Deep Soil Mixing for Mitigation of Problematic Soils

Mahdi Z. M. Alnunu

Submitted to the
Institute of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
in
Civil Engineering

Eastern Mediterranean University
February 2023
Gazimağusa, North Cyprus

Approval of the Institute of Graduate Studies and Research

Prof. Dr. Ali Hakan Ulusoy
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Doctor of Philosophy in Civil Engineering.

Assoc. Prof. Dr. Eriş Uygar
Chair, Department of Civil Engineering

We certify that we have read this thesis and that in our opinion it is fully adequate in scope and quality as a thesis for the degree of Doctor of Philosophy in Civil Engineering.

Prof. Dr. Zalihe Nalbantoğlu Sezai
Supervisor

Examining Committee

1. Prof. Dr. İlknur Bozbey
2. Prof. Dr. Sabriye Banu İkizler
3. Prof. Dr. Zalihe Nalbantoğlu Sezai
4. Assoc. Prof. Dr. Ayşe Pekrioğlu Balkıs
5. Assoc. Prof. Dr. Eriş Uygar

ABSTRACT

Deep soil mixing (DSM) is a method that is commonly employed in the field of civil engineering construction in order to improve the physical and engineering properties of weak problematic soils. The process involves penetrating the rotary augers into the problematic soil and mixing it with different types of binder materials such as cement, lime-cement or some waste materials, resulting in an increase in the strength and reduction of compressibility of the soil. This study investigates the strength and stability of loose sand that has been modified with Portland cement alone and in combination with different waste replacement materials such as waste brick dust (WBD) and waste marble dust (WMD) through a series of laboratory tests. The study aims to develop a design procedure for assessing the highest strength and volume change in deep soil mixing (DSM) application, considering the factors such as the type of binder, binder-soil ratio (B/S), water-binder ratio (W/B) and curing time. The study consists of two parts. The first part includes the determination of the most effective soil-binder mixtures that will be used in the construction of the DSM columns. The experimental investigations include sitting time, bulk density, unconfined compression test, and microscopic image analysis using a stereoscopic microscope. In addition, stress-strain behavior and modulus of elasticity of the soil-binder mixtures are analyzed at different curing periods of 7 and 28 days. Second part of the study evaluates the performance of the DSM columns constructed in the model test tank with the loose sand placed in it. The behavior and performance of the DSM columns constructed with using different replacement binder materials (WBD and WMD) and with different binder-soil ratios (10, 15 and 20) are analyzed in the model test tank by using one dimensional loading frame. In the study, ex-situ deep soil mixing method is used for the construction of the DSM columns. From the loading test, the load-deformation curves are obtained for each binder-soil ratio and the failure modes of the DSM columns, bearing capacity and subgrade modulus values are obtained. The findings of the research indicate that utilization of 20% waste brick dust as a replacement material in a binder-soil ratio of 20% leads to better improvement due to strong interlocking between the sand particles and the binder materials and results in higher strength of the DSM columns. Similarly, the optimal replacement percentage of waste marble dust (WMD) is determined to be 10% at a binder-soil ratio of 20%. In DSM model reinforced sand, it is observed that the bearing capacity of sand soil is enhanced in all cases of DSM applications: single and group of ex-situ DSM column. The columns with WMD exhibit the greatest bearing capacity and subgrade modulus in both single and group of DSM columns and also in both end-bearing and floating column application. Overall, the incorporation of WBD and WMD as replacement materials in loose sand mitigation seems to be a promising technique for improving the geotechnical properties of such soils and has the potential to generate significant cost savings and environmental benefits.

Keywords: bearing capacity, binder-soil ratio, brick dust, deep soil mixing (DSM), end-bearing, ex-situ mixing, floating column, group of columns, improvement, load-deformation curve, loose sand, marble dust, model tank, settlement, waste, water-binder ratio

ÖZ

Derin zemin Derin zemin karıştırma (DSM), zayıf problemli zeminlerin fiziksel ve mühendislik özelliklerini iyileştirmek için inşaat mühendisliği inşaat alanında yaygın olarak kullanılan bir yöntemdir. Derin zemin karıştırma (DSM), döner burguların problemli zemine nüfuz etmesini ve çimento, kireç-çimento veya bazı atık maddeler gibi farklı bağlayıcı malzemelerle karıştırılmasını içerir, bu da toprağın mukavemetini arttırır ve sıkıştırılabilirliğini azaltır. Bu çalışma, tek başına Portland çimentosu ve atık tuğla tozu (WBD) ve atık mermer tozu (WMD) gibi farklı atık çimento ikame malzemeleri ile kombinasyon halinde modifiye edilmiş gevşek kumun mukavemetini ve stabilitesini bir dizi laboratuvar testiyle araştırmaktadır. Çalışma, bağlayıcı türü, bağlayıcı-zemin oranı (B/S), su-bağlayıcı oranı (W/B) ve kür süresi gibi faktörleri göz önünde bulundurarak derin zemin karıştırma (DSM) uygulamasında en yüksek dayanım ve hacim değişimini değerlendirmek için bir tasarım prosedürü geliştirmeyi amaçlamaktadır. Çalışma iki bölümden oluşmaktadır. Birinci bölüm, DSM kolonlarının yapımında kullanılacak en etkili toprak-bağlayıcı karışımlarının belirlenmesini içermektedir. Deneysel incelemeler arasında oturma süresi, kütle yoğunluğu, serbest basınç testi ve stereoskopik mikroskop kullanılarak mikroskobik görüntü analizi yer alır. Ayrıca, 7 ve 28 günlük farklı kür sürelerinde zemin-bağlayıcı karışımlarının gerilme-deformasyon davranışı ve elastisite modülü analiz edilmiştir. Çalışmanın ikinci bölümünde, model test tankı içerisine yerleştirilen gevşek kum içerisinde oluşturulan DSM kolonlarının performansı değerlendirilmektedir. Farklı ikame bağlayıcı malzemeleri (WBD ve WMD) kullanılarak ve farklı bağlayıcı-zemin oranlarına (10, 15 ve 20) sahip olarak inşa edilen DSM kolonlarının davranışı ve performansı, tek boyutlu yükleme çerçevesi kullanılarak model test tankında analiz edilmiştir. Çalışmada DSM kolonlarının yapımında ex-situ derin zemin karıştırma yöntemi kullanılmıştır. Yükleme testinden, her bağlayıcı-zemin oranı için yük-deformasyon eğrileri elde edilirek DSM kolonlarının göçme modları, taşıma gücü ve zemin yatak katsayısı değerleri elde edilmiştir. Araştırmanın bulguları, %20 atık tuğla tozunun %20'lik bir bağlayıcı-zemin oranında ikame malzeme olarak kullanılmasının, kum parçacıkları ile bağlayıcı malzemeler arasındaki güçlü kenetlenme nedeniyle DSM sütunlarında daha iyi bir iyileştirmeye yol açtığını ve daha yüksek mukavemetle sonuçlandığını göstermektedir. Benzer şekilde, atık mermer tozunun (WMD) optimum ikame yüzdesi, %20'lik bir bağlayıcı-zemin oranında %10 olarak belirlenmiştir. DSM model donatılı kumda, DSM uygulamalarının tüm durumlarında: tek ve grup ex-situ DSM kolonu, kum zeminin taşıma gücünün arttığı gözlemlenmiştir. WMD'li sütunlar, hem tekli hem de gurup DSM sütunlarında ve ayrıca hem uç taşıyıcı hem de yüzer sütun uygulamasında en yüksek taşıma kapasitesini ve yatak katsayısı değerlerini sergiler. Genel olarak, WBD ve WMD'nin gevşek kum iyileştirmesinde ikame malzemeler olarak kullanılmaları, bu tür zeminlerin geoteknik özelliklerini iyileştirmede umut verici bir teknik gibi görünmektedir ve önemli maliyet tasarrufları ve çevresel faydalar sağlama potansiyeline sahiptir.

Anahtar kelimeler: taşıma gücü, bağlayıcı-zemin oranı, tuğla tozu, derin zemin karıştırma (DSM), uç-direnci, ex-situ karıştırma, yüzer kolon, kolon gurubu, iyileştirme, yük-deformasyon eğrisi, gevşek kum, mermer tozu, model tank, oturma, atık, su-bağlayıcı oranı.

ACKNOWLEDGEMENT

The road to this day has not been an easy one, but I have persevered and accomplished something truly remarkable.

To my dear family, as I always say " ***Family comes first*** " I would not be here without your endless support.

To all my fellow graduates and my best friends: *Mosab, Waseem, Huseyin,* and *Yazan* I wish you a successful future in your academic, professional, and personal lives.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1

INTRODUCTION

1.1 General Introduction

The primary goal of using binders in deep soil mixing is to improve the characteristics of problematic soils in such a way that the soils become similar to those of a soft rock, such as clay shale or lightly cemented sandstone (Kazemian & Huat, 2009; Majik & Savoikar, 2022). The strength properties of stabilized soil are affected by a range of factors, including the type of soil, the type and the quantity of binder, and the curing conditions under various stress conditions (Liu et al., 2022; Luo et al., 2022). Currently, different improvement techniques have been used to enhance the engineering properties of problematic soils such as loose sand and soft clays by increasing the strength and the compressibility of such soils. Some of the techniques used in the field are preloading, deep compaction, stone columns, jet grouting, etc. (Caraşca, 2016). Deep soil mixing method is applicable for the improvement of most soil types (Kitazume & Terashi, 2013).

In the present study, deep soil mixing (DSM) method will be applied for the improvement of the problematic soil; loose sand and different waste materials such as waste brick dust (WBD) and waste marble dust (WMD) will be used together with cement as a binder material in the construction of the DSM columns. Series of laboratory test will be performed and the findings of the test results will be analyzed and compared in order to better understand the behavior of loose sand reinforced with DSM method.

1.2 Aim of the Study

The quality of the soil can significantly influence the stability and integrity of existing structures. In situations where the soil conditions are problematic, special soil improvement methods may be required before the construction of the foundations in order to mitigate any potential negative impacts on the structure and allow the project to proceed as planned. These soil improvement techniques can range from the incorporation of binders or reinforcement elements to more advance methods such as deep soil mixing (Ajorloo, 2010).

Nowadays, researchers are currently looking for new waste materials that can be used to replace cement in various civil engineering projects. Some of these waste materials are waste brick dust (WBD), and waste marble dust (WMD), which are both a byproduct of industry and the usage of these wastes in civil engineering constructions is both environmentally friendly and cost-effective (Arel, 2016; Khan et al., 2018; Kinuthia & Nidzam, 2011; Li et al., 2018; S. Rogers, 2011; Tugrul Tunc, 2019).

In the field of deep soil mixing, (DSM), various waste materials such as glass powder, fiber, fly ash, and blast furnace slag have been utilized as replacements for cement (Arulrajah et al., 2018; Chenari et al., 2018; Gullu et al., 2017; Guo et al., 2016; Mohammadinia et al., 2019). However, relatively little research has been conducted on the use of brick dust and marble dust as cement replacement material in DSM applications.

In the present study, unlike the materials used in the previous studies in the literature, WBD and WMD will be used in the construction of the DSM columns. The aim of the study is to evaluate the effect of these waste materials in DSM applications by studying their performance and comparing the findings from laboratory test. The research aims to contribute to the understanding of the potential use of these materials in DSM applications and the potential benefits and limitations of their use in civil engineering application.

