Evaluation of the Structural Characteristics of Cement and Fly Ash Stabilized Desert Sand

by

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Évaluation des caractéristiques structurales des fondations en sable du désert, stabilisées au ciment et aux cendres volantes

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RÉSUMÉ

L'amélioration voire la stabilisation des sols sont des processus qui consistent à modifier leurs caractéristiques physiques pour améliorer leur rhéologie, et particulièrement leur résistance au cisaillement. Ces processus sont bénéfiques lorsque les sols disponibles à proximité de l'alignement de la route à construire, ne peuvent pas soutenir le trafic projeté. Que seule la couche de fondation ou la couche de sous-fondation soit améliorée ou stabilisée, ou bien les deux, la capacité portante de l'ensemble de la chaussée en est augmentée. Ceci constitue en soi une plus-value technique par l'accroissement de la portance, économique par la réduction des coûts et environnementale par la réduction de la pollution associée.

Il est par ailleurs bien établi que le sable naturel du désert (SND) dit sable des dunes, n'est pas adapté à la construction. Sculpté par le vent, il est composé de particules fines, arrondies et lisses qui s'enchevêtrent difficilement, le rendant physiquement instable sous chargement vertical, et prône à une rupture par cisaillement. Le SND n'a ni la taille ni l'angularité requises des granulats concassés (GC) mécaniquement, auxquels on a couramment recours pour la construction de nouvelles chaussées. En effet, les GC créent un maillage entrecroisé, résultant en un squelette de granulats imbriqués, plus robuste. Force est donc d'admettre que les fondations ou les sous-fondations à base de SND ne fournissent pas un support adéquat pour les routes, même à faible trafic, en comparaison avec celles qui sont construites avec des GC. C'est à cause de cela, que des GC doivent souvent être transportés sur de longues distances, voire importés par camion ou par barges dans la majorité des pays d'Afrique tels que le Sénégal, le Mali, le Bénin, le Tchad, la Côte d'Ivoire, l'Algérie et la Libye.

Largement disponible partout sur la planète, le Ciment Portland Ordinaire (CPO) est utilisé depuis de nombreuses décennies, en petites quantités, pour améliorer le comportement des sols en compression. On parle alors d'amélioration. Avec plus de CPO, on peut même stabiliser les sols en augmentant également leur comportement en flexion, en leur conférant une plus grande rigidité, auquel cas on parle plutôt de stabilisation.

En sus du recours au CPO, le recours aussi, *dans des proportions raisonnables*, à du SND, moins cher et accessible, *car adjacent au tracé prévu de la route*, est d'intérêt pour réduire les quantités rares de sable manufacturé à obtenir par concassage et à transporter, qui ne sont alors utilisés que pour améliorer la granulométrie du SND. Dans l'esprit du développement durable, cette thèse contribuerait à réduire le gaspillage de précieuses ressources en roches de carrière, qui auraient autrement fourni la taille et l'angularité nécessaires.

C’est dans cet esprit que cette thèse examine l'amélioration *(comportement flexible en **compression**)* voire la stabilisation *(comportement rigide en **flexion**)* des SND avec du CPO, avec et sans le recours aux cendres volantes (CV), pour utilisation à titre de fondations dans les routes à faible débit de trafic dans les régions désertiques et sujettes à de lourdes charges. En augmentant donc avec ces liants, la résistance à la déformation de la couche de fondation ou de la sous-fondation, l'épaisseur de la couche d’enrobé bitumineux sera considérablement diminuée. Ceci est dû au support beaucoup plus rigide, résultant en une contrainte en traction significativement réduite à la base de la couche de l’enrobé, et une contrainte en compression également beaucoup plus faible, au haut de la sous-fondation et de la plateforme, réduisant de facto la sollicitation sur le sol et augmentant la durée de la vie structurale de la route et le coût environnemental sur le cycle de vie. L’intérêt de stabiliser également la sous-fondation, pour accroître la durée de vie structurale, est également évalué dans cette thèse afin de promouvoir des routes plus résistantes et donc plus durables lorsque fortement sollicitées.

Pour apprécier l'augmentation de la portance des sols par l'ajout de CPO, avec ou sans CV, plusieurs essais sont réalisés, soit des essais de compactage, de résistance à la compression (f'_{c}), de résistance à la déformation (CBR), de perméabilité et d’essais triaxiaux.

Ces essais ont été effectués sur un nombre d’échantillons adéquatement proportionné afin de tirer des conclusions et des recommandations utiles pour un dimensionnement structural visant une optimisation économique sur le cycle de vie.

Il découle des essais et des analyses entreprises dans cette recherche que les modifications des propriétés physiques de la fondation, *voire de la sous-fondation*, affectent de manière appréciable leur comportement mécanique selon la teneur de SND vs GC d’une part et de la teneur de CPO et de CV d’autre part, et par ricochet l’optimisation de la conception structurale de la chaussée aux niveaux à la fois économique et environnemental.

Il ressort aussi que la composition finale optimale avec un sable naturel du désert (SND), provenant de la Libye, dépend du dosage de trois facteurs: le rapport entre le SND et les GC, le type de liant (CPO et/ou CV), et le rapport eau / ciment, et que cette composition affecte de façon significative le comportement mécanique de la chaussée qui en est constituée. En effet, les échantillons ont été mélangés avec deux ratios différents d'agrégats (50:50 GC:SND et 30:70 GC:SND). Chaque échantillon a été mélangé respectivement avec quatre différents pourcentages de CPO (0 % témoin, 3 %, 5 % et 7 %) et quatre pourcentages différents de CV (0% témoin, 3%, 5% et 7%) pour un total de 32 échantillons testés. Les résultats expérimentaux montrent que le mélange optimal pour un SND Libyen et la granulométrie des GC utilisée pour articuler le squelette granulaire, est composé de 30:70 GC:SND, avec une teneur optimale en liant de 7 % de CPO et de 7 % de CV.

Une analyse économique est effectuée pour différents pourcentages de ciment et de combinaisons de ciment et de cendres volantes. Malgré les quantités importantes de liant, le recours au SND aisément accessible, se traduit à la fois par une consommation moindre en ressources non renouvelables, par une moindre consommation en énergie d’extraction et de concassage et surtout, par moins de transport sur de longues distances, et donc des avantages

sociaux et environnementaux liés à la réduction du bruit, des émissions polluantes et des poussières. On observe également des avantages économiques liés à la réduction des coûts sur le cycle de vie pour l'administration routière et pour les usagers, à cause de la résistance accrue de la chaussée, ce qui en prolonge la durée de vie, améliore la performance et par ricochet maintient les coûts d'exploitation des véhicules plus bas.

En résumé, l'amélioration au ciment et aux cendres volantes, en augmentant la résistance de la chaussée, diminue les épaisseurs de l'enrobé bitumineux, de la fondation et de la sous-fondation ainsi que les coûts de construction, d'entretien et de réhabilitation subséquents et les coûts d'exploitation des véhicules.

Cette thèse s'inscrit dans l'esprit des accords de Paris, dans leur portée mondiale, et reconnaît que les perspectives de développement durable en infrastructures, exigent un équilibre entre l'économie, le social et l'environnement. Il en ressort un transfert vers le Sud d'un savoir-faire qui repose sur une démarche scientifique saine. Cette thèse fournit une démonstration de la pratique d'une ingénierie civile durable en conception lorsque les bons matériaux de construction sont rares, une réalité en Afrique du Nord (région du Sahara) dans le cadre de laquelle cette recherche est établie, mais aussi en Afrique Sub-Saharienne.

Elle propose une méthodologie permettant d'utiliser des matériaux de mauvaise qualité pour construire des routes durables. En effet, ce n'est pas tant les proportions trouvées dans la présente qui en sont la contribution, mais la démarche suivie pour trouver cette combinaison, laquelle pourrait être appliquée pour chaque projet d'envergure.

Enfin, cette thèse contribue à mettre en évidence la rentabilité de l'amélioration du sable naturel du désert, en réduisant la quantité de matériaux nouveaux et importés ainsi qu'en optimisant l'épaisseur de la couche d'enrobé bitumineux.

Mots-clés: Sable naturel du désert, Ciment Portland Ordinaire, Amélioration au ciment, Stabilisation au ciment, Cendres volantes, Essais de compactage, Résistance en compression, Résistance structurale, Développement durable.

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ABSTRACT

Soil improvement or stabilization is a process of altering the physical characteristics of soils to improve their rheology, namely their shear strength characteristics. This process is beneficial when the readily available soils for road construction, is unable to withstand the projected traffic loads. Whether the improvement or stabilization focuses on the base layer or the subbase layer, or both, the bearing capacity of the whole pavement is increased, which results in meaningful technical due to added strength, economic due to reduced costs and environmental consequences because of lesser transport associated pollution.

It is well documented that Natural Desert Sand (NDS) referred to as dune sand is unfit for road construction. NDS is made up of fine and rounded particles, and therefore, it lacks the coarseness and angularity found in mechanically controlled and Crushed Fine Aggregate (CFA) that inherently creates an interlocking mesh, resulting in a stronger aggregate skeleton.

As a result, bases or subbases made of NDS do not provide adequate support for even low-volume roads, compared to bases or subbases made of CFA. Therefore, adequate road construction material needs to be hauled, imported and even shipped over long distances in African countries like Senegal, Mali, Benin, Chad, Cote d'Ivoire, Algeria and Libya.

Ordinary Portland Cement (OPC) has however been used for many decades in small quantities to **improve** soils performance in compression, or in larger quantities to **stabilize** and increase flexural strength by increasing the rigidity of the soils.

In addition to the recourse to OPC, recourse in reasonable quantities to cheaper and readily available NDS, *adjacent to the projected road alignment*, saves on extracting, crushing, importing and hauling or shipping over long distances, good quality materials. This ultimately saves valuable and scarce aggregate resources which would have otherwise provided the needed coarseness and angularity.

This thesis investigates the improvement *(flexible behaviour of the pavement in* ***compression****)* and even the stabilization (*rigid behaviour of the pavement in* ***flexure****)* of NDS with OPC and with a combination of OPC-fly ash (FA), for bases and subbases of low-volume roads crossing desert land and subject to overloaded trucks. By increasing the base and subbase strength with these cementitious binders, the thickness of the asphalt concrete (AC), base and subbase layers can be substantially reduced. This is due to the stiffer support, resulting in lower tensile strain at the bottom of the AC layer, and lower compression strain at the top of the subbase and the

subgrade, thereby reducing the effect on the native soil, the result of which is an increased structural life of the pavement and a reduced environmental life cycle cost.

The value of also improving or stabilizing the subbase, to increase the structural life is equally investigated in this thesis, in order to promote more sustainable roads.

To assess the increase in structural characteristics of stabilized soils for use as base and/or subbase layers with the addition of OPC and OPC-FA, several tests were performed such as compaction, unconfined compressive strength (UCS), resistance to deformation (CBR), permeability, and triaxial tests.

These tests were adequately proportioned and repeated on different samples in order to show how to draw relevant conclusions and recommendations leading to the least cost structural design, in economic and environmental terms.

The findings for instance with Libyan dune sand (NDS) are such that changes in the physical properties of the base or subbase, significantly affect their mechanical behavior. It is found that the optimal composition depends on three factors: the ratio of NDS and CFA, the type of stabilizer (OPC and/or FA), and the water / cement ratio.

Samples were mixed with two different ratios of aggregates (50:50 CFA: NDS and 30:70 CFA: NDS). Each sample was respectively mixed with the four different percentages of OPC (0% control, 3%, 5%, and 7%) and four different percentages of FA (0% control, 3%, 5%, and 7%) for a total of 32 samples tested.

The result show that the optimal mix would be composed of 30:70 CFA: NDS for the aggregate portions, with an optimal binder content of 7% of OPC and 7 % of FA. An economic analysis is performed for various percentages of cement and combinations of cement and fly ash. It is shown that despite high binder contents, the recourse to locally available NDS results in lesser consumption of non-renewable resources, lesser extraction, crushing and transport associated energy consumption and therefore, in social and environmental benefits from reduced noise, lower pollution emission and dust due to hauling. Additional and meaningful economic benefits also stem from reduced life cycle costs to the agency and also to the users, as a result of the increased structural capacity and therefore improved pavement performance.

In summary, cement and/or fly ash stabilization, whilst increasing the pavement strength, reduces the asphalt concrete, base and subbase thicknesses and associated construction and future maintenance costs.

This is in line with sustainable development objectives of the Paris Agreements, and their world reach, which require a balance between the economic, the social and the environmental aspects, and capacity building in Southern countries based on sound engineering principles.

In a strategic perspective, this research is in line with the above stated sustainable development objectives and is a demonstration on how to practice sustainable engineering in today’s civil engineering design in areas where good construction materials are scarce, a harsh reality in Northern Africa (Sahara) whereby the approach is validated, but also, albeit to a lesser extent, in Sub-Saharan Africa (SSA).

In an empirical and practical perspective, this research provides a methodology to use poor material to build sustainable roads by substantially reducing hauling over long distances and saving scarce and good quality materials. In fact, it is not so much the proportions found hereafter that are important but the methodology by which these findings are obtained. It is therefore hoped that this methodology is conducted as part of the preliminary design of projects of magnitude in areas suffering from scarce materials, as is too common in Africa.

Another contribution of this thesis is to highlight the cost-effectiveness of desert sand improvement or stabilization, by reducing the amount of new and imported material and optimizing the thickness of the asphalt concrete course.

Keywords: Desert sand, Ordinary Portland Cement, Cement improvement, Cement stabilization, Fly ash, Compaction Tests, Compressive Strength, Triaxial tests, Structural Strength, Sustainable Development.

TABLE OF CONTENT

Page

LIST OF TABLES

Page

LIST OF FIGURES

Page

LIST OF SYMBOLS AND UNITS OF MEASUREMENTS

NDS	Natural Desert Sand
CFA	Crushed Fine aggregate
OPC	Ordinary Portland Cement
FA	Fly Ash
DSC	Desert Sand Concrete
DC	Direct Current
SSIS	Soil Stabilization Index System
PCA	Portland Concrete Association
ASTM	American Society for Testing and Materials
AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt Concrete
A	Cross section of specimen
CBR	California Bearing Ratio
CP	Collapse Potential
HMA	Hot Mix Asphalt
H	High
LL	liquid limit
L	Low
LOI	Loss on Ignition
LCMB	Pavement and Bituminous Materials Laboratory
LVRs	Low Volume Roads

PI	Plasticity Index
UCS	Unconfined Compressive Strength
CAH	Calcium Aluminate Hydrate
CSH	Calcium Silicate Hydrate
C3S	Tricalcium Silicate
C_2S	Dicalcium Silicate
CO_2	Carbon dioxide
CaO	Quicklime
SC	Soil Cement
MDD	Maximum Dry Density
OMC	Optimum Moisture Content
USCS	Unified Soil Classification System
GW	Well-graded Gravel
SP	Poorly graded Sand
Cu	Coefficient of Uniformity
Cc	Coefficient of Curvature
XRF	X-Ray Fluorescence
μ	Poisson's Ratio
Ø°	Friction Angle
C	Cohesion
SCM	Supplementary Cementitious Materials

EWL	Equivalent Wheel Load
RRC	Roller-compacted concrete
SSF	Sub-Saharan Africa
GBS	Granular Base Stabilisation
CMS	Cement-modified soils
SSA	Sub-Saharan Africa
G_s	Specific gravity
KN	Kilo Newton
KPa	Kilo Pascal
mm	Millimeter
MPa	Mega Pascal
K	Hydraulic conductivity
Mr	Modulus of Resilient
ε_t	Horizontal tensile strain at the bottom of asphalt layer
N_f	Number of load applications to failure
E	Elastic Modulus of asphalt concrete

INTRODUCTION

Economic development in any country partially depends on the quality of an expensive to construct and maintain, and an environmentally challenging road network, considering the substantial earthly resources at stake, and equally substantial vehicle transportation footprint. As the economy grows, roads experience higher volumes of traffic and heavier axle loads. Road networks then deteriorate and need to be upgraded at equally high costs (Wu, Molenaar, and Houben 2011). Otherwise, users will have to pay exponentially higher vehicle operating costs because of pavement distress such as potholes, which in turn result in more pollution. To reduce these costs, asphalt roads subject to heavy loads require strong base layers so that the entire road structure performs well and can provide good service for many years, delaying the need for rehabilitation. New roadwork projects have many constraints: they need to be cost-effective to build, resistant to natural disasters such as strong desert winds or flooding, and use techniques and materials that minimize environmental impacts, such as recourse to readily available materials, adjacent to the road alignment.

While there are many types of aggregates or soils that can be used for road base construction, each type comes with its own compromise. For example, some are susceptible to environmental factors, such as wet-dry cycles, and others have a low-bearing capacity; both these outcomes lead to pavement distresses and ultimately shorten service life. Nonetheless, soil strength characteristics can be improved by adding improving or stabilizing agents, *e.g., bitumen, lime, fly ash, and cement*. Soils that are bound with cement, gain strength, durability and stiffness, and can result in increased years of good performance. Nearly any mix of gravel, silt, sand, or crushed aggregate can be improved or stabilized. As such, cement can be used to transform some poor soils into better quality base or subbase layers (Hein et al. 2017).

Due to the scarcity of good aggregates in many regions of the world, the financial and ecological cost of hauling crushed fine aggregate (CFA) from quarries, over long distances have important economic and environmental impacts on projects in remote areas. For instance, in the desert areas of southern Libya, quality materials are not locally available. A practical solution to this problem is to optimally upgrade the readily available materials so that they can be used to build low-cost lasting roads, resistant to overloaded trucks. The stability of these materials can be improved through cementitious admixtures (Yoder and Witczak 1991). Broadly, soils can be improved or stabilized to increase the compressive or flexural strength, waterproofing, and durability of subsequent mixes. Additionally, stabilizing admixtures improve cohesion, which itself leads to an overall drop in project costs (Xuan et al. 2012).

The success of these initiatives has often depended on the chemical qualities of the soil, particularly as these affect the performance of the binder. The selection of the proper binder proportion is critical in projects involving the construction of a base and a subbase, whereby substantial amounts of materials are needed. It is also well established that the properties of NDS can be made better using Ordinary Portland Cement (OPC) or in combination with fly ash (FA) (Kasim et al. 2015).

Stabilization is achieved through several methods. All these methods fall into two broad categories namely; mechanical and chemical (Makusa 2012). Stabilization with mechanical means is done through compaction and most importantly the blending of more than one coarser soil to obtain the targeted gradation; this improves the soil's bearing capacity and reduces its plasticity (Melese 2014). The physical characteristics of the soil particles themselves can be changed by means of induced vibration or compaction; how they perform can also be affected through the use of techniques such as barriers and nailing (Makusa 2013). Chemical improvement in compression, or stabilization in flexure, results from the addition of chemical binders, e.g., OPC, FA, or both; as these affect the granular properties as well as the cementation characteristics of the soil, resulting in a bound material that has a more rigidly structured characteristic (Firoozi et al. 2017).

Road pavement behaviour in the long-term is, in part, a function of the stability of both the base and subbase layers. The base and subbase layers need to have adequate resistance to shear and compression stresses because these can cause rutting because of either shear failure of the asphalt (*asphalt going sideways*) exacerbated by poor support, or rupture in compression and settlement of the base and/or subbase layers. Fatigue cracking due to excessive fatigue cumulated vertical deformations and rupture in tension at the bottom of the asphalt concrete is often due to a poor base support (Yoder and Witczak 1991).

Readily available soil materials, adjacent to a road construction alignment, are not necessarily adequate to withstand the above referenced failure mechanisms. They can however be substantially upgraded with improvement or stabilization in order to perform adequately (Mahvash, López-Querol, and Bahadori-Jahromi 2018). As such, cement-treated soils, with or without FA, can improve the structural performance by addressing the structural failure mechanisms common with poor soil materials.

Lower cement contents result in an improvement of the resistance to compression. The material behaves like a granular material, works in compression and does not deflect. It remains rather loose although its modulus of rigidity is increased. Higher cement content results in stabilization of the material and a resistance to flexural moments. The material behaves like a bound layer and works in flexure and therefore deflects (Racine 2018).

Base and subbase layers of pavements constructed in desert areas also require angular and coarse aggregates. Because NDS consists of rather fine and rounded particles, the concept is to amend them with the addition of angular and coarse particles that create stability in these base and subbase layers. Thus, the partial use of locally available NDS, combined with a lesser proportion of CFA and improving or stabilizing it with OPC and possibly FA is a way to construct using low-quality aggregate sources in desert area.

CHAPTER 1

RESEARCH FOCUS AND OBJECTIVES

1.1 Problem Statement

Approximately on third of the earth's land surface is a desert, characterized with little precipitations and heavy winds. Deserts are often covered with NDS, inappropriate for road construction because of its fineness, roundness and little natural cohesion between the grains. This is exacerbated by heavy blowing winds that keep eliminating the angularity of the sand grains, thereby reducing the friction between them, which ultimately results in poor shear strength. NDS therefore needs treatment before it can be used in road construction. In desert areas, the cost of construction materials is a critical issue because traffic volumes are usually low but very heavy, and distances substantial. Therefore, rehabilitating poorly fit NDS for road construction and reducing the thickness of the asphalt concrete, the base and the subbase layers result in substantial savings.

The methodology, which is the main contribution of this thesis, shows how NDS can be optimally utilized so that it is both suitable for use in base and subbase courses, and minimizes the thickness of the asphalt concrete surface with two measures: (1) adding quarry manufactured sand and (2) adding OPC with and without FA.

The research is empirical and involves laboratory testing of materials obtained from the South of Libya, in the area around the city of Sabha. In desert areas, quality construction materials are becoming rare, if available at all, especially for all-weather roads where traffic volumes are low (less than about 300-500 vehicles per day) but are often heavily overloaded. The climate in those countries, in and around the Saharan Desert, is subtropical, warm, or hot and dry. In most these countries, it is a challenge to find suitable rock sources for the construction of road base layers within a reasonable hauling distance that is economically viable.

In addition, newly constructed asphalt pavements in deserts, have, to date, shown poor performance with substantial distress in their first few years of operation. This is due to heavily overloaded trucks seeking to reduce the cost of transport over those long distances, and the lack of weight stations and subsequent enforcement of axle-load limits.

The aim of this research is to develop means to adapt locally available materials, so that they may be used for road construction, and at the same time reduce the thickness of the AC to obtain a strong and low-cost road.

1.2 Scope and objectives

The focus of this study is to improve the bearing capacity of pavement base and sub-base courses to prevent the aforementioned distress, **by using as much NDS as possible**, thereby reducing the need for good quality aggregates and **reducing the thickness of the AC** cover as a result of the increased support provided by the added binder.

The outcomes of this study are: (1) to reduce agency construction and periodic maintenance costs, (2) to increase the bearing capacity of soils, (3) to reduce road vehicle user costs resulting from better road performance, and equally important (4) to protect the environment by using freely available local materials, adjacent to the alignment or constructions site.

This thesis demonstrates how to investigate the effects of quarry manufactured sand, cement and fly ash proportions added to NDS, to optimize the compromise between pavement bearing capacity and total costs of the base, subbase and asphalt concrete, the latter benefiting from a stiffer support.

The result is an assessment of the potential improvement in base and subbase strength and decrease in the cost of pavement materials by combining these stabilizers with CFA and NDS.

The specific objectives of this research are:

1. To develop a technically-sound approach to reduce as much as possible, the need for CFA and maximize the recourse to locally available NDS in the construction of the base and subbase courses of desert roads; and,
2. To investigate the improvement of the engineering properties of optimal NDS: CFA mixtures found under Objective 1, by adding an optimal content of OPC and FA and to demonstrate the technical and economic benefits thereof.

1.3 Research Methodology

1.3.1 Introduction

This research provides a methodology to use a maximum content of poor road construction materials adjacent to the site, to build technically strong, economically optimized and environmentally sustainable roads. The former is obtained with conventional road engineering tests and analysis. The second and third are obtained by substantially reducing the need for quarry aggregates or quarry manufactured sand, and their hauling over long distances, thereby diminishing costs, delays and nuisances in construction due to transport. An increasingly important, if not critical requirement in road construction in Canada and around the globe, is to minimize environmental impacts, including the use of non-renewable resources and replacing them with more energy-efficient solutions with minimal disturbances to the natural environment. One intuitive application is to use existing materials across the projected road alignment, either directly or by amending their characteristics.

Most countries in the northern to mid portion of Africa are part of the Sahara Desert where daytime surface temperatures range from 30^{o} to 50^{o} C. There is an abundance of round-shaped sand but there is no local natural source of angular aggregate for road building; an aggregate of gravel and crushed sand that transmits forces because of the interlocked skeleton.

Rounded sand does not satisfy generally accepted industry requirements for use as a pavement material in its untreated state. In standard base course layer construction, mechanically crushed sand provides an angular grain that resists compaction because the particles naturally imbricate with each other. The problem with naturally occurring sand is that it has a rounded grain. Roads built from sand with this rounded grain develop premature rutting because the particles do not interlock with each other. Although a road using only sand as an aggregate will only ever be suitable for Low Volume Roads (LVRs), a better understanding of how to integrate and process the naturally found sand will save a great deal of time and money. Beside the fact that desert sand is freely available, there is a need to develop a design system for roads that would account for load, materials, and climate to produce mixtures with more stability and durability.

The framework in Figure 1.1 briefly illustrates the main steps undertaken as part of the experimental program. Materials used in this research were aggregates (NDS and CFA), OPC, and FA in order to evaluate the behavior and the performance of these mixes. All mixes were prepared in accordance with the standard specifications for road construction published by the American Society for Testing and Materials (ASTM) and the American Association of State Highway and Transportation Officials (AASHTO). These standards were followed by testing performed in the laboratory, using materials aimed at fulfilling the conditions for road work construction in hot and arid environments.

1.3.2 Laboratory Tests for Mix Design

The laboratory work consisted of two phases of tests with the first tests performed prior to mixing and second phase being tests done on prepared specimens. Sieve analysis tests were conducted during the first phase; these determined the specific gravity of the aggregates (NDS and CFA). The NDS aggregate brought from Libya was sieved to separate the aggregate into different sizes for later use. Washed sieve analysis was performed to determine the percentage of dust and silt-clay material in order to check the need for filler material. Also, the physical and chemical properties for OPC and FA were evaluated.

The second phase involved the mix design. The sample preparation incorporated the mix, by taking into account the degree of compaction, the curing time and the optimum water content of each material. The tests were performed on two fine aggregates stabilized with OPC and FA as follows: compaction, unconfined compressive strength (UCS), resistance to deformation (CBR), permeability, and triaxial tests.

The laboratory tests methods are described in detail in the methodology section of the published articles, which are presented in Chapters 3, 4, and 5. All tests were performed in the Pavement and Mechanics Laboratory at the *École de Technologie Supérieure (ETS), Université du Québec.*

By comparing the results obtained from different experiments and evaluating the effects of various percentages of additives in the tests, conclusions were drawn about the effects of OPC and FA on the soil properties. A subsequent structural design analysis was performed to assess the reduction in asphalt concrete thickness resulting from the stabilization process.

The conclusions showed that, depending on the required parameters, either OPC, with or without fly ash, could be used for soil improvement or stabilization.

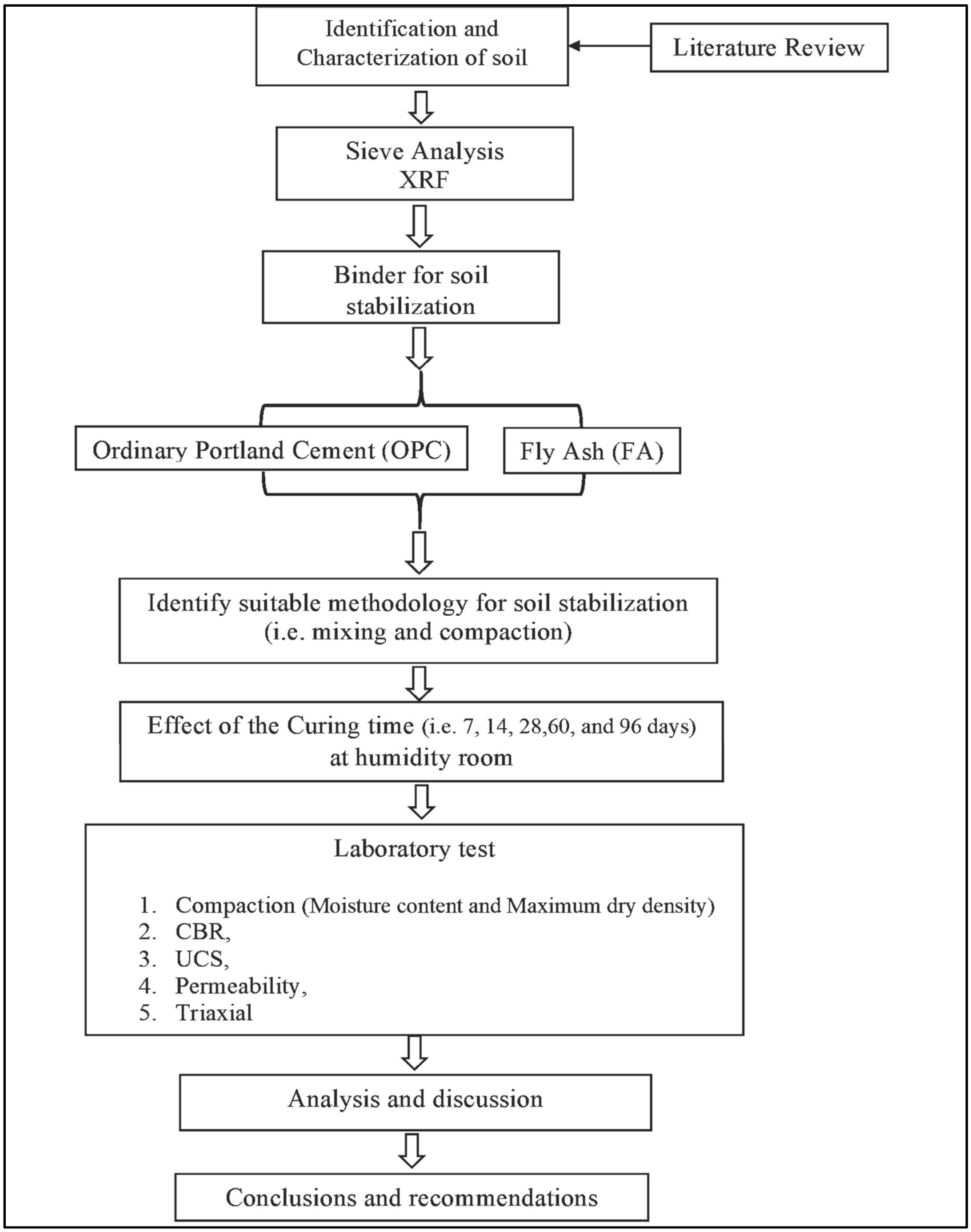

Figure 1.1 General Framework of the Experimental Research

1.4 Dissertation Overview

This Ph.D. thesis is manuscript based, with most chapters already published or submitted as independent journal papers. The outline of the dissertation is as described below, followed by an overall discussion and conclusion.

Chapter 1- Introduces the thesis, namely the overview, the outline of the research problem, the aim and objectives, the significance of the contribution and the research methodology.

Chapter 2- Summarizes the relevant literature review, namely a synthesis of the literature deemed valuable to the conduct of this research.

Chapter 3- Provides the first article titled "Assessment of Strength Development of Cemented Desert Soils", published in the International Journal of Low-Carbon Technologies (IJLCT), Oxford University Press. This paper compares different proportions of NDS and concludes that the maximum possible **NDS proportion is 70% with 7% cement** based on CBR and UCS tests.

Chapter 4- Provides the second article titled "Strength and Permeability Potentials of Cement Modified Desert Sand for Road Construction Purpose", published in the Journal of Innovative Infrastructure Solutions, Springer. This paper verifies the previous findings with the conduct of additional permeability tests and triaxial tests to estimate the modulus of the improved or stabilized material for **pavement design optimization** of the asphalt concrete.

Chapter 5- Provides the third submitted article titled "Improvement of Pavement Subgrade by Adding Cement and Fly Ash to Natural Desert Sand" published in the Journal of Infrastructure, MDPI. This paper justifies the advantages to add fly ash (*waste material*) to **reduce the amount of OPC to only 5%**.

Appendixes I and II are additional relevant conference papers.

1.5 Research Significance and Contribution

As described in the next literature review chapter, multiple researchers have tackled the addition of OPC with and without FA to sand, with limited work on improving or stabilizing round and fine desert sand and with poor results.

No work has considered the mixture of quarry manufactured aggregate and natural desert sand, with the combined interaction effect of OPC, with and without FA, or demonstrated the methodology to conduct such work.

This research establishes with success, that improving or stabilizing desert sand with OPC can be a cost-effective solution, if only 30% of CFA is also added.

This finding is supported with structural strength, permeability and triaxial tests.

In addition, the resulting increase in the modulus of rigidity of the stabilized base and subbase layers is assessed and the reduction of the asphalt concrete layer is also calculated with a mechanistic pavement design method.

This research provides a methodology to conduct such an investigation and how new knowledge on how low-grade desert sand, unfit for construction, **if improved or stabilized on a stand-alone basis or amended with a coarser aggregate**, can be used in the construction of roads in remote desert areas.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

2.1 Introduction

Pavement base layers made of aggregates, support the loads applied on the surface of the asphalt concrete layer and transfer these loads to the granular subbase underneath. Therefore, the base course constitutes an important component that provides stability and performance. In turn, the performance of the base course depends on the properties and characteristics of the constitutive particles and their interaction (Titi et al. 2018).

Documented relevant particle properties, include size, shape, texture, angularity, durability, specific gravity, absorption, toughness, and mineralogical composition. Relevant properties of the confined granular base course include shear strength, stiffness, density, resistance to permanent deformation and permeability (Saeed, Hall Jr, and Barker 2001).

Natural desert sand (NDS), also known as dune sand, is defined as a low-grade fine and round-shaped aggregate soil that contains small quantities of silt. NDS creates a structure that is prone to instability and collapse when moisture is introduced or force is exerted; therefore, it is not considered suitable for road construction (Mohamedzein, Al-Aghbari, and Taha 2006).

To improve the engineering properties of NDS, and similar low-grade soils, it must be treated with stabilizers. Among the techniques used to improve or stabilize NDS are coal fly ash, bentonite, cement, cement-by-pass dust, and fibers (Kaniraj and Havanagi 2001; Karimi et al. 2011). The factors that contribute to effective improvement or stabilization include: (i) properties, kind, and amount of stabilizing agent; (ii) projected application means of the agent; (iii) technique of mixing and incorporating the agent in the field (Mohamedzein and Al-Aghbari 2012).

