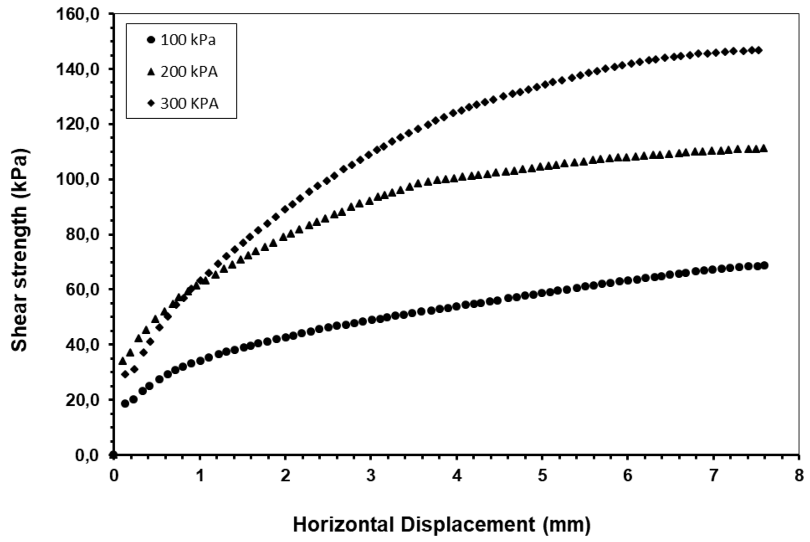



*Figure 4. 44- Shear stress-strain curves for the control soil at different normal stresses*

#### *4.6.3.5 Influence of 10% of cement addition on the control soil shear strength*

The relation between shear stress and horizontal displacement of the control soil and the stabilized soil with 10% cement, subjected to the axial stress values of 100, 200 and 300 kPa is illustrated in Figure 4.45. It can be seen from this figure that the effect of the addition of the cement to the clayey soil is significant at all normal stresses except for the axial stress of 100 kPa. The soil specimens did not indicate a distinct peak value before reaching the constant critical stress. It is noted that for the axial stress value of 200 kPa and 300 kPa, the shear stress of the soil stabilized with 10% cement is not higher than that of the control soil up to the shear corresponding to the horizontal displacement value of 5.6 mm. Over this value, the soil stabilized with 10% cement shows a clear increase at both normal stress of 200 and 300 kPa with a regard to that of the control soil. The rate of shear strength increase is 12% and 15% at the normal stress of 200 and 300 kPa respectively. Such observation is reported in some research works (Zambri and Ghazaly 2018). It is deduced that the addition of 10% of cement to the clayey soil results in an improvement of the soil strength characteristics. Some authors explain this change by the decrease of the liquid limit of the mixing soil (Huat, et al., 2005). Other investigators said that the improved compressive strength results indicated previously will be reflected on the engineering properties as shear strength (Maaitah et al., 2018). At high normal stress (300 kPa), the shear strength of the stabilized soil shows a peak strength equal to 168 kPa at 7.5 mm of the horizontal displacement.

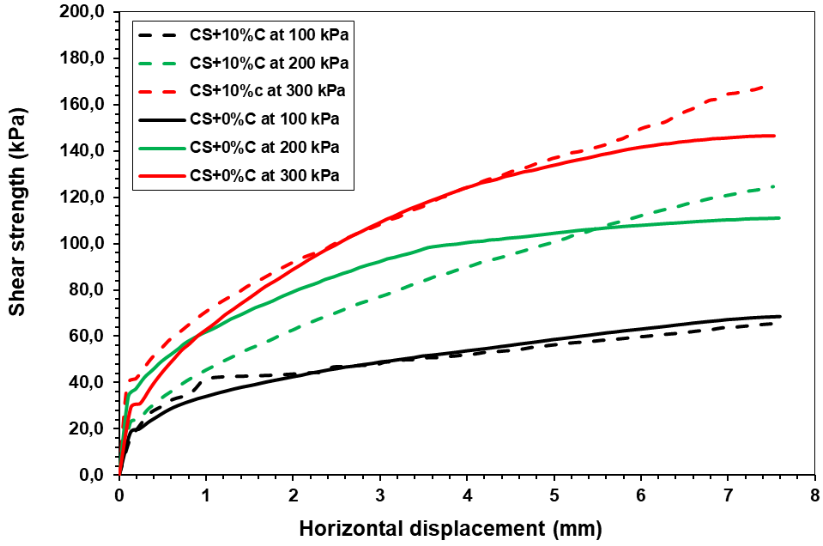



*Figure 4. 45- Shear stress vs. strain of stabilized soil with 10% cement at different normal stress*

### *4.6.3.6 Influence of chicken feather fibers on the stabilized soil shear strength*

In Figure 4.46, it is represented the stress- strain relationship of the clayey soil stabilized with 10% cement incorporating different percentages of chicken feather fibers at different normal stresses. The introduction of the chicken feather fibers leads to the increase of the shear stress at failure of the stabilized soil at all the normal stresses. This finding is consistent with the works reported by Naeini and Sadjadi (2008).