Most of the researches on the use of DSM method has focused on the improvement of soft clays, while only a few studies have examined its use on loose sands. (Esmaeili et al., 2014; Zakaria et al., 2020). Moreover, there is a need for further research on the use of DSM with different materials as additives. The current study has two parts: in the first part of the study, small specimens will be prepared by using different percentage of WBD and WMD together with cement and the most effective percentages of binder-soil mixture for the construction of DSM columns will be determined whereas in the second part of the study, according to the test results obtained in the first part, DSM columns will be constructed in loose sand placed in a model test tank and the columns will be subjected to uniaxial loading to get the stress-settlement behavior of the sand-DSM composite in the test tank. The second part of the research work, following the completion of the small control specimens, aims to investigate the performance, bearing capacity, stability, and settlement behavior of deep soil mixing (DSM) column in model test tank under different conditions such as: single and group of DSM columns, as well as end-bearing and floating DSM columns. In order to achieve the purposes of the research work, a series of laboratory tests on control specimens were conducted, including measurements of sitting time, bulk density, unconfined compressive strength, and microscopic-image analysis using a stereoscopic microscope. Additionally, the modulus of elasticity, stress-strain behavior, and deformation behavior after failure were analyzed. Based on the results of these tests, DSM columns were constructed in loose sand placed in a model test tank using an ex-situ replacement method.

1.3 Layout of the Thesis

The dissertation is organized into five chapters that deals with various aspects of the deep soil mixing method. Following this general introduction, Chapter 2 presents a literature review that endeavors to provide a comprehensive analysis of the current state of research in ground improvement studies, with a specific focus on the deep soil mixing method. Chapter 3 focuses on the materials and testing methods employed in this study, including the descriptions of the sand taken from the field, cement binder properties, and waste replacement materials: WBD and WMD used, as well as a detailed explanation of the experimental procedures that will be followed. Chapter 3 also discusses the preparation processes that will be implemented for the construction of DSM columns in the model test tank. Chapter 4 presents the results and discussion of the experimental findings, including the experimental results for both small-scale quality control samples and large-scale model of deep soil mixing columns in the test tank. Finally, Chapter 5 provides a summary of the main findings of the study and offers recommendations for future studies.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

Chapter 2 presents some previous studies that describe the application of deep soil mixing, DSM including the theory and technology applied, the mechanisms and the advancements of DSM. By reviewing the previous studies, it was decided what other further studies could be done within the scope of this study on DSM applications.

2.2 Overview in Deep Soil Mixing, DSM

Deep soil mixing, DSM is a method of soil stabilization techniques that depends on using different types of stabilizing agents. This method was applied first in Japan and in the Scandinavian countries in the 1970s. Scandinavian countries used this method especially in the stabilization of very soft compressible clays. DSM was applied by creating lime or lime/cement columns in clays in order to control the settlement under embankment loads (Arulrajah et al., 2018). DSM was found to be cost-effective and economical method compared to conventional techniques such as; bioremediation techniques, jet grouting, etc. DSM method is used in stabilization of problematic soils such as; loose sandy soils, peats, liquefiable soils and soft compressible clays (Esmaeili et al., 2021; Jung et al., 2020). DSM is normally preferred especially in improving soil strength characteristics (Bhadriraju et al., 2008; M. Bruce et al., 2013; Porbaha et al., 2015).

Due to its wide applicability and high efficiency in stabilizing problematic soils, the method has become popular in many countries. This method has been frequently applied for many improvement purposes in different construction projects (M. Bruce et al., 2013; Kitazume & Terashi, 2013). The engineering properties of the reinforced soils by DSM depend on the many factors including the binder type, original characteristics of soil, existing area that will be improved, mixing method, and curing conditions at a particular work site (Topolnicki, 2016).

2.3 Deep Soil Mixing Technique

Deep soil mixing, DSM is a soil improvement technique that can be applied for various engineering purposes such as; increasing foundation strength, stabilizing large field, constructing cut-off or retaining walls, and treating contaminated soils (Hasheminezhad & Bahadori, 2020; Rabbani et al., 2019). This method can be accomplished with constructing DSM columns in existing soil in the field. DSM column resulted from mixing the existing soil with binder materials such as cement, lime or lime-cement. Binder materials can be added and mechanically mixed into the existing soil (Tatarniuk, 20104).

(C. D. F. Rogers & Glendinning, 1996) used cement with small amount of lime as binder materials. It has been observed that lime has presented significant mineralogical changes in clay soils and provided a better soil strength. In DSM application, the binder material is mixed with soil through "mixing auger" which contains shaft, nozzles, tipped blades and paddles for rotation. Different types of methods and mixing blades were designed to be suitable for different soil types existing on site. DSM column is formed from the rotational movement of blades along the shaft. Usually, DSM columns range from 0.6 m to 1.5 m in diameter and up to 40 m in depth (D. A. Bruce

& Bruce, 2003). The DSM technique is applied by injecting a high pressure binder-slurry through nozzles, and mixing it with existing soil by cutting tools (blades and paddles) as shown in Figure 2.1 (Tatarniuk, 20104).

In DSM application, generally cement is used in order to increase the soil strength, reduce the permeability and improve the compressibility characteristics of problematic soils. The properties of stabilized soil by DSM depend on nature of native soil, method of mixing, operational parameters (dimensions of auger) and the binder characteristics (D. A. Bruce & Bruce, 2003). The binder materials in DSM can be used in two forms: dry or slurry form. Both of them are injected and mixed with soils by auger machine to increase the efficiency of the mixing process. The shafts that are used in the auger machines can be either single shaft or more than one shaft. The shafts penetrate into the existing soil and rotate about the vertical axis and produce individual or overlapping soil-cement or soil-lime columns (Topolnicki, 2016).

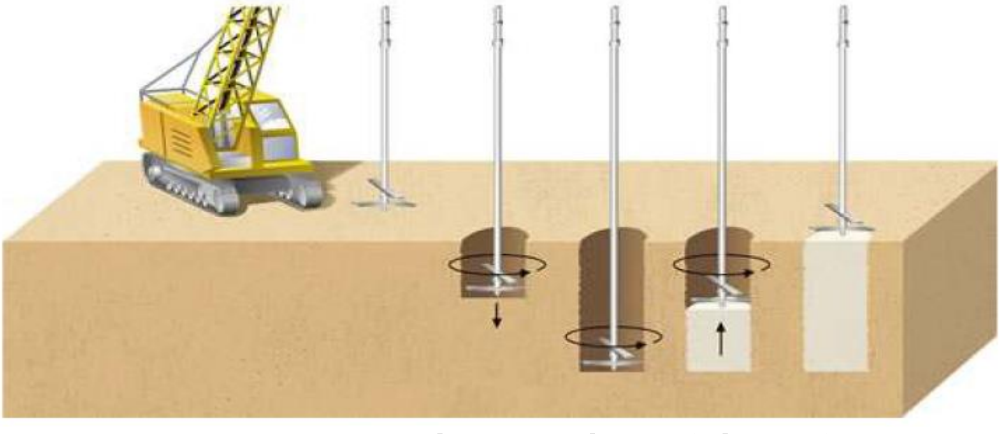

Figure 2.1: Deep soil mixing technique (Filz, 2007)

2.4 Classification of Deep Soil Mixing Methods

Deep soil mixing, DSM method can be classified into different groups according to the type of mixing method used. The methods are: mechanical mixing, high pressure injection and combination of mechanical and high-pressure injection (Kitazume, 2020). Figure 2.2 shows the main classification groups of deep soil mixing methods.

In the mechanical mixing, the binder materials can be injected into soft ground and mixed by blades. In this mixing, the binder materials can be dry or slurry. Dry form of the binder material usually is lime powder, while in slurry form, the binder material usually is cement mixed with water (Cement Deep Mixing Method Association, 1999).

High pressure injection is classified into three methods as shown in Figure 2.2: the dry jet mixing (DJM) method, in which a powder binder material is usually applied on soil high water content. In the high-pressure injection method, the original soil is disturbed and softened by high pressure injection which contains the binder material: water and/or air that can be mixed with the existing soil at the same time. The third technique by which DSM columns are constructed is the combination of both mechanical mixing and high-pressure injection (Dry Jet Mixing Method Association, 2006).

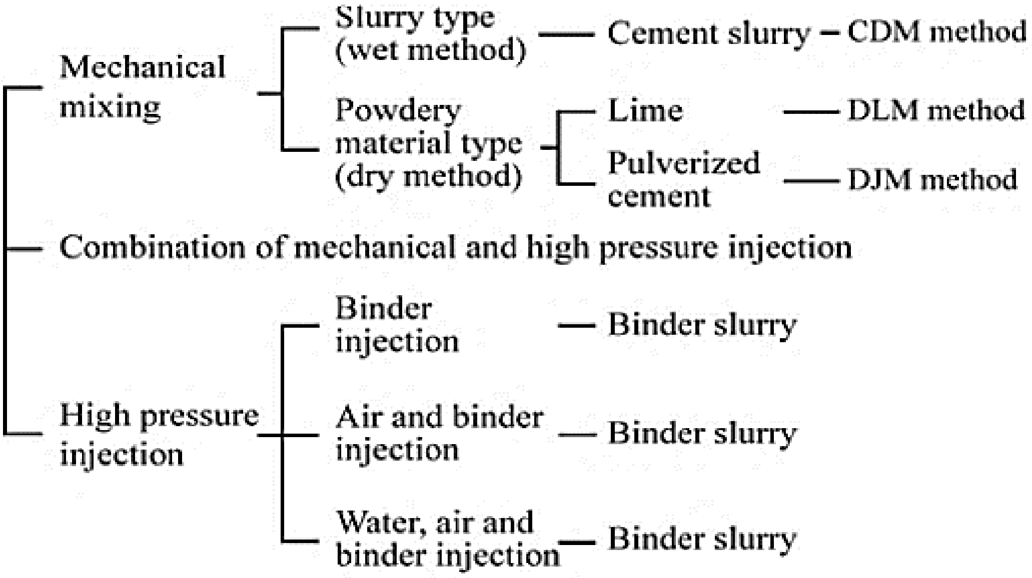

Figure 2.2: Classification of deep soil mixing method (Kitazume, 2020)

2.4.1 Dry Soil Mixing

Dry mixing, DM method can be conducted with gentle procedures and less vibration. This method is considered as a clean method since it does not produce spoil for disposal. This method can be summarized as a powdery binder injected into soil with compressed air without any need for the binder to be slurry. DM method starts with rotating the auger and blades in order to make cavity in the soft ground and then the auger injects the powder with air to fill the voids in the soft ground (Mokrousova, 2010).

DM method can be used effectively in soils with high moisture content. The common equipment consists of station provided with compressed air which is used to transport the binder materials into the ground soil and mix them together. The process of injection of the binder materials start to take place when lifting up the auger. During this process, the auger is rotated in the reverse direction than the direction during the penetration of the blades. The diameter of dry deep soil mixing column vary from 60 to 80 cm and with depth, extend up to 10 m. This method gives many advantages since it can be performed in low temperatures, lack of dredged material, ability to strengthen very weak soils and relatively low price compared to many other improvement techniques (Egorova et al., 2017).

2.4.2 Wet Soil Mixing

Wet mixing, WM method is a ground improvement technique that depends on mixing a problematic soil with binder slurry material in order to improve the characteristics of soils (Akrouch et al., 2018). WM is an in-situ technique where the weak soils with cementitious properties are mixed with the binder slurry. The slurry is injected through an augering shaft, which this is hollowed in order to flow the binder slurry inside it. WM method usually uses cement-based slurries to create cemented columns inside the in-situ soil. The cemented elements can be shaped in many forms such as single column, continuous walls or blocks depending on number of shafts (Lee et al., 2005). WM is used to increase the strength and the bearing resistance of soils and reduce the settlement in soft clays (A Rashid et al., 2017).

Wet mixing equipment comprises a batch plant to supply slurry, mixing machine to prepare the slurry in the site and augering machine to mix the slurry into the ground soil (D. A. Bruce & Bruce, 2003; Ju et al., 2019) Wet mixing method can be used for dry soils, in arid environments or in case of deep water-table in the ground (A. Puppala et al., 2008).

This method depends mainly on the quality of binder slurry, cement dosage, water content of the slurry and particle size of an in-situ soil (Kelly Costello et al., 2016).