NDS has been used in desert areas for budgetary reasons, because it is freely available and higher-grade aggregates would have to be shipped long distances, adding to the cost of construction but with poor to very poor results.

All techniques for soil modification or stabilization have the objective of improving a soil's physical or chemical properties so that it might be used for a specific engineering task. Soil modification usually refers to the modification of a soil's gradation, consistency, or swelling properties immediately prior or following mixing (Little and Nair 2009). In contrast, soil stabilization pertains to substantial improvements in a soil's strength because of long-term chemical reactions between the stabilizing agent and the soil. Generally, stabilization is an improvement in the soil by mixing an agent into the target soil that will change its chemical or mechanical nature such that it could be used as a component in a road's base or subbase layer (Rahman, Freer-Hewish, and Ghataora 2008). Also, two soils can be mixed to achieve this desired characteristics of commercially available additives in order to alter the texture, plasticity, or gradation of the soil or else function as a soil binder (Little and Nair 2009). As such, stabilized and modified soils can be achieved through various means but, generally, these are all based on the inherent strength of the treated soils.

2.2 Engineering Properties of Sand

The collapse potential (CP) of soils is a central issue with regards to NDS. NDS, unlike manufactured fine aggregate (MFA), has rounded edges and therefore there is very little capacity to naturally interlock; nonetheless, they may still have an open structure with a high air void percentage because of the tendency to form iron oxide, clay, and hydroxide bridges between the aggregate particles. On the other hand, if the soil becomes wet, the iron oxide, clay, and hydroxide bridges holding the structure together start to break down. As shown in Figure 2.1, loads above a threshold limit will cause those bridges to break down, whereupon the structure loses as much as 20% of its volume. In areas that are subject to flooding, the effect on the pavement is immediate (Brink 1985).

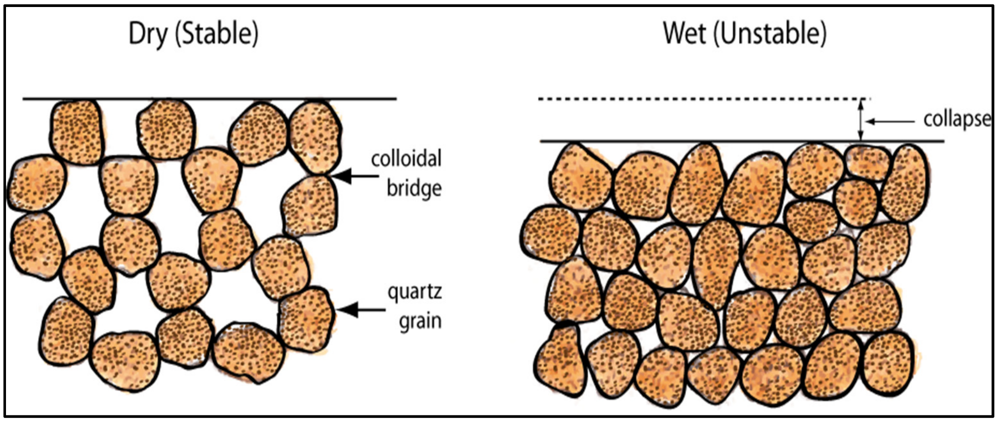

Figure 2.1 Graphical representation of mechanism of collapse
and collapsible sand fabric
Taken from Brink (1985)

To lower the probability of collapse, modern guidelines specify that subgrade soils that have this potential for collapse should be identified as deep as 1 m from the surface (Brink and van Rooy 2015). While this may appear unnecessary in dry or semi-dry areas where flooding or heavy rains are uncommon, collapse may occur when the exerted stress is comparable to that of stripping pavement pressure: At moisture saturation levels, it would normally be in the range of 36 kPa for a road going over a low-level bridge. The description and classification of the potential for collapse is shown in Table 2.1, which was originally developed to measure the severity of differential settlement of structures, but can be useful road guide (Weston 1980).

Table 2.1 CP related to severity problem
Taken from Weston (1980)

Collapse Potential	**Severity of the Problem**
0-1%	No problem
1-5%	Moderate trouble
5-10%	Trouble
10-20%	Severe trouble
>20%	Very severe trouble

2.3 Mechanical and Hydraulic Aspects

Mineral substances including crushed stone, gravel, and sand can be described by the general term “granular materials”. Granular materials are commonly used in both base and subbase courses in the construction of both rigid and flexible pavements. These granular materials may be manufactured from quarry rocks or natural. Usually, natural aggregates come from the excavation of existing rock formations. There is good demand for granular materials of sufficient quality because the performance of granular pavements strongly depends on the quality of the granular materials used. Quality is defined according to performance metrics such as its workability, shear strength, unconfined compressive strength, and hydraulic conductivity as described below (Mohsenian Hadad Amlashi 2018).

2.3.1 Workability

The workability of improved or stabilized soils is largely dependent on the shape and angularity of the particles, and how easy it is to place and compact the resulting mixture. The compaction characteristics will have a direct impact on the workability (Mohsenian Hadad Amlashi 2018). The effect of heavy compaction equipment in the field is modelled in the laboratory by the modified Proctor compaction method (Landris 2007).

During the soil compaction process, mechanical action pushes solid particles together and this increases the soil density by lowering the air volume or voids in the mix. Compaction effectiveness is strongly affected by the soil’s moisture content. The addition of water, up to a certain level, causes air to be expelled, thereby improving the level of compaction (Head 1994). The mix’s dry density can then by calculated with regards to water content (Figure 2.2).

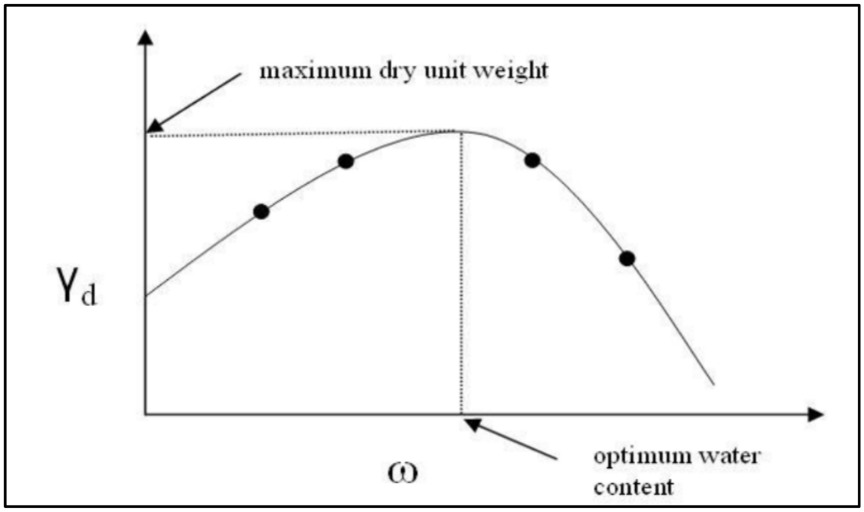

Figure 2.2 Moisture Density Relationship and Compaction Curve

2.3.2 Shear Strength

Parameters for shear strength help predict the behaviour of a mixture when under applied loads particularly when the aggregate functions in load-carrying. Because the principal load is carried by the aggregate, the friction that exists between aggregate particles has a great effect on its shear strength. Factors affecting inter-particle friction are particle shape, particle size gradations, degree of compaction (i.e., void ratio), and surface texture (Mohsenian Hadad Amlashi 2018). The California Bearing Ratio (CBR) and the triaxial test are the most used methods to determine shear strength parameters.

2.3.2.1 California Bearing Ratio

Soil shear strength can be indirectly measured with the CBR test; this test measures the penetration resistance of a piston or plunger that penetrates the soil at a set rate for a set penetration distance; the test also takes into consideration the soil's compaction level and moisture content (FHWA 2006). The National Cooperative Highway Research Program recommends at least a CBR of 80% and 100% with regards to subbase and base courses, respectively, when constructing low volume roads (NCHRP 2003), Figure 2.3 shows the CBR test equipment.

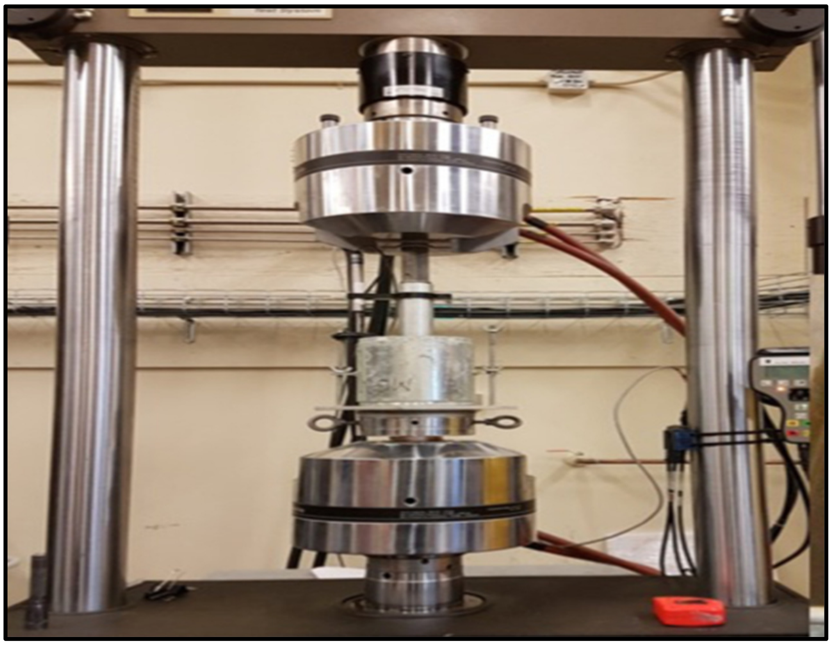

Figure 2.3 CBR Test Machine

2.3.2.2 Triaxial Test

A triaxial test typically requires placing a cylindrical soil sample in a pressurized container where stress conditions can be simulated; it is then sheared to failure, thereby determining the sample's shear strength characteristics. Triaxial tests are generally conducted on samples that are both of high quality and not otherwise degraded. These samples generally are between 38 mm -100 mm; nonetheless, with the right equipment much larger samples can also be tested. Test specimens usually have a ratio of height to diameter of 2:1. Samples are normally saturated, then consolidated before they are sheared. For the course of the test, stress conditions are imposed on the specimen to simulate stresses that would occur in the field. Figure 2.4 illustrates the normal experimental setup, where a specimen is being subjected to laboratory stress conditions (Mohsenian Hadad Amlashi 2018).

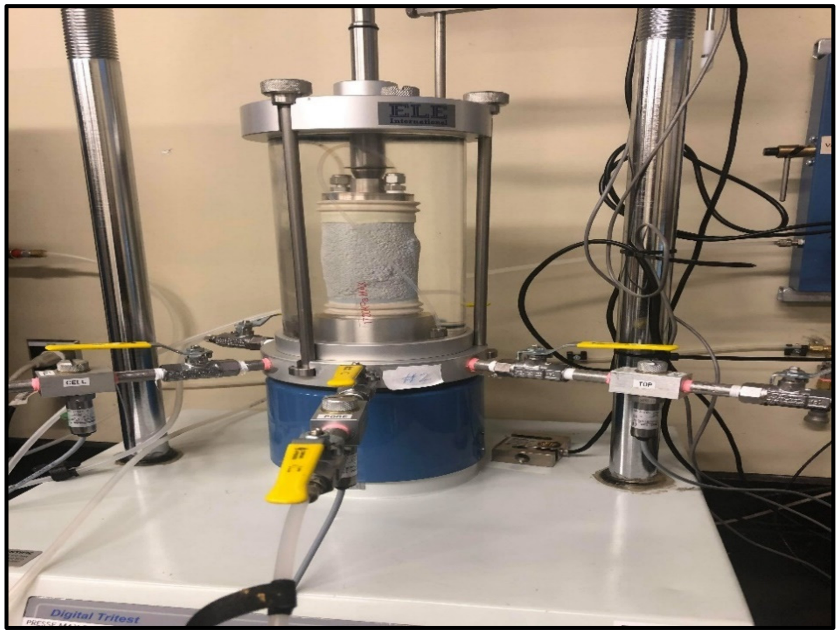

Figure 2.4 Typical test stress conditions on specimen

2.3.3 Unconfined Compressive Strength (UCS)

Among the most stringent and popular means of evaluating a soil's compressive strength is the UCS test. This is one of the most valuable mechanical tests for subbase and base layers because it is in this test that they are subjected to high compressive stresses. Material strength is partly a function of compressive strength, namely to what degree a specimen can resist compressive stress under various conditions. To determine the UCS, specimens are made into cylinders; these are subject to axial compression (with no lateral forces). To enhance the compressive soil strength, fly ash may or may not be used to prepare the cement. A minimum compressive strength is recommended to be 50 psi with seven days left to cure the specimen; for a stabilized subbase layer, the minimum compressive strength is 150 psi over seven days (Gaudreau, Zhang, and Wu, 2010).

2.3.4 Hydraulic Conductivity

The drainage properties of an aggregate are also critical to good pavement design. Within a pavement structure, the granular layers play a fundamental part. First of all, they are needed as mechanical support in the upper layers; second of all, they provide the necessary means to allow water to drain out of a pavement structure (Mohsenian Hadad Amlashi 2018).

Permeability is affected by particle size distribution, void ratios, particle texture and shape, etc. The permeability of granular soils is affected by the distribution of particle size and, most of all, by fine particles. This is important because smaller particles create smaller air voids and so water flow resistance is greater as particles size decreases (and permeability along with it) (Head 1994).

Test samples are compacted to 98% (±2%) of MDD, calculated according to compaction tests. Granular materials need adequate drainage so that water and other moisture do not cause excessive pavement damage (Côté and Konrad 2003). Therefore, understanding effective drainage features of base aggregate is critical to the design and performance of pavements (Dawson 1995). Overly compacted soil offers limited permeability, and this is shown with the coefficients of various sands in Table 2.2.

Table 2.2 Typical Permeability Coefficients for Sands
Taken from Elhakim (2016)

Sand Type	Coefficient Permeability (cm/sec)	Qualitative Description
Clean coarse sand	$1\text{-}10^{-2}$	Medium
Graded sand	$10^{-2}\text{-}5\times10^{-3}$	Medium
Fine sand	$5\times10^{-3}\text{-}10^{-3}$	Medium to Low
Silty sand	$2\times10^{-3}\text{-}10^{-4}$	Low
Very fine uniform sand	$6\times10^{-3}\text{-}10^{-4}$	Low
Dune sand	0.3	High

2.4 Pavement Structural Design

Asphalt pavement structures are made up of surface, subbase, and base courses (Figure 2.5). Every course makes up a layer that has a very specific function in terms of drainage and bearing capacity. As defined by the resilient modulus, the stiffer layer in flexible asphalt pavements is the surface course and it is usually comprised of Hot Mix Asphalt (HMA) with the bitumen binder providing the required cohesion and the aggregates providing the structural skeleton to resist mechanical tensile and compressive strains.

The lower layers, although not as rigid as the surface, play nonetheless an important role in the overall strength of the road structure; they also protect against the actions of freezing and water erosion by providing adequate drain ability. In terms of strength, it is standard that the highest quality materials are used in the upper layers and the lower-grade materials are used in the lower layers (Mohamed and Zaltuom 2011) because of the stress-dependent rigidity of the pavement layers.

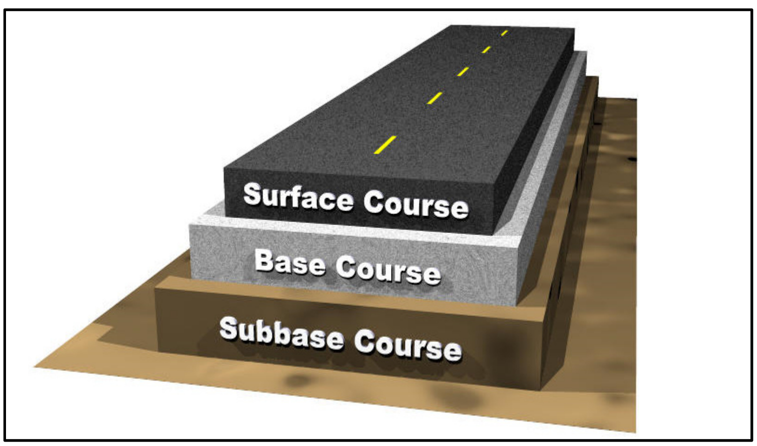

Figure 2.5 Flexible Pavement Structure
Taken from Gupta and Kumar (2014)

The topmost road surface in contact with the axle loads provides smoothness, noise reduction, friction, drainage, and resistance to shoving and rutting. The surface course is sometimes made up of a single layer, though it is often comprised of two such layers, the wearing course and the asphalt intermediate course. When the surface course is composed of two layers, the wearing course is the top layer that vehicles drive on. The wearing course is most worn by traffic and will be subject to removal and replacement through what is referred to as periodic maintenance. Under the wearing course, there can be an intermediate course to distribute the axle loads weight to the underlying base course. The function of the base course is to further distribute the axle loads to the layer underneath, to drain water and to also insulate the lower layers from the actions of freezing which causes upheaving in northern climates.

The layer built between the subgrade and the base course is called the subbase course. Its principal purpose is that of structural support, but it also helps to:

1. Provide better drainage.
2. Help prevent fines from intruding into the pavement structure from the subgrade.
3. Minimize damage from freezing and thawing cycles in northern climates.
4. Provide a platform for further construction.

The resistance to deformation of the subbase is usually lower than that of the base course but higher than that of the subgrade. A subbase is mandatory when the subgrade is silty or clayey. Pavement design optimization requires to provide minimal layer thicknesses and stiffness to minimize the total life cycle cost. This requires preventing compressive failure at the top of every layer and tension failure at the bottom of bound layers over the life of the structure.

2.5 Soil Improvement or Stabilization

The process of upgrading the strength of pavement layers to prevent the aforementioned modes of failures in compression and more importantly in tension of materials is called soil improvement or soil stabilization. This usually involves mixing different soils or binding agents to achieve a suitable strength. Soil improvement is associated to the soil behaving in compression under loading as a result of a lower binder content and a modulus of approximately 1,500 MPa or lower whereas soil stabilization is associated to the soil behaving in flexure instead as a result of a higher binder content and a modulus above approximately

1,500 MPa. Benefits of stabilization include: 1) increasing the shear resistance; 2) preventing permanent compressive deformation through densification; 3) reducing elastic deflection that might otherwise permit fatigue cracking in superior courses; 4) diffuse the axle loads over a wider area in soils at lower levels, and 5) avoiding excessive tensile stress in the bound layer. An optimal design will reduce the thickness of the costly AC layer (Makusa 2013).

2.6 Stabilizer Selection Guidelines

The soil-additive interaction is influenced by soil characteristics including mineralogy, gradation, and physiochemical properties of fine-grained soils. Therefore, the selection of stabilizers is always based on the efficacy of a given stabilizer to improve the physio-chemical properties of the selected soil (Little and Nair 2009). Indexing systems for soil properties, including moisture content, sieve analysis, and consistency tests, are all derived from field sample testing in the laboratory. Samples are prepared according to AASHTO T 87. Most soils are first subject to careful air drying or drying at temperatures below 60˚C. Prior to the drying process, the soil is broken down into its constituent particles as much as is practical. A typical soil sample is selected for tests according to AASTHO T 248. The necessary quantity of soil particles smaller than 0.425 mm (No. 40 sieve) is used to calculate the indexing of soil characteristics (Little and Nair 2009). Liquid limit tests are performed according to AASHTO T 89. Plasticity index (PI) plastic limit tests are measured according to AASHTO T 90.

2.7 Techniques for Binder Selection

In order to select a suitable soil binder, the Unified Soil Classification System (USCS) or the AASHTO soil classification system may be used. The Soil Stabilization Index System (SSIS) is also commonly used. The US Air Force developed this technique focusing on the percentage of particles that passes a No. 200 sieve, as well as the soil's PI (TM 1994). The necessary tests are straight forward to execute in a laboratory and their inputs are needed for both the USCS and AASHTO soil classification systems. These properties can be analyzed with regards to the engineering properties of the soil and their engineering application can then be determined. The percentage of soil that passes a No. 200 sieve (percentage under 75 µm) and PI are index properties that can be used for soils (Figure 2.6) and base materials (Figure 2.7) to determine the optimal stabilizer. After a stabilizer is chosen, a set of tests are carried out in the laboratory to evaluate the soil's performance characteristics and strength (Branch 2005).

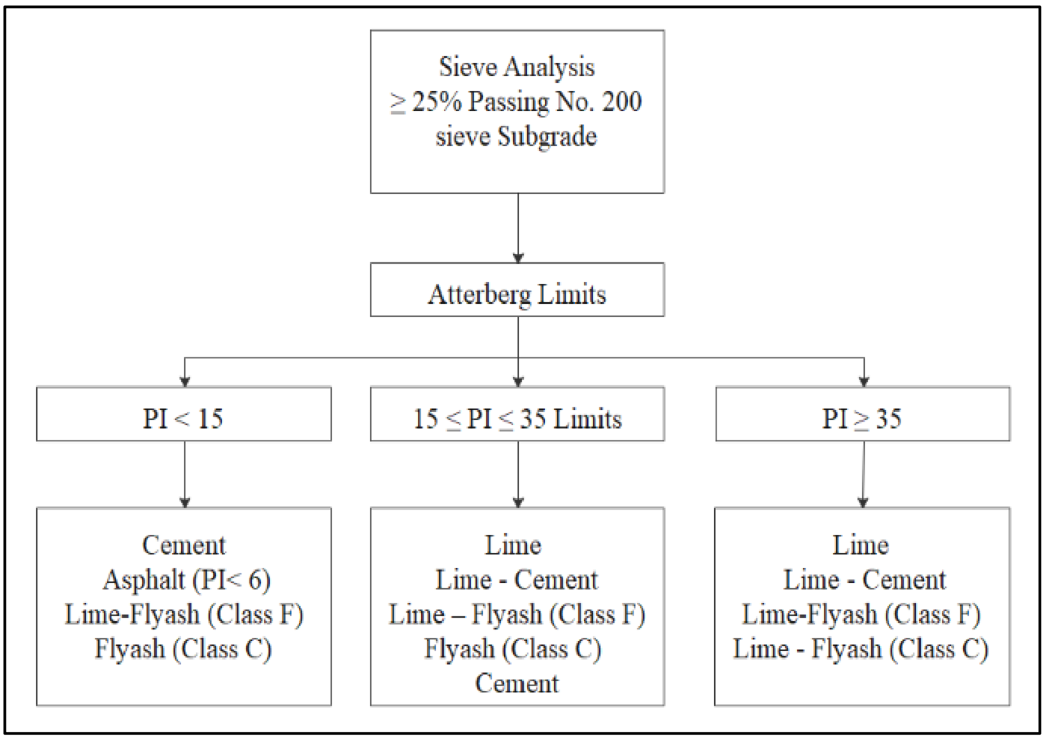

Figure 2.6 Decision Tree for the Selection of Stabilizers for Subgrade Soils (I)
Taken from Little and Nair (2009)

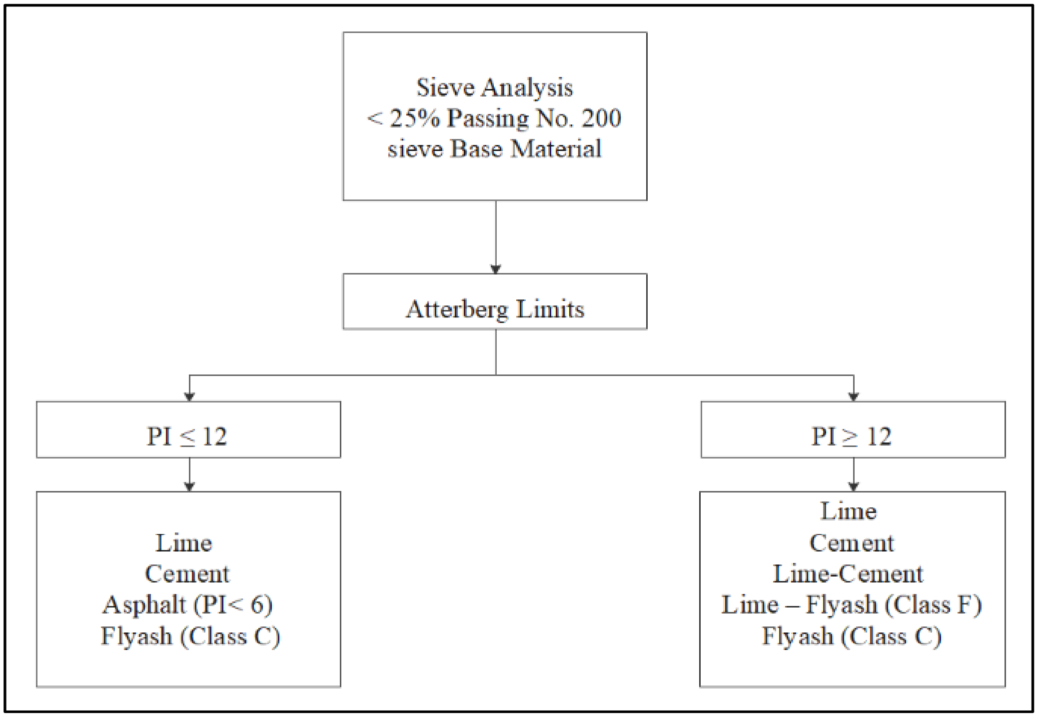

Figure 2.7 Decision Tree for the Selection of Stabilizers for Subgrade Soils (II) Taken from Little and Nair (2009)

A trial-and-error laboratory investigation may indicate that multiple stabilizers are suitable for the treatment of a given soil. In such cases, the stabilizer selection can use criteria such as soil texture, plasticity, and granularity, to converge to the final choice. Well-graded and granular soil that contains a high enough level of fine matter can benefit from treatment with Ordinary Portland Cement (OPC). Nonetheless, OPC cannot be recommended for stabilizing highly plastic soils because of the difficulties involved with mixing OPC with highly plastic clays (Mahvash-Mohammadi 2017). When using OPC in the stabilization of plastic clays, these plastic clays must first be treated with lime to make them more usable; a standard treatment is about 2% lime (Epps et al. 1971).

2.8 Determining the Stabilizing Properties of Soil

To develop appropriate protocols for a construction project, appropriate step design, testing and evaluation methods need to be determined. A number of soil treatment variables must be reviewed, especially if the treatment has the objective of creating long-term properties in the soil to improve its durability and other engineering properties. The type of sand will determine what stabilizing techniques will have the best results. Therefore, it is not practical to develop a common procedure applicable to all types of stabilizers. In Figure 2.8 there is a flowchart showing a step-by-step process for determining the stabilizer properties (Little and Nair 2009).

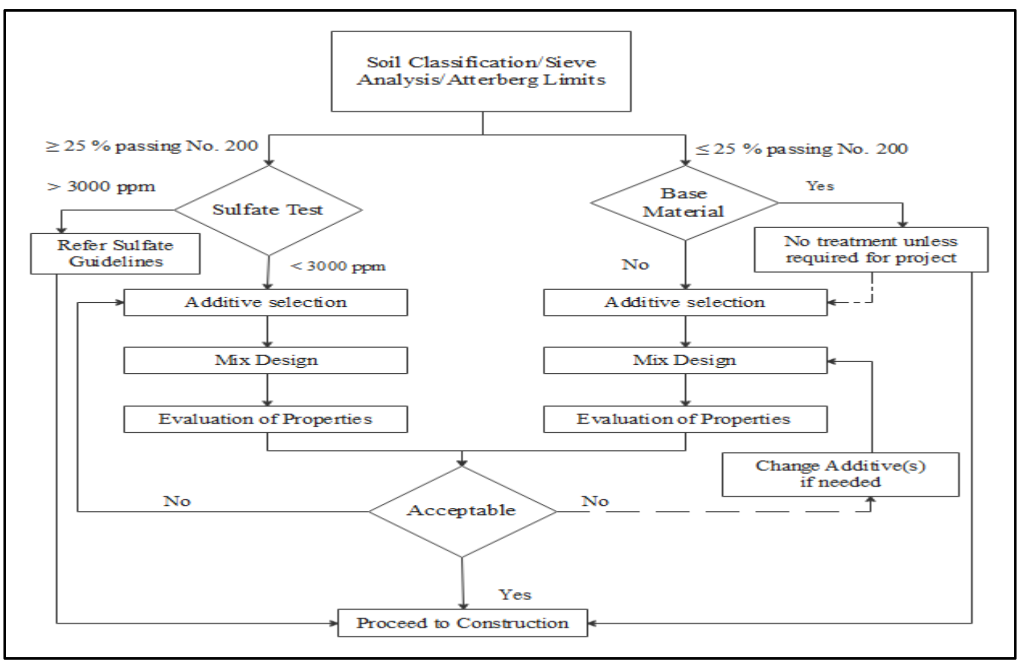

Figure 2.8 Manual for Soil Stabilization and Materials for Pavement
Taken from Little and Nair (2009)

Figure 2.9 and Table 2.3 show guidelines developed by the US Air Force and the US Army to help select appropriate soil stabilizers. The Atterberg limits, the distribution of particle sizes, and the soil class are the only parameters needed under these guidelines. If the output of these guidelines indicates that multiple stabilizers are appropriate for a given soil type, a further distinction will need to be made using other criteria, e.g., cost, construction ease, stabilizer availability (Melese 2014).

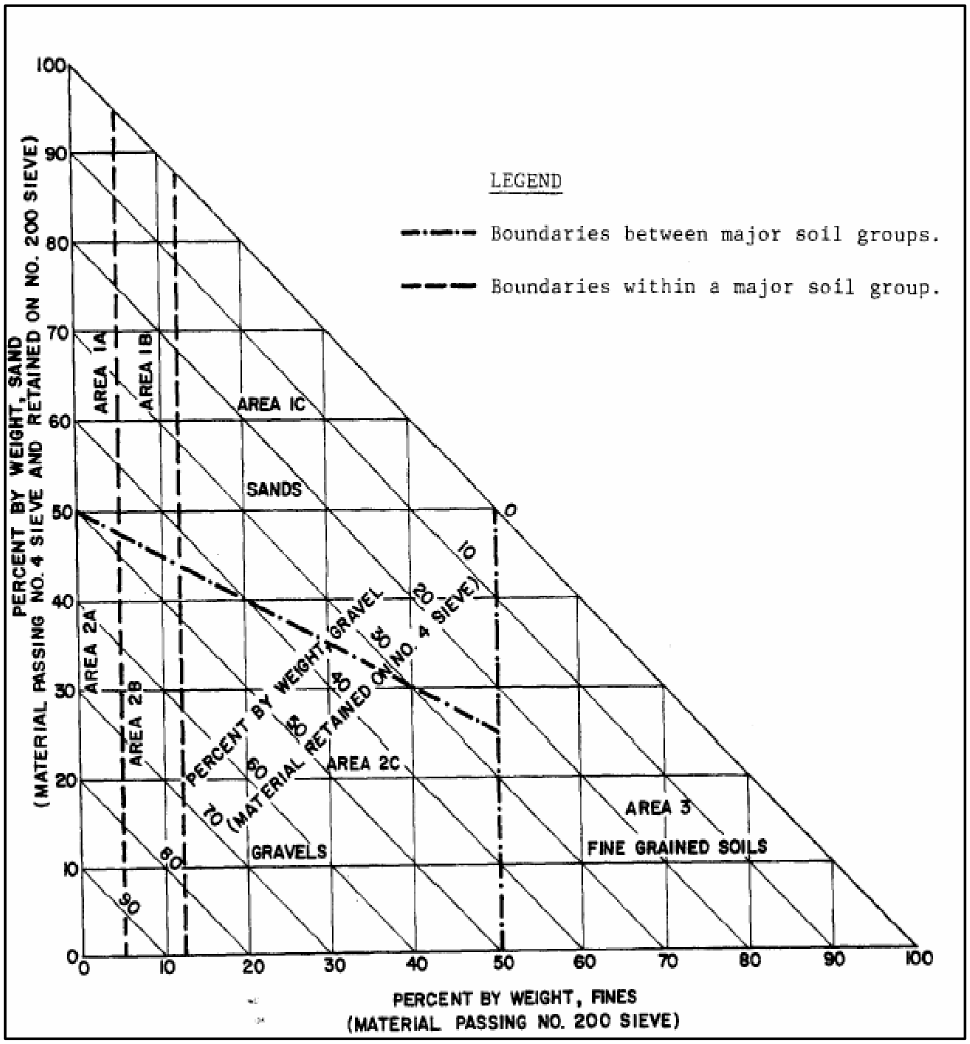

Figure 2.9 Gradation triangle for aid in selecting a stabilizing agent
Taken from Melese (2014)

Table 2.3 Guide for Selecting Stabilizing Additive
Taken from Melese (2014)

Area	Soil Class (a)	Type of stabilizing additive recommended	Restriction on LL and PI of soil	Restriction on percent passing No. 200 sieve (a)	Remarks
A1	SW or SP	1. Bituminous			
		2. Portland cement			
		3. Lime-cement-fly ash	PI not exceed 25		
1B	SW-SM or SP-SM or SW-SC or SP-SC	1. Bituminous	PI not exceed 10		
		2. Portland cement	PI not exceed 30		
		3. Lime	PI not exceed 12		
		4. Lime-cement-fly ash	PI not exceed 25		
1C	SM or SC or SM-SC	1. Bituminous	PI not exceed 10	Not to exceed 30% by weight	
		2. Portland cement	b		
		3. Lime	PI not exceed 12		
		4. Lime-cement-fly ash	PI not exceed 25		
2A	GW or GP	1. Bituminous			Well-graded materials only
		2. Portland cement			Material should contain at least 45% by weight of material passing No. 4 sieve
		4. Lime-cement-fly ash	PI not exceed 25		
2B	GW-GM or GP-GM or GW-GC or GP-GC	1. Bituminous	PI not exceed 10		Well-graded materials only
		2. Portland cement	PI not exceed 30		Material should contain at least 45% by weight of material
		3. Lime	PI not exceed 12		
		4. Lime-cement-fly ash	PI not exceed 25		
2C	GM or GC or GM-GC	1. Bituminous	PI not exceed 10	Not to exceed 30% by weight	Well-graded materials only
		2. Portland cement	b		Material should contain at least 45% by weight of material
		3. Lime	PI not exceed 12		
		4. Lime-cement-fly ash	PI not exceed 25		
3	CH or CL or MH or OH or OL or ML-CL	1. Portland cement	LL less than 40 and PI less than 20		Organic and strongly acid soils falling within this area are not susceptible to stabilization by ordinary means
		2. Lime	PI not exceed 12		

a. Soil classification corresponds to MIL-STD-619B. Restriction on liquid limit (LL) and plasticity index (PI) is in accordance with Method 103 in MIL-STD-621A.

b. PI ≤ 20 + (50 – percent passing No. 200 sieve)/4.