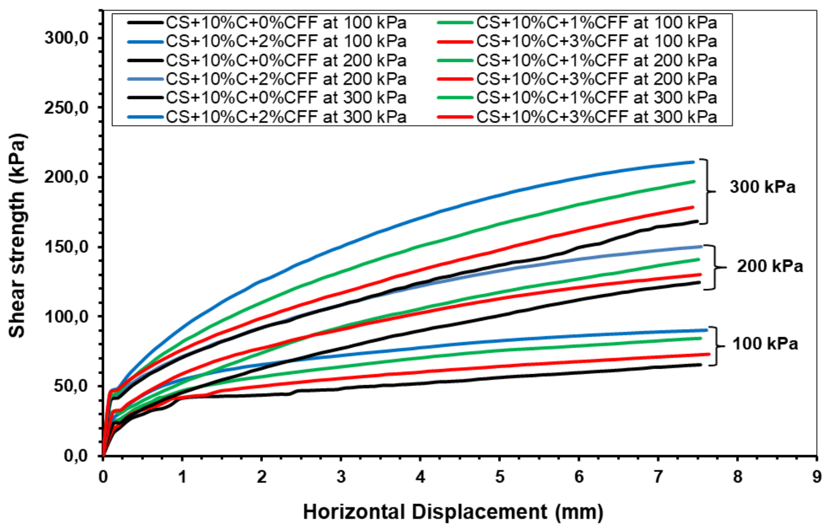



*Figure 4. 46- Shear stress-strain relationship of stabilized soil with 10% Cement incorporating different amounts of chicken feather fibers*

The increase in the shear strength soil is proportional to the increase in chicken feather fibers content till the percentage of 2% fibers. Beyond this rate, the shear strength is decreasing. Incorporation of randomly chicken feather fibers in the stabilized soil acts as plant roots, which fortifies the stabilized soil by additional frictions and interlocking (Hejazi et al., 2012). Some authors attribute the improvement of the behavior of the clayey soil to the soil-fiber interfacial friction. As the fiber content increases, the contribution of the interfacial friction becomes larger (Mali and Singh, 2013). Some other researchers states that fiber reinforced soil behave as a composite material in which fibers of relatively high tensile strength are embedded in a matrix of soil. Shear stresses in the soil mobilize tensile resistance in the fibers, which in turn imparts greater strength to the soil (Hejazi et al., 2012).

In Figure 4.47, it is shown the peak shear stress as function of the chicken feather fiber at all normal stresses. The influence of incorporating fibers is more significant at the percentage of 2% of CFF than that at 3% of CFF. For instance, the increase percentage in peak shear stress at the normal stress of 300 kPa is 17%, 25% and 6% corresponding to the inclusion fibers of 1%, 2% and 3% respectively. It is concluded that the amount of 2% of chicken feather fibers introduced in the stabilized clay constitutes the optimal value to get the higher shear stress.

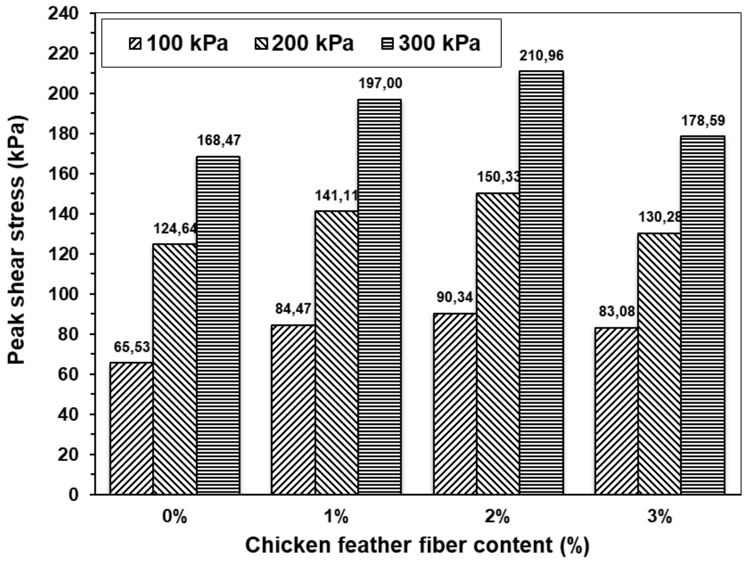



*Figure 4. 47- Peak shear stress of the stabilized soil as function of the fiber content*