2.5 Installation of Deep Soil Mixing Column

The installation method of DSM column is important, since the quality and capacity of DSM column depends mainly upon the method of installation (Egorova et al., 2017). Two different installation methods have been used in order to perform the DSM columns in soil:

1. In-situ mixing (mechanical method).
2. Ex-situ mixing (replacement method).

In the in-situ mixing method, the soil is stabilized in-situ with a binder material by means of a mechanical mixing or high pressure injection as described in Section 2.4. While, in the ex-situ mixing method, the soil is excavated and mixed with the binder material in plant or during the transportation of the mixture of the soil-binder material to the construction site (Kitazume & Terashi, 2013).

In the in-situ mixing method, the installation of soil-cement columns causes movements of the surrounding ground, which affects the adjacent underground structures (Chen et al., 2013). Field observations indicated that significant excess pore pressure was generated during installation of soil-cement columns (Wang et al., 2014).

The method of ex-situ has some advantages over the in-situ methods and it is intended to provide additional improvement for some soil problems such as liquefaction resistance, homogeneity to the improved ground, smaller volume compressibility and extremely high strength to the original soils (Ahmad et al., 2015; Shah et al., 2019; Zakaria et al., 2020). In the present study, because of the aforementioned advantages of the ex-situ method, it was decided to use ex-situ replacement method in order to construct the DSM columns with the less disturbance to the surrounding soil during the installation of DSM columns.

2.6 Properties in Deep Soil Mixing

The characteristics and properties of the stabilized soils are important in DSM mixing technique. The interaction between the binder material and soil (i.e., soft fine grained soil or loose coarse-grained soil) depends on many important factors that can affect the quality of DSM column. The mechanical, physical and chemical aspects in soil mixing play an important role in improving the soil, starting from cementitious bonds in soil-binder mixture to the mechanical and physical properties of the stabilized soil such as bearing capacity, shrinkage/settlement, hydraulic conductivity and liquefaction susceptibility (Mohammadinia et al., 2019).

The mechanical properties are considered as the most common engineering properties of the stabilized soil by DSM method. The mechanical properties of these soils should be measured so that the shear and compressive strength, modulus of compressibility, unit density and permeability of the stabilized soil could be evaluated. In general, the DSM column has higher strength and it is stiffer than the surrounding soil and because of this, DSM column starts to control the design parameters of the foundation soil. The interaction and load transformation between the DSM columns and surrounding soil are described in Figure 2.3 (Topolnicki, 2009). The further details of the load transfer mechanism of DSM are given in Section 2.8.

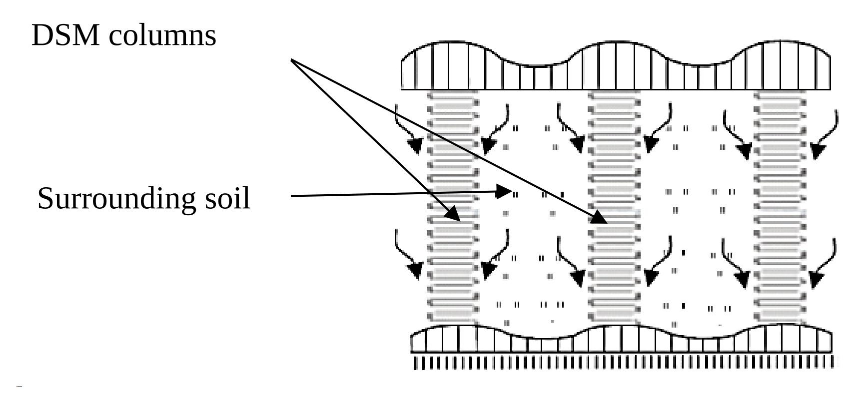

Figure 2.3: Mechanism of load carrying of DSM columns (EuroSoilStab, 2002)

In order to understand the interaction between DSM columns and the surrounding soil, both the laboratory and field tests such as: cone penetration tests (CPT), laboratory unconfined compression tests, vane shear tests, undrained shear strength tests should be conducted so that the improved soil conditions by DSM method could be checked (Rashid et al., 2017; Shen et al., 2005; Shi et al., 2016).

2.7 Patterns of Deep Soil Mixing Installations

Soil mixing depends on many factors such as, binder material content, mixing method and the area to be treated. There are different types of installation-patterns of DSM columns. Some of these are spaced or overlapping columns and single or combined columns as shown in Figure 2.4.

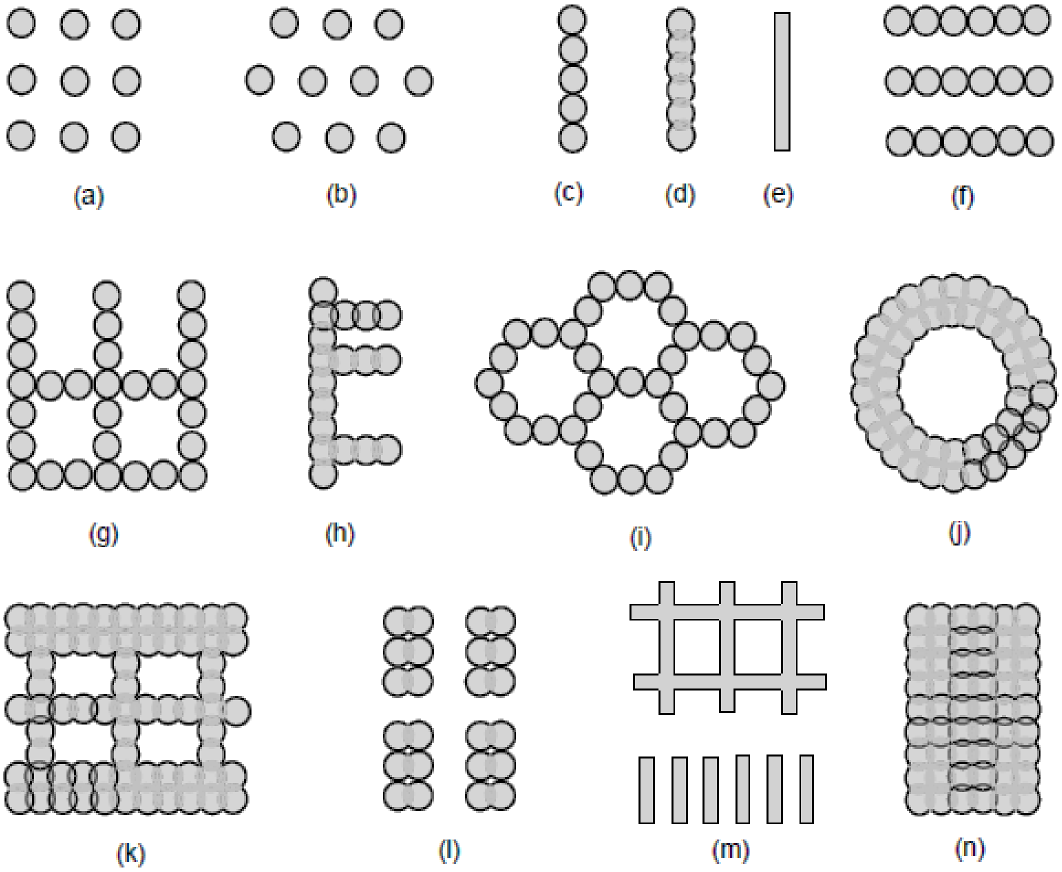

Figure 2.4: Examples of deep soil mixing patterns: (a), (b) square and triangular, (c) tangent wall, (d) overlapped wall, I trench/CSM wall, (f) tangent walls, (g) tangent grid, (h) overlapped wall with buttresses, (i) tangent cells, (j) ring, (k) lattice, (l-n) group

The choice of installation pattern depends mainly on the purpose of DSM column Single or combined columns in square or triangle patterns are usually applied when the settlement beneath embankments is found to be a problem (Archeewa et al., 2011). While wall pattern can be applied in case of excavation to control the side from falling and to protect the structure from the horizontal sliding forces (Vervoorn & Barros, 2021). Walls can be done in overlapping or tangential columns as a trench structure. The overlapping is essentially in case of cut-off walls and embankments in order to increase the bearing capacity (Pan et al., 2019). Overlapping columns in U and circle shapes are usually used to improve the interaction with the treated soil (T. Muttuvel & S. Iyathurai, 1999). This form is considered as a cost-effective method since it combines between wall and block pattern. In case of making high stable structure or large volume of DSM, full blocks can be used to act as a gravity structure (Topolnicki, 2016).

2.8 The Load Transfer Mechanism of DSM

The area around the diameter of DSM column which contributes to the improvement of the soil is very important. Some studies have been conducted in order to understand the behavior of DSM columns and surrounding soil (Khalili et al., 2020; Larsson et al., 2005; Oliaei et al., 2021). The area around the DSM column can be divided into three main zones. These zones are; expansion zone, transition zone and boundary layer. Figure 2.5 shows these three zones around the DSM column. The expansion zone is the external diameter of the existed DSM column which surrounds the enclosing boundary of DSM column. The expansion zone is the difference between the actual DSM column diameter and the diameter of the auger that used during the mixing process (Larsson et al., 2005). The expansion zone is important because it depends on the in-situ soil characteristics, stiffness and the process of the grouting. In soft soils, the expansion zone can be bigger when a high pressure applied during the grouting, while in case of soil with high stiffness, the effect of expansion zone could be lower or not existed. The biggest zone is the transition zone which can extends around of 1.5-2 times the diameter of DSM column considering the center of column. The transition zone is the place where the migration of calcium ions can take place in order to increase the undrained shear strength of the soil that surrounds the DSM column. The boundary layer is a very thin layer located around the transition zone with

10-20 mm thickness. At the boundary layer, strength characteristics of the soil starts to mitigate because ion migration cannot reach to the boundary layer (Shen et al., 2005; Tatarniuk, 20104).

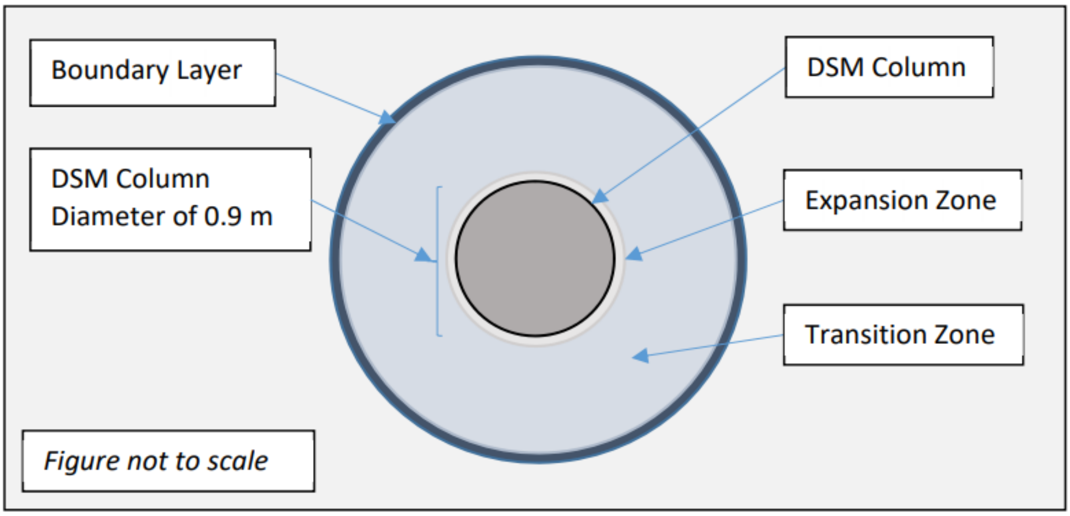

Figure 2.5: Main zones around DSM columns (Larsson et al., 2005; Tatarniuk, 2014)

2.9 Grouping Effects of DSM Columns

The performance of the group of DSM columns is a critical factor for improving the soil in order to support the foundations. From the field experiments and conducted projects, the efficiency of the group of DSM columns is related to the design of foundation and site specification parameters (Dehghanbanadaki et al., 2014). By installing the DSM columns into the soil, during the process of injection, the binder slurry forms the soil-binder columns. The volume of each column increases in the soil, which causes an increase in the lateral stress in the surrounding soil and results in confinement in the soil fabric and creating a series of zones of interaction (Foy, 2017).