2.9 Stabilization Methods

2.9.1 Mechanical Stabilization

Whatever the costs involved, the process of soil stabilization results in overall cost savings, reducing earthworks and providing methods to modify, sustain, or otherwise improve the performance characteristics of the soil (Branch 2005). Stabilization techniques are implemented either mechanically (e.g., by altering a soil's gradation) or chemically, by changing the chemical makeup of a soil (Patel and Patel 2012).

Stabilization through mechanical means is possible by blending more than one soil with another to create a soil mix that is of a higher grade than the original natural soils that went into the mix. To blend the soils to the targeted characteristics, the ratios of coarse and fine aggregates are added or subtracted until the optimal balance is found. Once the desired mix is determined, it is compacted. The new mix should control the internal cohesion and friction and therefore increase the soil's strength and load-carrying capacity; the objective is that the composite is more stable (Amiralian, Chegenizadeh, and Nikraz 2012a).

2.9.2 Chemical Stabilization

Chemical admixture or chemical stabilization is carried out by means of cation exchanges and chemical reactions that change the structure of the soil. This can be categorized into traditional materials such as OPC, lime, and fly ash as well as less traditional chemical reactants such as ammonium chloride, potassium compounds, sulfonated oils. The chemical processes underlying the traditional materials principally involve pozzolanic reactions and calcium exchanges. This contrasts with non-traditional materials that use different unpublished and proprietary mixes (Khemissa and Mahamedi 2014).

Stabilization lowers construction costs and improves the strength characteristics of weak soils by increasing cohesion, reinforcing various structures (e.g., the embankment)(Patel and Patel 2012). Various studies discuss the successful use of materials including silica fume, fly ash, rice husk, cement, and lime to stabilize low quality soils (Zumrawi 1991).

Locally available industrial and natural resources, namely fly ash and lime have been shown to have a significant effect on the improvement of soil properties (Amiralian, Chegenizadeh, and Nikraz 2012b). Physical, environmental, and economic conditions will inform the stabilizer choice. An example is that in Nigeria, because of economic restrictions, research on chemical stabilization has been restricted to lime (Castro-Fresno et al. 2011).

2.9.3 Cement Stabilization

The optimal use of cement stabilization is with well-graded aggregates that have enough fine particles to fill the air void between the aggregate and to suspend the coarse particles in the mix. Guidelines for stabilization of sandy soils generally specify a PI of under 30. For especially fine-grained soils, i.e., those that pass over 50% (by weight) through a 75µm sieve (0.075 in the equation), the guidelines specify that the liquid limit (LL) must be under 40 and the PI must be under 20 so that the mix can be properly blended (Harichane, Ghrici, and Kenai 2011). The equation below provides a guideline that is based on fine content defining the upper limit of the PI for cement stabilization soil selection (Kavak and Baykal 2012).

$$PI \leq 20 + \frac{5 - (\text{ \% smaller than } 0.075)}{4} \tag{2.1}$$

Soil-cement (SC), as defined by the American Concrete Institute, is a measured blend of soil, cement, and water (Degirmenci, Okucu, and Turabi 2007). Cement stabilization is a term that describes cement-modified soils (CMS) as well as compacted SC. These two kinds of cement stabilization have different purposes. Compacted SC uses cement to create a material that is both well compacted and strong; this is contrasted with soils that have been modified by cement where the cement is used to change the basic character of the soil, e.g., create volumetric shrinkage or a reduction in overall plasticity (Kim and Prezzi 2008). CMS may result in modest improvements to strength due to the small amounts of cement. A week of UCS of 0.8 MPa may be a compromise of CMS and cement-stabilized soils, which is to say that, when a cement treated soil shows over 0.8MPa in improvement, it could then be considered cement-stabilized; the reverse is also true (Molenaar 1998).

Adding OPC to a pulverized soil and leaving it to harden (through cement hydration) results in cement stabilization. The SC physical and chemical properties are due to soil type, quantity of cement, mixing and compaction methods and parameters (including curing time), soil conditioning (pulverization, etc.), soil pH, and the compacted mixture's dry density (Gourley and Greening 1999).

The interactions of the SC are affected by pozzolanic reactions, carbonation, cation exchange, and hydration; of these, the last two are the most important. Hydration reactions occur by means of tricalcium silicate (C_3S) and dicalcium silicate (C_2S) reactions with water. C_3S and C_2S make up 45% and 27% of OPC respectively. The relevant hydration reaction is free lime, CH, is formed following the formation of the insoluble silicate gel which crystallizes very slowly into an interlocking matrix. The free lime helps to modify the soil through cation exchange. Based on previous experience a soil is considered to be suitable for cement stabilization provided that it fulfills the requirement (Xuan et al. 2012).

$$C_3S+2H=C_2SH+CH \tag{2.2}$$

$$C_2S+2H=C_2SH+CH \tag{2.3}$$

Or

$$3CaO.SiO_2+2H_2O = 2CaO.SiO_2.H_2O +Ca(OH)_2 \tag{2.4}$$

$$2CaO.SiO_2+2H_2O = 2CaO.SiO_2.H_2O +Ca(OH)_2 \tag{2.5}$$

Free lime occurs when insoluble silicate gel slowly forms a crystalline matrix. The soil is modified by the free lime by means of a cation exchange. Such a soil is recommenced for cement stabilization as long as it meets the physical requirements in Table 2.4 (Molenaar 1998).

Table 2.4 Physical Requirements of Soils
Taken from Molenaar (1998)

Parameters	**Limits**
% ≤ 0.075mm	< 35 %
% > 0.075 mm	> 55%
Maximum grain-size	<75mm
Liquid Limit	< 50%
Plastic Limit	< 25%

The quantity of cement needed to stabilize soils has been codified into a general guideline, as seen in Table 2.5; this also depends on practical factors. Sand with high levels of sand or gravel need less cement to develop sufficient hardness. This contrasts with soils having a lot of silt and clay and these soils will require more cement to achieve the same hardness. At the same time, sandy soils that have a small amount of clay or silt need less cement than clean, poorly graded soils with lots of sand (Melese 2014).

Table 2.5 General guidelines on how much cement is needed
Taken from Melese (2014)

AASHTO Soil Group	**Usual Range in Cement Requirement**		**Estimated CC, Percent by Weight**
	Percent by Volume	Percent by Weight	
A-1-a	5-7	3-5	5
A-1-b	7-9	5-8	6
A-2	7-10	5-9	7
A-3	8-12	7-11	9
A-4	8-12	7-12	10
A-5	8-12	8-13	10
A-6	10-14	9-15	12
A-7	10-14	10-16	13

The SC Laboratory Handbook from edited by the Portland Concrete Association (PCA) states that the optimal binder mix should be based on the durability test results; the test itself can be either the wet-dry test or the freeze-thaw test. The cement ratio is considered optimal when the result is an SC mix that is able to resist the stress created in the durability tests (Melese 2014). The criteria can then be used to identify the best SC mix depending on the base-course construction, in this case, these were:

1. SC loss after 12 cycles of the freeze-thaw test or the wet-dry test will adhere to these limits:

- less or equal to 14% for Soil Groups A-1, A-2-4, A-2-5, and A-3;
- less or equal to 10% for Soil Groups A-2-6, A-2-7, A-4, and A-5;
- less or equal to 7% for Soil Groups A-6 and A-7.

2. The compressive strength increases with rises in cement content and with age but only in cement mixes that conform to specifications in #1.

According to PCA guidelines, compressive strength is a secondary criterion designed to verify the effect of cement in the SC mix. In other words, as long as the SC mix strength goes up along with cement percentage and age, the second condition is met.

2.10 Temperature and Curing of Cement Treated Materials

Cement curing is a critical technique to limit moisture loss from cement-stabilized material. Materials that have been treated with cement in the sub-base need to be cured for seven consecutive days after being set. This curing period has a number of benefits for the quality of the resulting stabilized materials, particularly as follows:

1. That enough moisture is kept in the layer, allowing the stabilizer to further hydrate over time.
2. That drying shrinkage is limited so that the hydration reaction can continue and therefore that the materials continue strengthening.
3. That the carbonation risk in the upper stabilized layer is limited.

In the field, a number of precise techniques are used to cure stabilized materials. Two of the most common techniques are to spray water onto the outside of the stabilized materials or to envelop the stabilized layer with a watertight substance. When water is used for curing, it is important that the outside of the layer to be stabilized is covered with 30 to 40 mm of sand to reduce filtering the stabilizers. Watertight covers, on the other hand, can be applied using bituminous materials, plastic sheets, or waterproof paper. With this method, an extremely light initial coating of water is sprayed on the outside of the layer to be stabilized; following that, plastic sheets, slow-setting emulsions, or a viscous bitumen (e.g., MC 3000) are applied. No axle-loads can be permitted during the 7 days of curing. Laboratory samples are cured in airtight bags that are sealed and kept at a constant temperature (Melese 2014).

2.11 Stabilization with Fly ash

2.11.1 Application and History of Fly ash

Industrial minerals and other natural resources have recently been used for soil stabilization with fly ash showing good results. Chemical stabilization is particularly effective. During coal combustion, three types of ash are generated: pond ash, bottom ash, and fly ash (Dutta et al. 2010; Kumar Bera, and Ghosh 2007). Besides fly ash is one of the most versatile and abundant waste products. Fly ash is a by-product of powdered coal when it is combusted in thermal power plants; physically, fly ash is a non-combustible grey powder containing crystalline particles. The combustion that creates it is caused by flue gases in coal plant boilers; afterwards, it is collected mechanically or by means of cyclone separators and filter bags or with electrostatic precipitators (Sezer et al. 2006). Bottom ash, on the other hand, is made from the ash that ends up at the base of the coal furnace. Pond ash is a mix of bottom and fly ash and then stored in what is called an ash pond; it is the most plentiful of the three (Dutta et al. 2010).

2.11.2 Fly ash Production

Fly ash is a waste material by-product of burning coal at electric power plants (Behera and Mishra 2012); compared with cement and lime, its binding properties are limited. The hardening process pertaining to high calcium fly ash can be divided into both long- and short-term mechanisms. At first, once fly ash is mixed into soil, the soil properties are enhanced; this is a short-term effect. In contrast, a long-term effect affecting the modified soil's strength, comes about due to the pozzolanic reactions (Horpibulsuk et al., 2009). This reaction is slow and becomes stronger once a shell of CSH gel forms around the particles of fly ash. This rate of reaction is dependent on the pozzolanic reaction's consumption of $Ca\ (OH)_2$. Over a long timescale, the $Ca\ (OH)_2$ consumption decreases because of the pozzolanic reaction (Kang et al., 2014). Fly ash is an effective agent for chemical and/or mechanical stabilization of soils. Soil density, water content, plasticity, and strength performance of soils (Behera and Mishra 2012).

2.12 Cement-Based Materials for Pavement Construction

It is well documented how cement interacts and strengthen subgrade, subbase, and base materials. Many different methods and equipment for stabilizing soils are reported in the literature, particularly with regard to **cement-stabilization** vs **cement-treatment**. Some researchers classify these techniques according to the relative amount of cement in the final material (Racine 2018); others classify them according to material strength. An example of the former is to refer to cement-treated materials as SC and CMS (Baghdadi 1982). SC is defined as a material that contains sufficient cement and water to provide targeted durability and strength. SC is most often used in subbase and base construction. CMS, on the other hand, is when the material has only had a small amount of cement added to it, sufficient to reduce possible volume changes and plasticity such as for subgrades. The term "cement stabilized base" is sometimes used to characterize both SC and CMS (Halsted, 2011).

Little (1995) classified cement-added materials into light, moderate, strong stabilized and stabilized subgrade based on the amount of cement added. They contain less than 2%, 2 to 4%, more than 4% cement for materials with low, medium and high degree of stabilization, respectively. In contrast, Paul et al (2013) consider that any mixture with less than 5% cement is lightly stabilized. The term stabilized subgrade applies to subgrade soils to which small quantities of cement have been used to change the workability of the soil or to reduce the soil's potential for shrinkage or swelling. Other research has drawn a distinction between what contributes to the material's final strength; this is shown in Table 2.6. Categorizing various mixtures according to the material's final strength is a practical approach, given that this strength is not only due to the cement but to the strength of the aggregate and the cement, in combination (Foley 2002).

Table 2.6 Properties of Modified Heavily and Lightly Bound Materials
Taken from Foley (2002)

Degree of binding	**Design Strength (MPa)**	**Design flexural modulus**
Modified	UCS <1.0	<1,000
Lightly bound	UCS=1-4	1,500-3,000
Heavily bound	UCS>4	>5,000

On the other hand, bound materials carry traffic loads with particle interlock, shear strength, cohesion, and chemical bonding. In contrast to the behavior of unbound mixtures, there may be significant rigidity and therefore tensile strength in bound materials; as illustrated in Figure 2.10, this enables them to distribute loads over a broader area; at the same time, this protects the soils in the subgrade from rutting excessively because bound materials reduce the applied vertical stresses. Beyond this, by using bound materials, a project can help reduce fatigue failure that may otherwise occur on the surface course (Garber, Rasmussen, and Harrington 2011) because of the stiffer support reducing the bending in flexure of the asphalt concrete under heavy loading. Bound materials reduce the deflection in the pavement.

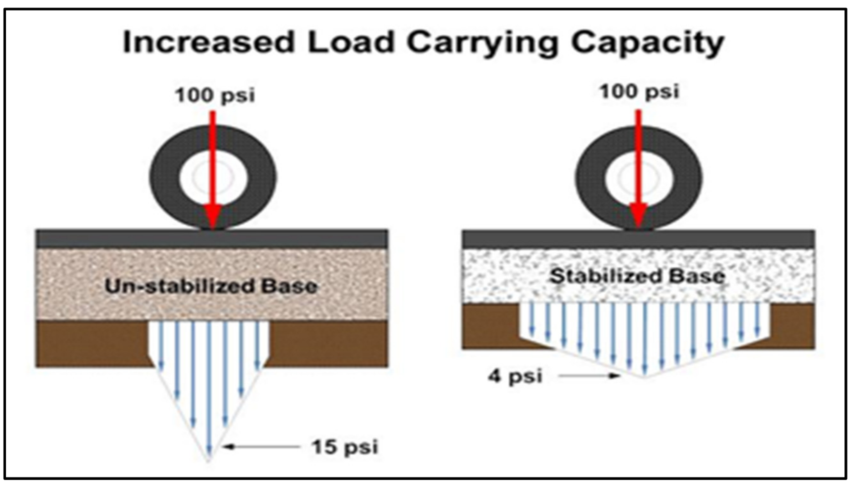

Figure 2.10 Stress Distribution on Subgrade
Taken from Garber et al. (2011)

2.13 Classification and Practice

2.13.1 PCA Practice

As illustrated in Figure 2.11, the PCA (2005) categorizes certain cemented materials based on the cement content and the water content. These categories encompass standard concrete applications, flowable fill, roller-compacted concrete, and SC. The figure below shows that both CMS *(where small percentages of cement are added to better certain characteristics)* and cement-treated bases *(where a larger amount of cement is used to fulfill specific structural capacities)* are both considered to be SC (Garber et al. 2011). Roller-compacted concrete (RCC), like SC, uses low water content; unlike SC, RCC is used in its construction and it has a comparable strength to standard concrete (Balbo 1997). Other differences in the construction of RCC include the use of admixtures, e.g., retarders (Idris, Sadek, and Hassan 2020). In a discussion of their work, (Choi and Hansen 2005) position the characteristics of cement-treated soils between those of SC and RCC.

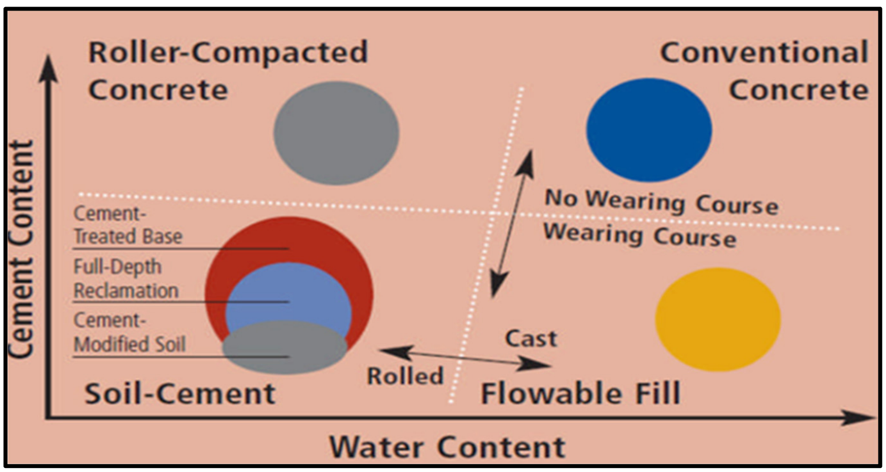

Figure 2.11 Different types of materials that use cement
Taken from PCA (2005)

2.13.2 South African Practice

The notion of "cemented materials" has been used in South Africa to describe all building materials that use added cement (Theyse et al. 1996). As seen in Table 2.7, these materials are separated into four classifications (C1, C2, C3, C4), largely based on strength. Note that there are also limits as to the type of aggregate in each classification.

Table 2.7 Classification of cemented materials in the South African
Taken from Theyse et al. (1996)

Category	UCS, MPa	Parent Material
C1	6-12	Crushed stone
C2	3-6	Crushed stone
C3	1.5-3	Gravel
C4	0.75-1.5	Gravel

2.13.3 International Practices

Overall, different countries use different terms and have different specifications when it comes to cement-modified soils; this is especially true with regard to such things as cement content, minimum strength, gradation, curing times. Table 2.8 shows the various specifications required by different countries regarding how cement-stabilized soils can be used as a subbase or base layer for semi-rigid pavement. From this table, can be concluded that countries carefully control material gradation in the construction of base courses. The objective is often to achieve maximum density leading to strength and stiffness increases (Thoegersen, Busch, and Henrichsen 2004).

Table 2.8 Criteria and practices of cement-stabilized materials in various countries Taken from Thoegersen, Busch, and Henrichsen (2004)

Country	**Austria**	**Belgium**		**Switzerland**	**Germany**		**Spain**		
Pavement Layer	Sub-base/base	Base			Sub-Base		Base	Sub-Base	
		Light Traffic	Heavy Traffic		Light Traffic	Heavy Traffic		Light Traffic	Heavy Traffic
Minimum strength C (Compression) or St (Splitting tensile) (days)	$R_{c\,7} \geq 2.5$	$R_{c\,90} \geq 10$ (Average)	$R_{c\,90} \geq 10$ (Single value)	$R_{c\,7} \geq 2\text{-}4$	$R_{c\,28} \sim 7$		$R_{c\,7} \geq 2.5$ Or $R_{c\,28} \geq 3.8$	$R_{c\,7} \geq 6$ or $R_{c\,90} \geq 9$ $R_{St\,7} \geq 0.5$ or $R_{St\,7} \geq 0.75$	
Cement content (kg/m³)	Min. 90	Min. 100		Min. 60	Uniform sand ~ 180 Well-graded aggregate ~ 95		Usually 100 ~ 120	Usually 90 ~ 100	
Cement Type	CEM II 32.5	CEM I or CEM III/A 32.5 or CEM III/A 42.5		CEM II 32.5	CEM II 32.5		CEM IV/B 32.5		
Fly ash / slag content (%)	≤ 35	≤ 35		0	0		36 - 55		
Gradation prescribed	NO	NO			NO		NO	YES	
Crushed aggregate prescribed	NO	YES		NO	NO		NO	YES MIN. 50%	
Compaction (% Proctor)	Min.97			97	Min 98		100	97 mod.	
Curing	Bitumen emulsion	Bitumen emulsion + sand		Bitumen emulsion	keep moist		Bitumen emulsion + sand		
Groover joints	no	no		no	Per 2.5 m (asphalt < 14 cm)	Per 5 m (asphalt < 14 cm)	no	no since 1997	
Asphalt cover (cm)	15-17 (heavy traffic)	15	17-18		≥ 12	30	12	15	
CTB thickness (cm)	25-30	20	20			15-20	20	20-25	
Reflection cracking	yes	often		often	None when groove joints			Often when groove joints	
Experience (year)	35	25		30	Groove joints since 1982			Since 1988 300 km with groove joints	
Max. axle load (KN)	105	130		100	115		130		

Table 2.8 Criteria and practices of cement-stabilized materials (Continue)

Country	France			UK			Italy
Pavement Layer	Sub-base	Base		Sub-Base	Base		Sub-Base for heavy traffic
		Light Traffic	Heavy Traffic		Light Traffic	Heavy Traffic	
Minimum strength C (Compression) or St (Splitting tensile) (days)	$R_{St\,360} \geq 1.1$ ($R_{St\,28} \geq 0.66$)			$R_{c\,7} \geq 2$-4	$R_{c\,28} \sim 7$		$R_{c\,7} \geq 2.5$-4.5 Or R_{St7} 0.25
Cement content (kg/m³)	Min. 70						60-100
Cement Type	CEM I, II or III 32.5						CEM II 32.5
Fly ash / slag content (%)	≤ 80	≤ 35					40 FA
Gradation prescribed	Partly	Yes	Yes	No	Yes		Yes
Crushed aggregate prescribed	No	Partly	Yes	No	No		Yes
Compaction (% Proctor)	95 mod		98 mod	Min. 97			100 (mod. AASHTO)
Curing	Bitumen emulsion + sand			Bitumen emulsion			Bitumen emulsion
Groover joints	Yes	Per 3 m		Being Investigated			No
Asphalt cover (cm)		6-8	14	0	10-15	30	20-25
CTB thickness (cm)	15-25	15-25 Depending on traffic and subbase		Min. 15	15-25 Depending on traffic and CTB type		20-30 Depending Subbase
Reflection cracking	No			Yes, with no groove joints			No
Experience (year)	25 years, 5000 km main road, 1500 km motorways			25 Years			20 Years, 3500 Km
Max. axle load (KN)	130			105			120

2.14 Literature Review of Some Applications of Stabilization by OPC and FA

2.14.1 Cement Application

There are many publications on using cement to improve soil functionality. One research paper discusses methods of stabilizing soil so it can be used in foundation-bearing soils (Al-Aghbari, Mohamedzein, and Taha 2009). In order to determine the engineering properties of the treated soil, the following tests were carried out: shear box, unconfined compression, and compaction. The tests indicated marked gains in shear strength, unconfined compressive strength, and maximum dry density values Melese 2014; Guyer 2018).

Characteristics of cement-stabilized soil include permeability, unconfined compressive strength, durability, shear strength and compaction values (Al-Aghbari and Dutta 2005). Findings demonstrate that a cement treatment generally leads to better cohesion, angle of friction, curing time, and overall strength. In particular, permeability went down as the cement content and the curing periods were increased. The addition of 3-16% OPC to coarse- and fine-grained soils affected its unconfined compressive strength when it was allowed to cure for 28 days (Mitchell 1976). For both coarse- and fine-grained soils, the unconfined compressive strength increased along with increases in the percentage of cement. Of the two soils, coarse-grained soils showed a more pronounced effect. Specifically, for fine-grained soils, soil strength was shown to be between 40 to 80 times greater depending on the percentage of cement; for coarse-grained soils, it was 80 to 150 times greater depending on the percentage of cement. Unconfined compressive strength was also observed to increase with the cement content and with time (Melese 2014).

Halsted (2011) reports success in adding 2-6% cement to silt-clay and granular soils, thereby improving the CBR. Once again, better results were found with an increase in curing time for adequate cement hydration and with cement percentages. More specifically, CBR improvements were greater with granular soils than with silt-clay soils. It was also demonstrated that the PI was immediately lower for silt-clay soils and this PI reduction became more marked with additional curing; again, PI continued to drop as the percentage of cement went up. It was observed that these indications were constant over long periods. Other soils, particularly dredged marine clay, also responded well to cement treatment, as reported by (Subramaniam, Sreenadh, and Banerjee 2016). In a triaxial test series, using cement percentages between 2.5% and 10%, stress-strain behaviour and peak stress were found to improve as cement content and curing times were increased. At the same time, peak strain, related to peak stress, went down as cement content and curing times went up.

2.14.2 Application of Fly ash and Cement

This section reports on studies addressing how a blend of fly ash and cement improve soil characteristics. Cement-activated fly ash has been found to be an effective stabilizer when added to soils (Zumrawi 2015). Treated and untreated soils were tested for CBR, compaction, consistency limit, swell potential and pressure. Test results confirm that the fly ash and cement mixture greatly affected soil characteristics. The most effective mixture was 15% fly ash and 5% cement; this reduced the PI and swelling while increasing strength and durability. Given the results and the low cost of fly ash, a fly ash and cement admixture are recommended to stabilize expansive subgrades.

Rice husk ash and cement have also been found to be an effective admixture to improve the CBR and unconfined compressive strength; the maximum dry density decreased, and the optimum moisture content increased (Roy 2014).

Silty-clay soils with a high PI have responded well to a mixture of 10% class F fly ash and different percentages of OPC (Horpibulsuk, Rachan, and Raksachon 2009). The addition of this admixture markedly raised the plastic limit and lowered the liquid limit; these had the effect of reducing the PI. The class F fly ash and cement admixture raised the maximum dry unit weight while leaving the optimum water content unaffected.

CHAPTER 3

ASSESSMENT OF STRENGTH DEVELOPMENT OF CEMENTED DESERT SOIL

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3.1 Abstract

For highway construction or any superstructure resting on dune sand, designers and construction contractors must ensure that the foundation soil is stable enough to provide support for the applied loads. Sand dunes are stretched across Libyan deserts making road construction a challenge because of the poor soil subgrade. Road construction on such a weak soil is very expensive and not economically feasible for low volume roads. This study uses two different mix designs aimed at stabilizing a base course using a combination of inappropriate dune sand and manufactured sand with a small percentage of Portland cement. Compaction, unconfined compressive strength (UCS) and California bearing ratio (CBR) tests were conducted on the treated sample with a varying cement proportion of 0%, 3%, 5% and 7% by weight. The first tests, with a mix of 50% dune sand and 50% crushed sand, have shown excellent results. For a more economic design, this study also included testing of another mix design with 70% dune sand and 30% crushed sand; laboratory results show this 70%:30% mixture was also appropriate to use as a base-treated material for road construction material. This mix resulted in overall superior performance. Its use will reduce the cost of road construction by saving materials and time, and it will also have lower environmental impacts in desert areas. This study has shown that the stabilization of weak material (desert sand) by using crushed quarry aggregates and ordinary cement improves the strength characteristics of the treated soil.

Keywords: Desert Sand, Base Course, Cement, Soil Stabilization, California Bearing Ratio, Unconfined Compressive Strength.

3.2 Introduction and Background

In the southern region of Libya, the presence of abundant silica sand should ideally be used as a local material in the construction of roads. This will help in preserving scarce good quality regional materials and avoid excessive pollution due to hauling such over long distances. When the available soil is very weak, the stabilization process increases its engineering characteristics. This process reduces the compressibility and permeability of the targeted soil mass thereby substantially increasing its strength and bearing capacity. This improves durability and reduces the cost of construction by using the local available materials (Almadwi and Assaf 2018; Panwar and Ameta 2016).

Using cement as a binding agent to stabilize soils is common in road pavement construction. A ratio of up to 2% cement added to a soil usually will keep it flexible enough to absorb any stress load in compression. Quantities greater than this can result in substantial property changes (Bell 1993) and then the stabilized soil will behave in flexure. Soils with >2% organic materials do not respond well to stabilization with cement due to the hydration effects introduced by the organic materials; this hydration may adversely affect the strength of the resulting soil (Barclay et al. 1990). The resulting characteristics of these cement-stabilized sands can be described as having properties of both rock and soil (Collins and Sitar 2011). The exact results depend on factors including soil type, method of compaction, stabilizing agent and the exact percentage of agent used. Adding cement affects the maximum dry density (MDD), as well as its optimum moisture content (OMC); nonetheless, rates of change are not standard (Barclay et al. 1990). The OMC and the MDD of soil vary with the amount of cement kiln dust (Miller and Azad 2000).

3.3 Literature Review

Road construction greatly depends on the practice of improving soils on which pavement materials are constructed. Soil stabilization can be defined as any process that results in a more stable soil. In contrast, the traditional approach of chemical stabilization is to add lime, bitumen or Portland cement (Thagesen 2003). Broadly, soil stabilization allows engineers to enhance or create a given property to make it useful for an engineering application. Through stabilization, many soils that previously had to be rejected can now be used in engineering projects (Amu, Bamisaye, and Komolafe 2011) . The following are engineering qualities that can be made better or made usable by stabilization: deformation resistance (i.e. stiffness), shearing resistance (i.e. improving soil strength) and wears resistance (i.e. durability); other factors affected are a lowering of levels of dust, a lowering of the tendency of wet clay soils to swell, and an increase in the overall water resistance of unsealed roads (Zumrawi 2014). Soil stabilization requires a binding agent, such as cement. Cement can be used as the primary binding agent for stabilization, or it can be used in combination with lime and fly ash. As such, the chemical reaction of the cement does not depend on the minerals in the soil; it only needs water that can be found in most soils (Makusa 2013).

To improve the geotechnical properties of fine sands that do not meet industry values for roads (Almadwi and Assaf 2017), one method is to eliminate poor-quality sand and instead use a higher value, crushed sand that was treated chemically or mechanically (Amhadi and Assaf 2018). Such methods can increase the level of the geotechnical property of the entire structure and provide greater stiffness and strength through approaches that can be applied at the construction site itself (Amhadi and Assaf 2018). Therefore, reinforcement of the soil is a technique for improving the engineering properties of the soil that lead to developing parameters such as shear strength, compressibility, density, and permeability (Hejazi et al. 2012). Thus, the main purpose of strengthening the mass of the soil is to increase its stability, increase its carrying capacity, as well as decrease lateral deformation and settlements (Binici, Aksogan, and Shah 2005).

Several studies have examined the use of sand in road construction and proposed various methods for its stabilization and efficiency (Tingle et al. 2007). Some authors suggest sand stabilization using bitumen or polymer emulsions. Due to the difficulties with the delivery of polymer and bitumen binders and the presence of local, hydraulic cement that was produced in many developing countries, pressed sand concrete was adopted as the preferred choice for the sand material (El Euch Khay, Neji, and Loulizi 2010). In other studies, the mechanical properties offered by the treatment of hydraulic binders or by the production of sandy concrete are improved (Asi et al. 2002).

Ajayi et al. (1991) carried out research on the effect of using an epoxy resin and polyamide hardener to stabilize soils composed of clay and silt. They used a one-to-one ratio of epoxy resin to polyamide hardener for their additive mixture, concluding that admixing as much as 4% stabilizer to the clay-silt soil made substantial improvements to the load bearing of the soil, defined by its unsoaked California bearing ratio (CBR). Increasing the curing environment temperature leads to greater strength formation. The curing time was as low as 3 hours for the stabilization agent.

Typically, at the point of cement stabilization, all necessary components are added. Hydration occurs with the addition of water, and calcium silicate hydration strengthens the soil or bonds soil particles. The properties of the subgrade are improved at a low cost by stabilizing with cement and substituting, adding or discarding material. An additional thickness of the base directly relates to lower subgrade stress (Prusinski and Bhattacharja 1999). Bitumen can also be incorporated with moist or diverse aggregates. Specific optimal moisture is also needed to certify an equal dispersion of the bitumen throughout the mix. The resilient modulus parameter is raised through bitumen stabilization of the raw material (Saleh 2004). Adding emulsion to the layers of pavement improves the water-resistant qualities and improves surface cohesion; this allows a road to be opened for use soon after construction, while at the same time limiting the raveling of the base layer (Liebenberg and Visser 2003). Soil stabilization is done upon determining that it is more economical to improve the qualities of an abundantly available material than to transport a better material to the job site (Al-Swaidani, Hammoud, and Meziab

2016). It is often the best economic solution. Other economic advantages include reducing the project duration. Soil stabilization can be 30% cheaper than transporting new materials to a site (Al-Swaidani et al. 2016). Soil stabilization brings a number of environmental benefits compared to traditional methods due to the energy savings by making use of locally sourced materials and the consequent reduction in the impact of transport (Rammal and Jubair 2015).

The quality construction materials are becoming rare in desert regions. Therefore, where traffic volumes are low, roads become less cost-effective due to the higher price of manufactured aggregate. The desert has a lot of dune sand; however, it has relatively little of the good quality material that is necessary for the road structure. So far, road construction in the south of Libya has depended on a combination of good quality material (gravel and sand), brought from the northern part of Libya. The soil in the southern part of Libya is not of a quality that makes good roads; therefore, to use it, engineers must improve soil characteristics such as strength, compressibility and permeability. This is because the foundation of all the structure is ultimately supported by the soil. The underlying hypothesis is that a cement–soil mix is the best way for construction roads.

The main goal of this paper is to study the feasibility of developing and using an improved dune–sand cement mix as a pavement construction material in desert regions where dune sand is prevalent. This study uses two different mix designs, 50% natural and 50% manufactured sands (50%:50%) and 70% natural and 30% manufactured sands (30%:70%) to compare the results for each mixture to stabilize the base course layer using dune sand and manufactured sand with a small percentage of Portland cement content. The laboratory tests were conducted for compaction, CBR and unconfined compressive strength (UCS).

3.4 Materials and Experimental Studies

More efficient soil stabilization can be designed only with a better understanding of the pertinent physicochemical processes and related stabilization mechanisms. Research on chemical conditioning of natural desert sands indicates that increasing soil aggregation is the principal factor in soil improvement. Stabilizing sand with cement is a good technique to gain strength. This research rests on the premise that the recourse to cement and a mixture of fine natural sand aggregates and manufactured sand will lead to a good performance of the underlying pavement layers. A schematic representation of the methodology conducted in this study is shown in Figure 3.1.