### *4.6.3.7 Influence of the chicken feather fibers incorporated in the stabilized soil on the geotechnical parameters*

The cohesion and the friction angle can be calculated with respect to the relationship shear stress-axial stress and trend line of the stabilized soil are shown in Figure 4.48. Addition amounts of animal fiber have a significant effect on the development of the cohesion and the internal friction. As stated in Figure 4.48, the cohesion increases with the increase of the amount of fibers added to the clayey soil up to 2% and then decreases slightly with addition amounts of fibers. This finding is consistent with the work conducted by Naeini and Sadjadi (2008) on the effect of waste polymer on shear strength of unsaturated clays. The increase in cohesion of the fiber reinforced soil may be due to the increase in the confining pressure because of the development of tension in the fiber. The decrease in cohesion of the fiber reinforced soil with addition amount of fibers (more than 2% fiber content) may be due to separation of clay particles due to the addition of fibers (Naeini and Sadjadi, 2008).

*Table 4. 7 - Influence of the chicken feather fibers on the cohesion and the friction angle of the clayey soil*

| Mixture soil | Cohesion (kPa) | Friction Angle (Deg) |
|---|---|---|
| CS + 10%C+ 0% CFF | 16.61 | 27.23 |
| CS + 10%C+ 1% CFF | 28.33 | 29.36 |
| CS + 10%C+ 2% CFF | 29.92 | 31.10 |
| CS + 10%C+ 3% CFF | 21.82 | 27.68 |

The internal friction angle of the fiber reinforced soil follows the same trend as the cohesion (see Table 4.7). Increasing the fiber content in the clayey soil leads to the increase of the friction angle. The maximum friction angle is observed at 2% fiber content, which indicates the optimum chicken feather fiber based on shear strength results. Beyond this optimum rate, the observed shear parameters decrease. It is thought that high fiber content resulted in poor mixing with less contact between soil particles, reducing the availability of soil matrix for holding the fiber and the development of a sufficient bond between the fibers and the soil (Anagnostopoulos et al., 2014).

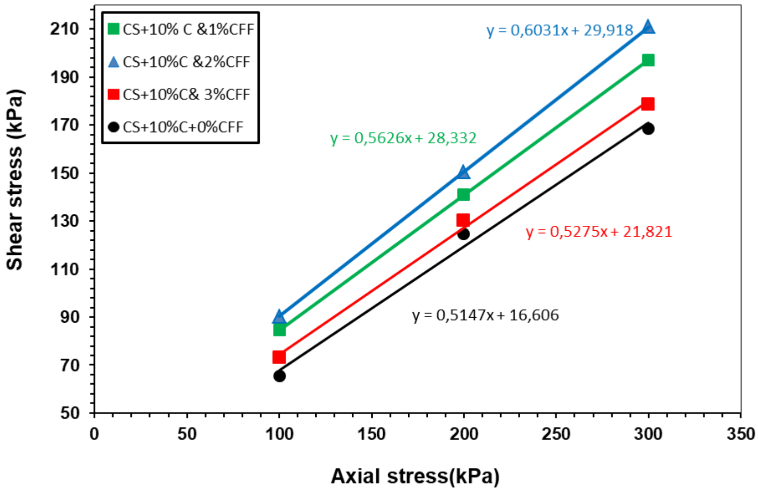



*Figure 4. 48- Variation of the shear stress as function of the axial stress for different amounts of chicken feather fibers*

### 4.6.4 Conclusions

An experimental program was conducted to investigate the individual and combined effects of cement stabilization and chicken feather fibers inclusions on the unconfined compressive strength and shear strength parameters of the clayey soil. The results showed that the enhancement of the compression strength of the clayey soil reached its maximum value (1720 kPa) for 10% cement content. The latter is considered the optimum content of cement needed for stabilizing the clay of Zebabdja region. It is also found that the inclusion of the chicken feather fibers into the treated soil (clay) has improved the compressive strength of the clay three times compared to that of the untreated soil and the best performance was obtained at 2% of fiber content. For comparison purpose, it is noted that the addition of the cement to the control has the most effect observed on the mechanical behavior of the soil sample and the effect of incorporating the animal fibers in the clayey soil was less. When applying normal stresses, the soil control shear stresses increase with the increase of the horizontal displacement and reach the peak value without indicating any clear reduction.

The present study demonstrates that incorporating randomly chicken feather fibers in the clayey soil stabilized with 10% cement is able to increase the shear strength soil proportionally to the fibers content. The amount of 2% of chicken feather fibers introduced constitutes the optimal value to get the highest shear stress and pervades a ductile behavior to the material. The addition of the chicken feather fibers to the clayey soil results in a substantial increase of both shear parameters; the friction angle and the cohesion and consequently contribute to the increase of the total strength of the soil mixture.

Finally, the technique of using a waste material such as chicken feather fibers in a soil stabilized with cement is a very effective method of improving the load bearing capacity of the soil and its engineering parameters.