For DSM column design, usually triangle pattern is used for soil improvement and liquefaction mitigation (O’Sullivan et al., 2009). The group of DSM columns should be placed in rows (single or double) regarding to the loads plan in order to increase the efficiency of the group of DSM column. In the case of group of DSM columns, row arrangement of DSM column can be used in order to increase the stability of soil, since the length of rows and the number of columns play an important role in controlling the stability of soil (Topolnicki, 2016).

2.10 Parameters Affecting Deep Soil Mixing

In DSM application, some factors were identified as effective factors on the behavior of DSM columns. These factors are listed below (Bagherinia & Lu, 2021; Bhadriraju et al., 2008; Frikha et al., 2017):

- Soil type,
- Type of binder material,
- Proportions and percentages of binder material,
- Amount of mixed water,
- Preparations and mixing technique, and
- Curing conditions.

Other factors related to mixing specifications and equipment can also affect the behavior of treated soils such as; shape of blade of auger shaft, penetration type (forward and backward) and rate, speed of auger during the rotation (Chen et al., 2013; Jung et al., 2020; Pittaro, 2019). According to (Egorova et al., 2017), choosing the suitable method for DSM depends on some aspects which are considered as:

- The moisture content of soil: in case of high water content, dry mixing method is required while at low water content, wet mixing method is preferred due to hydration.

- Multi-layered soils: due the difference of the strength and stiffness of each soil layer, wet mixing method in case of multi-layered gives opportunity to vertical movement of soils at the length of DSM column.
- The quality of mixture: optimum homogeneous of soil-binder mixture can be obtained by wet mixing method due to the presence of water.

2.10.1 Binder Content

Soil stabilization by DSM is summarized as mixing the binder materials with other fillers and then mixing them together with the soil to form strengthened columns in the ground. Binder materials such as; Ordinary Portland Cement (OPC) and lime (CaO) have been used in treating soil by using DSM. Figure 2.6 describes some factors affecting binder materials in DSM (Wong et al., 2020).

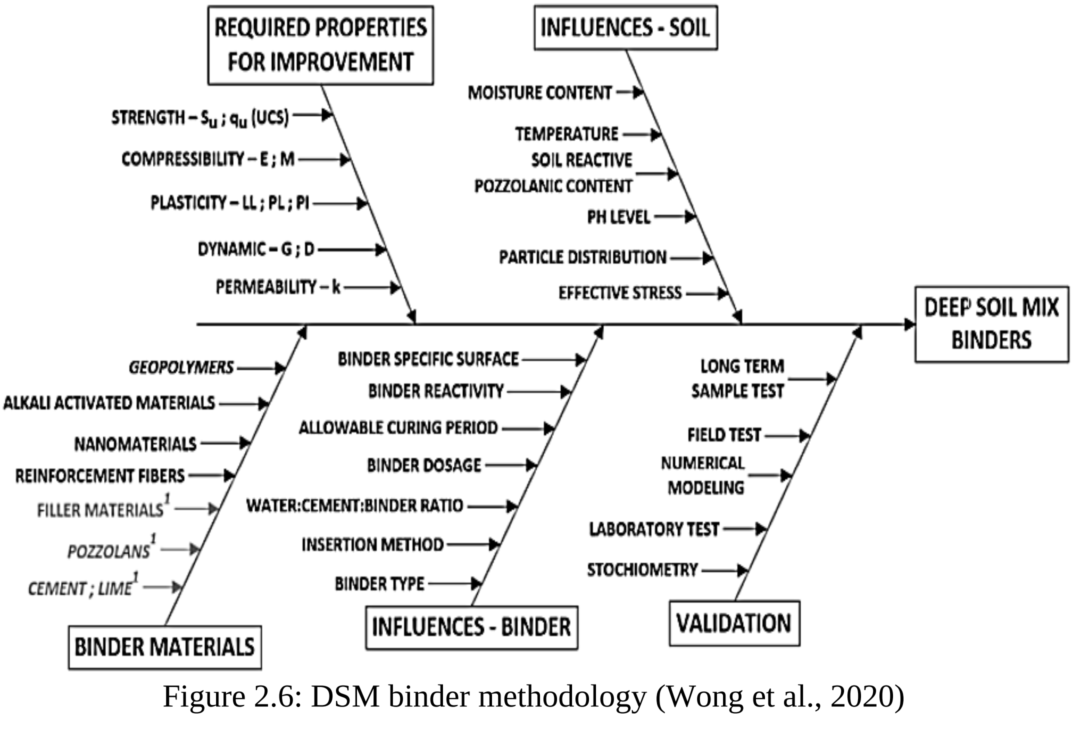

Figure 2.6: DSM binder methodology (Wong et al., 2020)

2.10.2 Effect of Water Content in Deep Soil Mixing

Water is essential in mixing the cement with the soil. Water is required during hydration process of cement. It is also required for good and efficient mixing. Besides, water is a medium that enables the cementing ions to disperse within the voids of soil mass. In case of partially saturated soil, the presence of air space in the soil hinders the free dispersion of the cementing ions. While in oversaturated clay, due the high amount of water content, it requires more cement to bind the soil particles together that have been loosely dispersed by the presence of excess water. Figure 2.7 shows the effect of water content on the soil mixing (Bergado & Lorenzo, 2005).

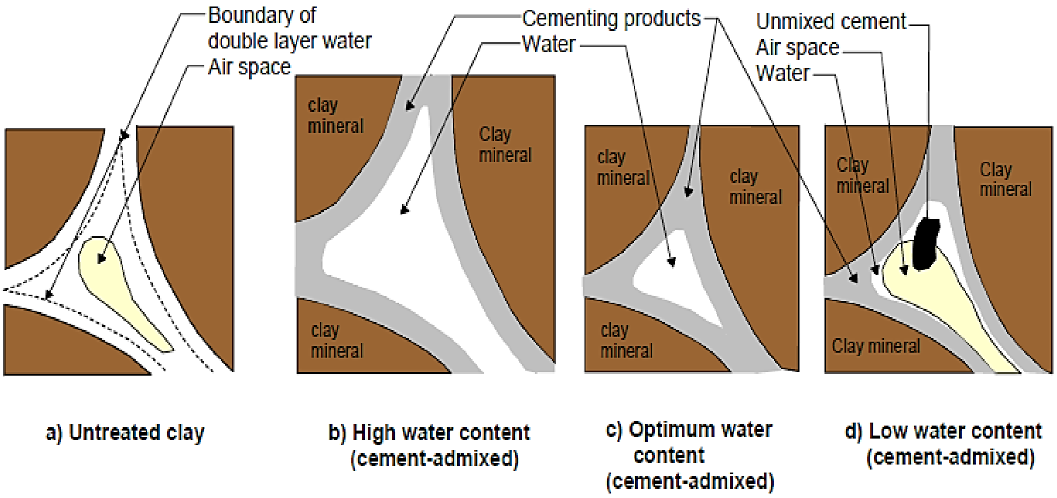

Figure 2.7: Effect of water content in soil mixing (Bergado & Lorenzo, 2005)

2.10.3 DSM Column Installation

DSM installation mainly involves mechanical mixing of existing soil with injected slurry of cement binder which sets-up after installation due to the pozzolanic reaction in binder (Jendrysik et al., 2018). The DSM method uses a relatively low injection pressure and the induced ground movements are generally related to the different lateral pressure between the wet mix and the surrounding soil (Dong & Whittle, 2018). During the installation of DSM columns, the unconfined compressive strength and the tensile strength can be conducted in order to check the effectiveness of DSM column application (Kacar & Ho, 2019).

Effectiveness of DSM column installation method depends mainly on the moisture content of the existing soil layer. Generally, dry mixing techniques achieve less strength for the same soil type than wet mixing, which is suitable for soft clays, silts, fine-grained sands with lower water content, and multiple interbedded soft and dense soil layers (Wong et al., 2020).

In terms of binder injection, there are two basic execution procedures depending on the injection sequence of the binder: (a) injecting binder during the penetration of mixing shafts and (b) injecting binder during the withdrawal of the mixing shafts. Each injection sequence has its respective advantages and disadvantages. The penetration injection is beneficial for the homogeneity of strength of the stabilized soil column. However, it is possible to deadlock or cause serious damage to the machine if any trouble occurs in the mixing machine during the penetration (Kitazume & Terashi, 2013).

2.11 Quality Assurance and Quality Control

In deep soil mixing process quality control QC and quality assurance QA procedures are required to ensure that the construction is performed according to the design requirements (Forsman et al., 2017; Spross et al., 2021). A flowchart showing the typical steps involved in executing a quality management program is shown in Figure 2.8. Quality control, QC essentially comprises of evaluating the binder quality and quantity, mixing efficiency due to different penetration/withdrawal speeds of the auger, the rate of rotation of mixing blade, and geometry length, diameter, and spacing of columns throughout the construction process (Madhyannapu et al., 2010).

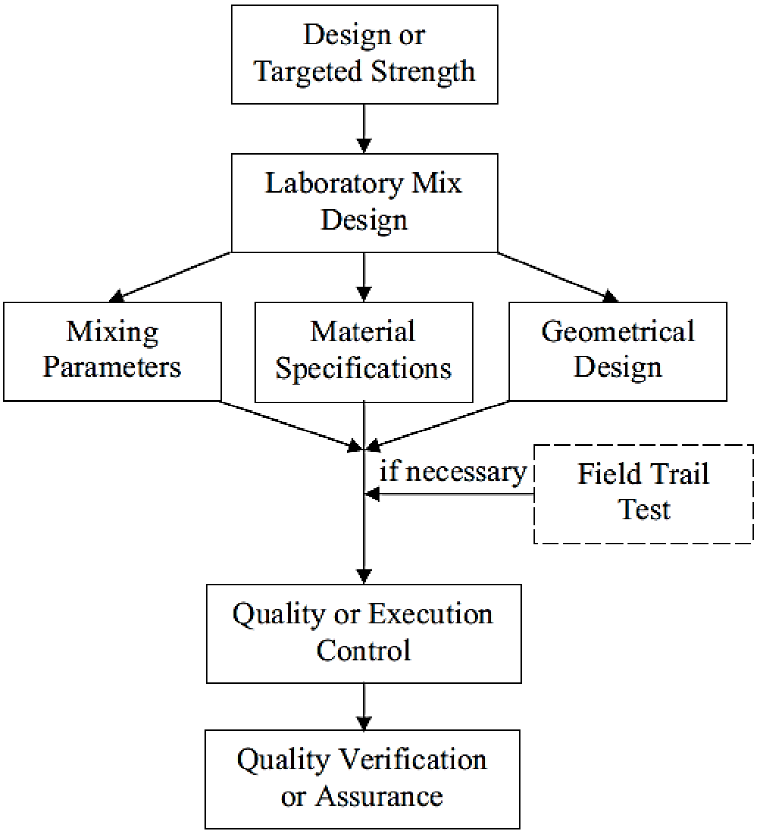

Figure 2.8: Typical QA/QC procedure for DSM method (Madhyannapu et al., 2010)

Subsequent QA tests are also necessary to confirm the quality of the DSM columns installed in soil. QA can be carried out through laboratory tests on cores retrieved from the site or in-situ tests including penetration methods, geophysical methods, loading test methods, and nondestructive methods on installed columns (Porbaha et al., 2015).

For the QA purpose, the laboratory testing on the performance of DSM columns has largely been focused on the columns themselves (Brasse et al., 2018; Dong & Whittle, 2018; Jung et al., 2020). Laboratory testings on the soil surrounding DSM columns are performed in order to determine the soil engineering properties such as: unconfined compressive strength (UCS) (Jendrysik et al., 2018; Prokopowicz, 2019; Yohannes & Daramalinggam, 2019), undrained shear strength (Bouassida et al., 2020; Tyagi et al., 2019), and bearing capacity (Hasheminezhad & Bahadori, 2020; Youventharan et al., 2020; Zaika et al., 2017). The shear strength or unconfined compressive strength of a soil cement column is a function of many factors, including soil type, binder content, construction method, time, and temperature (Liu & Hryciw, 2003).