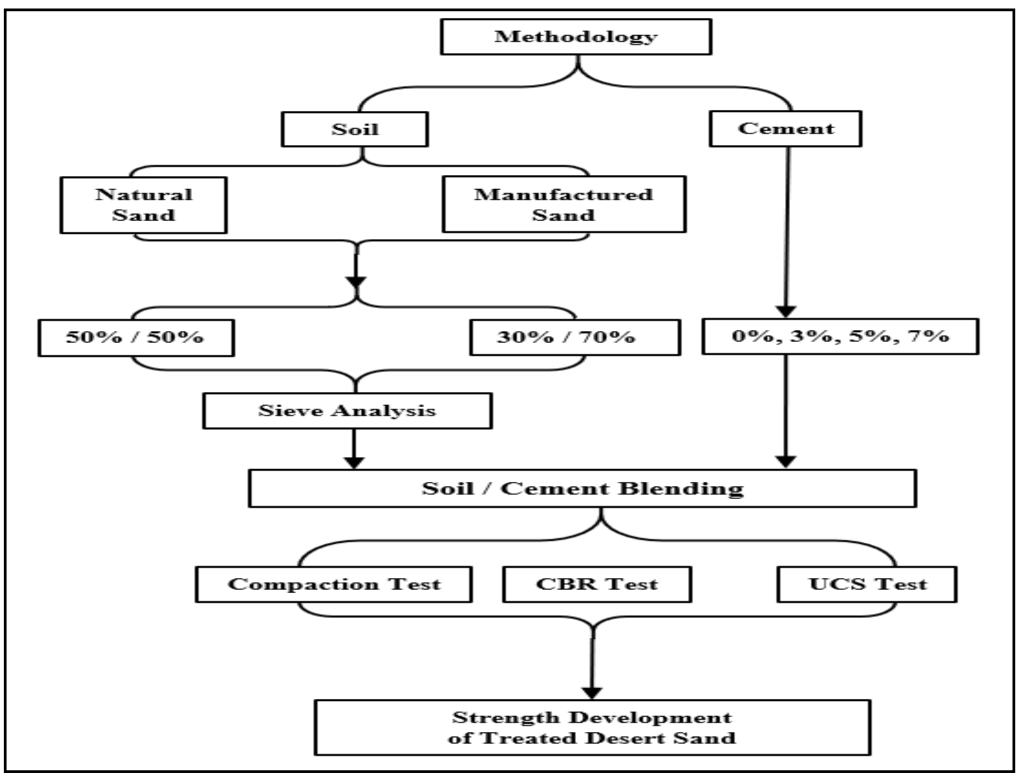

Figure 3.1 Flow Chart of the Experimental Program

3.4.1 Materials

The fine aggregates in the current study were brought from the southern part of the Libyan desert. Particles size ranges from 0 to 5.0 mm, i.e. fine round natural sand and angular manufactured particles shape according to USCS; the results of the two mixtures are shown in Table 3.1.

The grain size distribution for two mixtures of sand is illustrated in Figure 3.2. A great variety of cement is commercially available, depending on the soil in question and the targeted strength of the final soil. For this project, a Libyan-made Portland cement was chosen and applied in small quantities. The properties of the Portland cement are in Table 3.2.

Table 3.1 Physical and Geotechnical properties

Properties	**Mixture (30%-70%)**	**Mixture (50%-50%)**
Fineness modulus	5.19	4.84
Medium Size (D50)	5.00	3.50
Uniformity of the coefficient (Cu)	4.59	3.81
Coefficient of curvature (Cc)	1.12	0.61
Liquid limit, LL (%)	-	-
Plastic limit, PL (%)	-	-
Plasticity index, PI (%)	-	-
Soil Classification (USCS)	GW	SP
Soil Fraction	Parameter	
Silt & Clay size (%) Gravel (%) Sand (%)	0.25 % 58.23 % 41.53 %	0.18 % 59.53 % 40. 30 %

∗USCS: Unified Soil Classification System

∗GW: Well-graded gravel

∗SP: Poorly graded sand

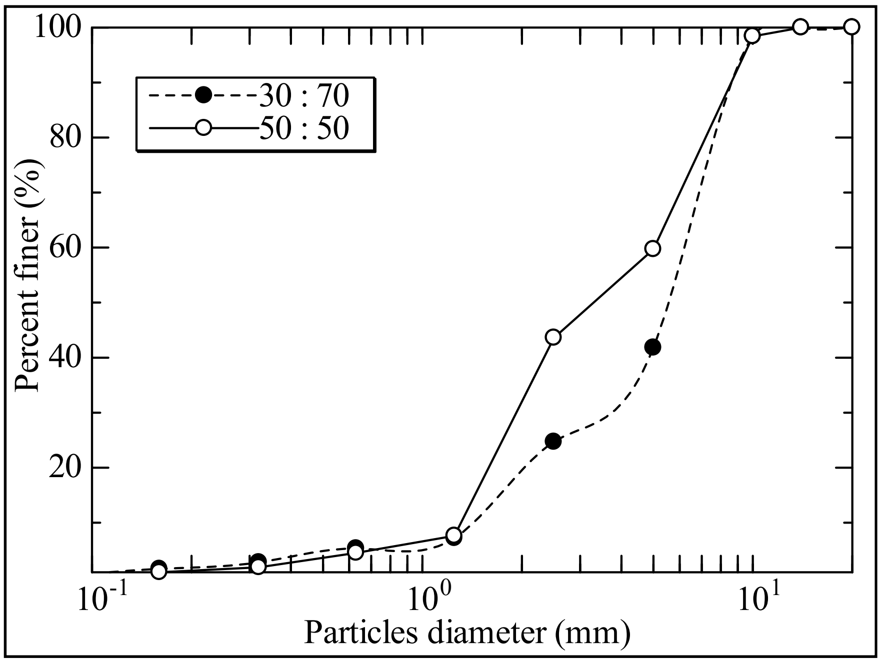

Figure 3.2 Gradation curves for two mixtures of sand

Table 3.2 The properties of the Portland cement

Compound	**%**
SiO_2	18.20
CaO	59.03
MgO	1.80
Al_2O_3	5.09
Fe_2O_3	3.15
Na_2O	0.18
K2O	0.29
SO_3	2.65
Loss on Ignition (LOI)	7.91
Materials not solvent	1.02
Properties	Test result
Time setting: Vicat test (min) - Initial set - Final set	 172 247
Air contents of mortar (%)	7.3
Autoclave expansion (%)	0.8
Compressive strength (MPa) - Three days - Twenty-eight days - Seven days	 10 30.5 Min 42.5- Max 62.5

3.5 Experimental Studies

3.5.1 Compaction Test

Laboratory compaction tests were conducted to determine the percentage of compaction and the water content required, in accordance with ASTM D 1557. The compaction test was carried out for both mixtures, the first mixture consisting of 50% of the sand manufactured and 50% of natural sand and using 0%, 3%, 5% and 7% cement. The second mixture consisted of 30% of manufactured sand and 70% of natural sand with the same 0%, 3%, 5% and 7% cement ratios. Water was added as needed to facilitate mixing and compaction.

3.5.2 CBR Test

To determine the bearing capacity of the compacted soils, all samples with optimum moisture content were placed in a five-layers mold. Each layer of the mixture was compacted with a hammer of 4.5 kg with 25 blows. Total weight of each the sample was 4.5 kg. After the compaction was completed, the upper ring of the mold was removed, and the surface of 8 samples was smoothed by using the steel ruler. Finally, samples were tested using CBR testing according to ASTM D 1883. The dial gauge that measured penetration was tared to zero and then the load was applied. Values for each 0.5 mm of penetration were noted and the final CBR values were obtained, pertaining to the greater of 2.5 mm and 5.0 mm penetration. These eight mixes underwent penetration testing with the loading machine. The initial mix used 50% manufactured sand and 50% natural sand and using 0%, 3%, 5%, and 7% of Portland cement. The second mixes used 30% manufactured sand and 70% of natural sand with the same percentages of Portland cement.

3.5.3 UCS Test

The (UCS) is to determine the compressive strength of the mixture. The mixture was prepared in accordance with ASTM D 2166, using samples with a diameter of 50 mm and a height of 100 mm as shown in Figure 3.3. For each sample, thorough mixing assured a homogeneous paste, taking care to limit the time to set up of the specimens (mix and compact) to less than 1 h, which is shorter than the initial setting time of the Portland cement used. Three specimens of every cement-soil mixture were tested at 0.1 mm/min. The diameter should be at least 30 mm, and the ratio of height to diameter should be from 2 to 2.5. The samples were placed in a humidity room for 7, 14, and 28 days. The average of UCS for three samples treated with cement after 7, 14 and 28 days of curing time was obtained using a hydraulic machine for the value of compressive strength with a load of 140 ± 70 kPa/s as shown in Figure 3.3. Finally, the value of compressive strength (MPa) was computed by dividing the maximum load (N) by the cross-sectional area (mm^2).

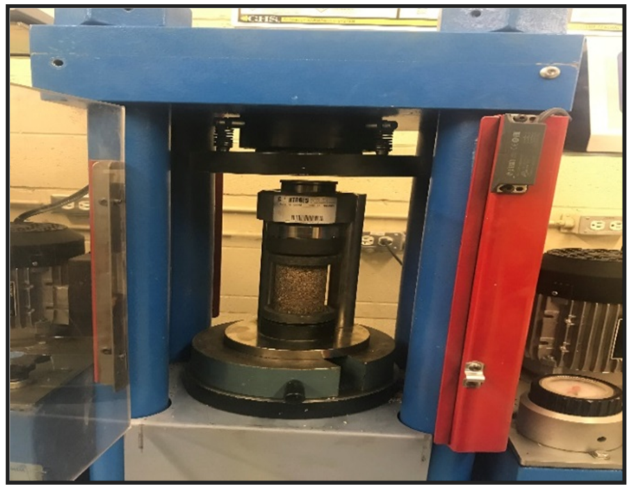

Figure 3.3 UCS machine test and specimen

3.6 Results and Discussion

3.6.1 Moisture-Density Test Results

Figures 3.4 and 3.5 portray the influence of different percentages of cement on the water content and dry density for both mixtures 50%:50% and 30%:70%, the important factors that affect the strength of the cement-soil stabilization is the dry density of the compacted soil. In fact, MDD of cement hydration varies by adding water. This can be explained by using a form of experimental results of the total void ratio of a mixture containing soils with different grain sizes. When small particles are found added to a matrix of large particles, the overall ratio of void decreases until all voids are filled with small particles. This means that the density of the dry density increases to a certain ratio of mixing small particles to large particles. Figure 3.4 presented the values of MDD with cement content for both mixes 50%:50% and 30%:70%, respectively. From these figures, there is a slight increase in the MDD of sand-cement mixes with an increase in the cement content. The variation of OMC for each of the various cement contents has relatively the same trend is illustrated in Figure 3.5, for both mixtures 50%:50% and 30%:70%. Finally, the sand mixture 30%:70% have obtained high values of MDD than those from the sand mixture 50%:50%.

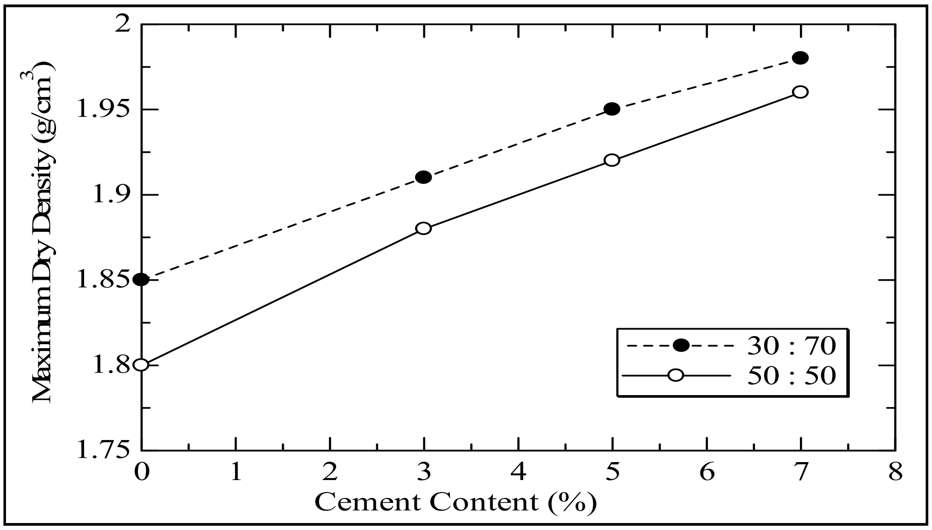

Figure 3.4 Effect of cement content on dry density of treated soil

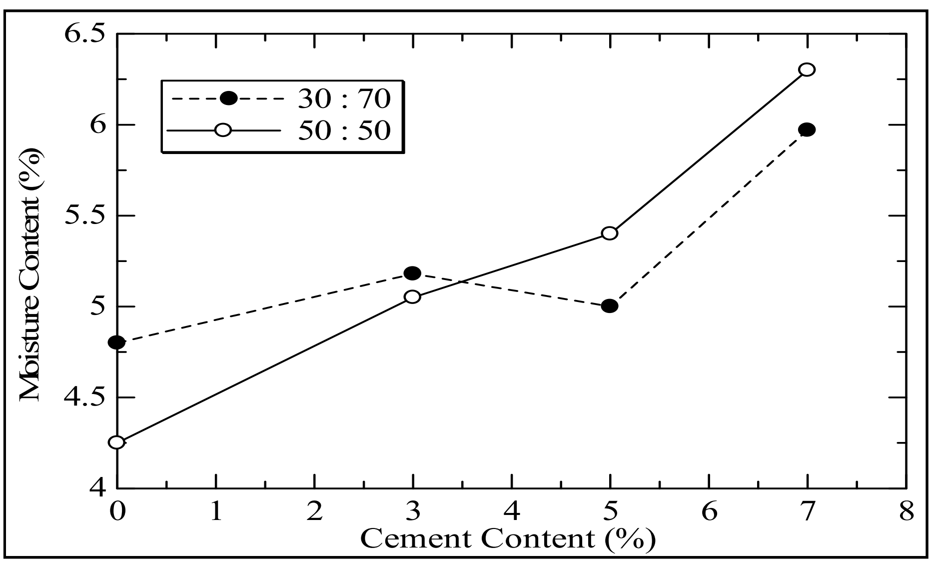

Figure 3.5 Effect of cement content on moisture content of treated soil

3.6.2 CBR Results

The CBR values measured on the natural sand at 5 mm and 2.5 mm penetrations ranged respectively from 20.5% to 23%. The CBR results improved substantially with the mixture of 50%:50%, natural and manufactured sands using different percentages of Portland cement, of

0%, 3%, 5%, 7% as shown in Figure 3.6; the values of CBR at the penetration of 2.5 mm for this mixture increased from 23% to 51.59%, 53.70%, 58.86%, and 59.19 %, respectively. At 5 mm penetration, the values increased from 20.5% to 49.29%, 50.86%, 54.85%, and 52.50%. Figure 3.7 shows the results of the mixture 30%/70% manufactured and natural sands with the same percentages of Portland cement, where the CBR value, at the penetration of 2.5 mm are 59.26%, 61.64%, 64.02%, and 67.72 %, respectively. At the penetration of 5 mm, the values are 58.5%, 60.01%, 57.59%, and 60.01 % respectively. The CBR values of mix 30%:70% for both penetration 2.5 mm and 5 mm are shown in superior performance than the values of the mix 50%:50% and definitely better than the natural sand alone. Moreover, the highest value of CBR at (30%:70%) was achieved by the stabilized soil with 7% cement for both penetration at 2.5 mm is 67.72% and 58.26 at 5 mm, respectively. This result suggests using a higher percentage of natural sand and gives a better outcome in terms of CBR values compared to other mixtures.

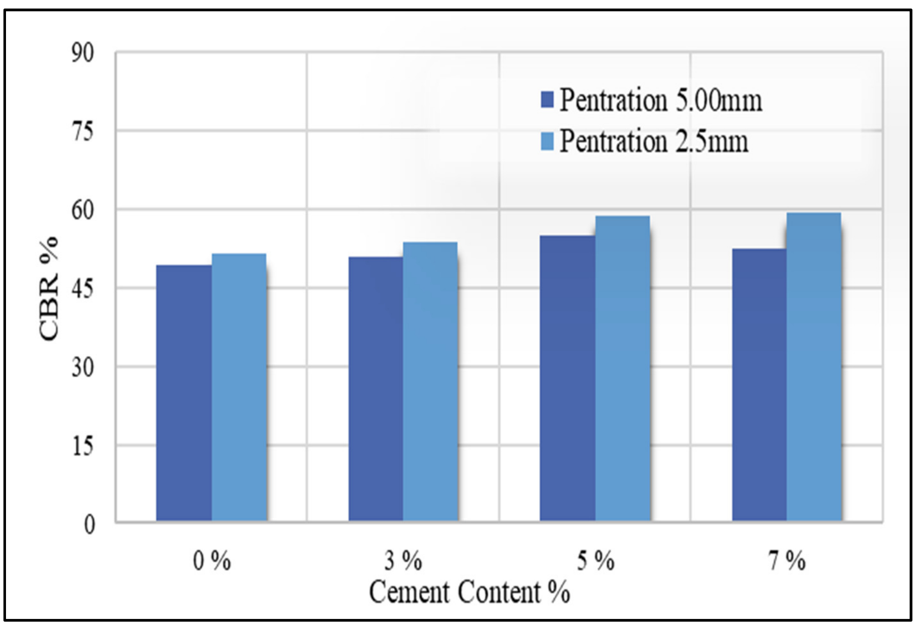

Figure 3.6 Variation of CBR value with Cement content (50%:50%)

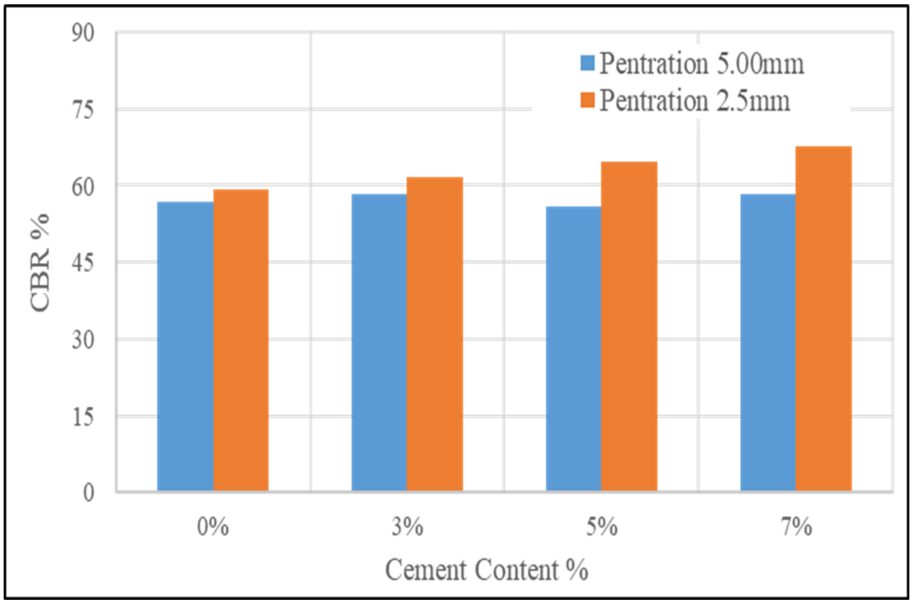

Figure 3.7 Variation of CBR value with Cement content (30%:70%)

3.6.3 UCS Results

From the UCS test results indicated in Figures 3.8 and 3.9, it is obvious that the cement and curing days have significant effects on the UCS of the specimens. This shows mutual dependence when an increase in the cement content increases the strength of the mixture due to cement hydration, which fills the pores of the voids, thus increasing the rigidity of its structure, forming a large number of rigid bonds in the soil. For the cement-only treated soils, after 28 days of curing, the UCS increased significantly from 0.6 MPs to 3.8 MPs and 0.5 MPs to 1.5 MPs, respectively by increasing the percentage of cement from 3 to 7% for the two mixtures 30%:70% and 50%:50%. However, for mixture 30%:70% after 28 curing days, the stabilized specimen with 7% cement provided the highest value of UCS at 3.8 MPs, which was about 7 times more than the untreated soil. As results, an increase in the cement content led to an increase in UCS.

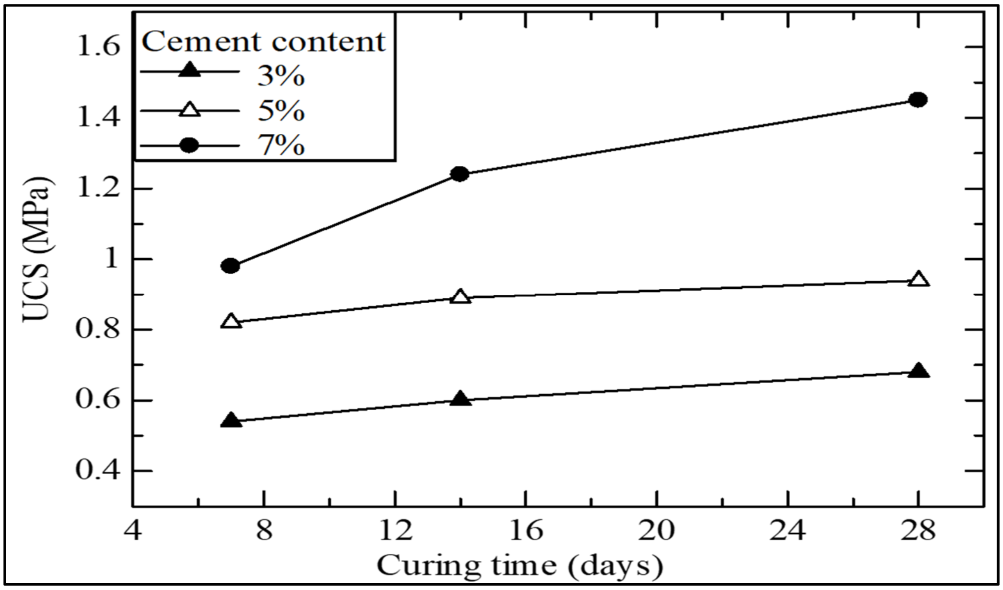

Figure 3.8 The compressive strength vs the percentage of cement (50%:50%)

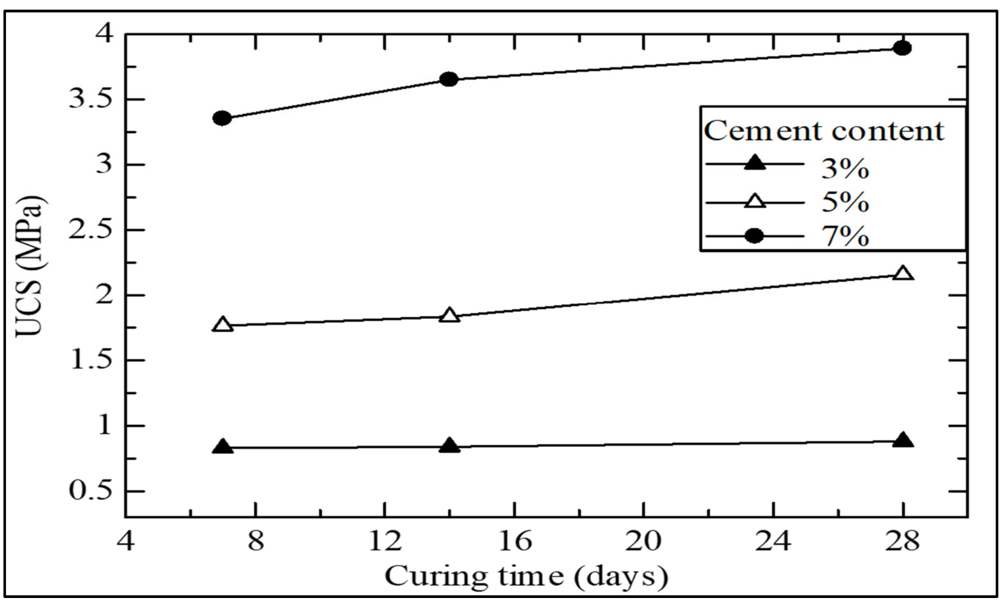

Figure 3.9 The compressive strength vs the percentage of cement (30%:70%)

3.7 Structural Analysis

The increase in CBR from 23% for natural sand on a standalone basis to 68% as a result of the addition of coarse aggregates (30%:70%) and 7% cement has a meaningful impact on the structural design of the pavement.

Assuming that the modulus of resilience of the base and subbase course can be estimated with the equation: M_r (MPa) = 10.34 * CBR (Hussein and Alshkane 2018), then we can safely assume an increase of the modulus from 230 MPa to 700 MPa. Figure 3.10 compares the tensile strain at the bottom of a 50 mm asphalt concrete surface with a conventional modulus of 1,000 MPa resting on a base course with a modulus of 230 MPa (strain Y of 476 microns) vs 700 MPa (strain Y of 196 microns).

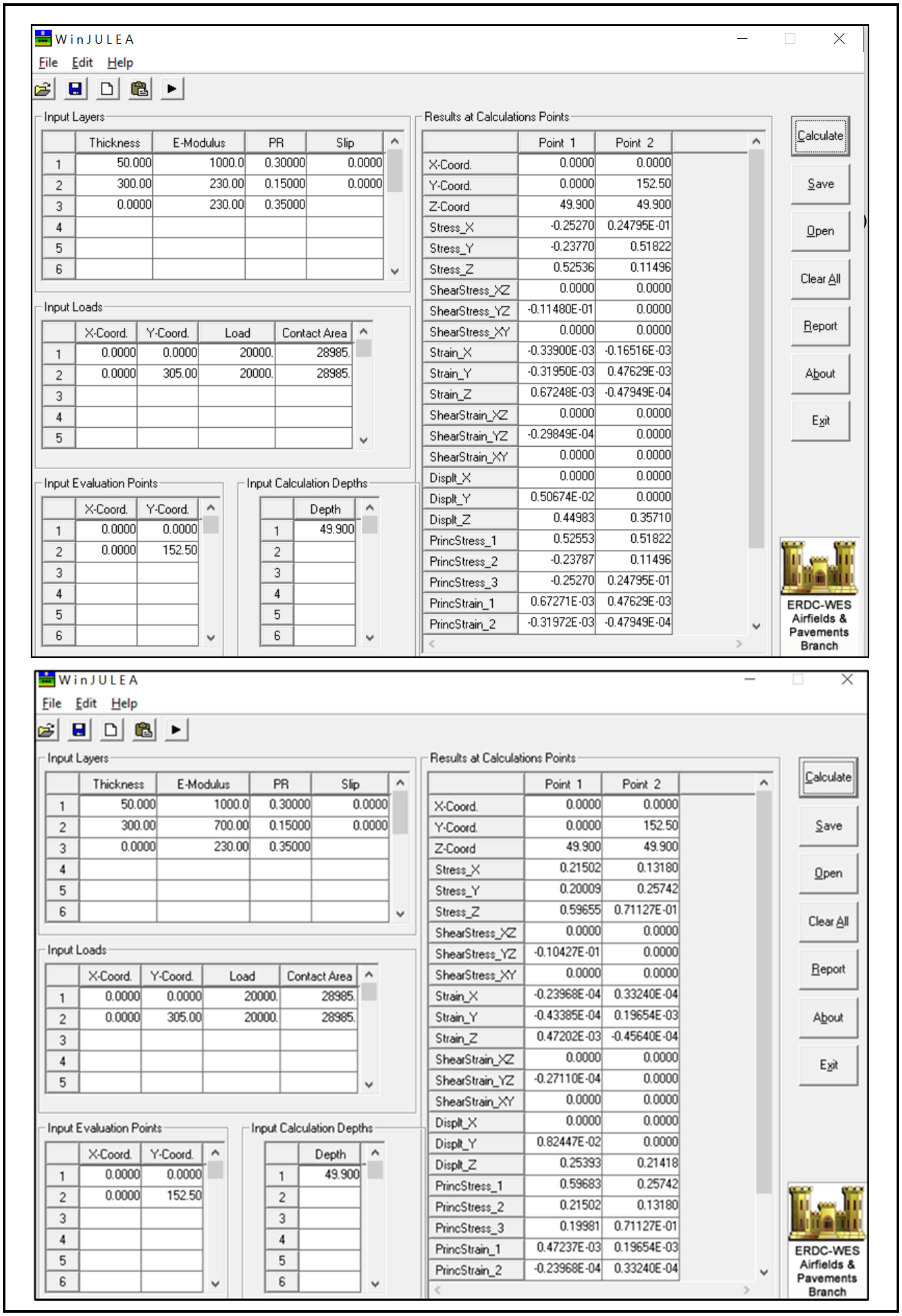

Figure 3.10 Comparative Structural Analysis (100%; 0%)
on top of figure vs (30%:70%) and 7% OPC at bottom of figure

The Asphalt Institute (1982) relationship (Ekwulo and Eme 2009) between tensile strain at the bottom of the asphalt concrete (AC) under one single axle load, and the number of repetitions of the axle load until fatigue failure of the AC occurs, is as follows:

$$N_f = 0.0796(\varepsilon_t)^{-3.291} (E)^{-0.854} \quad (3.1)$$

Where:

N_f: Number of 8-ton axle load applications to failure, i.e., cracking occurs at bottom of AC

ε_t: Horizontal tensile strain at the bottom of asphalt layer ($476 * 10^{-6}$ or $196 * 10^{-6}$)

E: Elastic Modulus of the AC (1,000 MPa or 145,000 psi).

As such, the structural life of the pavement is increased from 267,000 8-ton axle loads to 4,957,000 8-ton axle loads or over eighteen times (18X), in accordance with the Asphalt Institute formula (E in psi), before fatigue cracking is developed in the asphalt concrete wheel paths.

3.8 Conclusion

This research evaluated the effects of using soil stabilization on locally sourced desert sand in a base or subbase layers in flexible road pavements. For this purpose, compaction, CBR and UCS tests were performed on the two mixtures of sands with diverse percentages of cement. The test results indicate that the MDD and the OMC of mix 50%:50% and mix 30%:70% were found to increase with the increase in the cement content. The soil particles in the 30%:70% mix are more consistently coated with cement, resulting in an increase of the CBR at 2.5 mm penetration from 23% to 68% and therefore a substantial increase in structural life (18 times). Because of this improved skeleton matrix, the sand particles can tolerate higher loads, shown in the higher CBR results and structural life. The increase in the CBR in terms of the cement percentages is predictable, with the higher amounts of cement showing slightly better results. The high percent of the natural sand in the mix 30%:70% demonstrates the slightly beneficial effect of the cement in salvaging a poor material. The increase in UCS is not linear for both the mixtures of sands. The value of UCS strength increases by adding the proportion of cement content and curing time. Overall, this study has shown that there are both economic and practical reasons to favor using mixes with a higher percentage of desert sand.

CHAPTER 4

STRENGTH AND PERMEABILITY POTENTIALS OF CEMENT-MODIFIED DESERT SAND FOR ROADS CONSTRUCTION PURPOSE

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4.1 Abstract

The costs associated with the extraction, crushing, transportation over long distances and stockpiling of crushed fine aggregate (CFA) as a material for base and subbase layers in roads construction can be very prohibitive in areas where good construction material is scarce. An example is the 12B USD East-West highway in Algeria at a cost of over 10 M USD per km. This creates the need for an assessment of improvement strategies of local materials, such as natural desert sand (NDS). NDS is considered unfit for road construction, mainly because of the poor cohesion between particles and its low bearing capacity. However, when mixed with CFA and a small amount of ordinary Portland cement (OPC), it may be used successfully, and project costs can be limited while creating an exceptionally strong pavement. This experimental research builds on a previous study that evaluated the optimal ratio of NDS versus CFA. In addition, this paper examines the optimal percentage of OPC in the fine aggregate mix. The percentages tested were 0, 3, 5, and 7% of OPC. The tests carried out are California bearing ratio (CBR), compaction, permeability, unconfined compressive strength (UCS), and shear strength parameters. The UCS test was used to determine the critical level of OPC that improved the mixture's mechanical properties. Factors that substantially impact mechanical properties, were the cement ration, curing time, dry density, and moisture content.

Keywords: Desert sand; Cement; Permeability; CBR, UCS; Road construction.

4.2 Introduction

Infrastructure construction in Libya often uses natural desert sand (NDS) from local deserts that cover a great proportion of 70% of the country. While it is possible to use NDS, the rounded shape of the sand grains do not allow to produce a base or subbase with a sufficient bearing capacity to support traffic loads. This is because the grains of NDS have been rounded after many years of movement created by the wind and the environment. This results in a low-quality foundation that, in turn, results in a road that will deteriorate rapidly and reach its design service life faster (Little 1998). In order to use this plentiful resource of NDS, soil stabilization must be done on the supporting base and subbase layers to create a suitable foundation for the road (Kalantari and Huat 2008). Soil stabilization is done by introducing a binding material, either a kind of cement, chemical, or other nonreactive binders; these are mixed with the NDS or other low-quality soils (Haeri et al. 2005). However, a common method for low-quality soils is to use ordinary Portland cement (OPC) to increase the shear strength and capacity of the soil (Haeri et al. 2005; Schnaid, Prietto, and Consoli 2001); this allows engineers to design roads using non-cohesive materials that have not enough strength to bear heavy loads over its service life, such as sand or gravel (Onyelowe 2016).

Furthermore, every soil type has particular properties that engineers must account for in order to design a road that can distribute the various stresses it will receive over its service life. Roads that are built from poor grade soils suffer from premature failure due to the following: firstly, high total axle-loads combined with low tire pressure; secondly, excessive moisture content in the soil; and thirdly, use of complicated design and maintenance techniques (Magafu and Li 2010).

Generally, engineers employ the standard estimate for tire pressure, i.e. 900-1000 kPa. This is a higher tire pressure than is the one used during laboratory experiments, including the AASHTO standard test (conducted at 500 kPa). When designing a roadway, the engineer uses the standard estimate for tire pressure of 900-1000 kPa. This is a higher tire pressure than that which is used during laboratory experiments, including the AASHTO standard (conducted at 500 kPa). The materials in the flexible pavement layers are assumed to be homogeneous, elastic, and isotropic. Figure 4.1 shows vertical stresses are greatest at the surface (i.e., at a depth of 0 cm) and the stresses go down as the depth increases (Johansen and Senstad 1992).