## 4.7 Physical and mechanical behavior of the tuffs for their valorization in the building construction. Application to the Chlef Extra Quarry (Algeria)

### 4.7.1 Results of the modified Proctor test

Figure 4.49 shows the variation of the optimal dry density as a function of the cement content. It is found that the optimal water content increases according to the cement content, while the maximum dry density decreases of the order of 11% of cement.

*Table 4. 8 - Results of the modified proctor test*

| Percentage of added Cement | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0% | | 3% | | 5% | | 7% | | 9% | | 11% | |
| W% | $\gamma_d$ (t/m$^3$) | W% | $\gamma_d$ (t/m$^3$) | W% | $\gamma_d$ (t/m$^3$) | W% | $\gamma_d$ (t/m$^3$) | W% | $\gamma_d$ (t/m$^3$) | W% | $\gamma_d$ (t/m$^3$) |
| 9.412 | 1.861 | 8.889 | 1.841 | 8,672 | 1,906 | 8,592 | 1,923 | 8,483 | 1,923 | 7.867 | 1,898 |
| 10.98 | 1.89 | 10.977 | 1.884 | 10.44 | 1.929 | 10.390 | 1.937 | 10.284 | 1,949 | 10.132 | 1,932 |
| 12.936 | 1.88 | 12.745 | 1.92 | 12.605 | 1.942 | 12.329 | 1.969 | 12.267 | 1,975 | 11.287 | 1,948 |
| 14.849 | **1.85** | 14.79 | 1.898 | 14.501 | 1.926 | 14.389 | 1.943 | 14.336 | 1,952 | 14.296 | 1,939 |

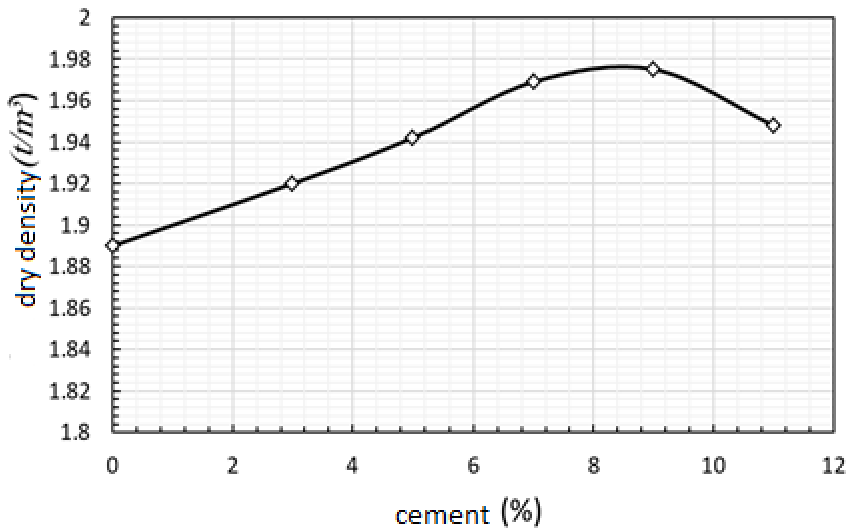



*Figure 4. 49- Variation of the dry density according to the percentage of cement*

The Proctor curves for EXTRA tuff mixed with cement according to the amount in percentages of (3%, 5%, 7%, 9%, 11%) respectively and presented on the (Figure 4.50) has a pointed shape which explains that these percentages are at the same percentage at the moisture content.

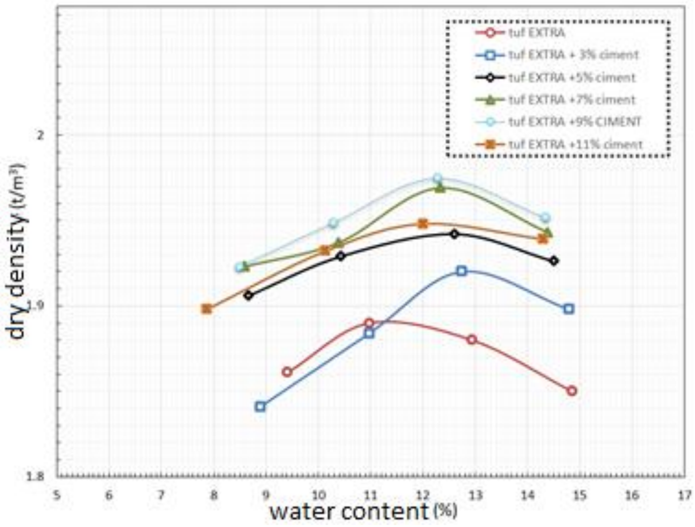



*Figure 4. 50- Proctor Normal Tuff EXTRA with addition of (3%, 5%, 7%, 9%, 11%) cement*

### 4.7.2 Influence of 9% cement addition on extra tuff content on results of: "Soaked and Unsoaked CBR Index"

In order to investigate the performance of stabilized extra tuff with 9% cement inclusion, the results of CBR Index Values (soaked and unsoaked) are presented in Table 4.9 and 4.10 respectively.