QA studies not only help in addressing the mixing process in the field, but also to assess the degree of improvement obtained by comparing the properties of treated and untreated sections. QC of the stabilized soil includes binder storage, binder slurry preparation, and control of the mixing process (Juha et al., 2018). Storage and proportioning of binder, additives and mixing water are normally controlled, monitored and recorded at the plant placed in the construction site (A. Puppala et al., 2008; A. J. Puppala, 2005).

2.12 Using Waste Materials in Ground Improvement

In recent years, the increasing amount of waste materials in our environment resulted in environmental pollution and because of this, recycling of industrial waste materials in ground improvement application has become very significant. Ever-increasing waste production in nature has led researchers to use waste materials in different fields so that disposal of industrial wastes in nature would be greatly reduced (Bahraq et al., 2020; El-Bondkly et al., 2021; Peixoto et al., 2021). There are many possibilities to use waste materials in civil engineering applications (Carvalho et al., 2018; Khurshid et al., 2019; Kishore & Gupta, 2020). Cement which is vastly used in almost in all civil engineering applications is manufactured from natural resources such as chalk or limestone heated at very high temperatures by using large amounts of energy from natural resources. In recent years, industrial wastes have been used as aggregate or cement in concrete production (Borhan et al., 2020; Mohammadhosseini et al., 2019). Waste materials have also been used for soil improvement purposes in geotechnical engineering applications (Deshmukh et al., 2021; Khazaei & Moayedi, 2017; Thomas et al., 2018). Nowadays, finding new waste materials that can be used as cement replacement materials in different civil engineering applications is a significant challenge for the researchers. Due to the success of deep soil mixing techniques worldwide, there are many projects which are using different additives either in dry or wet forms in DSM application in order to stabilize subsoils at considerable depths (Venkatarama Reddy & Prasanna Kumar, 2011).

Chapter 3

MATERIALS AND METHODS

3.1 Introduction

Deep soil mixing, DSM is an important improvement technique for the improvement of soft compressible clays and other problematic soils. Although, this application and the new installation methods have been used extensively in many projects (Abe et al., 2022). There are still wide variety of methods and varying protocols used in deep soil mixing application. At the same time, standard laboratory test procedures have not yet been clearly developed for the improvement of different types of problematic soils by using DSM (Filz et al., 2005).

This chapter provides the procedures and the standards that have been followed during the specimen's preparation and mixing in the laboratory. This chapter also contains the material properties used in this study and the in-situ soil testing results of the soil investigated in this study. This chapter is divided into four main parts as follow:

- Soil properties used in this study,
- Binder materials,
- Mix proportion design, and
- Specimens' preparation.

3.2 Problematic Soils in North Cyprus

Cyprus island is considered as the largest island in the Mediterranean Sea. The northern part of Cyprus covers an area of approximately 3355 km^2 (Ozbafli & Jenkins, 2016). Most of the soils that exist in North Cyprus contain alluvial soils and some clay types as shown in Figure 3.1. There are different types of problematic soils in North Cyprus such as fully saturated loose sand, soft compressible clays and expansive soils which are distributed over different parts of North Cyprus (Alnunu & Nalbantoglu, 2020; Farah & Nalbantoglu, 2019; Golhashem & Uygar, 2019; Nalbantoglu & Gucbilmez, 2001). These types of problematic soils result in high compressibility and low resistance to settlement (soft clay), have liquefaction problem in loose sands (Abiodun & Nalbantoglu, 2015) and they have heave problems in shallow foundations (Nalbantoglu & Tawfiq, 2006). In the past history of Cyprus, because of the poor soil conditions of loose sands, these soils faced some serious liquefaction problems (Atalar & Das, 2009; Harrison et al., 2004).

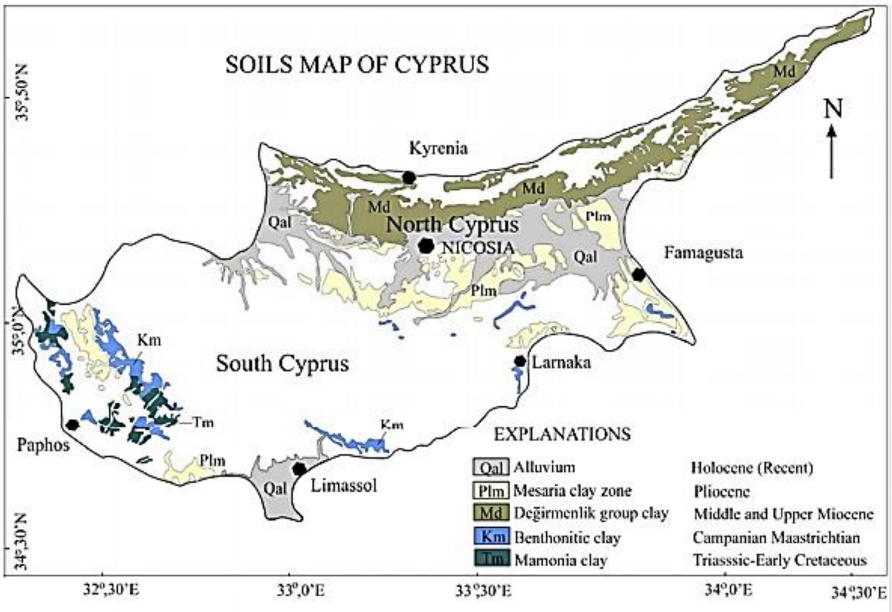

Figure 3.1: Cyprus soils (Geological Survey Department, 1995)

3.3 Properties of Soil Used in this Study

The problematic soil that is chosen to be studied in this study is poorly graded loose sand collected from Glapsides-Beach in Famagusta – North Cyprus. The sand is composed of quarts, feldspar and silicon dioxide with some carbonate minerals. The soil site location is shown in Figure 3.2.

Figure 3.2: Soil location studied in this study

The soil was excavated in one meter below the ground surface and then the soil was extracted beneath this depth. The extracted sand was classified as a poorly graded (SP) sand according to the Unified Soil Classification System (USCS). The particle size distribution was determined following ASTM D6913 standard. The particle size distribution of loose sand is shown in Figure 3.3, and the geotechnical properties of the sand are also given in Table 3.1. According to the in-situ relative density, D_r of the soil which was calculated to be 19.7%, the sand was found to be a loose sand.

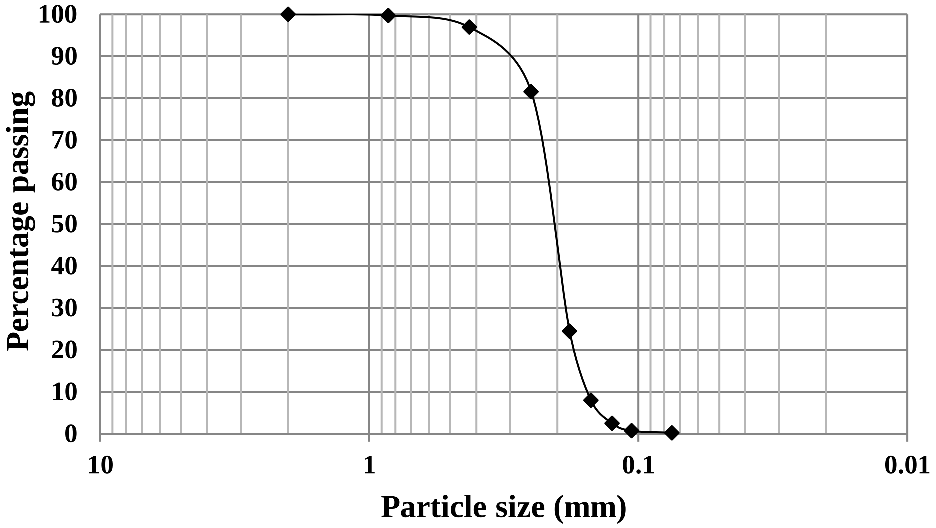

Figure 3.3: Particle size distribution of the sand used in this study

Table 3.1: Geotechnical properties of the sand used in this study

Soil properties	**values**
In situ bulk density, ρ_b (g/cm^3) [a]	1.6
In situ water content, w (%)	15.0
Specific gravity, G_s [b]	2.67
Effective size, D_{10} (mm)	0.16
Median particle size, D_{50} (mm)	0.20
Uniformity coefficient, C_u	1.37
Coefficient of curvature, C_c	0.92
Soil classification (USCS) [c]	SP
Maximum dry unit weight, γ_{dmax} (kN/m^3)[d]	16.4
Minimum dry unit weight, γ_{dmin} (kN/m^3)[e]	13.4
In situ relative density, D_r (%)	19.7

a ASTM D1556
b ASTM D854
c ASTM D2487
d ASTM D7382
e ASTM D4254

3.4 Binder Materials

The primary function of binder materials is to provide the necessary strength and homogeneity between the soil particles (Kouakou & Morel, 2009a). Proper binder materials and mixture proportioning allow the adequate characteristics of treated soil to be obtained. Different binder materials such as, cement, lime or cement-lime have been used in different studies in the literature (Alnunu & Nalbantoglu, 2022b; Dhar & Hussain, 2018; Jendrysik et al., 2018). Also, different methods of soil-binder mixture preparation have been used and followed by international standard such as Japanese Geotechnical Society (JGS) standard for soil mixing. In the present study, three different binder materials: cement and the waste materials brick dust, and marble dust have been used. The use of waste materials such as brick dust, marble dust and similar industrial by-products is economic as well as environmental advantages of using them to achieve sustainable infrastructure development with near zero industrial waste (Kinuthia & Nidzam, 2011; Tugrul Tunc, 2019). The main binder materials is cement and the two waste materials shown in Figure 3.4 were used as cement replacement in order to reduce the usage of cement which is very costly and environmental unfriendly.

Figure 3.4: Binder materials used in the study

3.4.1 Cement

Cement is a hydraulic binder which can be used in different soil stabilization applications. Cement does not dependent on minerals to react with, it reacts by itself with the presence of water (Alnunu & Nalbantoglu, 2022a; Knapen & van Gemert, 2009). Type I or Type II Portland cement have been successfully used in DSM applications (Chen et al., 2013; Tremblay et al., 2011). In general, ordinary Portland cement is used for stabilization purposes because of its extreme fine particles which make it more reactive (McLaughlin, 2017). The addition of cement to soil produces cementitious components in the soil–cement matrix. The primary cementation compound is formed by hydration reactions and comprises hydrated calcium silicates (C_3S, C_2S), calcium aluminates (C_3A, C_4AF) and hydrated lime $Ca(OH)_2$ (Saeed et al., 2014).

In the present study, Portland cement Type I, CEM 142.5 R is used for DSM application. Table 3.2 describes the physical and chemical properties of the cement used in this study.