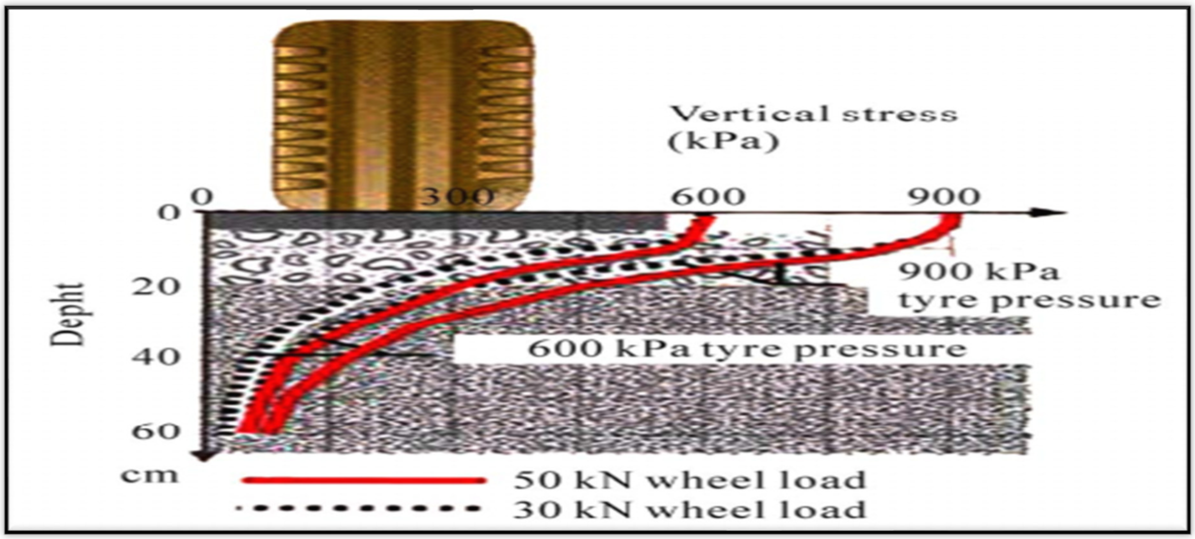

Figure 4.1 Stresses in flexible pavement with tire pressures of 500 kPa, 600kPa and 900 kPa respectively
Taken from Johansen and Senstad (1992)

Previous studies have examined how the addition of various kinds of cement and how much time is given for it to cure both affect the unconfined compressive strength (UCS) and the stress-strain behavior of sands in the base and subbase layers that have been treated with cement. The most important variables affecting the strength of cement-treated sand were the following: (1) the ratio of porosity and volume, (2) the total cement content, and (3) the total water content (Consoli et al. 2007). With regard to internal friction angle, there is disagreement among researchers as to how much cement stabilization affects it (Lo 2002).

Some researchers such as Fonseca et al. (2009) reported successfull soil stabilization with cement in gravel soils, because it improves both durability and strength of constructions including river rehabilitation works, airfield construction, and roads. In all of these cases, the elastic modulus and the peak strength both increased. However, these samples also exhibit greater brittleness in their stress–strain behavior, notably when there is a high cement percentage (Schnaid et al. 2001). Finally, improving drainage and compaction, reinforcing, and adding natural or manufactured materials (chemical or physical) or some combination of these, are all means of soil improvement (Abbasi, Bahramloo, and Movahedan 2015; Joel and Agbede 2010).

Specimens were prepared with respect to their optimum moisture composition and maximum dry density after determining the aggregate and initial cement mixture (by dry weight of soil). After the aggregate was mixed with cement, samples were cured for 7 days; they were then measured with the hydraulic compressive-strength test; this determined the optimum cement content. For reference, Table 4.1 shows the UCS requirements for a cement treated base that was cured for seven (7) days. The class of road greatly affected the UCS and the material type requirements.

Table 4.1 Cement treated base strength requirements

Country	**UCS (psi)**	**References**
Base course (South Africa)	580-1160	(Baghini et al. 2017)
Base course (United Kingdom)	363-653	(Xuan et al. 2012)
Base course (Australia)	Min-435	(Molenaar et al. 2011)
Base course (China)	435-725	(China 2000)
Base course (New Zealand)	Min-435	(Linares-Unamunzaga et al. 2019)
Sand and gravelly	300-600	(Little and Nair 2009)
United States (ASTM)	3–5	(International 2004)
United States (AASHTO)	3–5	(Highway and Officials 1993)

Haralambos (2009) claimed that the addition of cement to the soil, i.e. desert sand, significantly influences the UCS. Usually, when cement is added to most types of soils (except peat soils), the stiffness and compressive strength of the resulting mixture are increased (Firoozi et al. 2017). Also, Consoli et al. (2009) found that when up to 10% of cement (by dry weight) was added to sand, there was a notable increase in strength and stiffness, changing the characteristics of the sand mix. In addition, the ratio of air voids to cement (η/Cv) was studied by Consoli et al. (2010) which they showed that this ratio is a useful parameter for understanding the UCS and splitting the tensile strength of the sand-cement mixtures. Furthermore, Al-Aghbari et al. (2009) found that shear strength increased as both the percentage of the stabilizer in the mix and the curing time given to the mix increased. Finally, the main objective of this research is to reduce project cost by using CFA and small amount of ordinary Portland cement (OPC). The tests carried out by California bearing ratio (CBR), compaction, permeability, unconfined compressive strength (UCS), and shear strength parameters. Other important factors that substantially impact mechanical properties, were cement percentage, curing time, dry density, and moisture content.

4.3 Materials and Methods

4.3.1 Selection of Aggregates, Cement and Water

In this research, NDS was collected from the deserts in the south of Libya. Figure 4.2 shows the location of collected specimens and Figure 4.3 introduces gradation curves of CFA and NDS. Table 4.1 and 4.2 show the critical engineering properties of these fine aggregates and X-Ray Fluorescence (XRF) results, before any treatment. Furthermore, Table 4.3 illustrates the characteristics of ordinary Portland cement used in the experimental protocol, in conformance with the ASTM C150 and ASTM C114 standards for chemical properties. Cement that did not meet these criteria were rejected. Water free of oils, alkalis, acids, and otherwise, as defined in ASTM D 4972 standard was used for this research.

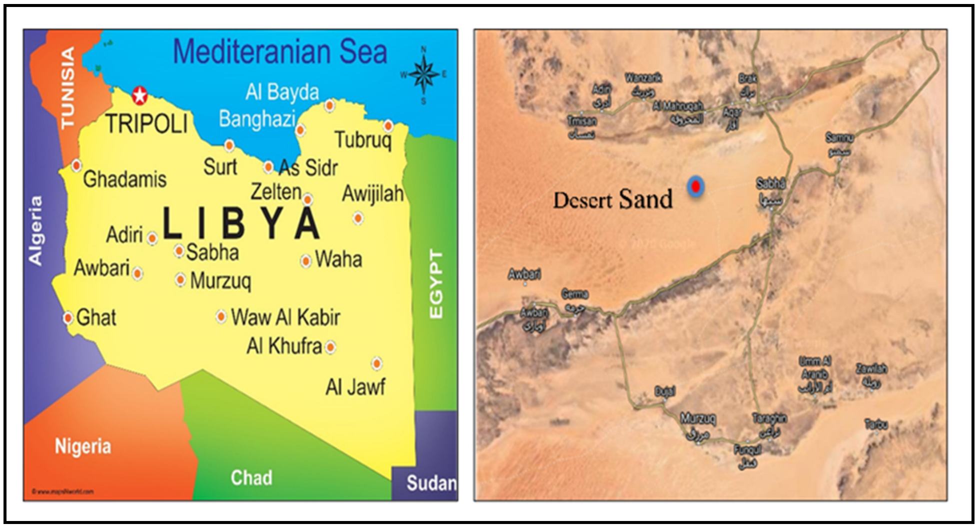

Figure 4.2 Location of collected desert sand for this research study

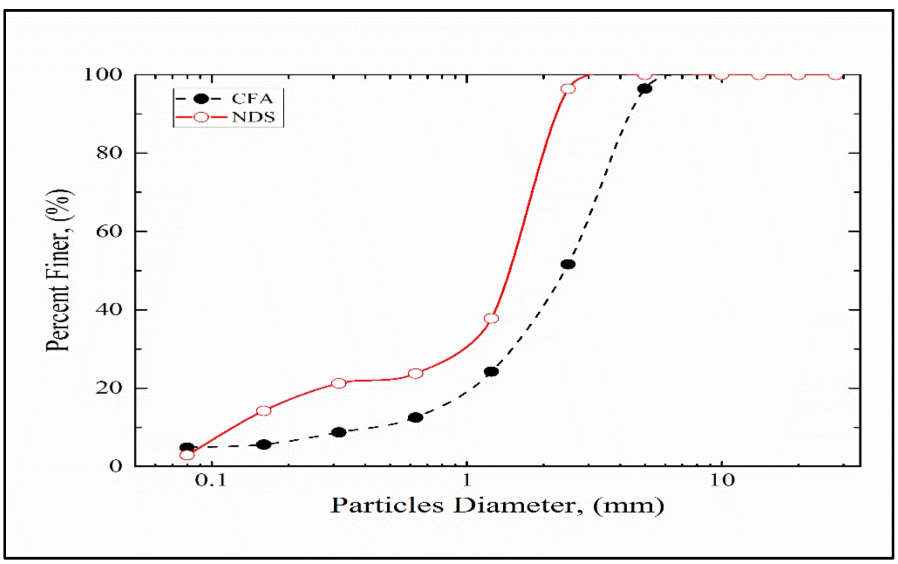

Figure 4.3 Distribution of grain size for collected CFA and NDS

Table 4.2 Properties of the sand mixture

Sand properties	Test result	Standard
Coefficient of uniformity (Cu)	4.59	ASTM D2487
Coefficient of curvature (Cc)	1.12	ASTM D2487
Specific gravity	2.64	ASTM C 127/C 128
Classification	GW	ASTM D 2487
Gravel (80 - 4.75 mm), %	58.23%	ASTM C 127/C 128
Sand (4.75 - 0.075 mm), %	41.53%	ASTM C 127/C 128
Silt & Clay, %	0.25%	ASTM C 127/C 128

Table 4.3 XRF results of Natural Desert Sand (NDS)
and Crushed Fine Aggregate (CFA)

Chemical composition	NFS (%)	CFA (%)
Silica (SiO_2)	83.12	87.10
Aluminum (Al_2O_3)	11.51	8.04
Iron (Fe_2O_3)	2.53	1.31
Potassium (K_2O)	0.34	0.12
Titanium (TiO2)	0.51	0.18
Calcium (CaO)	0.23	0.08
Magnesium (MgO)	0.11	2.16
Sulphur (SO_3)	1.33	0.08
Sodium (Na_2O)	0.12	0.93
Barium (BaO)	0.13	-
Manganese (MnO)	0.07	-

Table 4.4 Chemical Component of OPC

Compound	%
SiO_2	18.20
CaO	59.03
MgO	1.80
AL_2O_3	5.09
Fe_2O_3	3.15
Na_2O	0.18
K_2O	0.29
SO_3	2.65
Loss on ignition (LOI)	7.91
	1.02

4.4 Experimental Procedures

4.4.1 Relationship of Moisture Content to Dry Density

A modified Proctor test was carried out on the untreated sample and treated samples with OPC (with 3, 5 and 7% of OPC). Compaction parameters were evaluated according to ASTM D 1557. One of the overriding factors affecting the strength of the final cement-stabilized soil is the dry density of the compacted aggregate. Water is required to reach maximum density, as well as for simple cement hydration. The experimental compaction method determines balance between the dry density and the water content of the aggregate/cement mix. Specimens for the modified Proctor test, are produced with a metal mold in the form of a cylinder with an internal diameter of 101.60 mm and a total volume of 944 cm^3. In this test, the hammer had a 4.5 kg mass and falls freely from a height of 457 mm. Samples were prepared with the given percentage of cement and then added to the aggregate; the OPC in the test followed by ASTM C150 and C595 specifications. Finally, the mixture was mixed until it showed a consistent color. The compaction curve was used to calculate both the maximum dry density (MDD) and the optimum moisture content (OMC).

4.4.2 California Bearing Ratio (CBR)

CBR index, as main parameter of the foundation of pavement structure, is used to design all types of pavements: flexible and treated ones. The CBR test was used in the experiments and the test was verified according to ASTM D1883 standard, used to predict the strength of the stabilized soil mix for use in a base or subbase. The samples were packed into a cylindrical metal mold having an inside diameter of 152.4 mm and a height of 177.8 mm, treated soils were compacted layer by layer, for a total of five layers. The tests were carried out for unsoaked samples. Equations (4.1) and (4.2) are then used in the calculation of CBR values as follow:

$$\mathrm{CBR\%} = \frac{P}{6.9} * 100 \tag{4.1}$$

$$CBR\% = \frac{P}{6.9} * 100 \tag{4.2}$$

Where:

CBR, California Bearing Ratio (%);

P, Load (MPa).

4.4.3 Unconfined Compressive Strength (UCS)

One of the main objectives of the UCS test is to evaluate the mixture's compressive strength and to be sure that it shows enough cohesion to allow tests when the samples are no longer confined in the cylinder. The samples were therefore first prepared following ASTM D 2166 guidelines in a metal cylindrical mold having an internal diameter of 50 mm and a height of 100 mm. Also, treated specimens were then cured for 7, 14, 28, 60, and 96 days. Figure 4.4 shows the UCS machine used in this research (image on the left) and some treated samples after compression test (image on the right).

Figure 4.4 UCS apparatus (image on the left) and treated samples after failure (image on the right)

4.4.4 Triaxial Test

The preparation of the triaxial test samples followed ASTM D7181 standards and were used to determine parameters of shear strength pertaining to cohesion, poison ratio, and frictional angle of the sample mix, each with their given cement percentage. Each sample had a height of 100 mm and a diameter of 50 mm; to achieve target density, each was compacted in the split mold in three (3) stages, each with an equal amount of mix. For this, they were packed into the triaxial chamber, and this was filled with water; the sample was then subjected to a total pressure of 50 kPa. Within 24 h, the sample reached saturation. At this point, drainage valves were opened, and the confining pressure was raised to the target value. In the consolidation stage, lasting about 1 h, the samples were subject to this confining pressure. Afterward, the shear test was applied. Pressures were kept constant throughout the test. Figure 4.5 shows the sample from triaxial machine test, before (image on the left) and after failure (image on the right).

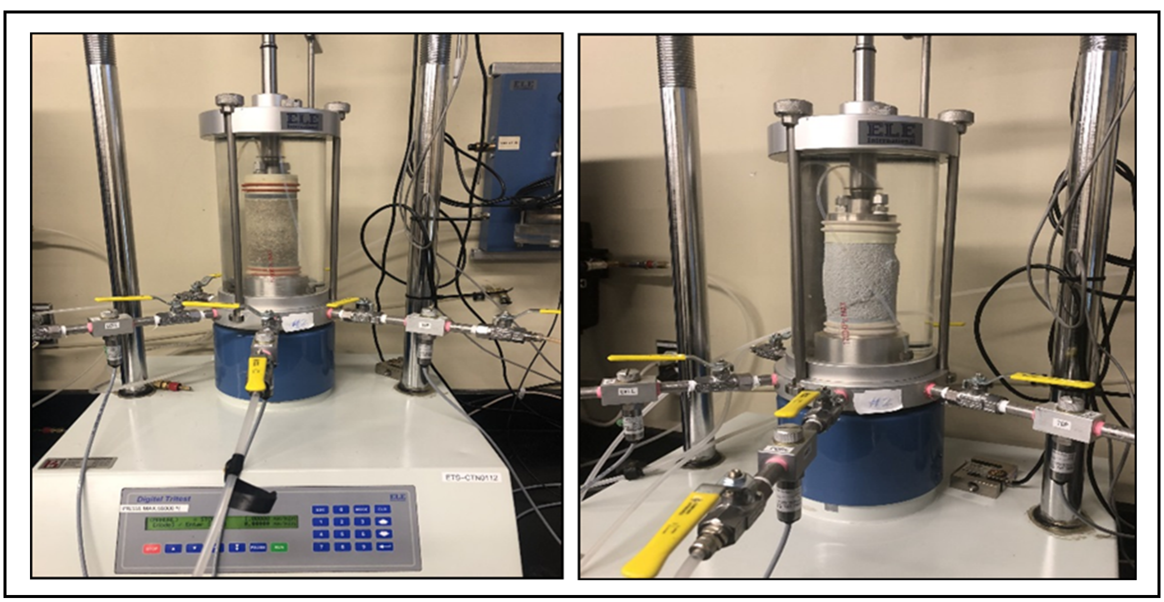

Figure 4. 5 Triaxial machine test setup (left) and the sample after shear stress (right)

4.4.5 Permeability Test

The triaxial instrument was employed to assess the coefficient of permeability (*K*) for treated samples, according to ASTM D5084. The samples were 100 mm high and 50 mm in diameter, as shown in Figure 4.6. Furthermore, samples were compacted at OMC and MDD after being cured for 28 days. The constant head permeability for the untreated sample was 3.1×10^{-3} cm/s. Also, hydraulic conductivity for treated samples have been conducted after saturation, usually a period of 24 to 48 hours. Once these parameters were measured, hydraulic conductivity was calculated using Darcy's law, as in the equation below:

$$K=\frac{Q.L}{A.t\ .\Delta h} \tag{4.3}$$

Where: Δh, Water head represented by the difference of the water supply level and the overflow level (cm); A, area of the sample cross section with regard to the flow direction (cm^2); L, Sample length (cm); Q, water quantity collected over time (t), shown in (cm^3).

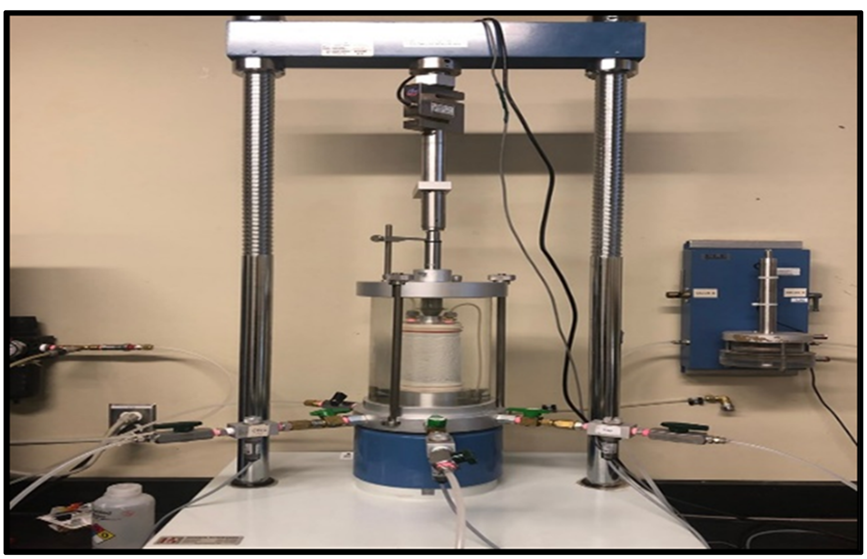

Figure 4.6 Triaxial apparatus and setup for the permeability test

4.5 Results and Discussion

4.5.1 Moisture Density Relation

Figure 4.7 shows the Proctor compaction test results. As discussed by Lade et al. (1998), when fine particles are added to a matrix of coarse particles, the result is an overall reduction in the air void ratio until the point where fine particles have filled all the voids. The result is an increase in the dry density until a given mix ratio (fine to coarse particles) is met. Figure 4.8 shows the maximum dry unit weight variation when cement is added to the sample mixture. There is an observable marginal increase in the dry unit maximum weight of the sand/cement mixture as the cement percentage increases. Also, the relation between cement and moisture is shown in Figure 4.8.

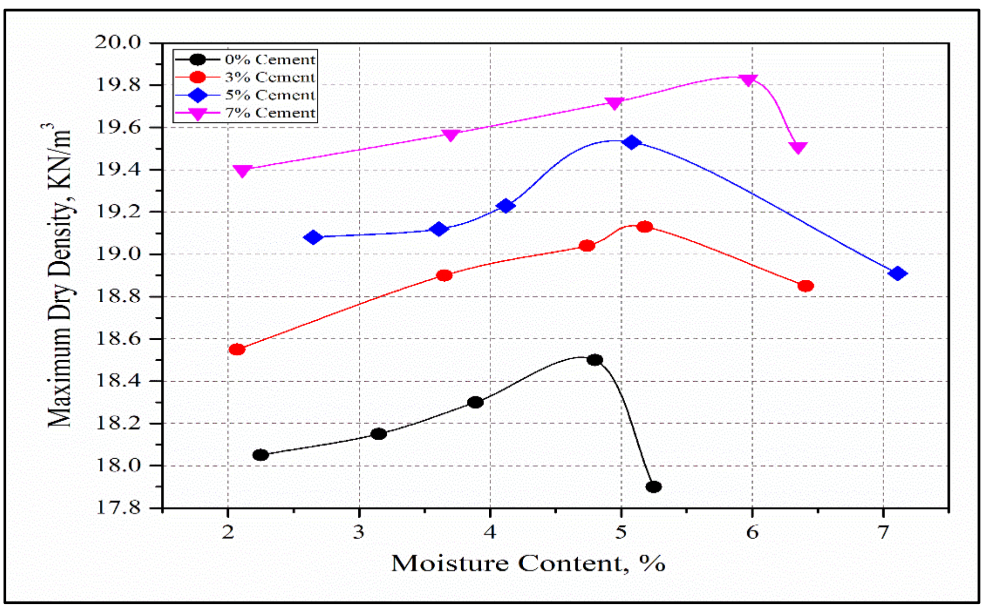

Figure 4.7 Compaction curves for mixture sand at different Cement content

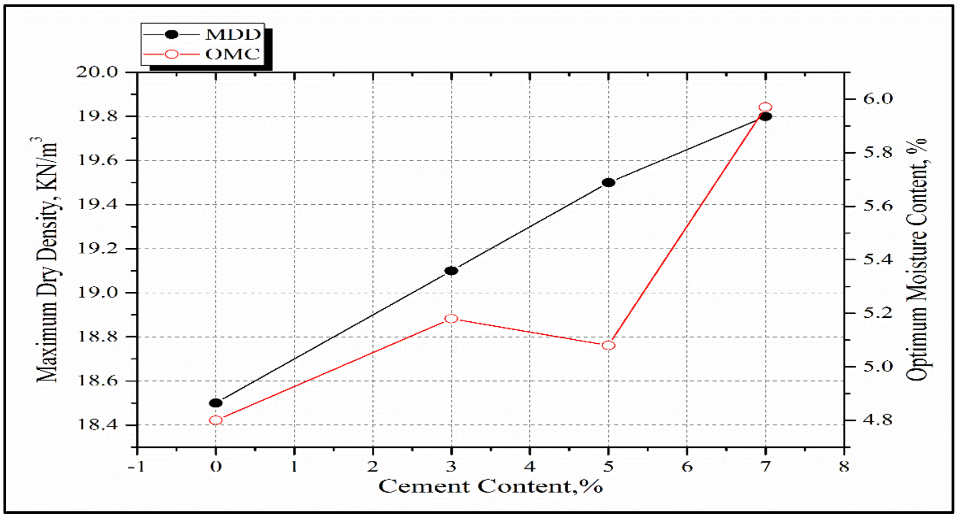

Figure 4.8 Effect of different percentages of cement on MDD and OMC

4.5.2 Impact on the California Bearing Ratio (CBR)

One of the main objectives from this experimental research was the effects of OPC on NDS mixture. Figure 4.9 shows the results from samples that treated by 0, 3, 5, and 7% cement and shows the correlation load-stress versus penetration depth. In addition, Figure 4.10 shows the CBR's effect on the cement content mixture: CBR values, with a 2.5 mm penetration, were 59.26, 61.64, 64.02, and 67.72 %, respectively. With a 5 mm penetration, the CBR values were 58.5, 60.01, 57.59, and 60.01 % respectively. The CBR values at 2.5 mm penetration are higher than the CBR values at 5 mm penetration for all amounts of cement. Beyond this, the highest CBR value was found by stabilizing the sand with 7% OPC for 2.5 mm and 5 mm penetrations, respectively, at 67.72% and 58.26 %. This finding suggests that the use of high percentages of OPC results in a higher CBR.

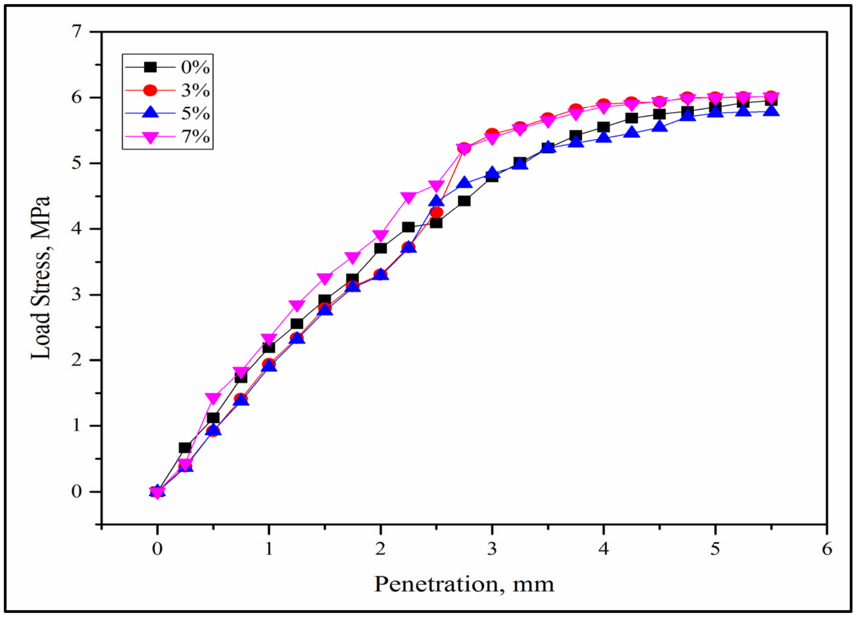

Figure 4.9 Penetration curves for CBR test for mixture soils stabilized with cement

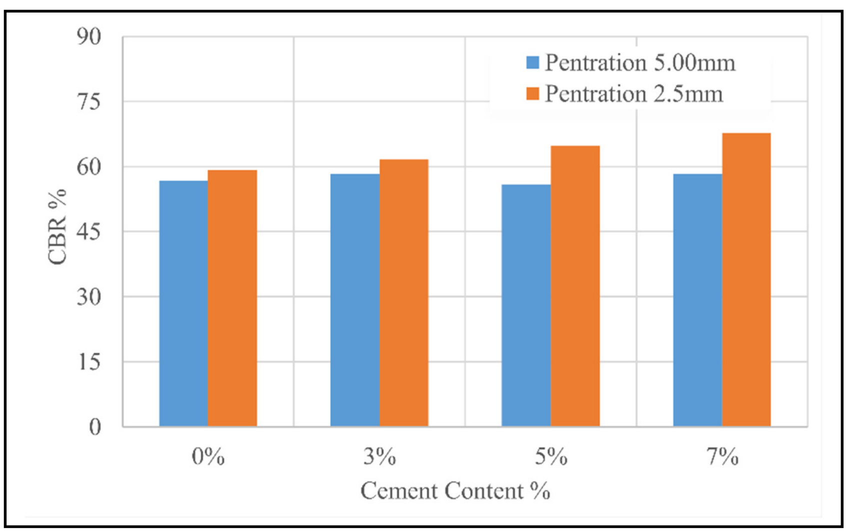

Figure 4.10 Variation of CBR value with varying cement content

4.5.3 Compressive Strength Changes

Figures 4.11 and 4.12 show the effect on UCS of OPC percentages and curing times of 7, 14, 28, 60, and 90 days. As shown in these figures after seven (7) days, UCS significantly raises with higher amounts of OPC added. The values go from 0.89 MPa with the addition of 3% OPC to 3.352 MPa with the addition of 7% OPC (refer to figure 4.11). Also, strength increase is nearly linear, as shown figure 4.11. A similar trend can be noted with a curing time of 14, 28, 60, and 96 days.

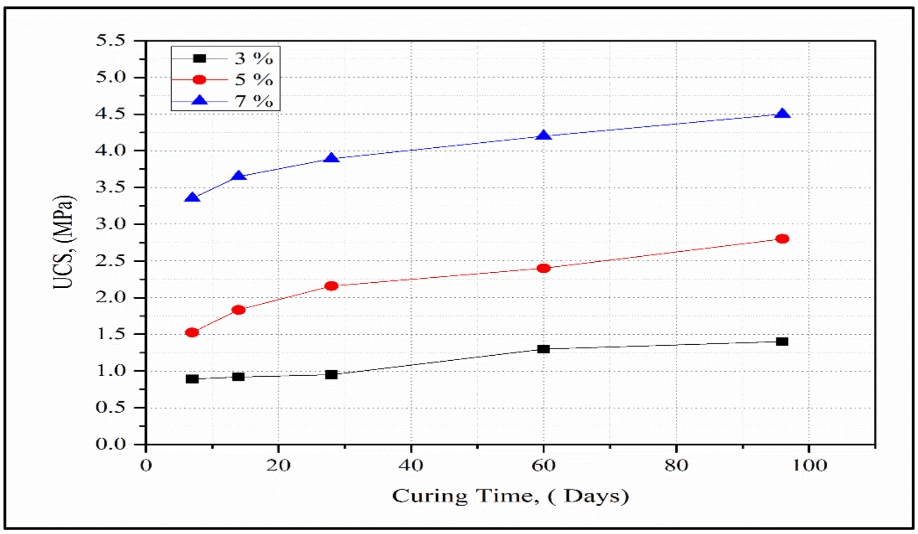

Figure 4.11 Effect of various percentages cement on UCS test results

Figure 4.12 shows how USC varies with regard to curing time. These data indicate that 3% OPC content with a 7-day curing time gives a UCS value of 0.89 MPa and UCS increases to 1.35 MPa with a 96-day curing time. Other OPC amounts show similar increases.

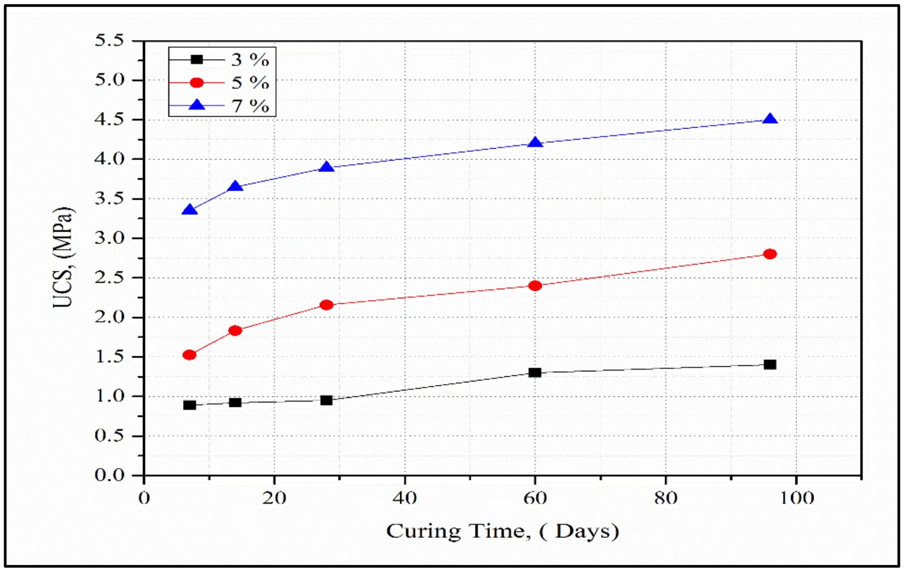

Figure 4.12 Effect of curing times (7, 14, 28, 60, and 96 days) on treated samples

4.5.4 Triaxial behavior of Sand Mixture Treated by OPC

Resistance to shearing was evaluated by means of triaxial testing; these results are shown in Table 4.3 and Figure 4.13. With the addition of 3, 5, and 7% OPC, the behavior of the sand, with respect to shearing factors, was predictable: Poisson's ratio (μ), cohesion (C), and the friction angle (Ø°) are all improved. Also, both cohesion and friction angles showed improvement with the addition of 7% OPC.

Table 4.5 Triaxial behavior NDS when treated with OPC

Triaxial property	**Proportion of cement by weight additive (%)**		
	3	5	7
C (kPa)	160	170	194
Ø (°)	24	35	40
μ	0.42	0.41	0.39

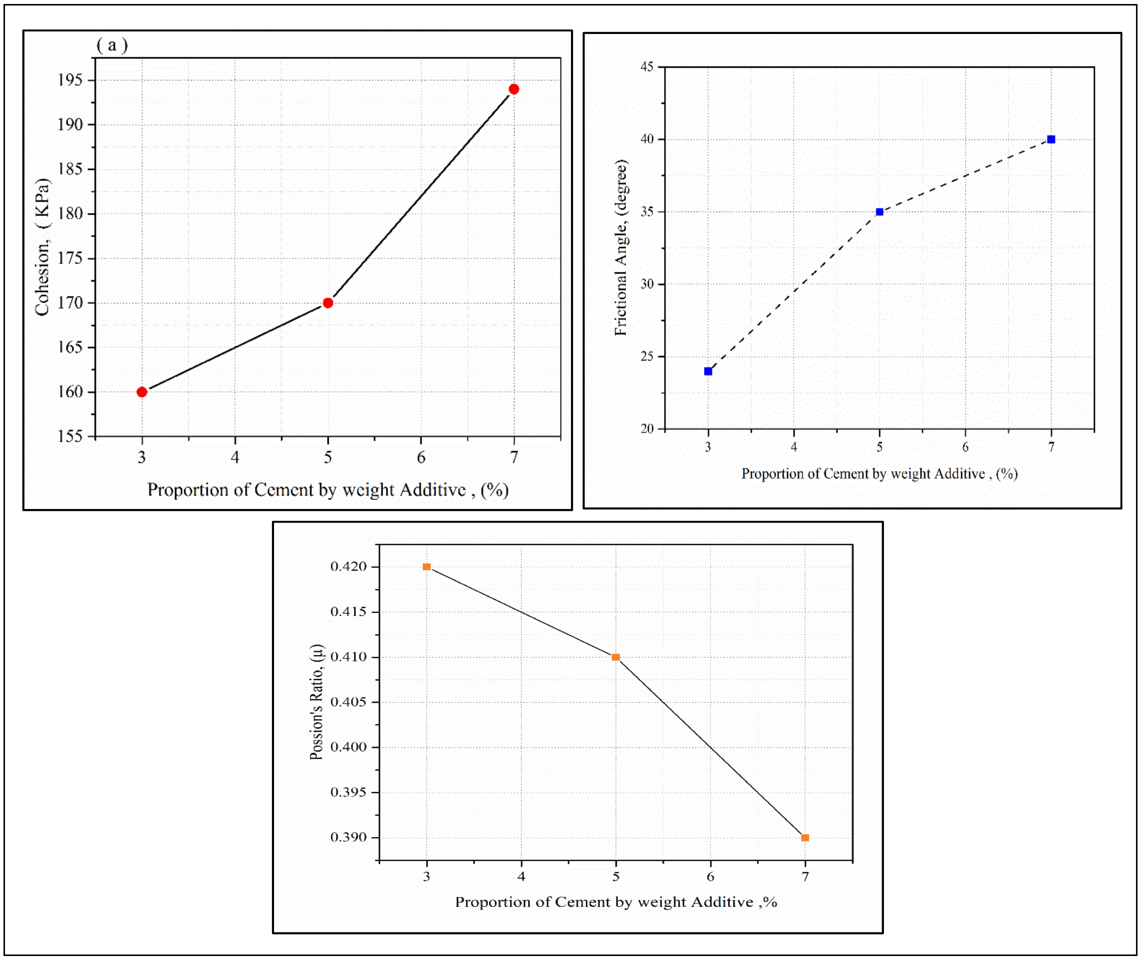

Figure 4.13 Triaxial behavior of OPC treated aggregate

4.5.5 Sand-Cement Mix Permeability

The samples were prepared at optimum moisture content, cured for 28 days then subjected to permeability tests. Figure 14 shows the effects of OPC percentages and of curing times on the aggregate mix permeability. At 3% OPC, the coefficient of permeability of the mixture is about 8.63×10^{-5}cm/s while at 7% OPC, it goes down to 1.33×10^{-5} cm/s.