*Table 4.9 - Results of soaked CBR Index Values*

| Number of blows | 10 | 25 | 56 |
|---|---|---|---|
| mass of water added at each compaction | 12,26% | 12,26% | 12,26% |
| total wet mass (gr) | 10 090,000 | 10 432,000 | 10 589,000 |
| mass of Mold (gr) | 5 500,000 | 5 500,000 | 5 500,000 |
| mass of wet soil (gr) | 4 590,000 | 4 932,000 | 5 089,000 |
| mass of soil sec (gr) | 4 085,835 | 4 364,820 | 4 504,786 |
| volume of Mold ($cm^3$) | 2 295,000 | 2 295,000 | 2 295,000 |
| wet density (t/m3) | 1,782 | 1,914 | 1,975 |
| dry density ($t/m^3$) | 1,780 | 1,902 | 1,963 |
| Mass tare (gr) | 500,000 | 500,000 | 500,000 |
| wet density+ tare (gr) | 937,000 | 900,000 | 861,500 |
| dry soil mass + tare (gr) | 889,000 | 854,000 | 820,000 |
| mass of water (gr) | 48,000 | 46,000 | 41,500 |
| mass of dry soil (gr) | 389,000 | 354,000 | 320,000 |
| Water content % | 12,339 | 12,994 | 12,969 |
| After immersion | | | |
| tare mass (gr) | 137,000 | 142,000 | 843,000 |
| mass soil humide + tare (gr) | 617,000 | 1 205,000 | 2 100,000 |
| mass soil sec + tare (gr) | 552,500 | 1 057,000 | 1 942,000 |
| Water mass (gr) | 64,500 | 148,000 | 158,000 |

| | | | |
|---|---|---|---|
| mass of dry soil sec (gr) | 415,500 | 915,000 | 1 099,000 |
| water content % | 15,523 | 16,175 | 14,377 |
| Approximative mass du soil imbibe | | | |
| total wet mass after imbibition (gr) | 10178 | 10347 | 10313 |
| total wet mass before imbibition (gr) | 10 090,000 | 10 432,000 | 10 589,000 |
| mass of absorbed water (gr) | 88,000 | -85,000 | -276,000 |
| Difference in water content (%) | 3,184 | 3,181 | 1,408 |
| Approximate mass of Imbibed soil | 4 678,000 | 4 847,000 | 4 813,000 |
| conventional depth of imbibition (mm) | 200 | 200 | 200 |
| Index CBR imbibe | | | |
| Penetration effort at 2.5 mm penetration (kN) | 10,26 | 13,87 | 20,14 |
| Penetration effort at 5 mm penetration (kN) | 15,95 | 21,97 | 30,32 |
| I CBR 1 | 76,85 | 103,90 | 150,86 |
| I CBR 2 | 80,03 | 110,24 | 152,13 |
| CBR Index | 80,03 | 110,24 | 152,13 |

*Table 4.10 - Results of unsoaked CBR Index Values*

| Number of shots | 10 | 25 | 56 |
|---|---|---|---|
| mass of water added at each compaction | 12,26% | 12,26% | 12,26% |
| total wet mass (gr) | 10 000,000 | 10 321,000 | 10 410,000 |
| mass of Mold (gr) | 5 500,000 | 5 500,000 | 5 349,000 |
| mass of humid soil (gr) | 4 500,000 | 4 821,000 | 5 061,000 |
| mass of dry soil (gr) | 4 080,420 | 4 338,900 | 4 503,174 |
| volume of Mold (cm3) | 2 295,000 | 2 295,000 | 2 295,000 |
| wet density(t/m3) | 1,747 | 1,871 | 1,964 |
| dry density (t/m3) | 1,778 | 1,891 | 1,962 |
| tare mass (gr) | 500,000 | 500,000 | 612,000 |
| mass of wet soil + tare (gr) | 929,000 | 900,000 | 861,500 |
| mass of dry soil + tare (gr) | 889,000 | 860,000 | 834,000 |
| mass of water (gr) | 40,000 | 40,000 | 27,500 |
| mass of dry soil (gr) | 389,000 | 360,000 | 222,000 |
| water content% | 10,283 | 11,111 | 12,387 |
| Immediate CBR Index | | | |
| Penetration effort at 2.5 mm penetration (kN) | 6,942 | 10,94 | 16,23 |
| Penetration effort at 5 mm penetration (kN) | 13 | 16,43 | 26 |
| I CBR 1 | 52,00 | 81,95 | 121,57 |
| I CBR 2 | 65,23 | 82,44 | 130,46 |
| Index CBR | 65,23 | 82,44 | 130,46 |

Figure 4.51 shows the effect of the cement treatment on the unsoaked bearing ratio after 4 days of immersion.