Table 3.2: Physical and chemical properties of cement used in this study

Properties	**Value**
SiO_2 (%)	19.95
Al_2O_3 (%)	5.06
Fe_2O_3 (%)	3.04
CaO (%)	63.09
MgO (%)	2.34
SO_3 (%)	3.32
Na_2O (%)	0.80
Loss on ignition (%)	2.27
Specific gravity	3.13
Specific surface area (cm^2/gr)	3810
Clinker mineralogical composition	
C_3S	> 60
C_2S	< 15

C_3A	< 10
C_4AF	> 8

3.4.2 Waste Marble Dust, WMD

The waste marble dust, WMD used in the present study was taken from the construction waste materials that was located in the industrial zone in Famagusta, North Cyprus. In this industrial zone, many factories produced marble blocks in different forms and during the cutting and polishing operation of these marble blocks, marble dust was generated as waste material. In recent years, using marble dust in concrete production is very common (Arel, 2016; Ruiz-Sanchez et al., 2019; Singh et al., 2019). Marble dust can be used as a mineral admixture to replace Portland cement to enhance the early compressive and the flexural strength of mortar (Demirel, 2010; Li et al., 2018; Nadu, 2015). The addition of calcium carbonate which exists in marble dust in the cement mixture provides better particle packing (Ali et al., 2015). Marble dust can also be used for improving the shear strength and reducing the swelling potential of clayey soils (A. K. Jain et al., 2020; Saygili, 2015; Zorluer & Gucek, 2014). The performance of problematic soils can also be improved by using WMD, due to its high calcium content which can help in cation exchange reaction (A. K. Jain et al., 2021) and alter the soil plasticity. The high amount of calcium carbonate that exists in MWD react with tricalcium aluminate (C3A) that is available in cement and accelerate the hydration reactions, which contribute to the improvement of compressive strength of soil-cement mixtures (Arel, 2016; N. Jain & Garg, 2008). In the present study, the WMD particles passing from 75 μm sieve was utilized as a partial cement replacement material in soil-cement mixtures. The physical and chemical properties of the WMD used in this study are presented in Table 3.3. The particle size distribution curve of the WMD is also shown in Figure 3.5.

Table 3.3: Physical and chemical properties of WMD

Properties	Value
Na_2O (%)	0.19
MgO (%)	1.13
Al_2O_3 (%)	0.88
SiO_2 (%)	3.24
CaO (%)	92.24
SO_3 (%)	0.13
Fe_2O_3 (%)	1.43
Silt content (%)	87
Clay content (%)	13
Specific gravity	2.68

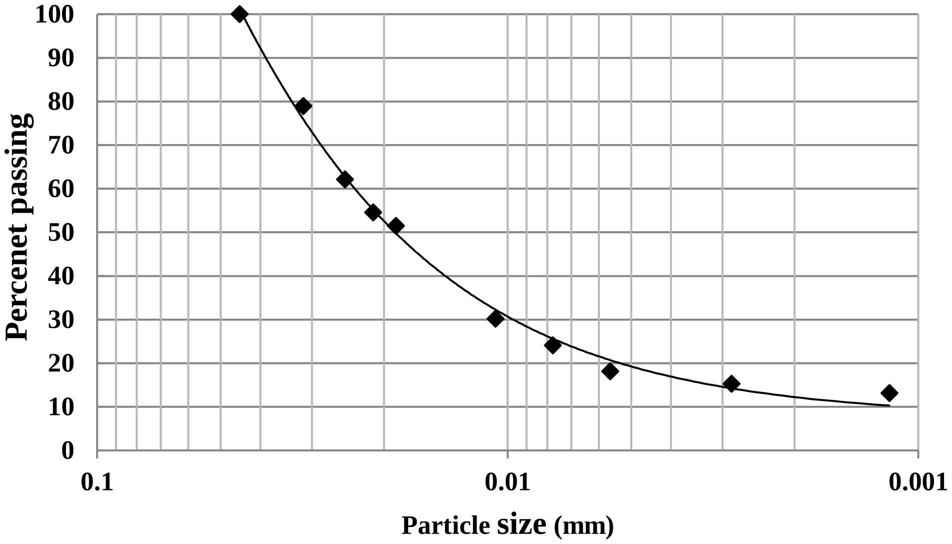

Figure 3.5: Particle size distribution of WMD used in this study

3.4.3 Waste Brick Dust, WBD

In brick industry, the demolition of brick masonry structures due to large-scale urbanization produces huge amount of construction waste, including large quantities of clay brick which is normally ended in landfills. However, the landfilling of waste clay brick occupies the rare land resources, especially for cities with limited disposal sites (Ge et al., 2015). Therefore, using recycled bricks as a part of cementitious material could simultaneously help to settle the environmental impacts caused by cement production and waste clay brick disposal. Brick dust is considered to be an eco-friendly alternative material when it is used in DSM application. Brick dust contains sand and clay particles which consist of chemical compounds such as silica, alumina, carbonates and oxides which are needed for pozzolanic reaction (Khan et al., 2018). Because of its constituents, clay gains pozzolanic activity when it reacts with lime in the presence of water (S. Rogers, 2011). Brick dust exhibited high strength in concrete and mortar due to its pozzolanic activity (Demir et al., 2011; Ge et al., 2015). The substitution of cement with ground brick in mortar increases compressive strength in proportion with increasing curing period (Zhao et al., 2021). The strength enhancement is attributed to pronounced C–S–H gel formation, resulting from the pozzolanic reactions between the ground brick and free lime from the hydrating cement (Kinuthia & Nidzam, 2011). In the present study, the WBD particles passing from 75 μm sieve was utilized as a partial cement replacement material in soil-cement mixtures. The physical and chemical properties of the WBD used in this study are presented in Table 3.4. The particle size distribution curve of the WBD is also shown in Figure 3.6.

Table 3.4: Physical and chemical properties of WBD

Index properties	**Value**
SiO_2 (%)	38.64
Al_2O_3 (%)	12.2
Fe_2O_3 (%)	8.53
MgO (%)	6.18
CaO (%)	14.49
Na_2O (%)	1.21
K_2O(%)	1.89
Silt content (%)	86
Clay content (%)	14
Specific gravity	2.78

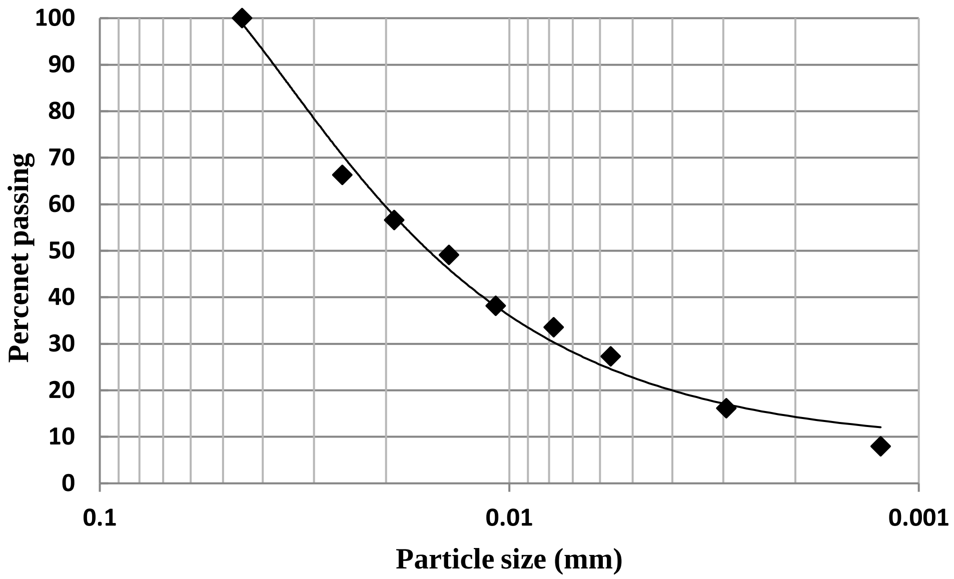

Figure 3.6: Particle size distribution of WBD used in this study.

3.5 Mix Proportion Design

Due to the success of deep mixing (DM) techniques worldwide, there have been various improved, novel construction and installation technologies that use different additives either in dry or wet forms to stabilize subsoils at considerable depths (Bhadriraju et al., 2008).

Based on the findings of previous researchers, the following factors were found to be effective on the characteristics of soil mixture (Al-Tabba et al., 2000; Kitazume & Terashi, 2013; Shen et al., 2005):

- Soil type
- Binder type
- Binder dosage rates and proportions
- Binder-water ratio
- Soil-binder mixing and specimen preparation techniques
- Curing conditions.

Table 3.5 illustrates the mix proportions that have been used in this study. Each mix proportion was coded according to binder soil (B/S) ratios and percentage of waste material replacement (WMR). Herein, 10/WMR0, 15/WMR0 and 20/WMR0 demonstrate the treated specimens with cement only.

Table 3.5: Mix proportions used in this study

Mix designation	**B/S ratio (%)**	**W/B ratio**	**Replacement percentage of waste material, WMR**	**Cement percentage as binder material**	**Density of the mix g/cm^3**
10/WMR0	10	1.2	0	100	1.7
10/WMR10	10		10	90	
10/WMR20	10		20	80	
10/WMR30	10		30	70	
15/WMR0	15	1.2	0	100	1.85
15/WMR10	15		10	90	
15/WMR20	15		20	80	
15/WMR30	15		30	70	
20/WMR0	20	1.2	0	100	2.0
20/WMR10	20		10	90	
20/WMR20	20		20	80	
20/WMR30	20		30	70	

B/S: Binder-soil ratio
W/B: Water-binder ratio
WMR: Percentage of waste material replacement

3.5.1 Binder-Soil Ratio (B/S)

The strength characteristics of any soil mixed with binder material is a function of many factors, including soil type, binder content, construction method, time, and the ambient environment, specifically temperature (Chenari et al., 2018; Kouakou & Morel, 2009b). The binder material in DSM application is typically cement, but occasionally a lime-cement mixture is used as a binder in soil mixing and the binder material content is usually 10% to 15% of the soil by dry weight (Liu & Hryciw, 2003).

Some studies in the literature (Gullu et al., 2017; Lorenzo & Bergado, 2006) stated that for more effective and economic soil improvement, the binder–soil ratio, B/S should not be greater than 20% of the total weight of the untreated soil. In the present study, three binder-soil ratios, B/S: 10%, 15% and 20%, were used to form the soil-binder mixtures. For the replacement of cement with waste material (WMR), 12 different mix proportions were used as indicated in Figure 3.7. Soil–cement–waste material mixtures were prepared for investigating the effect of different replacement percentages of WM on the properties of the binder–soil mixtures. The replacement percentages, WMR which have been used in the present study were 10%, 20% and 30% by the weight of cement. Figure 3.7 illustrates the binder-soil ratios (B/S) and the replacement percentage of waste material (WMR) used in this study.

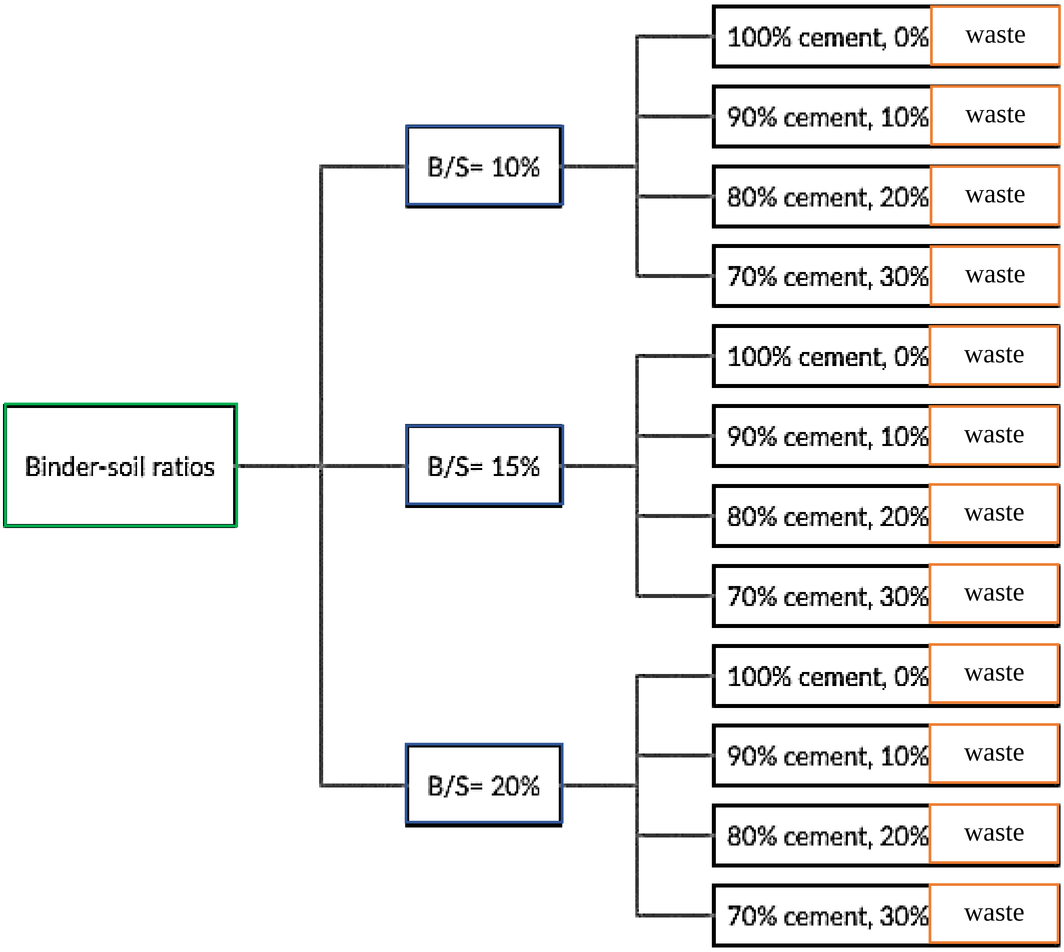

Figure 3.7: Binder-soil ratio, B//S and replacement percentage of waste material, WMR used in this study

3.5.2 Water-Binder Ratio (W/B)

The water-binder ratio, W/B is an important factor in the improvement aspect in DSM during the field implementation phase. This factor should be carefully accounted in laboratory investigations for easy handling of binders and for getting better degree of improvement for the soil/binder mixtures (Bergado & Lorenzo, 2005; Horpibulsuk et al., 2005).