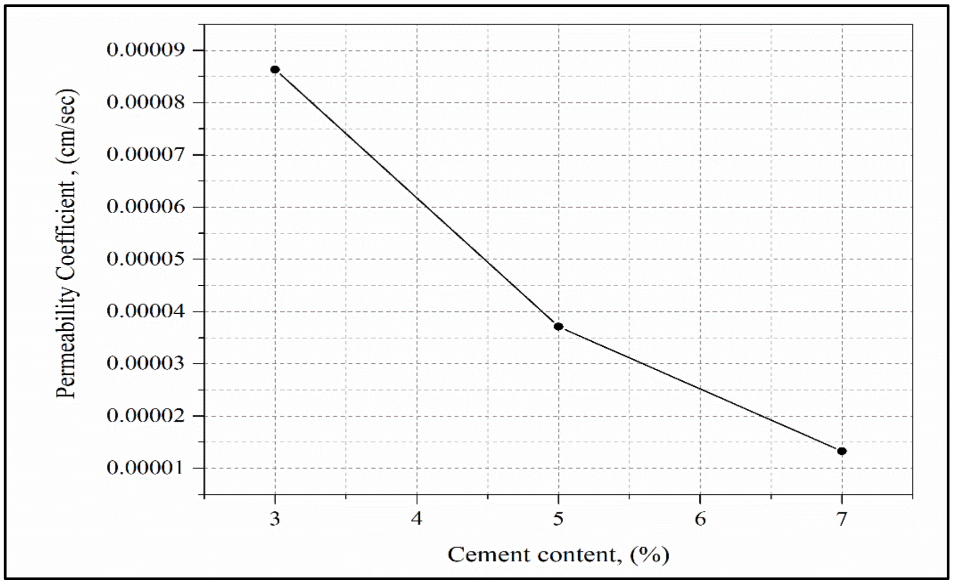

Figure 4.14 Permeability coefficient variation with specified OPC content

4.6 Conclusion

The main achievement of this research is the assessment of the behavior of NDS, with the addition of 7% OPC and sufficient curing time, when placed as a base and subbase layers in roads construction. For laboratory testing, samples were made with 70% NDS and 30% manufactured fine aggregate. These exhibited three times higher strength and bearing capacity when treated with OPC than samples without the addition of OPC. Samples with higher percentages of OPC (i.e., 7%) gave superior results to samples with lower percentages or zero OPC content.

The characteristics evaluated are compaction, gradation, CBR, UCS, shear strength parameters and permeability. The study findings are as follows:

1. A combined aggregate mix including NDS and mechanically crushed sand, benefits from OPC stabilization because the aggregate gains strength and stability, thereby creating quality

base and subbase layers. Compressive strength was also increased with the addition of more OPC.

2. There is a significant change in the behavior of NDS when mixed with mechanically crushed sand and treated with various percentages of OPC, namely 0, 3, 5, and 7%.
3. The maximum dry density and the optimum moisture content increased with greater OPC content. Mixes with 7% OPC showed lower permeability compare with other treated samples.
4. The base and subbase layers reinforced with OPC had high CBR values. Therefore, the overall thickness of the individual layers could be reduced, limiting project costs.
5. With added OPC in the fine aggregate mix and a sufficiently long curing time, cohesion and angle of friction are greatly improved. This is a practical strategy for building base and subbase layers of acceptable quality while keeping costs under control.
6. A fine aggregate mix with NDS, once stabilized with OPC, is a practical alternative to other fine aggregate or granular mixes and it is suitable for use in pavement construction.
7. The mixes presented in this paper are suitable for industrial application for building cheap and reliable base and subbase layers.
8. This research contributes to the practical knowledge of how to best use commonly available materials for building highways and civil engineering projects.
9. Ordinary Portland cement (OPC) is recommended as an excellent material to improve both the mechanical and physical strength of construction projects; it also supports the long-term environmental use of natural soils such as natural desert sand.

CHAPTER 5

IMPROVEMENT OF PAVEMENT SUBGRADE BY ADDING CEMENT AND FLY ASH TO NATURAL DESERT SAND

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5.1 Abstract

Soil characteristics are paramount to design pavements and to assess the economic viability of a road. In the desert, such as that found in southern Libya, the very poor quality of soils leads to important pavement distress such as cracks, rutting, potholes and lateral shear failure on the edges. To improve the strength of desert sand, an innovative approach is proposed, consisting of adding manufactured sand, Portland cement and fly ash as binder. Portland cement and fly ash improve the characteristics of mixes of crushed fine aggregate (CFA) and natural desert sand (NDS). These results are based on a gradation of two sand sources to determine the particle distribution and X-Ray Fluorescence (XRF) to determine their chemical and physical properties, respectively. This research assesses the effect of cement and fly ash on the geotechnical behavior of two mixtures fine desert and manufactured sands (30:70% and 50:50%). The mix composed of 26% of CFA, 62% of NDS, 5% of Portland cement and 7% of fly ash, shows optimal results in terms of strength, compaction and bearing capacity characteristics.

Keywords: Cement, Fly ash, Pavement construction, UCS, Soil stabilization, CBR.

5.2 Introduction

Transportation network efficiency is crucial for the functioning of the world economy. Roads are some of the oldest and most popular modes of transportation (Raheel et al. 2018). The pavement materials used in the building of roads fall into two broad categories of rigid and flexible, respectively. The cement concrete layer in rigid pavement is primarily load bearing, while the asphalt layer in flexible pavement is the wearing course (Pasindu, Gamage, and Bandara 2020; Tsubota et al. 2018). Pavement design must account for the increase in road use and technological innovation that gives vehicles greater load-bearing capacity, since road structural integrity can be compromised from the corresponding increase in stress (Cheng et al. 2020; Chen, Saha, and Lytton 2020). Road structure is typically made up of four layers, which include the wearing course, base course, subbase course and subgrade. The effective transfer of design axle load from the top to the adjacent layers of the pavement depends on the materials, mechanical properties and thickness of the respective layers (Han et al. 2020). The subgrade layer has the lowest CBR and maximum dry density (MDD) of all other layers, and it is also the most plastic with the highest plasticity index (PI). As well, environmental conditions including high groundwater table can significantly weaken subgrade soil (Zhang et al. 2021). Pavement design accounts for these environmental issues by using thicker above subgrade road layers, a more robust material in lieu of subgrade, or overall stronger, more rigid pavement (Abukhettala and Fall 2021).

The characteristics of a soil for road construction is critical in a feasibility study: the poor quality of soils, especially in desert areas, challenges the pavement design and the economic viability of a road project. In deserts, the absence of water explains the formation of soils through the effects of erosion, heavily blowing winds, sedimentation, and important temperature changes between day and night, which results in the breakdown of the rocks into sand or gravel (Li et al. 2009). The fine-grained, round-shaped and smooth nature of desert sands leads to poor strength. The typical round-shape of desert sand grain affects the mechanical interlock between aggregates, and after adding cement, that affects the stability of the mixture and the fresh concrete properties (Neumann and Curbach 2018). Therefore, desert sand do not often meet the technical requirements to be used as a pavement subgrade, if untreated (Abderrahmane and Ratiba 2013).The use of desert sand for construction purposes has recently gained attention as it improves the physical and chemical properties of mortar (Al-Aghbari et al. 2009). The strength of the desert sand concrete (DSC) is equivalent to that of the ordinary concrete, as shown by (Amel et al. 2017; Haifeng et al. 2017; Luo et al. 2013). However, the physical and mineral composition of desert sands varies depending on regions where they are formed (Che et al. 2019).

Cost can be a significant barrier to implementing the above strategies, and it is best to exhaust all available options for improving the existing subgrade properties before replacing it. Subgrade can be stabilized using a variety of pozzolanic and industrial materials including lime, fly ash, silica fume, cement, and bentonite among others (Rahman et al. 2021). Additionally, sourcing usable road-building materials from construction waste can be an effective waste management strategy. Coal consumption produces large amounts of fly ash, which is a low-cost and reusable construction material (Miricioiu et al. 2021). Despite its common use in construction, fly ash remains an under-researched material and source of potentially useful compounds with interesting properties. One study uses the combination of cement, polymers, enzymes and fly ash for the stabilization of subgrade soil. The bearing capacity of soil was found to be improved using the mixture of fly ash, cement and enzymes, consequently reducing overall road layer thickness (Karami et al. 2021).

The process of stabilizing the desert soil with cement decreases its compressibility and its permeability, and further increases its strength, its bearing capacity and its durability. It also reduces construction cost by utilizing local materials (Amhadi and Assaf 2019; Teing et al. 2019). Furthermore, the use of cement to improve the engineering properties of soils has already been adopted (Cong, Longzhu, and Bing 2014; Rahgozar and Saberian 2016; Saberian and Khabiri 2018; Wong, Hashim, and Ali 2013) and this is mainly due to the hardening of cement in the presence of moisture and during the curing period (Al-Aghbari and Dutta 2005). Previous study on the effect of demolition waste on the compaction properties and unconfined compressive strength of weak soil (Rahardjo, Gofar, and Satyanaga 2018) showed that the addition of waste particles decreases the optimum water content and increases the dry unit weight of clay while the unconfined compressive strength increased quite significantly with addition of concrete particles.

Cement-lime has been used with good results to stabilize fine and granular soils as well as fine aggregates. Indeed, the lime (i.e. calcium hydroxide) interacts and modifies the clay found in the soil (Amu, Fajobi, and Afekhuai 2005). At the same time, fly ash creates a bond between the particles limiting the expansion and contraction of the material, and therefore the expansion in volume of plastic soils. This phenomenon is similar to the Portland cement effect which limits the fluctuation in concrete mixes. The main objectives of this study are to: (1) Protect the environment by using the cement-fly ash with NDS from quarry materials in engineering projects, (2) investigate the effect of using a combination of fly ash-cement as a stabilizer on the engineering properties of the subbase and base layers, and (3) develop useful and practical relationships between strength, compaction, and the California bearing ratio (CBR) of the treated desert sand materials for practical use in the construction industry.

5.3 Materials and Methods

The desert sand used in the following tests, comes from the desert of Libya where the desert is in excess abundance and even inhibits construction activities because of its characteristics. The sand was prepared in two forms; the natural desert sand and the crushed sand. Table 5.1 shows the results of XRF for natural desert sand (NDS) and crushed fine aggregate (CFA). The sands were mixed in the ratios of 30:70 and 50:50 for crushed sand is to natural desert sand respectively. Ordinary Portland cement (OPC) and fly ash (FA) were secured for use in this laboratory exercise. The OPC was used at a constant percentage of 5% to modify the desert sands while FA was applied in the proportions of 0, 3, 5, and 7% by weight proportion of treated sand. The OPC satisfied the conditions of ASTM C150 (1978) while FA satisfied the pozzolana conditions according to ASTM C618 (1978). The focuses of the stabilization and modification exercise were on compaction properties, California bearing ratio, and unconfined compression properties of the modified desert sands. The addition of these materials to the different properties of sand was investigated via the following experiments: the modified proctor test for evaluating OMC and MDD; CBR; as well as the unconfined compression test of the modified desert sands. In the modified proctor test, the weight of the hammer used was 4.54 kg and its height of fall was 203 mm. The internal diameter and effective height of the mold were 152.4 mm and 177.8 mm, respectively. The sample layers were compacted individually, after which point the OMC and MDD were calculated. In order to perform the CBR test, water of equal volume to the OMC was added to the soil samples. After compaction, the samples were placed in the CBR testing machine, and the test was verified according to ASTM D1883. To conduct the UCS test, the samples were prepared according to ASTM D2216 in a cylindrical metal mold with an internal diameter of 50 mm and a height of 100 mm. The samples were then subjected to an axial load as per the relevant ASTM. Treated specimens were then cured for 7, 14, and 28 hours. Figure 5.1 shows all materials and experimental procedure.

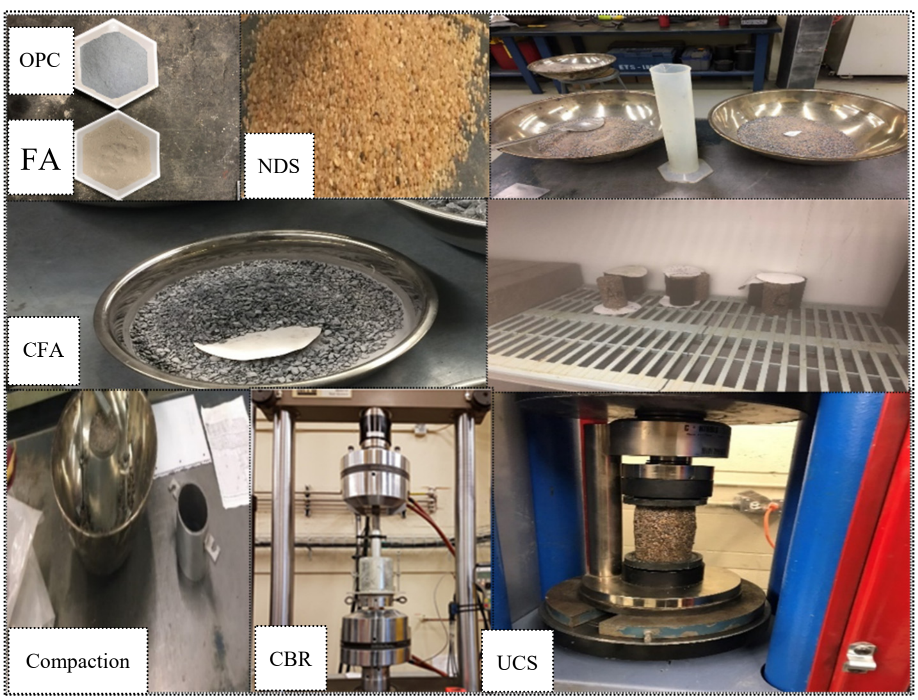

Figure 5.1 A detailed the materials and experimental work

Table 5.1 XRF results of NDS and CFA

Chemical Composition	NDS (%)	CFA (%)
Silica (SiO_2)	83.12	87.10
Aluminum (Al_2O_3)	11.51	8.04
Iron (Fe_2O_3)	2.53	1.31
Potassium (K_2O)	0.34	0.12
Titanium (TiO_2)	0.51	0.18
Calcium (CaO)	0.23	0.08
Magnesium (MgO)	0.11	2.16
Sulphur (SO_3)	1.33	0.08
Sodium (Na_2O)	0.12	0.93
Barium (BaO)	0.13	-
Manganese (MnO)	0.07	-

5.4 Results and Discussions

The compaction characteristics, UCS and CBR values were determined for all soil samples. The results are analyzed and discussed below:

5.4.1 General Classification of Test Materials

The results of the particle size distribution in Table 5.2 and Figure 5.2 showed that an equal percentage of both mixtures at 30:70% and 50:50% passed through sieve no 10 and variations were observed in percentage passing through the other sieves until a uniform percentage 0.2 passed through sieve no 0.080. According to the AASHTO system of soil classification, this soil mix is classified as A-3 (fine sand which would make a good plastering or construction material or modified mortar). Desert sands are classified as similar consistency with dune sands or river sand with no plasticity. Table 5.3 presents the composition of the chemical oxide of the binding materials which were cement utilized at a fixed 5% proportion by weight of treated desert sand. Table 5.3 shows that fly ash is predominantly rich in aluminosilicates than cement, which is predominantly rich in calcium oxide. According to the requirements for pozzolanas in American Standard for Testing and Materials ASTM C618-19, FA is considered pozzolanic materials with the sum of the composition of Silica, Alumina, and Ferrite is more than 70% as presented in Table 5.3. This property makes FA as a good environmentally friendly supplementary cementitious material (SCM) with special properties to resist shrinkage potentials, cracking effect, high temperatures, sulfate attacks, etc. unlike the ordinary Portland cement, which is prone to cracking, sulfate attacks and temperature effects.

Table 5.2 Particle size distribution of test sands

Diameter (mm)	Mixture 30:70 %	Mixture 50:50 %
28.00	100	100
20.00	100	100
14.00	100	100
10.00	98.4	98.4
5.00	41.8	59.7
2.50	24.7	43.6
1.25	7.2	7.6
0.63	5.3	4.5
0.32	2.8	1.9
0.16	1.6	1
0.080	0.2	0.2

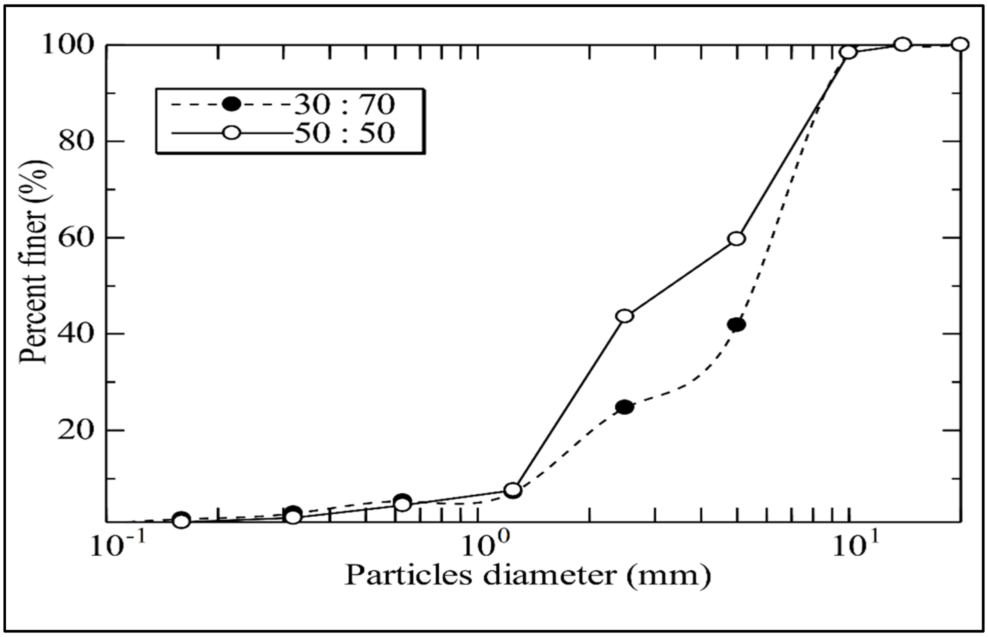

Figure 5.2 Gradation curves for two mixtures of sand (30:70% and 50:50%)

Table 5.3 Chemical composition of OPC and FA

Compound	OPC	FA
	% Composition	% Composition
SiO_2	18.20	62.04
CaO	59.03	9.10
MgO	1.80	1.03
Al_2O_3	5.09	17.21
Fe_2O_3	3.15	4.10
Na_2O	0.18	0.03
K_2O	0.29	1.21
SO_3	2.65	3.88
Loss on Ignition (LOI)	7.91	0.43
Un-solvent materials	1.02	-

5.4.2 Compaction behavior of FA Treated Desert Sand

The influence of a fixed percentage of the cement modified desert soil, mixed with the ratio of 30:70% and 50:50% for crushed and natural desert sands and, treated with FA at proportions of 3, 5 and 7% respectively by weight, on the dry density and moisture content of the soil mixture are shown in Figures 5.3 and 5.4. The maximum dry density (MDD) of both mixtures increases with an increase in fly ash content (i.e., 0 to 7%), was observed. It is found that the 30:70 mix specimen increased substantially with increased fly ash dosages and less than the improvement observed with 50:50 mixture. Also, it was found that the MDD increase from 1.8 to 2.10 gr/cm^3, while the optimum moisture content (OMC) decreases from 5.45% to 4.45% with an increase in the proportion of FA which it was 7% for the mixture of 30:70, and the same trend found for the 50:50 mixture. Furthermore, The MDD improved at an index of 3.96% with the 30:70 mix specimen treated with fly ash while it improved at an index of 3.16% with the 50:50 mix specimen. The result shows that the natural desert sand which is higher in the 30:70 mix specimen played a big role in the substantial improvement recorded. It can be assumed that the desert sand in its natural state will be better than the crushed sand. This is due to the loss of textural strength and particle-particle intergranular force during the crushing of desert sand. Furthermore, it concluded that the cation exchange reaction responsible for densification will more in the 30:70 mix with a higher proportion of natural desert sand than in 50:50 mix specimen. A hydration reaction resulted in an overall reduction in the use of the available moisture. This was because moisture was needed to chemically break down the materials into Ca_2+ and OH- ions thereby facilitating an exchange reaction giving rise to more Ca_2+ being released (Onyelowe, Aririguzo, and Ezugwu 2019). The results show that the use of OPC in the stabilized mix has played a major role in the improvement of the achieved CBR values. A similar result was also offered by (Kolias, Kasselouri-Rigopoulou, and Karahalios 2005), where samples with 4% cement content (5% FA content) proved to be much more viable than 2% cement content samples, where there was no significant improvement post 14 days of curing.

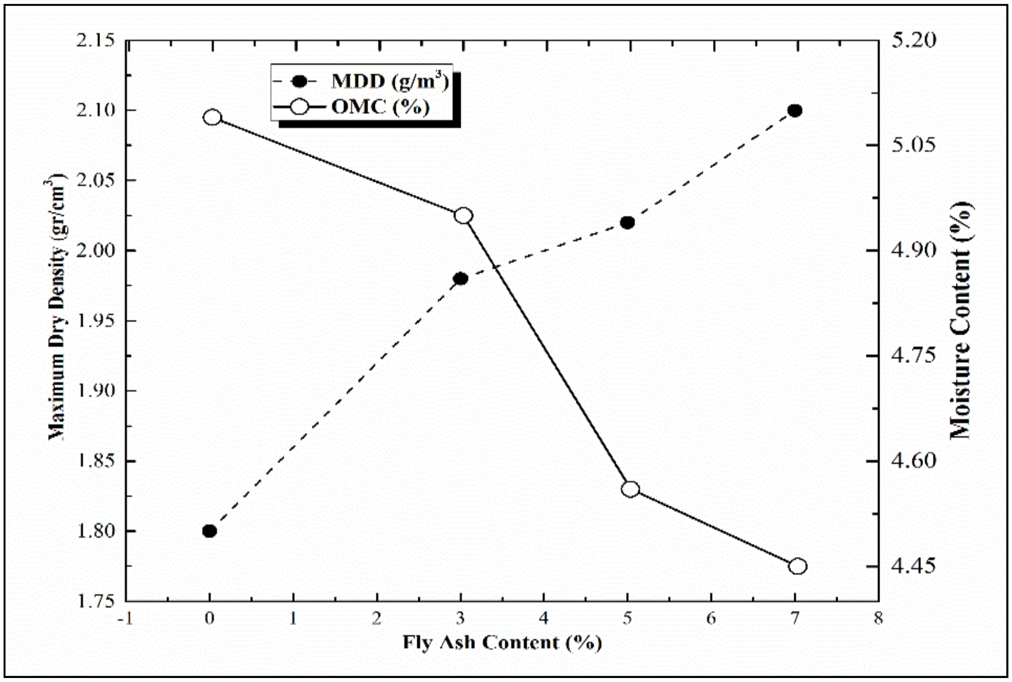

Figure 5.3 Effect of FA on the Compaction of cement modified desert sand (30:70%)

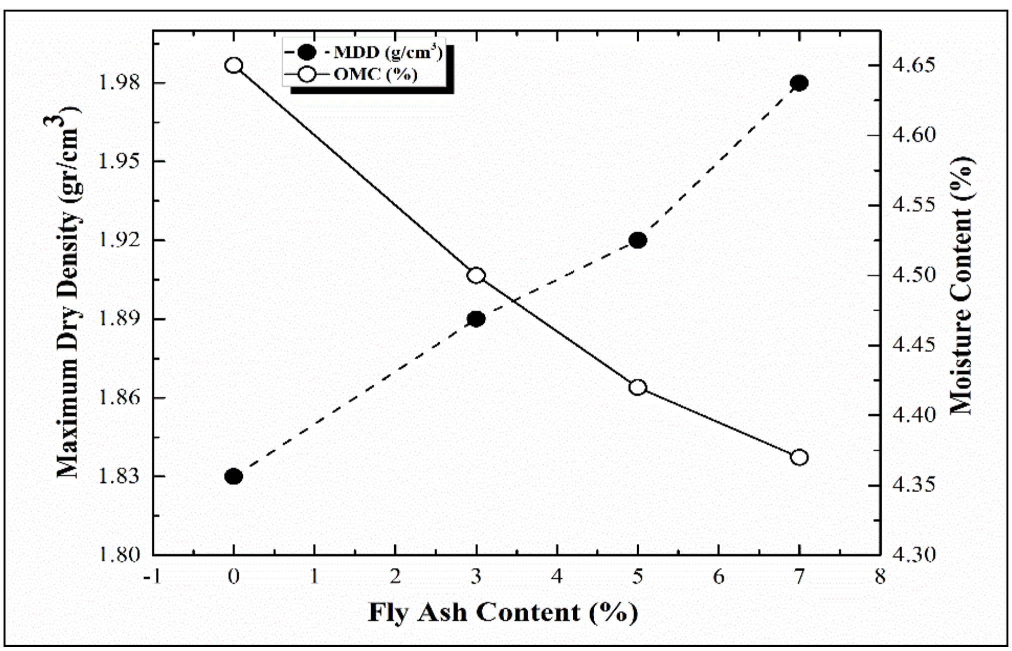

Figure 5.4 Effect of FA on the compaction of cement modified desert sand (50:50%)

5.4.3 Strength Behavior of FA Treated Desert Sand

The CBR test results for samples 30:70 and 50:50 treated with FA at the ratios of 0, 3, 5, 7% and cement kept at a constant proportion of 5% are shown in Table 5.4 and Figure 5.5. The CBR values of mix 30:70 for both 2.5mm and 5mm penetration have shown superior performance than the values of the mix 50:50. The earlier mix showed substantial improvement in the CBR due to the fines higher proportion in the crushed sand. With added FA, CBR shows regular improvement; this might be because enough calcium is freed when Calcium Aluminate hydrated (CAH) and Calcium Silicate hydrated (CSH) are formed; it is well established that these are the compounds that result in the improved strength. It should be noted that the greatest CBR values (30:70) were found when the soils were treated with a 7% addition of fly ash for both penetrations at 2.5mm and 5 mm. This result recommends that an increase in FA amount in cement-modified desert soil gives a better stabilization result in terms of CBR values.

Table 5. 4 Effect of fly ash on the CBR of cement modified desert soil

Penetration (mm)	**CFA / NDS Ratio 30:70 with 5 % cement**				**CFA / NDS Ratio 50:50 with 5 % cement**			
	0	3	5	7	0	3	5	7
2.5mm CBR (%)	82.20	83.20	84.80	86.30	52.17	52.1	52.75	53.81
5mm CBR (%)	62.40	63.40	64.10	64.70	49.32	49.11	49.87	50.04

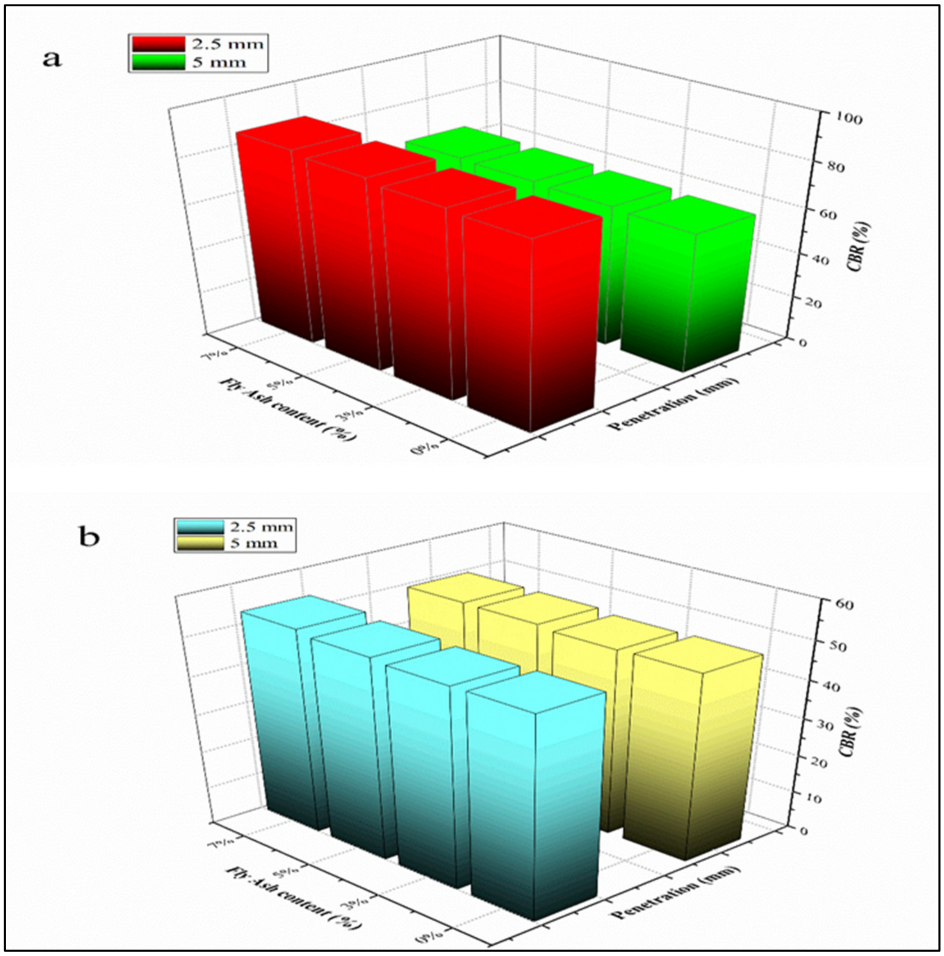

Figure 5.5 Effect of FA on the CBR of cement modified desert sand:
a). 30:70%, b). 50:50%

5.4.4 Compression behavior of FA Treated Desert Sand

Figures 5.6 and 5.7 show the UCS results test. The increase in FA and the resulting cement hydration result in improved bonding strength, indicating an interdependence within the mixture where the air voids are filled, and this makes the structure more rigid due to a greater number of bonds in the material. Following a 28-day curing period, the USC was found to be markedly better, going from, respectively, 0.88 MPa to 4.740 MPa and 0.88 MPa to 4.250 MPa, when the FA percentage was raised from 3% to 7% in both the 30:70 and in the 50:50 mixes. Nonetheless, the highest UCS value, 4.74 MPa, was found using a ratio of 30:70 and

7% FA, when the sample was given 28 days to cure, which was about 7 times more than the soil before treatment.

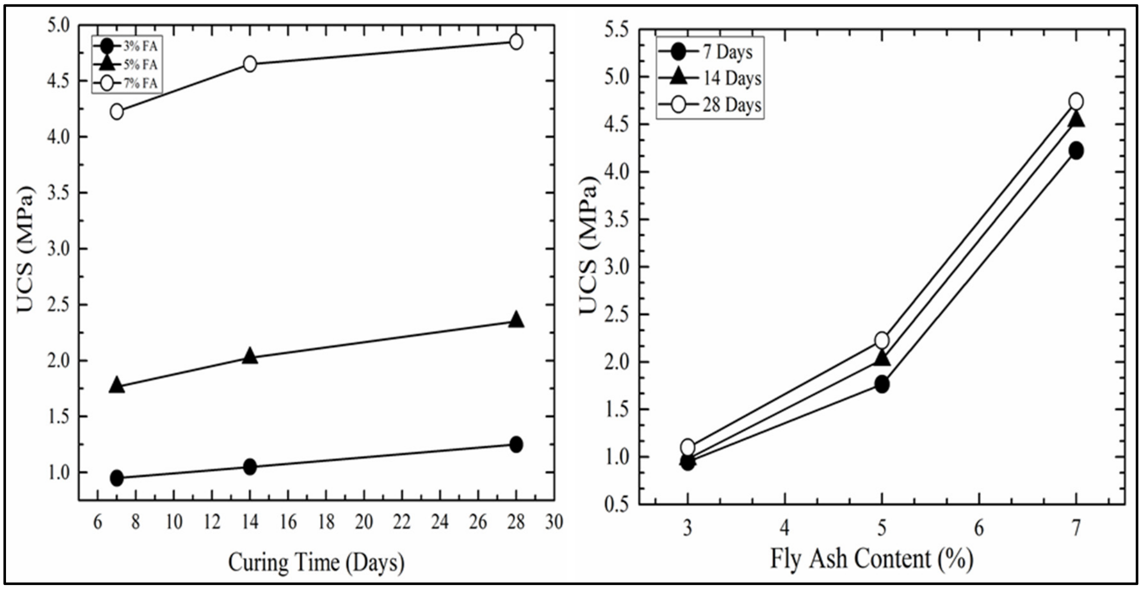

Figure 5.6 Effect of FA on the UCS and different curing time (7, 14, and 28 days) for the 30:70 treat mixture

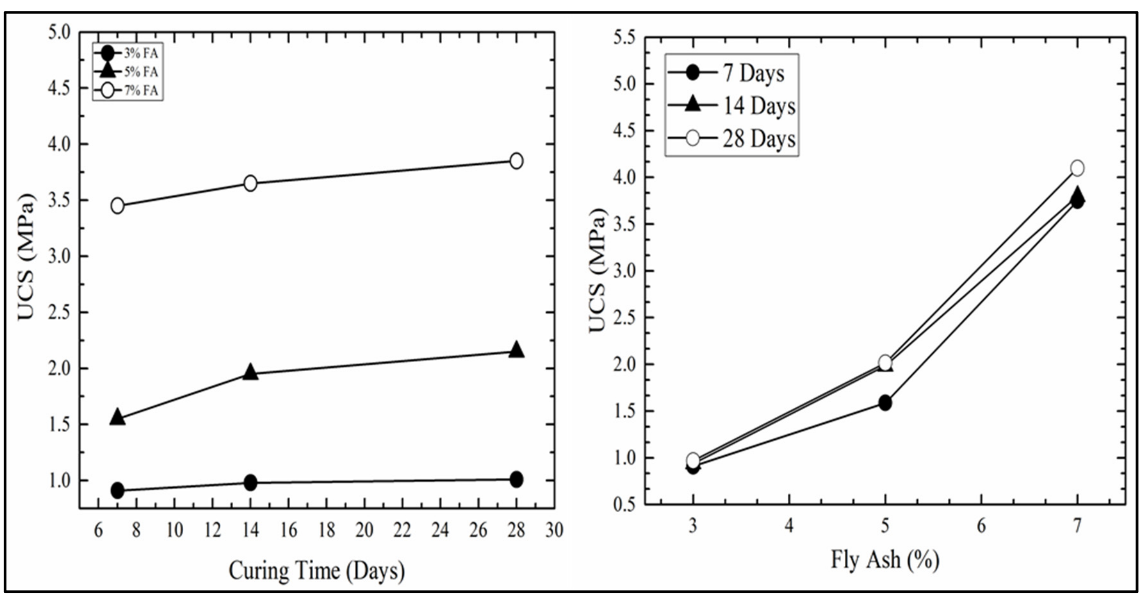

Figure 5.7 Effect of FA on the UCS and different curing time (7, 14, and 28 days) for the 50:50 treat mixture

5.4.5 Structural Analysis

The increase in the CBR of the natural sand from 23% to 86.3%, as a result of the addition of 30% coarse aggregates (30%:70%) with 7% FA and 5% cement, has a meaningful impact on the structural design of the pavement.