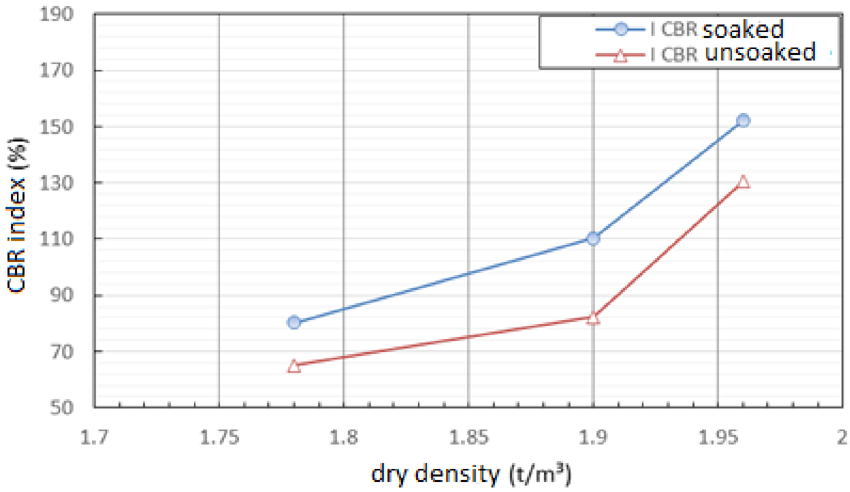



*Figure 4. 51- Variation of the unsoaked CBR index and soaked according to the dry density of EXTRA tuff + 9% cement.*

It is observed that the CBR indices increase with the cement content in both cases, unsoaked and soaked. In addition, the CBR values imbibed at different cement contents have higher values than those immediately present. This can be explained by the fact that the immersion favors the hydration reaction of the cement by analogy with the concrete.

### 4.7.3 Influence of hair content on unconfined compression strength.

Comparing the results of treated tuff EXTRA at different percentages and the control sample and for different cure periods is given on (figure 4.52), this one illustrates the evolution of the simple compression according to the percentage of reinforcement in hair for 7, 14 and 28 days of conservation. The curves obtained show the improvement of the unconfined compression strength with the increase of the percentage of hair up to the percentage 0.5% the resistance begins to fall. This improvement becomes more important when the conservation time is longer in the first percentage (0.5%) and with the percentage of (1%, 1.5%) each time one increases the conservation time it negatively influences the resistance (Table 4.11).

*Table 4.11 - Results of compressive strength of soil treated at different percentages of hair.*

| Curing time (days) | Content of hair % | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 0% | | 0.5% | | 1% | | 1.5% | |
| | F (kN) | σ (MPa) | F (kN) | σ (MPa) | F (kN) | σ (MPa) | F (kN) | σ (MPa) |
| 07 | 2.67 | 0.345 | 2.901 | 0.380 | 2.063 | 0.251 | 1.461 | 0.153 |
| 14 | 5.33 | 0.680 | 5.802 | 0.760 | 4.125 | 0.501 | 3.922 | 0.405 |
| 28 | 6.10 | 0.751 | 6.601 | 0.732 | 5.302 | 0.612 | 2.142 | 0.354 |

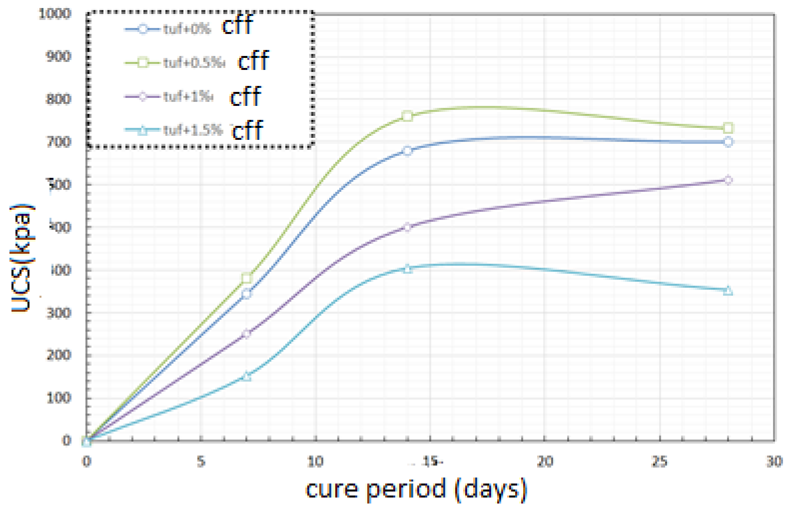



*Figure 4. 52- UCS vs. Hair reinforcement percentages in for 7, 14 and 28 days of cure*