Figure 3.8: Specimens prepared with different water–binder ratios, W/B

In the previous studies in the literature, in order to determine the best water–binder ratio (W/B) for achieving better homogeneity and optimum workability in soil–cement mixtures, different trail of W/B ratios, such as 1.0, 1.2 and 1.5 were tested (M. Bruce et al., 2013; Farouk & Shahien, 2013). In the present study, after a series of numerous preliminary test, the W/B ratios were decided to be in a range of 1.0–1.5. Figure 3.8 shows the trial specimens prepared for the preliminary tests with different W/B ratios. After trying various ratios it was detected that, W/B ratio of 1.0 was not enough to obtain a uniform mixture in the specimens. Due to insufficient W/B ratio, a structure with large pore spaces was formed and the workability of the specimens was very poor and it was difficult to mix the soil–binder materials together. With 1.5 W/B ratio, visible voids and bleeding problem were observed during the mixing of the specimens. Whereas with 1.2 W/B ratio, the best uniform and homogenous mixtures with less pore spaces were obtained. Moreover, during testing, it was observed that the workability of the mixture became better with W/B ratio of 1.2, since the mixture was poured easily and smoothly in the mold without bleeding or segregation and the void space generated after mixing was almost nothing. Therefore, in the present study, the W/B ratio of 1.2

was adopted for all mix proportions with different percentages of waste material replacement.

3.6 Sample Preparation Methods for Small Soil-Binder Specimens for DSM Application

3.6.1 Preparation of Soil-Binder Mixtures

Approximate quantity of the dry soil sample was obtained for the preparation of different batches. Batch is defined as sufficient numbers of treated soil sample for performing tests and obtaining the best soil/binder mixtures by considering the variables such as curing conditions and mixing method. For each mix proportion of waste material replacement, (WMR 10%, 15% and 20%) six batches were prepared for the two different curing periods 7 and 28 days. Three samples were tested after 7 days of curing and the other three samples were tested after 28 days of curing.

The soil-binder specimens preparation process was stared with the calculation of the exact amount of binder materials based on the binder-soil ratio that described in Figure 3.7. Subsequently, the amount of water content was determined according to the water-binder ratio (W/B of 1.2) that was needed to prepare the soil-binder mixture as explained in Section 3.5.2. In the soil mixing process, an electronic mixer with a hook was used in this study. The mixing rate of the outer spindle was preset at 50 r/min. The quantities of soil and binder material were mixed in dry conditions in a separate bowl prior to the addition of water as shown in Figure 3.9 (a). This stage was important to ensure that dry particles of soil and binder materials are mixed together. Then, the soil-binder mixture was mixed with water at the calculated water content value for approximately 10 min as shown in Figure 3.9 (b) to ensure a uniform soil-binder mixture without lumps.

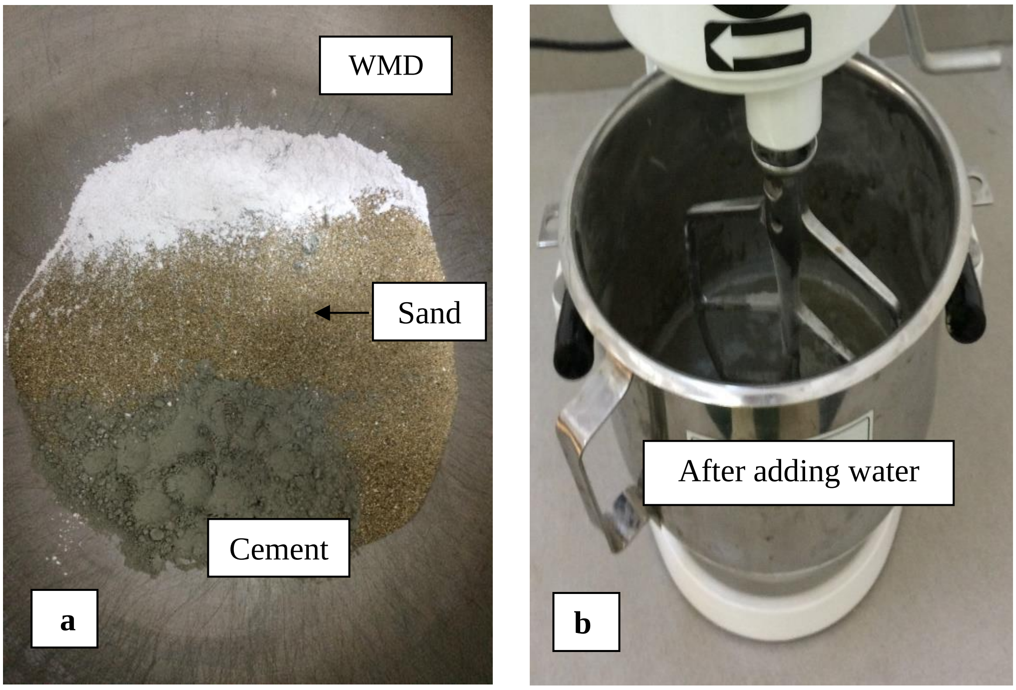

Figure 3. 9: Preparation of soil-binder mixture: (a) binder materials with sand (b) soil-binder mixture with water

3.6.2 Mold Used in the Preparation of Specimens

A split type steel mold shown in Figure 3.10 with 50 mm in inner diameter and 100 mm in length, with 10-mm thickness containing three cylindrical holes was used in the preparation of the cylindrical specimens. First, a thin layer of grease was smeared onto the inner surface of the mold to avoid any disturbance in the specimens during the extraction process as shown in Figure 3.10 (a). The details of the mold used in this study is shown in Figure 3.10 (b).

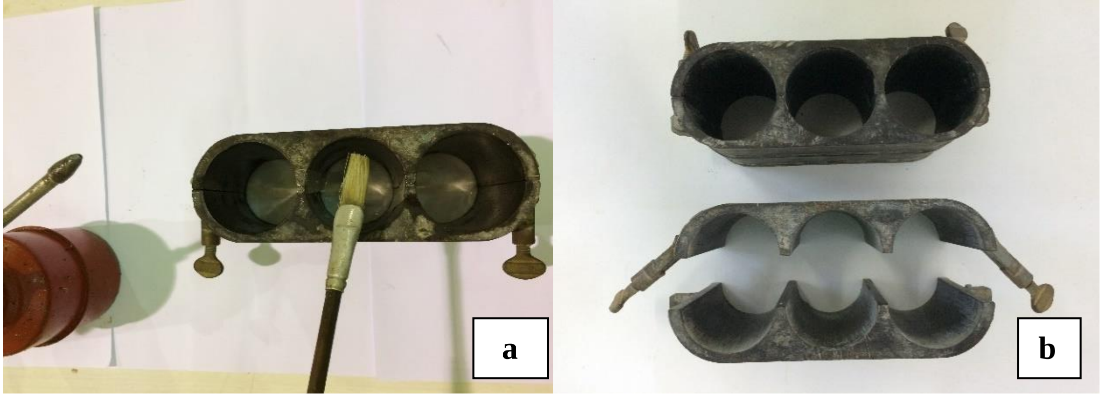

Figure 3.10: A split steel mold used in specimens’ preparation: (a) greasing stage (b) details of the split mold used in this study

3.6.3 Compaction and Extraction of Soil-Binder Mixtures from the Mold

Because the soil-binder mixture was not in a consistency to be poured into the molds, the soil-binder mixture was transferred into the mold by using a spoon. The soil-binder mixture was placed in the split mold in five equal layers. Each layer was compacted gently by wooden rod with rubber head in order to achieve the required densities: 1.70, 1.85 and 2.0 g/cm^3 for B/S ratios: 10%, 15% and 20%, respectively, as given in Table 3.5. Then, after compacting the top layer, the surface of the mold was trimmed and flattened by a spatula Figure 3.11 shows all these processes followed in sample preparation.

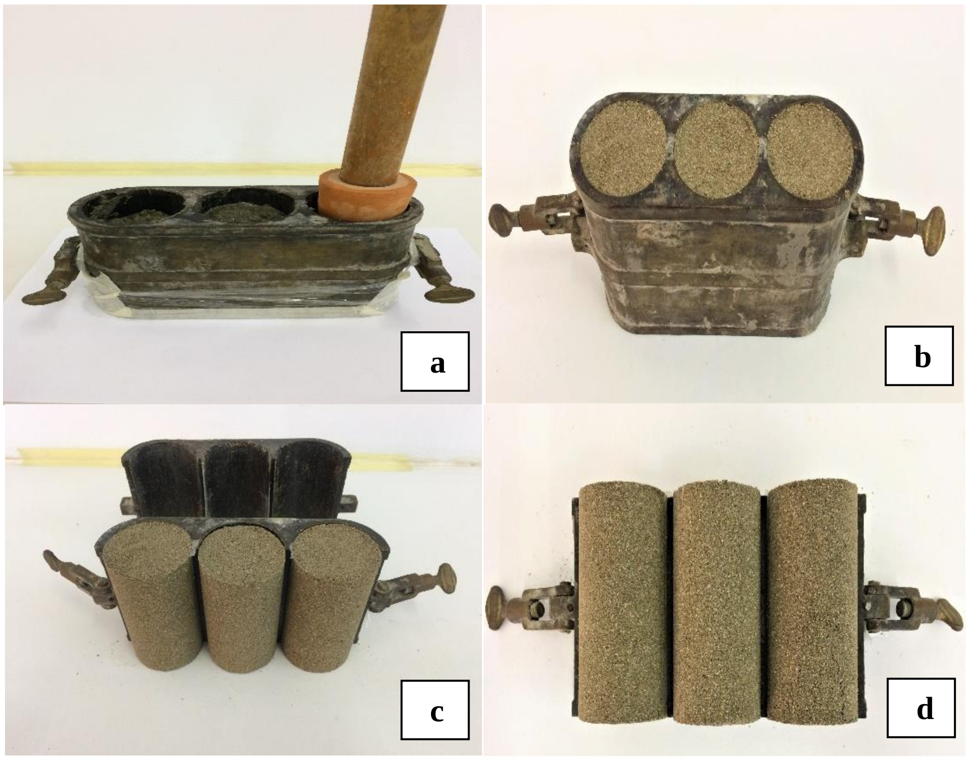

Figure 3.11: Specimens compaction and extraction processes in the mold: (a) compacting the mixture, (b) trimmed surface of the specimens, (c) splitting the mold, (d) extracting the specimens

After extracting the specimens from the mold, the specimens were left overnight in the air to dry in order to gain the initial strength as shown in Figure 3.12 (a). Then, the specimens were reserved in temperature-controlled room in electronic water bath that can keep the temperature of the specimens constant during the curing period as shown in Figure 3.12 (b). The specimens were cured at approximately 20 °C for durations: 7 and 28 days.