Considering that the modulus of resilience of the base and subbase courses can be estimated with the equation: $M_r = 10.34 * CBR$ (Hussein and Alshkane 2018) , then we can safely assume a three-fold increase of the modulus from 230 MPa to 890 MPa. As a result, Figure 5.8 compares the tensile strain at the bottom of a 50 mm thick asphalt concrete surface with a conventional modulus of 1,000 MPa resting on a base course with a modulus of 230 MPa (strain Y of 476 microns) vs 890 MPa (strain Y of 161 microns). The reduction in the maximum tensile strain at the bottom of the asphalt concrete, which controls wheel path cracking, from 476 microns down to 161 microns, has a substantial impact on the amount of equivalent single axle loads (ESAL) the pavement can withstand before such cracking occurs. This substantial extension of the pavement structural life is due to the logarithmic nature of the ESAL vs tensile strain relationship.

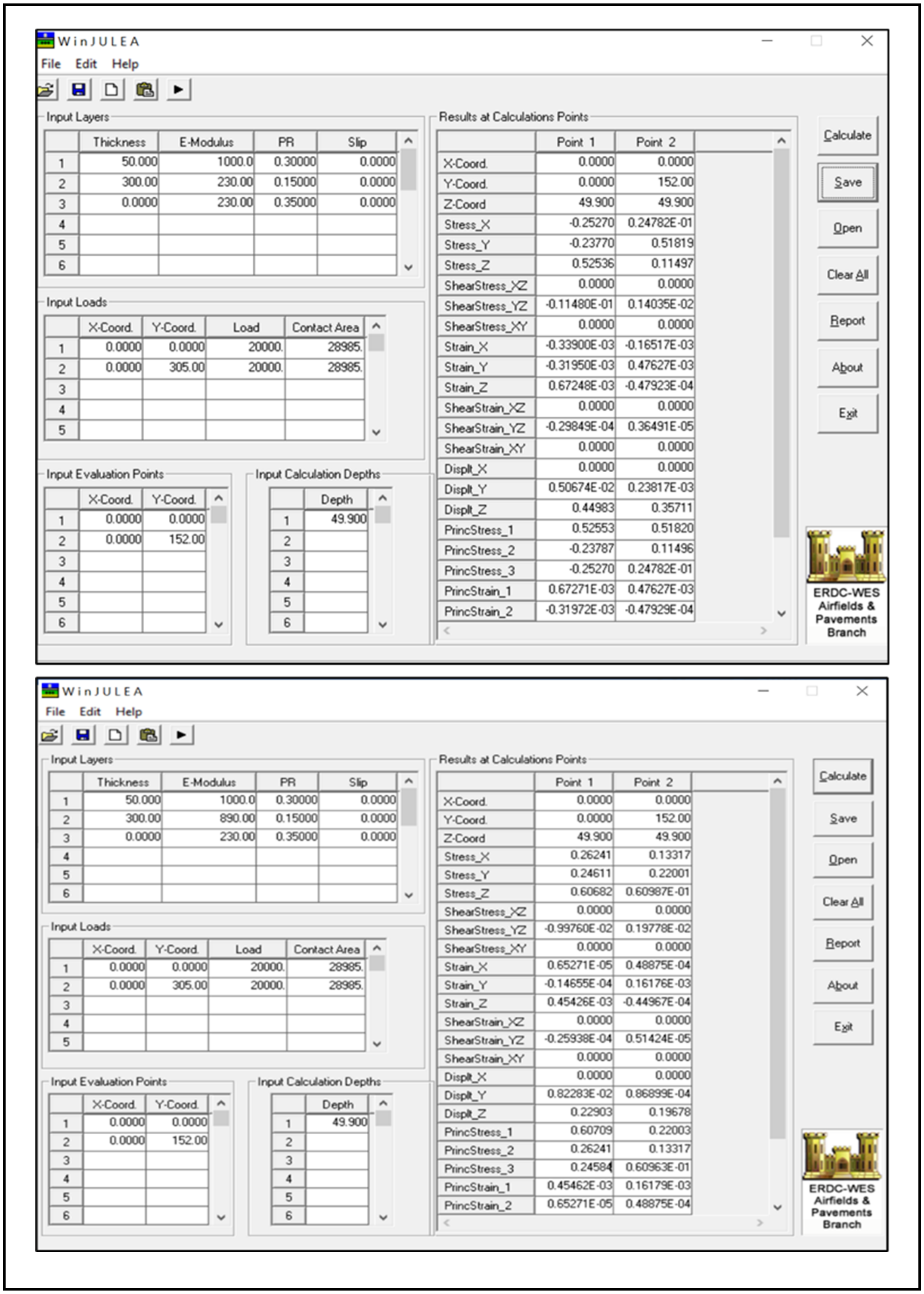

Figure 5.8 Comparative Structural Analysis (100%; 0%)
on top of figure vs (30%:70%) and 7% FA + 5% OPC at bottom of figure

The Asphalt Institute (1982) relationship (Ekwulo and Eme 2009) between tensile strain at the bottom of the asphalt concrete (AC) under one single axle load, and the number of repetitions of the axle load until fatigue failure of the AC occurs, is as follows:

$$N_f = 0.0796(\varepsilon_t)^{-3.291} (E)^{-0.854} \quad (5.1)$$

Where:

N_f: Number of 8-ton axle load applications to failure, i.e. cracking occurs at bottom of AC

ε_t: Horizontal tensile strain at the bottom of asphalt layer (476 10^{-6} or $161*10^{-6}$)

E: Elastic Modulus of the AC (1,000 MPa or 145,000 psi).

Therefore, the reduction of the tensile strain in the AC from 476 microns to 161 microns, results in an increase of the structural life of the pavement from 267,000 8-ton axle loads to 9,472,000 8-ton axle loads or over thirty-five times (35X), in accordance with the Asphalt Institute formula (E in psi), before fatigue cracking is developed in the AC wheel paths.

5.4.6 Cost Analysis

An assessment of the economic benefits was conducted on data obtained from Libyan ministry of bridges and roads on a proposed 120-km road in the south of Libya with varying subgrade soil conditions. A section of about 6 km, between the cities of Sabha and Al Mrugah, with subgrade soil properties similar to those of the control soil in this study was selected as a basis for comparison. From the comparison between the untreated base pavement and figure 5.8, the asphaltic layer thickness was decreased from 100 mm for untreated subgrade to 50 mm in case of treated subgrade. In addition, the base thickness was decreased from 400 mm to 300 mm for untreated and treated base course, respectively. Thickness reduction of these layers can, substantially, reduce the overall cost of the project without any adverse effects on the structural properties of the pavements system.

In Sahar desert in Libya, one square meter of asphaltic mixture and granular base with thickness of 10 mm costs about \$3 and \$0.25 respectively while the cost of cement is 110\$/ton. Therefore, the savings amount to 15\$/m^2 for the asphalt as a result of the reduction of thickness from 100 to 50mm, and an additional saving of 2.5\$/m^2 for the aggregate as a result of the reduction of thickness from 400 to 300mm. The cost of cement to stabilize 300 mm at a OPC of 5% equates to about 4\$/m^2 for the cement and 3.5\$/m^2 for mixing for a net saving of about <u>10\$/m^2</u> if the base is modified by the optimum FA dose and 5% OPC. The initial cost of 40\$/m^2 is therefore reduced to 30\$/m^2 or <u>25%</u>. as shown in Figure 5.9.

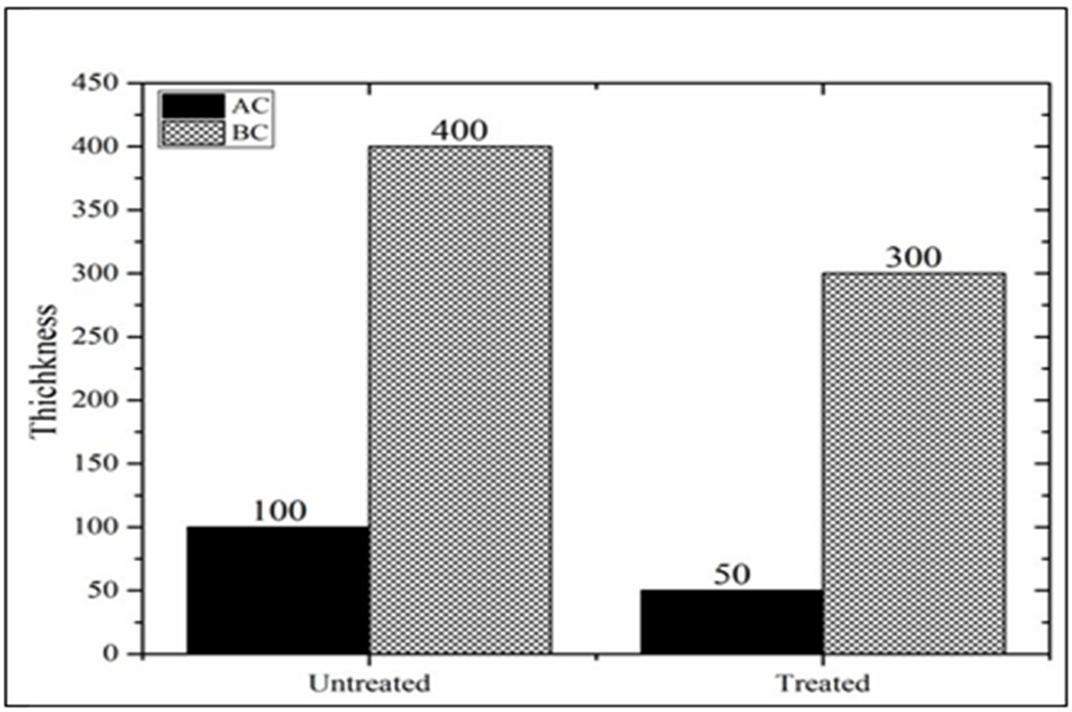

Figure 5.9 Thickness saving in pavement layers for Untreated and Treated bases

5.5 Conclusions

Based on the results of the different laboratory tests performed on the cement modified desert sand treated with fly ash, the following conclusions may be drawn:

1. Desert sand can be used as a reliable construction material if improved with cement to meet strength requirements and the thickness of both the base and asphalt layers may be substantially reduced (50% for the asphalt and 25% for the base) for a net saving of approximately 25% of the cost of the road.
2. The unconfined compressive strength and bearing resistance of the treated sand was found to increase with the increase in fly ash content and curing time. Using the high amount of FA (about 7%) can significantly improve the engineering properties of the natural sand.
3. The use of local and available material such as desert sand reduces polluting emissions of the production and the transportation.
4. Stabilized based using mixed cement and fly ash effectively improves the pavement properties. This causes a considerable increase in the number of permissible equivalent wheel load and consequently increases the lifetime of the road, respectively.
5. This technique will be also more competitive in coal producing countries, with great amounts of fly ash to dispose and lack of calcareous materials for cement production.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

This research investigates the effect of the addition of small amounts of locally available materials, including commonly found Portland cement and fly ash from local waste, on the properties of round desert sand unfit for road construction which was collected from the desert of South of Libya. The findings are that mixing cement and fly ash still requires the inclusion of 30% good quality coarse granular material to round and fine desert sand to obtain meaningful characteristics to use the mixture as a base and/or subbase course in low volume roads.

While the production of cement is polluting per se, adding is an economical and environmentally friendly solution because it reduces the hauling of 70% of granular coarse material for the base and subbase layers, which incidentally are the thickest layers of a pavement. The addition of cement also reduces the thickness of the needed asphalt concrete because of the much stiffer support resulting from the binders, compared to good quality granular material. Both the economic and environmental benefits are substantial. The latter is a result of the reduced hauling distances and therefore polluting emissions due to transport and protection of valuable scarce resources of good quarry material in desert countries. While this study focusses on desert areas, it is applicable to most countries in sub-Saharan Africa, with meagre quarry and coarse aggregate resources.

The experimental results have shown the following:

1. The laboratory compaction tests indicate that the increase of cement and/or fly ash results in an increase in the maximum dry density due to better stacking and void filling by the cement and the fly ash.

2. The addition of small binder amounts to the soil mixes has shown an increase in the strength of treated soil in both short-term and long-term perspectives. The increase can be attributed

to the type and quantity of binders, which are subsequently related to the cementitious products generated from hydration and pozzolanic reactions.

3. In hot and arid environments, the 30:70% mix indicates that the OPC-FA binder mixture has much higher strength (UCS) than the mix with OPC only.

4. Results show that adding FA to OPC improves the stiffness and strength. It also the use of local and available material such as desert sand reduces polluting emissions of the production and transportation. As fly ash is made of waste, an environmental liability becomes an environmental asset.

5. The stability and deformation behaviour after curing times were assessed for different mixes. The results show that NDS may be used at a substantial percentage, with OPC-FA as stabilizers with a significant improvement in the performance of the mix when subjected to high temperatures and heavy loads.

6. The mix with OPC-FA results in much higher CBR than the mix with OPC only. The addition of FA substantially increases the number of permissible equivalent axle wheel loads (ESAL) before fatigue failure and consequently increases the structural sustainability of the road.

7. The mechanical properties, expressed as shear strength of the cement-sand mix increases with cement content ratios. The cohesion and friction angle parameters of cement-treated sands are always higher than those of untreated sands. The increase in the mechanical properties is caused by the OPC bonding, which binds the grains of sand into larger and stronger particles as a result of further increases in OPC content. Self-cementation and self-hardening during curing become the main factor in that improvement.

8. Desert sand can be used as a reliable construction material if improved with cement to meet strength requirements and the thickness of both the base and asphalt layers may be

substantially reduced (50% for the asphalt and 25% for the base) for a net saving of approximately 25% of the cost of the road.

9. This technique will be also more competitive in coal producing countries, with great amounts of fly ash to dispose and lack of calcareous materials for cement production.

10. All conclusions, results, and recommendations are limited to the boundaries of this research experimentation.

Recommendations

In this research, analysis of different laboratory experiments was conducted to achieve an understanding of the mechanical behaviour of sand-cement and fly ash mixes. Based on the observations from this study, the following recommendations may be drawn:

- Investigations on the physical and engineering properties should be carried out by stabilizing the soils with other agents, e.g., bitumen, lime plus fly ash and cement plus lime in order to assess the most suitable type of additive for stabilizing in desert areas;
- The study focuses on a laboratory investigation. The curing condition of the mixtures in the laboratory may not be the same as in the field; therefore, field tests need to be conducted;
- Only one type of FA, OPC, and two gradation types of soil were used in this study; further investigations on the wide variety of soil gradations, OPC, and FA need to be conducted;
- This study underlines the importance of the scaling effect in the applied effort in compaction tests and therefore the estimate of soil strength, which is a key parameter. Different types of soil and additives should be tested to draw general conclusions;
- Soil improvement as an economical, sustainable, and environmentally friendly technique should be continued in asphalt pavement projects. The understanding of the main chemical components of stabilizers used to improve the soil stability performance might help optimize the mix design and reduce the financial costs and the environmental effects of

pavement construction projects in countries with scarce coarse aggregates or quarries;

- Complementary tests such as the appreciation of the loss of strength after immersion should be performed in order to understand the potential behavior of the treated desert soils subject to heavy rain, even for a few days a year;
- Microstructural and mineralogical studies should be conducted to comprehend the morphological arrangement of the mixed material to optimize pavement designs;
- Perform additional testing with different combinations and cost analysis to identify optimal least-cost solutions to implement;
- Based on the experimental work and the outcome of this research, it is recommended for hot arid regions such as Libya, that utilization of locally available desert sand should be given due consideration for upcoming road construction projects in locations with similar characteristics.

APPENDIX I

THE EFFECT OF USING DESERT SANDS AND CEMENT TO STABILIZE THE BASE COURSE LAYER OF ROADS IN LIBYA

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Abstract

This paper investigates using a mixture of natural sand, Portland cement, and manufactured aggregates to stabilize the base course layer for low-volume roads. Compaction and resistance to deformation (California Bearing Ratio) results are measured and guidelines provided with consideration for hot desert areas like Libya. These tests have been conducted to provide relevant statistical conclusions and recommendations as to how much round-shaped sand may be used versus manufactured crushed sand for various traffic loads. In the last 15-20 years, Libya, along with many other developing countries in the area, has undergone a sizeable move towards modernization, including upgrading the road infrastructure that services the growing population. Such a project runs into challenges in areas with lower population density, that require that roadwork projects be kept under sharp cost constraints. Using a mixture of sand cement to stabilize the base course has been common for decades because the properties of cement improve the characteristics of natural sand; furthermore, when the road is built in a sandy desert, the use of desert sand is an obvious solution to containing costs. Nonetheless, natural sands have been rounded by years of mechanical action by environmental forces and are therefore rounder and more prone to shifting than angular manufactured sand. Manufactured aggregates need to be imported from elsewhere in the country and so have higher

costs and environmental considerations, both of which give these projects incentives to use the local desert sand. This paper only considers the use of manufactured aggregate of 0-5 mm in the base course and examines how using local desert sand in the aggregate mix can reduce costs. This solution brings with it many problems because, due to natural sand's lower inherent stability with regards to manufactured sand, the road surface will degrade faster. The solution to this problem, presented here, is to relocate some of the strength of the road from the surface layer to the base course layer. This is done by reducing the thickness of the asphalt course to a minimum and introducing more structural strength in the base course layer by means of a cement-stabilized base layer.

Keywords: Sand, Cement, CBR, Compaction, Stabilization.

1. Introduction

There are a number of methods for improving the geotechnical characteristics of fine-grained and soft sands that do not meet industry standards for road construction. One approach is to remove the substandard sand and instead use a higher standard, manufactured sand that has been processed chemically or mechanically. Such techniques can raise the level of the geotechnical characteristics of the whole and provide greater rigidity and strength through methods that can be applied at the construction site itself. Preloading and compacting the fine aggregate make it denser. Other techniques such as electro-osmosis and dewatering affect how grains of sand bond together; related methods are grouting, chemical stabilization and ground freezing. Another common way to improve the stability of the fine aggregate is to use physical means to create structure, e.g. placing stone columns or geotextiles with the fine aggregate (Patel and Patel 2012). There is another approach to consider. Because of the general uniformity of the fine aggregate and the fact that there are still some gravel particles, the fine aggregate can be mixed with cement to stabilize it. This low grade, soft sand is found in great quantities in the deserts of Libya. Although there is a great financial incentive to use this sand, it can cause many problems because a base coarse layer made from desert sands tends to allow more erosion by the elements (rain, wind) and, in certain cases, will collapse when it becomes saturated by water. As the country develops, more construction is required for trade and transport, putting a strain on the supply of standard building materials such as aggregates (fine and coarse). If the desert sands could be suitably prepared for construction, it would save money and time. For this reason, this research is targeted at ways of making use of this natural desert sand while keeping to modern construction standards.

2. Background and Literature Review

2.1 A Survey of Pavement Stabilization Techniques

Stabilization, in its most basic sense, is a way of making the mechanical strength of a base layer more robust, and less affected by changes in wear resistance and swelling (from either heat or water) (Abderrahmane and Ratiba 2013). Typically, natural sands are low grade because of years of rounding from wind; when used as a base course their loose fabric structure is prone to erosion from both rain and the wind. Because of these factors, desert sands are a poor alternative for either road or dam construction; the low shear strength and the high permeability lead to higher maintenance costs and shorter life (Al-Aghbari and Dutta 2005). The process of soil stabilization is a question of altering the chemical and physical soil characteristics and thereby increasing the durability and overall strength of the base layer. Low-grade soils have been brought up to acceptable standards in this way for years. The added expense of this treatment is repaid in the superior service life and improved performance of the road (Azadegan, Yaghoubi, and Li 2013). A study of German road construction in recent decades found that using lime or cement to stabilize base layers had important and practical outcomes. Japan, the US and some Scandinavian countries have used the fly ash-soil stabilization method with success. On the other hand, in some countries stabilization with fly ash soil is not used simply because there are no standards for the method. When dealing with expansive or soft clayey soils, engineers must make choices to compensate for the soils that do not have sufficient stability to support the axel-loads required of the finished road. These soils must be treated to get them to a suitably stable quality of subgrade. This problem applies both to the finished road but also to the conditions during construction; if a suitable subgrade cannot support the loads during construction, then a platform must be created from which to build the pavement (Ismaiel 2006). A wide range of materials, including crushed stone and natural gravel and sand, which provide the necessary durability and strength. Alternatively, available local materials can be stabilized chemically or mechanically to achieve comparable results at a competitive price. In order to work well, the aggregates must be durable and strong and must satisfy the requirements of particular plasticity, strength, and gradation. The roads of Libya suffer from excessive deformation (primarily cracking and rutting) in hot and droughty conditions found throughout the country, especially in the southern regions of the desert. As this overview shows, aggregate distribution and grading in road construction are already being conducted in hot and arid regions, such as in the Middle East and North Africa. This is justified because obsolete mixing designs are ineffective. There is a need for data to determine which materials can be suitable for the performance parameters defined in these regions. This is important, because lower quality material might pass the design requirements, but may not meet other design requirements for the mixture (Almadwi and Assaf 2017).

2.2 Stabilizing Pavement Materials

The stabilizing agents that have been used for various soil types have been well studied. Lime and cement are often the best choice for stabilizing the subgrade and subbase layers. They are also used for base layer stabilization. Soils with too high a percentage of sand respond well to the stabilization created by the addition of lime. In terms of the plasticity index, and the plasticity and liquid limits, the addition of lime creates superior physical properties. Lime raises the California Bearing Ratio (CBR) from just 1% to approximately 30-50% when various percentages of lime are added to untreated soils. Furthermore, adding lime to a pavement allows for the use of pavement layers that are from 50 to 60% thinner compared with the requirements of pavement of untreated layers (Azadegan et al. 2013). This kind of stabilization has turned into standard practice nowadays and options to stabilization have been explored recently that apply different amounts of cement, lime, and bitumen to solve the problem. Aiban (1994) reported that a compacted sand mix that is then saturated with bitumen results in a more stable layer. Statistical and experimental analysis were made on the viscoelastic properties of the bitumen and lime mix. Sabbagh (1986) studied the effects of roads built on sand dunes with small inclines; these roads had a base layer formed from a mix of bitumen and hydrated lime; he found that this mix provided a suitable wearing course for low-volume roads and as a base layer any traffic volume. Aiban (1994) studied the effects of emulsification of fine sand aggregates using bitumen to stabilize the aggregate for low volume Saudi Arabian roads. Their conclusion was that when natural desert sands were emulsified with bitumen, the resulting asphalt was of poor quality. In contrast, adding Portland cement and manufactured fine aggregate to the mix greatly improved the road quality.

2.3 Methods of Stabilizing the Road Base

2.3.1 Mechanical Stabilization

Mechanical stabilization is the oldest technique for road building, and these involve changing the physical property of the original road base soil to affect its solidity and gradation, among other factors. Of these techniques, dynamic compaction is one of the most commonly used. To do this, a heavyweight is repeatedly dropped overall points of the road base to even out any irregularities and create an evenly compacted soil. A newer variation of this is known as Vibro compaction and it works in a similar way, with vibration taking the place of kinetic force deformation (Das 2003).

2.3.2 Chemical Stabilization

Stabilizing soil by adding a chemical that will change its properties by physically interacting with it is another standard stabilization method. Lime, kiln dust, cement, and fly ash are common chemical compounds that are used. Depending on the nature of the existing base, the chemical reactions are pozzolanic or cementitious (Das 2003).

2.4 Reasons for Soil Stabilization

By stabilizing the soil at the site of the construction, projects avoid the costs of removing the soil already there and transporting new materials to the site. In areas where extreme weather conditions would slow or stop construction during certain times of the year, soil stabilization can allow work to continue by stabilizing the original soil and allowing the work to continue. Therefore, stabilization techniques are a means of cost savings because work can continue through more weather conditions (Patel and Patel 2012).

3. Problem Statement

In desert areas, quality construction materials are becoming rare. Therefore, where traffic volumes are low, roads are less cost-effective. The Sahara Desert has a lot of sand but little rock and natural gravel, which is necessary for the structure of pavement. To date, the construction of roads in the south has depended on a combination of gravel and sand, brought from the northern part of Libya, hundreds of kilometres away. Development of methods to use sand available in the south will minimize material and shipping costs. The focus of this study is to adapt the methods developed in other places, and to use natural sand in pavement road construction. Sand-cement mixture is the best option for road construction in the region.

4. Objectives

The paper investigates the possibility of improving the engineering properties of desert sands in Libya using cement. Sources of material in southern Libya are limited and are quickly being used up because of the fast pace of development and road construction. Cement stabilization of base coarse layer in roads could save costs by using the freely available materials, but normally substandard, local fine aggregate. The properties of the stabilized sand such as compaction characteristics and California Bearing Ratio (CBR), were evaluated and their variations with the content of cement of the stabilizing agent are quantified.

5. Methodology

Optimum moisture content (OMC) and maximum dry density (γd_{max}) compaction tests were carried out on the samples in the laboratory, following ASTM D 698 methods. Also, California Bearing Ratio (CBR) tests were carried out, following the AASHTO NO. T 193 guidelines.

6. Material Mix Design

The study used two kinds of sand and one kind of cement. The first sample was 100% desert sand and is referred to as Type A. It has a 2.63 specific gravity with a mean particle diameter of 1.6 mm, a passing of D60, coefficient of uniformity (Cu) of 12.35 and a 4.8 coefficient of curvature (Cc). Type A sand is thereby considered to be SP (poorly graded). The second sample, referred to as Type B, is a manufactured sand. Type B has a specific gravity of 2.6395, mean particle diameter 2.8 mm, a passing of D60, coefficient of uniformity (Cu) of 7, and a 1.75 coefficient of curvature (Cc). Type B is thereby considered to be GW (sand graded). The grain size distribution for both sand samples is shown in Figure 1. The various physical properties such as specific gravity, fineness and water absorption are shown in Table 1. The ordinary Portland cement used in the investigation was bought from the local market with properties as shown in Table 2.

7. Laboratory Experiments

The grain size distribution of the fine aggregate mixture is shown in Figure 2. A laboratory investigation was carried out to determine the mechanical properties of the stabilized granular soils. 70% natural sand (SP) and 30% manufactured sand (GW), both with maximum particle size of 5 mm, have been stabilized with different percentages of cement (0%, 3%,5%, and 7% respectively) mixed to form bonded materials.

7.1 Compaction Test

The dry natural sand that passed through sieve No. 4 (4.75 mm) was mixed with the manufactured sand and then with the stated percentages of cement; this was mixed until it achieved a uniform color. At this stage, small amounts of water were added when needed to help mix and compact the sample. Proctor compaction tests were run on all four mixtures: the first with only the 70:30% sand mixture; the other three with the specified cement percentages. The results of the compaction test for different percentages of cement for sand Type A and Type B are shown in Figures 3, 4 and 5 respectively.

7.2 California Bearing Ratio Tests (CBR)

CBR tests were carried out to determine the bearing capacity and the strength of the sand and sand-cement mixtures. CBR tests were run on all four mixtures: the first with only the 70:30% sand mixture; the other three with the specified cement percentages. Figure 6 shows the variation of CBR with cement contents for the mixture.

8. Results

8.1 Compaction Test Result

The compaction results of sand-cement mix are shown in Figure 3. Figures 4 and 5 were shown results for the effect of the addition of cement to the 70:30% sand mixture in terms of maximum dry unit weight and in terms of optimum moisture content. Figure 4 shows that the 70:30% sand mixture has an increase in maximum dry unit weight. The lowest percentage of cement (3%) shows a marked increase in maximum dry unit weight over the 0% cement mix; further increases in cement percentage (5%, 7%) show a further increase but not as substantial a difference as between 0% and 3%.

This difference is due to the very fine nature of cement and the fact that it has greater surface area; therefore, it takes the place of the air voids between the grains of sand; this is what creates a greater dry unit weight. Figure 5 shows that the optimum moisture content for the sand mixture only increases to a marginal degree with the addition of the cement.

8.2 California Bearing Ratio Tests (CBR) Result

The results of the CBR tests are summarized in Table 3. It consists of the variations of OMC, Υd_{max}, CBR, and cement percentage. The CBR values increased with higher percentages of cement content, to a maximum value of 33.5% at 5% cement content, as shown in Figure 6. As can be seen, the CBR values decreased with further increase in cement content. This suggests that cement content between 4% and 5 % (on the basis of dry soil weight) can be recommended as an optimal content for improving the CBR. It can build up the CBR value up to 34% compared to the control sample.

9. Summary and Conclusions

This research has the aim of improving the marginal local materials available for base course road construction with chemical stabilization. The conclusions are material can be classified as low-quality or marginal for reasons including inadequate plasticity, strength, or gradation. Sources of material in southern Libya are limited and are quickly being used up because of the fast pace of development and road construction. Chemical stabilization could save costs by using the freely available, but normally substandard, local fine aggregate. Experiments show that the low-quality base materials were successfully stabilized with a mix of 70% natural sand with 30% crushed (manufactured) sand (both by weight) when mixed with various percentages of Portland cement (3%, 5%, 7%) to reach the necessary stability. The advantage of this research over the comparable performance of crushed sand is economic and practical because crushed sand is more expensive to transport than using the local materials with the Portland cement.