### 4.7.4 Comparison of test results on EXTRA tuff untreated and treated with cement and hair

The comparison of the results of untreated and 9% Cement treated EXTRA tufa and different storage times are given on (Figure 4.53) and this figure illustrates the evolution of simple compression as a function of the percentage of hair addition with cement for 7, 14 and 28 days of storage. The results obtained show the improvement of the simple compression with the increase of the percentage of hair up to the percentage 0.5% the resistance begins to fall. This improvement becomes more important when the conservation time is longer in the first percentages (0.5%) and with the percentage of (1%, 1.5%) their results give decreases by contribution 0.5%. It is noted that the percentage 0.5% is the best.

Soil-cement strength results with different hair percentages under unconfined compression strength are presented in (Table 4.12).

*Table 4.12 - Soil-cement results with hair*

| Days | 0% cheveux+0% cement | | 9% cement | | 9% cement +0.5% hair | | 9% cement +1% hair | | 9% cement +1.5% hair | |
|---|---|---|---|---|---|---|---|---|---|---|
| | F (kN) | σ (MPa) | F (kN) | σ (MPa) | F (kN) | σ (MPa) | F (kN) | σ (MPa) | F (kN) | σ (MPa) |
| 07 | 2.67 | 0.345 | 21.196 | 2.629 | 24.024 | 3.004 | 17.321 | 2.240 | 14.800 | 1.82 |
| 14 | 5.33 | 0.680 | 42.392 | 5.257 | 48.048 | 6.014 | 34.687 | 4.480 | 29.615 | 3.624 |
| 28 | 6.10 | 0.751 | 43.254 | 5.514 | 50.501 | 6.206 | 39.214 | 4.951 | 30.145 | 4.114 |

Results of compressive strength test of stabilized soil with 9% of cement are illustrated in Figure 4.53 as a function of fiber content. It can be seen that there is some enhancement as the volume of the hair inclusion is considered. Thus the UCS strength increases by increasing the

HHF percentage, after the addition of 0.5% of HHF the strength was decreased. The optimum percentage of hair fiber was then fixed as a 0.5% of the soil sample. The observed decline in strength is due to the balling effect of the hair fiber which concentrates in a local zone and causes a weak spot.

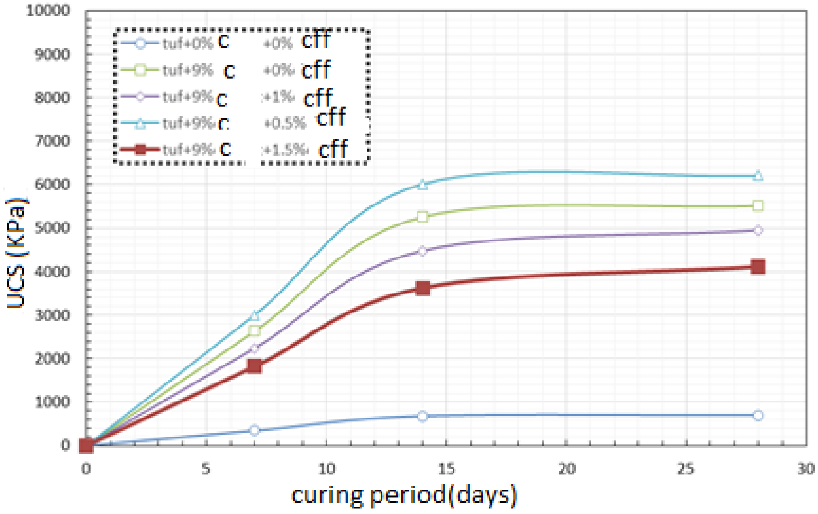



*Figure 4. 53– UCS curves for EXTRA tuff treated with (9% cement) with hair reinforcement percentages (0.5%, 1%, and 1.5%) vs. cure period of 7, 14 and 28 days.*

### 4.7.5 Conclusion

The interpretation and exploitation of the results obtained showed that:

- The compaction curves show strong improvements in the characteristics obtained by adding cement to the tuff than with the tuff alone. So good rigidities for the tuff-cement mixture.
- Immediate and soaked CBR tests show that adding cement up to 9% improves tufa lift. It is therefore concluded that cement tuff is a solution to promote tuff as a substitute for granular products in wadis and seascapes given the improvements in compaction and lift characteristics.
- The mechanical parameters of tuff are clearly influenced by the addition of fibers:
- The addition of fibers to EXTRA tuff has greatly influenced its Compacting characteristics. The increase in the compressive strength of the treated mixtures is well noticed from first preservation time 07 days up to 28 days.
- The addition of the fibers gives an increase of the resistance and ductility of the mixtures according to the percentage of the hair up to 0.5%.
- It was noted that the addition of EXTRA tuff fiber gave us a strong improvement in the simple compressive strength with the extension of shelf life up to 28 days.

# Conclusions

## Conclusions

Influence of human hair fibers, cement, and lime powders on the strength and durability of rammed earth walls were studied in this investigation. The main conclusions to be drawn from the experimental work reported in this dissertation can be summarized as follows:

1. Tests carried out here have established that it is possible to reinforce rammed walls with human hair fibers, lime, cement and a combination of human hair and cement, fly ash or lime. Mixing all the above mentioned ingredients with soil can be recommended as an efficient procedure for processing rammed earth walls repair for vanishing Algerian heritage in southern Algeria where especially human hair, lime and cement used in minimized contents is readily available.
2. The liquid limit and plasticity index of the artificial soil increases with increase in clay content and the increase is more pronounced in Bentonite and sand mixtures and Bentonite, kaolinite and sand mixtures.
3. Maximum dry density decreases and OMC increases with increase in Bentonite, sand and kaolinite, sand mixtures.
4. OMC increases with increase in Bentonite and decreases with the increase in kaolinite in Bentonite, kaolinite and sand mixtures for the same sand content.
5. Peak shear strength increases with increase in the clay content except for 50K50S mix which shows high strength.
6. In the Bentonite, kaolinite and sand mix B10K40S50 shows high strength.
7. Relationship between strength and index properties has been brought out based on the test.
8. For the sandy- clay (10%sand 90% Bentonite) addition of 3% lime increased the UCS by 292% and the treated soil with cement had an increase in UCS of 173% compared to the control soil. Based on these tests, it was noticed that specimens stabilized by lime showed higher failure strain than those stabilized by cement.
9. Addition of 3% of cement and lime increased the maximum dry density. The optimum water content of the sand clay showed an increase (6%) for the treated soil with lime while a decrease (5%) was noticed in treating the soil with cement.
10. For the clayey sand (S50%B50%) by comparing UCS of the different mixtures, it was seen that lime stabilized soils (3%) are 28% higher than the untreated soil. The addition of 3% cement showed an improvement of 102% in UCS compared to the control soil. Soils stabilized with cement had a higher failure strain (10%) compared to the soil treated with lime. Lime or cement had slight effect on the compaction properties (dry density and moisture content).
11. For the sandy clay soil (S90%B10%), addition of 3% lime to the soil improved the UCS by 102% compared to the untreated soil, while the failure strain increased by 47%. For this group of combination, soil treated with 3% cement had no effect on the control soil.
12. The addition of 3% of cement and lime reduced the maximum dry density by10% and 7% respectively, while the optimum water content decreased by 23% and 21% respectively for the sand clay.

13. Cement treated soils showed the highest strength and lowest plasticity. Dry density increased compared to the control soil. The water content decreased in all mixtures except for the sample treated with Bentonite.
14. The material dry density was obtained for the first mixture S80%B20% (which comprises 80% of sand and 20% of Bentonite). It decreases with the increase of the amount of Bentonite.
15. Compressive strength is maximum for the mixture S50% B50%.
16. The lowest modulus of elasticity is obtained with the use of optimum amount of Bentonite.
17. Energy is optimum for the mix S50%B50%.

**The use of engine oil:**

18. Improved $\gamma_{dry}$.
19. Decreased the strength.
20. Decreased cohesion of high plasticity clay.
21. The replacement of Bentonite by cement or fly ash improved $\gamma_{dry}$.
22. The compaction curves show strong improvements in the characteristics obtained by adding cement to the tuff than with the tuff alone. So good rigidities for the tuff-cement mixture.
23. Immediate and soaked CBR tests show that adding cement up to 9% improves tufa lift. It is therefore concluded that cement tuff is a solution to promote tuff as a substitute for granular products in wadis and seascapes given the improvements in compaction and lift characteristics.
24. The mechanical parameters of tuff are clearly influenced by the addition of fibers.
25. The addiction of fibers to EXTRA tuff has greatly influenced its Compacting characteristics. The increase in the compressive strength of the treated mixtures is well.
26. Noticed from first preservation time 07 days up to 28 days.
27. The addition of the fibers gives an increase of the resistance and ductility of the mixtures according to the percentage of the hair up to 0.5%.
28. It was noted that the addition of EXTRA tuff fiber gave us a strong improvement in the simple compressive strength with the extension of shelf life up to 28 days.

**Recommendations for futures work**

Since cement is a potential polluter, then it’s time to think about its replacement and develop other environmentally friendly cementitious products that is why our next interest is focused on:

- ❖ Development of a bio-adhesive (binder) based on agro-industrial waste for the improvement of problematic soils.
- ❖ Development of an ecological cementitious binder based on biochars from plant biomass waste.

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