Tables

Table-A I-1 Physical Properties of Fine Aggregates

Aggregate	**Bulk Specific Gravity**	**Apparent Specific Gravity (G_s)**	**Absorption (%)**
Natural Sand 0-5 mm	2.42	2.63	0.33
Manufactured Sand 0-5 mm	2.44	2.639	0.58

Table-A I-2 Chemical composition of OPC

Compound	**%**
SiO2	18.20
CaO	59.03
MgO	1.80
Al2O3	5.09
Fe2O3	3.15
Na2O	0.18
K2O	0.29
SO3	2.65
Loss on Ignition (LOI)	7.91
Materials not solvent	1.02

Table-A I-3 Compaction Test and CBR Test Results

% Cement Content	**% OMC**	**Υd_{max}**	**% CBR**
0	5.02	1.876	9
3	5.13	1.913	31
5	5.08	1.95	33.5
7	5.97	1.98	25

Figures

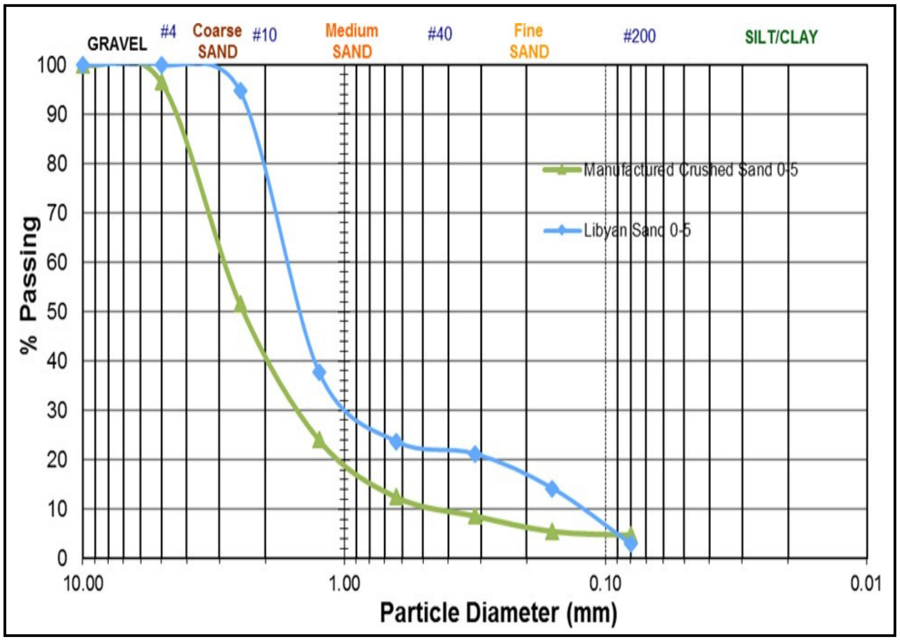

Figure-A I-1 The Grain Size Distribution for Both Sands

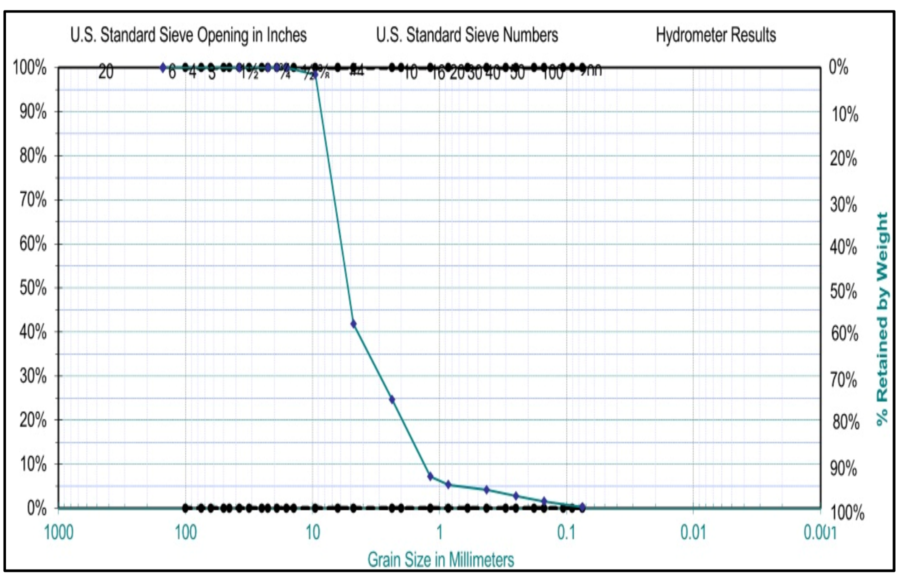

Figure-A I-2 The Grain Size Distribution for Fine Aggregate Mixture

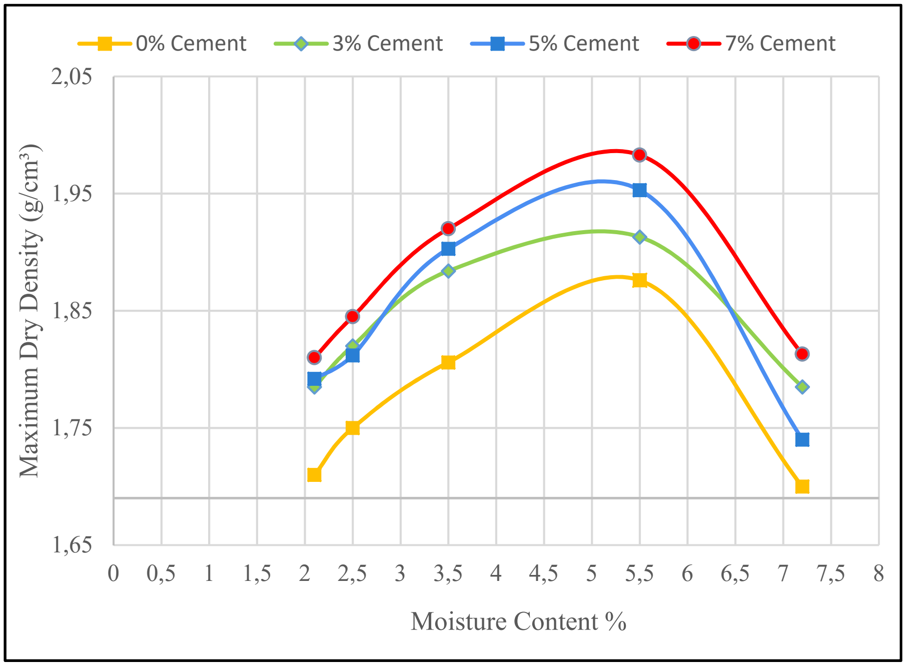

Figure-A I-3 Compaction curves for Fine Aggregate Mixture with different ration of cement

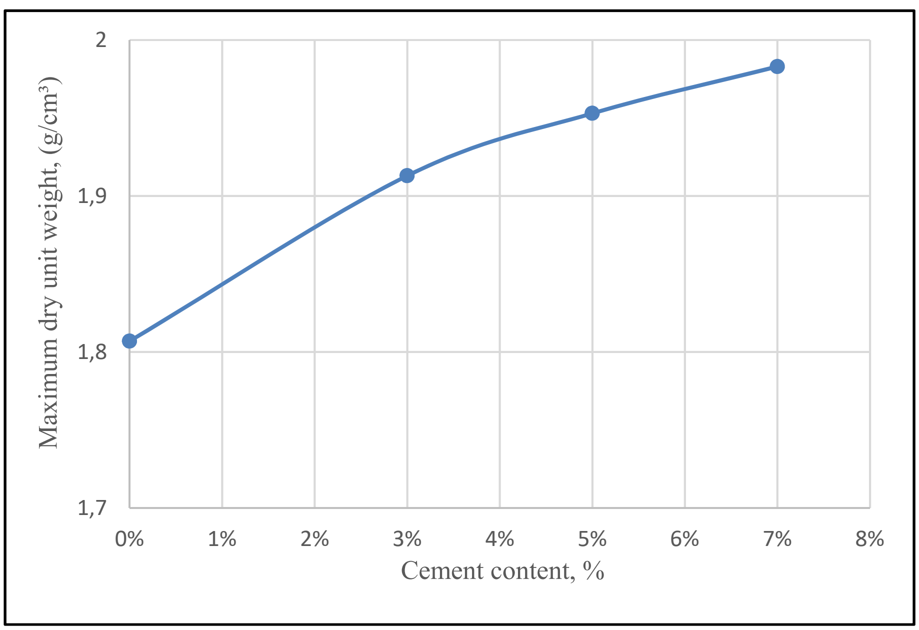

Figure-A I-4 Effect of Cement Content on the Maximum Dry Unit Weight for the Mixture

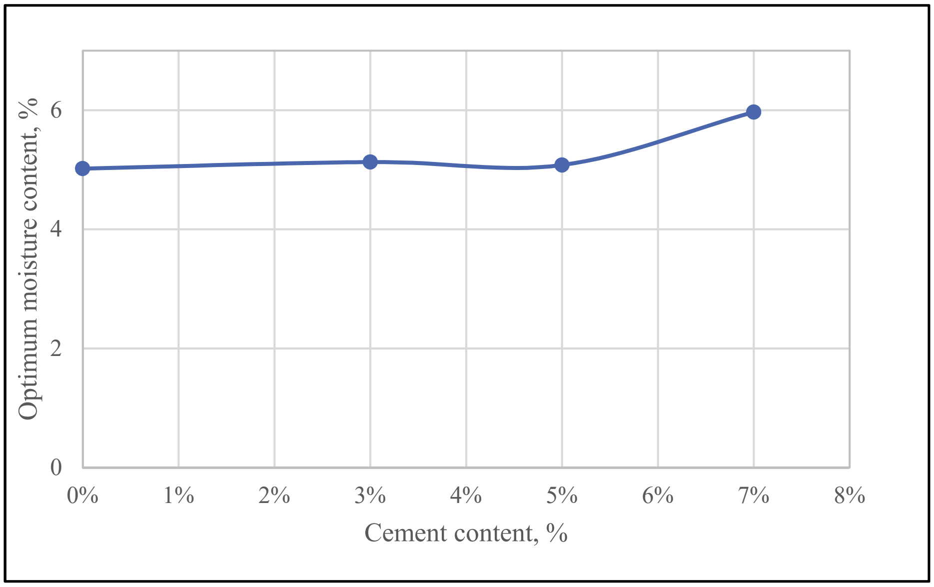

Figure-A I-5 Effect of Cement Content on the Optimum Moisture Content for the Mixture

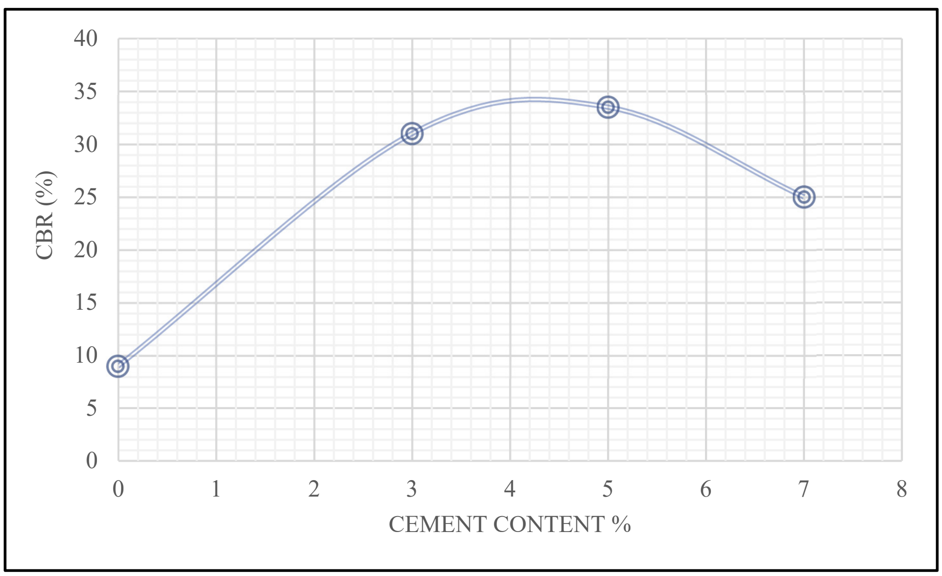

Figure-A I-6 Variation of CBR with Cement Contents

APPENDIX Π

Overview of Soil Stabilization Methods in Road Construction

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Abstract

Soil stabilization is the process of improving the shear strength parameters of soil and thus increasing its bearing capacity in road construction. It is required when the soil available for construction is not suitable to carry structural load. Generally, soils exhibit undesirable engineering properties unless they are treated to enhance their physical properties. Stabilization can increase the shear strength of a soil and control its shrink-swell properties, thereby improving the load bearing capacity of a sub-grade to support pavement and its foundations. Soil stabilization is used to reduce permeability and compressibility of the soil mass in earth structures and to increase its shear strength. Mixing additives into the reaction mechanism, positively affecting its strength, improving and maintaining the soil moisture content, achieve stabilization. Therefore, these soil stabilization processes are suggested for most construction systems and can be accomplished by several methods. All these methods fall into two broad categories, namely mechanical stabilization and chemical stabilization. Mechanical Stabilization is the process of improving the properties of the soil by changing its gradation; chemical stabilization is the process of adding a physico-synthetic substance to the soil which reacts with the clay particles to fill the voids so that less water is needed to maintain a stable mix and, finally, a stable framework.

Keywords: Soil stabilization, Mechanical stabilization, Chemical stabilization, Strength

1. Introduction

To prepare soil as a base for road construction, a process of soil stabilization must be undertaken to alter the soil properties, thereby improving the engineering qualities in terms of workability, stiffness, permeability, strength, and compressibility. In recent years, the practice of mixing cement into the soil has been adopted as a means of soil stabilization in asphalt road construction; this has become a reliable method due to the sizeable improvements that are observed in the properties of the treated soil. This technique is most important for the base or subbase layers, and it shows significant advantages over a simple granular base with similar axel loads. There are a few options to attain this stabilization; the most common is when the natural soil is mechanically mixed with the stabilizing material to finally create a homogeneous mix (e.g. of cement and natural soil); another option is to add the stabilizing material (e.g. cement or lime) to the surface of the soil and using compaction methods to make the stabilizing material penetrate into the voids in the soil (Bandara 2015). The use of stabilizing materials helps achieve particle cohesion in the soil, help achieve the desired moisture content of the soil, and help in the waterproofing and cementing of the soils (Addo, Sanders, and Chenard 2004). When the subgrade consists of clay soils, this creates obstacles for civil engineering because such soils tend to expand with increasing moisture content, and this affects the service life of the road (Okasha and Abduljauwad 1992). Researchers have experimented with different kinds and quantities of stabilizing agents and have found that, for roadworks, lime and cement are some of the best options. Most often, these are added to the subbase and subgrade of the road, but it is also effective to add these to the base layers of the road construction (O'Flaherty 2002). For roads, there are many soils or granular materials available for road construction, but they may have inadequate properties (e.g., low load-bearing capacity, susceptibility to frost damage, etc.), which results in a significant roadside disaster and reduction of the pavement life. However, the addition of a stabilizing agent can improve soil properties. The most common additives are fly ash, lime, cement, and bitumen; other, less traditional options include liquid polymers, acids, silicates, lignin derivatives, resins, ions, and enzymes. Of these, the cement-treated base (CTB) results in a high degree of stiffness with the resulting high pavement durability. This research extends back to 1917 and there has been a significant publication history since then (Baghini et al. 2017).

The main objectives of this research study are addressed to different types of stabilization and comparing the advantage and disadvantage of each method of stabilization.

2. Types of Soil

The soil is a blend of organic matter, minerals, liquids, gases and countless organisms that together support life on Earth. Soil is constantly changing due to any number of chemicals, biological, and physical processes, including climatic weathering, which involves erosion by wind and rain. Soft soils are most in need of stabilization if they are to be used in an engineering capacity; these soils include organic soils, and soils with notable amounts of peat, silt, or clay. Generally, the easiest soils to stabilize are fine-grained and granular because they have a relatively large surface area as compared to the diameter of the particle. Due to its elongated and flat shaped particles, clay soils have larger surface area relative to its particle size (Rogers, Olshansky, and Rogers 1993). Some materials, silty soils are more difficult to stabilize because they are very sensitive to even the smallest variation in levels of moisture (Sherwood 1993). Organic soils, as well as soils with high peat content, can have very high-water levels (as much as 2000%) and are highly porous. For example, peat soils can range from very muddy to quite fibrous; generally, peat soils have a shallow deposit but can, in some cases, go several meters deep (Al Tabbaa and Stegemann 2011; Pousette et al. 1999). Soil with high levels of organic content can also exchange large amounts of moisture, which can interfere with hydration because the soil keeps the calcium ions that are freed when and calcium aluminate and the calcium silicate are hydrated. Therefore, in these organic soils, stabilization is only effective with the correct binder selection and application (Hebib and Farrell 1999).

3. Stabilization of Soils

(Kearney and Huffman 1999), noted that the primary cause of premature asphalt pavement failure is because of unsuitable design, construction, and materials, with regard to environmental conditions, etc. Adding an agent to stabilize the soil is a means of improving the soil from an engineering point of view. Such a chemical means of stabilization using a manufactured product is only effective if it is added to the appropriate soil type and soil layer in the right amounts. Chemical agents for this purpose include fly ash, lime-cement, lime, Portland cement, or bitumen; these can be added individually or mixed with other agents (Olarewaju, Balogun, and Akinlolu 2011). Each stabilization agent has its own distinctive properties and will react with different soils differently depending on these properties and the properties of the soils. In Table 1, below, there is an overview of the different mechanisms and character of different stabilizing agents. It can be seen in the table that bitumen and cement are the best options for stabilizing non-plastic and granular soils; in contrast, for cohesive soils, lime is a better choice. Another case is the stabilization of granular soils; in this case it is more effective to add a coarse material (e.g., crushed gravel) to a fine material (e.g., sand).

4. Advantages and Disadvantages of Soil Stabilization

Many materials using as additives for Soil stabilization involve advantages and disadvantages. Some of the advantages and disadvantages of additives materials are discussed here.

4.1 Advantages of Soil Stabilization

By stabilizing the soil at the site of the construction, projects avoid the costs of removing the soil already there and transporting new materials to the site. In areas where extreme weather conditions would slow or stop construction during certain times of the year, soil stabilization can allow work to continue by stabilizing the original soil and allowing the work to continue. Therefore, stabilization techniques are a means of cost savings because work can continue through more weather conditions (Patel and Patel 2012).

The specific advantages of the treated soils are speeds up prior to the construction process since the required is usually much smaller and therefore less material and labor is required. Significantly improves strength and durability, especially where the local materials available soil is poor. May reduce or eliminate the need for the expensive surface treatment or rendering (Hall, Najim, and Dehdezi 2012).

Table-A II-1 Mechanisms and applicability of various stabilizing agents
Taken from Firoozi et al. 2017; Grogan, Weiss Jr, and Rollings (1999)

Mechanism	Effects	Suitable soils
Granular Blending to poorly graded soils, usually coarse into fine (not clayey) soils	Higher compacted density, more uniform mixing, increased shear strength	Gap-graded or gravel deficient (gravel, sand addition), or harsh aFcr (loam addition)
Cement Mixing small amounts (cement modification) or larger proportions (cement binding) into soil or aFCR	Improve shear strength, reduces moisture sensitivity (modification), greatly increases tensile strength and stiffness (binding)	Most soils, especially granular ones, large amounts of cement needed in clay rich and poorly graded sands, hence expensive
Lime Mixing hydrated lime or quick lime in small to moderate amounts into soils	Increases bearing capacity, dries wet soil, improves friability, reduces shrinkage	Cohesive soils, especially wet, high – PI clays
Lime Pozzolan Mixing lime plus fly ash or granulated slay into soil or aFCR	Similar to cement but slower acting and less ultimate strength	As for cement, plus clayey soils that do not react with lime
Bitumen Agglomeration, coating, and binding of granular particles	Waterproofs, imparts cohesion and stiffness	Granular, non-cohesive soils in hot climates
Fly ash Mixing with an activator to form cementitious compounds	Waterproof concrete	Some materials will activate the fly ash; lime or cement may be used to act as an activator by providing the required calcium hydroxide
Fiber The use of hair-sized polypropylene fibers in soil stabilization	Increases the stiffness of soil and also the immediate settlement of soil reduced considerably, the strength and angle of internal friction increase	Tropical soil, clay soil

4.2 Disadvantages of Soil Stabilization

The previous studies indicated the advantages of soil mixture. However, a number of disadvantages that are inherent in the treated soil, which can be identified as necessary stabilizing materials, may not be available in some developing countries or may be expensive for transportation. The mixing and building processes can be complicated depending on the type of stabilizer chosen. This can increase the likelihood of problems, which will affect the budget and time (Jawad et al. 2014). The deleterious chemical reactions there are two undesirable (deleterious) chemical reactions probably occur in the treated soil. The first is the carbonation and the second is the reaction with the sulfate salt existing in the soil. Carbonation is the reaction that occurs between the additives and atmospheric carbon dioxide (Umesha, Dinesh, and Sivapullaiah 2009). According to Cizer et al. (2006), the factors that controlling carbonation reaction are carbon dioxide diffusion through pores, calcium hydroxide and carbon dioxide dissolution in water, as well as the reaction of Ca^{2+} with CO_3^{2-} ions to form the $CaCO_3$ crystals.

5. The Process of Soil Stabilization

Proper design and testing are an important component of any stabilization project. Laboratory tests and on-site tests can establish proper design criteria when determining the appropriate rate for the addition of additives and impurities to achieve the desired engineering properties (Cortellazzo and Cola 1999). Stabilization of the soil is carried out in such a way that the stabilizing materials are distributed onto or mixed into the materials in need of stabilization.

Generally, the additives are mixed into the soil until the desired properties are achieved, as shown in Figure 1. Then the foundation or road materials are put in place. This process can vary depending on the necessary soils and additives (Cortellazzo and Cola 1999). In addition, it should be noted that the presence of sulfates, sulfides, carbon dioxide and organic substances in the stabilizing materials can contribute to unexpected or undesirable properties of the treated soil.

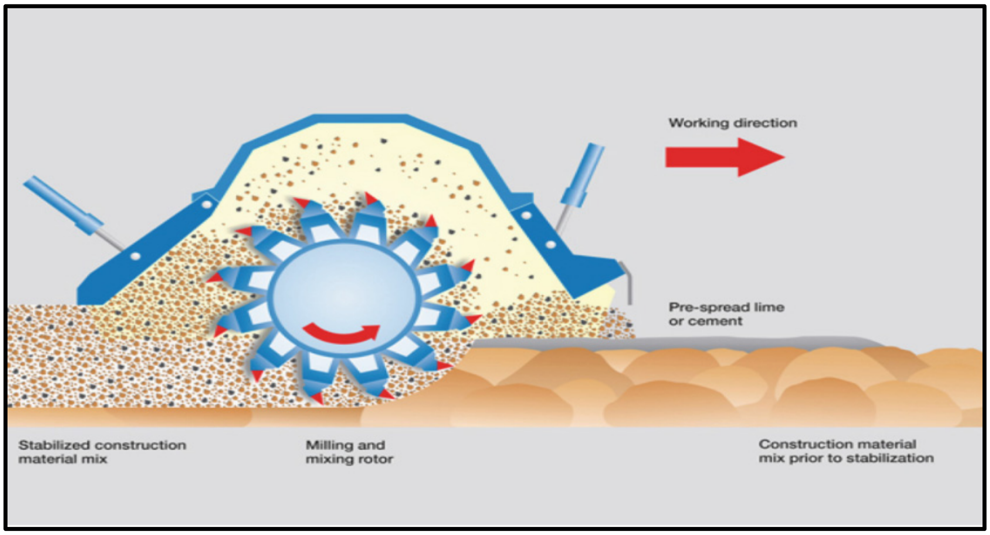

Figure-A II-1 Schematic soil stabilization process
Taken from Cortellazzo and Cola (1999)

6. Techniques for Soil Stabilization

Soil or coarse aggregate is often used in roadworks, to build up the mass of materials needed to support the layers of the road. These soils and aggregates need to have very specific qualities to withstand the numerous and variable forces that they will undergo with axel-loads in an in-service road. Loose materials must be stabilized with some kind of binding agent, such as bitumen, lime, fly ash, cement or some mix of these. The end results will have greater strength, less compressibility and permeability than the untreated soil (Keller 2011). The engineering characteristics that are most important are durability, compressibility, permeability, strength, and volume stability (Perera et al. 2011; Sherwood 1993; Al Tabbaa and Stegemann 2011). The following are some reliable stabilization techniques such as mechanical stabilization, lime stabilization, cement stabilization, fly ash stabilization, bituminous stabilization, thermal stabilization, electrical stabilization, stabilization by geo-textile and fabrics, recycled and waste products etc.

6.1 Mechanical Stabilization

Mechanical stabilization is the oldest technique for road building, and these involve changing the physically property of the original road base soil to affect its solidity and gradation, among other factors. Of these techniques, dynamic compaction is one of the most commonly used. To do this, a heavy weight is repeatedly dropped over all points of the road base to even out any irregularities and create an evenly compacted soil. A newer variation of this is known as Vibro compaction and it works in a similar way, with vibration taking the place of kinetic force deformation (Das 2003).

6.2 Lime Stabilization

Using lime is a cost-effective means of stabilizing and otherwise improving the material properties of soil. This technique is called lime stabilization and involves adding lime to the soil. The varieties of lime that are used to treat soil include dolomite lime, calcite quick lime, monohydrated dolomite lime, and hydrated high calcium lime. Soil stabilization can normally be achieved by using approximately 5% to 10% lime. The stabilizing properties from lime are caused by strengthening due to the cation exchange capacity as opposed to a cementing effect due to a pozzolanic reaction (Sherwood 1993). The most effective stabilization with lime can be done when the soil contains a lot of clay particles, which flocculate and therefore change natural plate-like clay particles into needle-like shapes with metalline structures that interlock. With the lime treatment, the clay soils become drier and are less affected by changes due to water content fluctuation (Keller 2011). Lime stabilization often creates pozzolanic reactions where, with added water, pozzolana materials have a chemical reaction with the lime and create cement-like compounds (White et al. 2005). The stabilization can be done with hydrated lime, $Ca\ (OH)_2$, or with quicklime, CaO. Another option is to use slurry lime when there are dry soils; in this case, water is needed to achieve optimal compaction (Rogers and Glendinning 1996).

The most effective and common type of lime is Quicklime and its advantages, when compared with hydrated lime, are: it has a greater (per unit mass) free lime content; it has more density than hydrated lime (as such it requires less space for storage); it is generally less dusty; it generates some heat when it is mixed, a by-product that adds to the strength of the final result; there is also a sizeable reduction in moisture levels, something that can be calculated with the following reaction equation:

$$CaO + H_2O \rightarrow Ca(OH)_2 + Heat(kJ/mol) \qquad \text{(A II-1)}$$

Once mixed into soils with high moisture content, Quicklime absorbs moisture from the soils (as much as 32% of its weight), and it then forms hydrated lime. This reaction generates heat, which in turn causes moisture in the soil to evaporate; the process of the soil drying out and absorbing water is increased and is known as the soil's plastic limit (Al Tabbaa and Stegemann 2011; Sherwood 1993).

6.3 Cement Stabilization

The underlying mechanism in cement-like soil stabilization is that hydration of the particles creates interlocking crystalline bonds resulting in an elevated compressive strength. A successful bond results from the cement particles coating the majority of the soil particles. It is necessary to mix the cement with a soil that has a particular distribution of particle sizes if good stabilization is to be had (i.e., achieve good contact between the cement and soil particles). The resulting mix is an extremely compacted mix of cement and soil, sometimes referred to as a "cement-stabilized base" and sometimes a "cement-treated aggregate base". When the cement undergoes hydration, the resulting material is hard and long-lasting. This process of cement stabilization must be done during the compaction process. The void ratio of the soil is reduced as the cement takes up the void fill between the soil particles.

Following this, if the soil takes on more water, the cement will react with the water and the mix becomes hard, causing the unit weight of the soil to increase. Through this process of hardening, the bearing capacity and the shear strength of the cement also increases. The effect that cement has on the clay-rich soils is that it decreases the soil's liquid limit and at the same time it increases the soil's workability and its plasticity index. The soil minerals do not affect the cement reaction, but the presence of water will affect the cement (Stab 2002). For this reason, cement is useful for soil stabilization across a broad range of soil types. There are a great number of cement types on the markets including high alumina cement, sulfate resistant cement, blast furnace cement and standard Portland cement. The choice of which cement to use is a question of soil type and the required strength of the stabilization.

The process of hydration is the process that causes the cement to harden. The process starts when the cement is mixed with other components and water for the desired application, which leads to its hardening. The solidification of the cement will cover the surface of the soil as a glue coating, but it will not change the soil structure (Stab 2002). The hydration reaction proceeds slowly from the surface of the cement grains, and the center of the grains may remain non-hydrated (Sherwood 1993). Hydration of cement is a complex process with a complex series of unknown chemical reactions (Hicks 2002). However, this process can be influenced by what impurities or foreign agents are in the soil, the curing temperature of the cement, various possible additives in the cement, the ratio of water to the cement, and the characteristics of the mixture surface.

The result and strength of the soil stabilized by cement depends on various factors and should be estimated during planning so as to attain the targeted strength. The two primary cementitious properties in standard Portland cement are C_3S and C_2S two calcium silicates that undergird its strength (Hebib and Farrell 1999; MacLaren and White 2003). Another product of the hydration of Portland cement is calcium hydroxide. It reacts with five pozzolanic materials found in cement stabilized soil; this results in more cementitious materials (Cortellazzo and Cola 1999). Typically, the necessary quantity of cement is small but still enough to augment the soil's engineering properties and improve the cation exchange with the clay particles. The typical properties of soils stabilized with cement include a decrease in the range of expansion or compression volume, a decrease in the plasticity (i.e., in the cohesiveness), and an increase in the strength of the soil.

6.4 Stabilization with Fly Ash

Stabilization with fly ash is becoming more common and important in recent years, due possibly to its low expense and quick application, compared with other techniques. Fly ash has been used as a material for engineering for a long time, including many successful geotechnical implementations. As a by-product of coal-fired electricity generation, fly ash has limited cementations properties when contrasted with cement or lime. The various kinds of fly ash are of use as secondary binders that do not exhibit cementitious effects by themselves. Nonetheless, when mixed with small quantities of activators, they can create chemical reactions that form cementitious mixes, helping to improve the strength of fine soils. The limitations of fly ash soil stabilization include the fact that fly ash and soil mixes that are cured at sub-zero temperatures and then is inundated with water are prone to strength loss and slaking (MacLaren and White 2003). Other limitations are that the target soil must have a much lower water content than with other methods (therefore dehydration may be needed prior to treatment). Finally, the sulfur content of the fly ash may bond with other elements in the mixture and form other minerals, thereby reducing the strength and lifespan of the stabilized soil.

6.5 Bituminous Stabilization

Bituminous soil stabilization is a method by which a controlled amount of bituminous material is thoroughly mixed with aggregate or an existing soil to form a wear surface or stable base. Bitumen increases the adhesion and bearing capacity of the soil and makes it resistant to the actions of water. Bitumen stabilization is carried out using asphalt, or asphalt emulsions. The bitumen type used depends on the kind of soil stabilized, the weather conditions, and the method of construction. In cold climates, the use of tar as a binder should be avoided because of its high-temperature maximum susceptibility. Tars and asphalts are bituminous materials that are used to stabilize the soil, usually for construction. Bituminous materials added to the soil impart cohesion and reduce water absorption (Kowalski, Starry, and America 2007).

6.6 Thermal Stabilization

Thermal changes cause marked alterations in soil properties. Thermal stabilization is carried out either by heating the soil or by cooling it. An example of heating is a follow. As the soil heats up, its water content decreases. Electric repulsion between clay particles is decreased and the strength of the soil is increased. Freezing has a markedly different effect where cooling causes a slight loss of strength in the clay soils due to the increased repulsion of the particles. However, if the temperature drops below freezing, the soil stabilizes, and the porous water freeze (Lim 1983).

6.7 Electrical Stabilization

Electric stabilization of clay soils is carried out by a method known as electro-osmosis. When direct current (DC) is passed through clay soil, the porous water migrates to the negative electrode (cathode). This is due to the attraction of positive ions (cations) that are present in the water as they move towards the cathode. The strength of the soil is greatly increased by the removal of water. Electro-osmosis is an expensive method and is mainly used to drain cohesive soils. At the same time, the soil properties also improve.

6.8 Stabilization by Geo-Textile and Fabrics

Past studies have shown that the load capacity of subgrades and base course materials and their strength can be improved by incorporating non-biodegradable reinforcing materials such as fibers, geocomposites, geogrids, and geotextiles. Geotextiles are porous fabrics made from synthetic materials such as polyester, polyvinyl chloride, nylons, and polyethylene. Varieties of mesh, woven, and nonwoven geotextiles are available. This method results in high strength stabilization. When it is properly introduced into the soil, it contributes to its stability. It is used in the construction of dirt roads on soft soils. A further means of strengthening the soil for stabilization is with metal strips woven into the geotextile, providing an anchor or a tie to restrain the skin cladding element of the geotextile (Stab 2002). These materials can be used to improve the durability and productivity of future highways and can reduce construction costs. At present, most of the research on these materials is based on tests conducted in the laboratory, which are only partially completed. Further laboratory tests and assessments will be required to develop design specifications based on the properties of the materials, and these specifications will need to be checked using large-scale field trials.

6.9 Recycled and Waste Products

For waste materials such as the previous asphalt, copper and zinc slag, paper mill slag and rubber tires, improved methods of chemical and mechanical stabilization are needed. Because it is necessary to process many potentially hazardous materials, it will be necessary to develop realistic, economical, and effective ways to assess the risk of contamination of these materials by leaching and emissions. In some cases, risk assessment is complicated by environmental regulations, and this issue must also be addressed.

7. Factors Influencing Soil Stabilization Strength

Organic materials, including, sulphides, sulphates, and carbon dioxide (CO_2) can affect the strength of soil stabilization (Sherwood 1993).

7.1 Organic Materials

Top layers of soil often contain a lot of organic material. In areas with good drainage, this organic material layer can be as deep as 1.5 m (Sherwood 1993). Organic materials in soil can react with products that stimulate hydration, for example calcium hydroxide ($Ca(OH)_2$). This lowers the pH of the soil. This lower pH can interfere with the 10-hydration process reduces the hardening of the stabilized soils, creating difficulties for compaction or making it completely impossible.

7.2 Sulphates

The use of a calcium-based stabilizer in sulphate-rich soils results in the stabilized sulphated soil reacting in the presence of excess moisture to form calcium sulphoaluminate (ettringite) or tamausite, a product that takes up more volume than the combined volume of reagents. However, in order to dissolve the sulphate, an excess of water is required for the mixing process. So that the reaction proceeds (Sherwood 1993; White et al. 2005).

7.3 Sulphides

Iron pyrites (FeS_2) sometimes occur in industrial by-products and waste materials. When FeS_2 is oxidized, it produces sulphuric acid (H_2SO_4); when H_2SO_4 is mixed with calcium carbonate (CaCO3), it can form gypsum (hydrated calcium sulphate) as seen in the following reactions:

$$2FeS_2+2H_2O+7O_2= 2FeSO_4 +2H_2SO_4 \quad \text{(A II-2)}$$

$$CaCO_3+H_2SO_4+HO_2= CaSO_4.2H_2+CO_2 \quad \text{(A II-3)}$$

Hydrated sulphate is the product of these reactions, and with excess water, it may undermine the soil stabilization, much lie sulphate would. That being said, gypsum also occurs in natural soil (Al Tabbaa and Stegemann 2011; Sherwood 1993).

7.4 Compaction

It is of considerable importance to consider the effect the binder creates with regard to the soil density. For any particular level of compaction, a stabilized mix will exhibit a maximum dry density that is lower than in unstabilized soil. With an increase in the amount of binders in the soil, the optimum moisture content also increases (Sherwood 1993). For example, in soils that have been stabilized with cement, the process of hydration occurs directly after cement is put in contact with the water. Because this instigates a hardening of the soil mix, it is critical to complete the soil compaction as soon as it can be done. In the case of delays, the compaction may have to account for the extra effort needed to compact a soil that has hardened due to the chemical reactions. Depending on the stage of the reactions, such mechanical compaction could result in significant breakdown of chemical bond the resulting strength reductions. On the other hand, soils that have been stabilized with lime have some advantages when there is a compaction delay. As opposed to cement stabilized soils, soils stabilized with lime need a curing period so that the lime can diffuse throughout the soil and provide the highest plasticity. Following this curing period, the soils stabilized with lime can be mixed and compacted again allowing for a much higher strength than without these extra steps (Sherwood 1993).

7.5 Moisture Content

Sufficient moisture content is needed for soil stabilization, for both the process of hydration and for effective compaction. Cement, when fully hydrated, can absorb approximately 20% its weight in water from its surroundings (Sherwood 1993). This contrasts with Quicklime (CaO) that can absorb approximately 32% its weight in water from its surroundings (Hebib and Farrell 1999). When moisture is lacking, chemical binders will be in competition with the surrounding soils for moisture. Where the soils have a great affinity for moisture, for example, organic soils, peat, and clay, the hydration of the stabilizing agent may be restricted, and this can negatively impact on the ultimate strength of the soil stabilization (White et al. 2005).

7.6 Temperature

The reaction of Pozzolanic is sensitive to changes in temperature. In the field, the temperature changes continuously throughout the day. Pozzolan reactions between binders and soil particles slow down at low temperature and lead to a decrease in the strength of the stabilized mass. In cold regions, it may be advisable to stabilize the soil in the warm season (Sherwood 1993).

7.7 Freeze-Thaw and Dry-Wet

Effect soils stabilization does not withstand freeze-thaw cycles well. Therefore, at the site, it may be necessary to protect stabilized soils from frost damage. Shrinkage forces in the stabilized soil will depend on the chemical reactions of the binder. Soil, stabilized with cement, is subject to frequent dry-wet (D-W) cycles due to diurnal temperature changes that can cause stress in the stabilized soil and, therefore, should be protected from such effects (Hebib and Farrell 1999; Sherwood 1993).

8. Conclusion

With technological advances and changing economic factors, engineers will have more choices of chemical agents that might be mixed into subgrades as a way of improving the strength, durability and compatibility of the soils. However, performance-based tests must be performed to verify the practicality of any agents used for stabilization. Beyond this, a number of chemicals now in use in the petrochemical industry have not been tested for soil stabilization. Other potential sources of soil stabilization that require research are processes including spray-on techniques and injections that may give rise to practical and economical options. At the same time, the process of global climate change has the potential to adversely affect soil stabilization in terms of both the application and the durability of treatments. As such, it is advisable to review how soil stabilization will be affected by such changes (MacLaren and White 2003). After reviewing the literature, the present research determines that the practical application of the materials discussed here have been proven to increase soil strength or stabilize loose soils. Nonetheless, more research must be conducted to determine the practicality in field conditions, as opposed to concentrating only on experimental research. As ever, the field will benefit from an openness to finding and testing other materials that might be of use for soil stabilization.

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