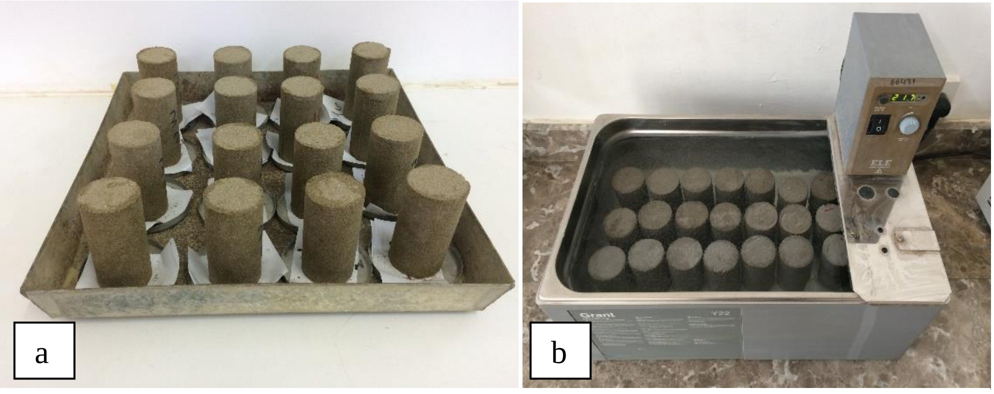

Figure 3.12: Curing process: (a) extracted specimens from the split mold left to air drying, and (b) extracted specimens left in the water tank

3.7 Tests Performed on Small Soil-Binder Specimens

In the study, Vicat test was performed according to ASTM C191 standard at room temperature in order to evaluate the effect of WMR on the setting time of cement paste. The bulk density of the specimens was determined after 28 days of curing in water treatment bath. The unconfined compressive strength (UCS) of the specimens were determined according to ASTM D1633 standard. The specimens' dimensions were 100 mm in height and 50 mm in diameter. After 28 days of curing, the specimens were left in the air until they became fully dry and then they were tested under uniaxial compression machine in order to investigate the effect of WMR on the deformation behaviour and cracking propagation after failure. A microscopic study was performed and the specimens were examined under a stereoscopic microscope at 300X magnification and the obtained microscopic images were analyzed and discussed.

3.8 Experiments in a Large-Scale Model Test Tank

3.8.1 Introduction

In DSM application, two different installation methods can be used in order to form the DSM columns in problematic soils. These are:

- In-situ mixing (mechanical method) (discussed in Section 2.5) and
- Ex-situ mixing (replacement method).

In the ex-situ mixing method, the soil is excavated and mixed with binder in plant or during the transportation to the construction site. This method is intended to provide additional characteristics such as liquefaction resistance, smaller volume compressibility and extremely high strength to the original soils as mentioned in the studies: Shah et al. (2019) and Zakaria et al. (2020).

In the present study, ex-situ replacement method is used for the construction of the DSM columns with which the disturbance to the surrounding soil during the installation process is thought to be minimized.

This section describes the materials and methods used to study the behaviour of single and group of DSM columns formed by the deep ex-situ mixing method. DSM column with and without waste materials are presented and the procedure used to form these columns in the model test tank is described.

3.8.2 Details of Test Performed in the Model Test Tank

3.8.2.1 Preparation of the Model Test Tank

The dimensions of the test tank used in this study are 40 cm in depth and 40 cm in diameter. The inner surface of the test tank wall is cleaned and smooth. The sand is placed in the test tank in three layers. In order to obtain a levelled surface of the sand in the test tank, the depth of each layer where the sand will be placed is marked on the inner wall of the test tank as shown in Figure 3.13 (a). Before placing the sand in the test tank, a bed of aggregates 10-20 mm in size and 10 cm high is placed at the bottom of the test tank as shown in Figure 3.13 (b).

Figure 3.13: Testing tank preparation: (a) marking the sand layers in the test tank (b) aggregates placed at the bottom of the test tank

3.8.2.2 Placement of the Sand in the Test Tank

In the study, the loose sand was placed in the test tank at the in-situ dry density of 1.39 g/cm^3. Before placing the sand in the test tank, lubricating oil was applied on the inner walls of the test tank. In all the tests, in order to achieve identical sand samples in the test tank, the required amount of sand required to fill each layer in the test tank was calculated and placed in the tank in three equal layers. Each layer was placed and compacted gently in the test tank by using a rubber head to achieve the required density as shown in in Figure 3. 14 (a). After placing the loose sand in the test tank, the surface of sand was trimmed and levelled as shown in Figure 3.14 (b).

Figure 3.14: Placement of the sand in the test tank: (a) compacting sand in the test tank (b) levelling the surface of the sand

3.8.3 Installation of DSM Columns in the Test Tank

In order to install the DSM column in the test tank, a PVC pipe with 2 mm thickness and 50 mm diameter was used to open a cylindrical hole at the required diameter in the center of loose sand in the test tank. First, the center of the test tank was marked and then PVC pipe was placed and pushed vertically into the loose sand until the required vertical depth of DSM column was attained (Figure 3.15). The verticality of the pipe was checked by a spirit level. Before placing the PVC pipe into the loose sand, the PVC pipe was coated internally and externally with oil in order to avoid the friction between the pipe and the surrounding soil. Then the sand filling the PVC pipe was vacuumed out and the pipe was emptied so that the soil-binder mixture could be poured inside the PVC pipe.

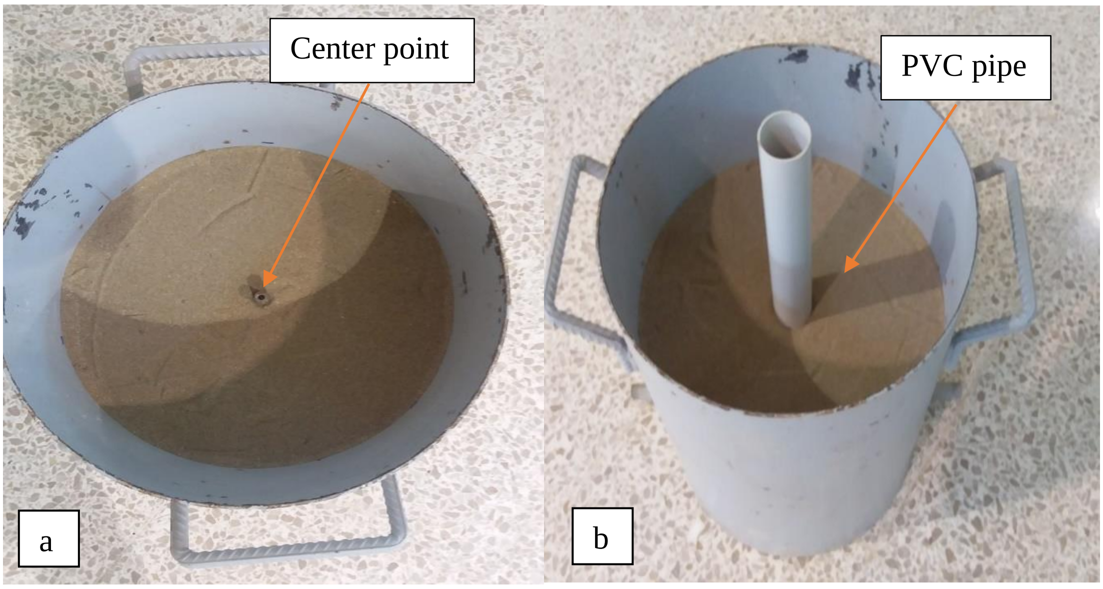

Figure 3.15: DSM column preparation in the test tank: (a) locating the center of test tank (b) placing the PVC pipe for forming DSM column

The soil-binder mixture to be placed inside the PVC pipe was prepared according to the optimum percentages of soil-binder mixture obtained from the small size specimens for quality control discussed in chapter 4. The required amount of the soil-binder mixture was partitioned into three equal batches, and each batch was poured into the hole with a height around of 6.6 cm through the pipe. The same procedure was applied by the researchers Zakaria et al. (2020). The pipe was then pulled out and compaction was applied each batch to attain the total height of 20 cm. Before compacting the soil-binder mixture into the PVC pipe, in order avoid the segregation problem and to achieve a uniform compaction, three soil-binder mixtures were compacted in three different pipes and for each layer of soil-binder mixture in the pipe, three different number of blows: 5, 10, and 15 were tried. The first soil-binder mixture was compacted with 5 number of blows for each layer, the second soil-binder mixture was compacted with 10 number of blows whereas the third mixture was compacted with 15 number of blows for each layer. Figure 3.16 shows the final shape of soil-binder mixtures compacted at three different number of blows.

It was observed that the best compaction was achieved with 10 number of blows. With this number of blows applied for each layer, uniform compaction was achieved throughout the soil-binder mixture whereas with 5 number of blows, less compaction was achieved and resulted in some pore spaces in the mixture. On the other hand, 15 number of blows was over compaction and resulted in lateral distortion of the soil-binder mixture and did not provide proper compaction. As Figure 3.16 indicates, the optimum compaction was achieved with 10 number of blows for each layer.

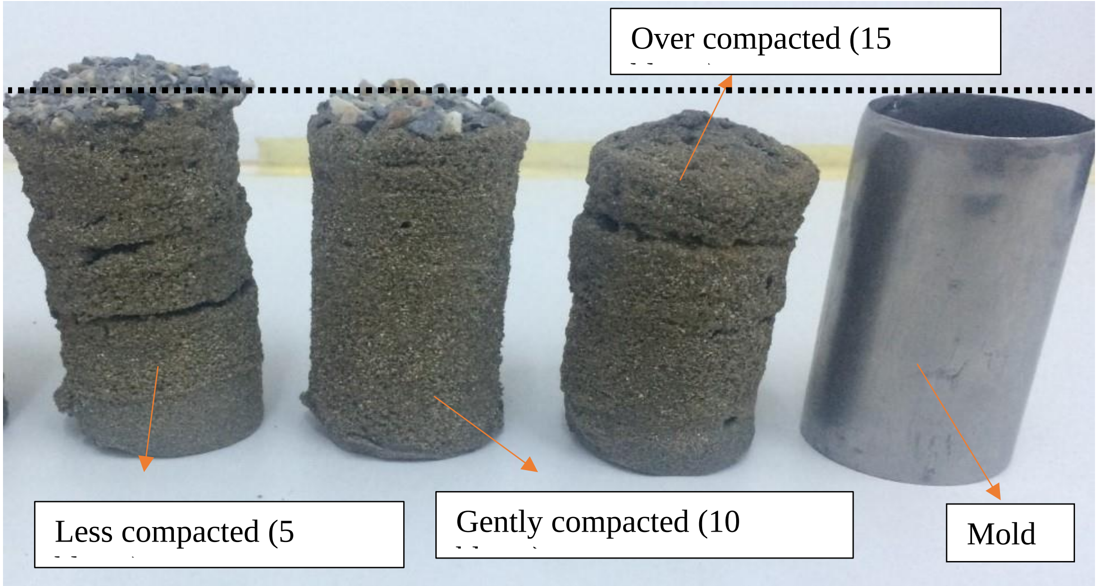

Figure 3.16: Different number of blows applied for the compaction of each layer of soil-binder mixture in the PVC pipe

Therefore, for avoiding the lateral distortion of the surrounding soil during the construction of DSM column and for achieving proper compaction, each layer in the PVC pipe was compacted with 10 number of blows by using a rod with rubber head as shown in Figure 3.17. The same procedure was applied for the construction of the group of DSM columns in the model test tank. The compacted single and group of DSM columns in the model test tank are presented in Figure 3.18.

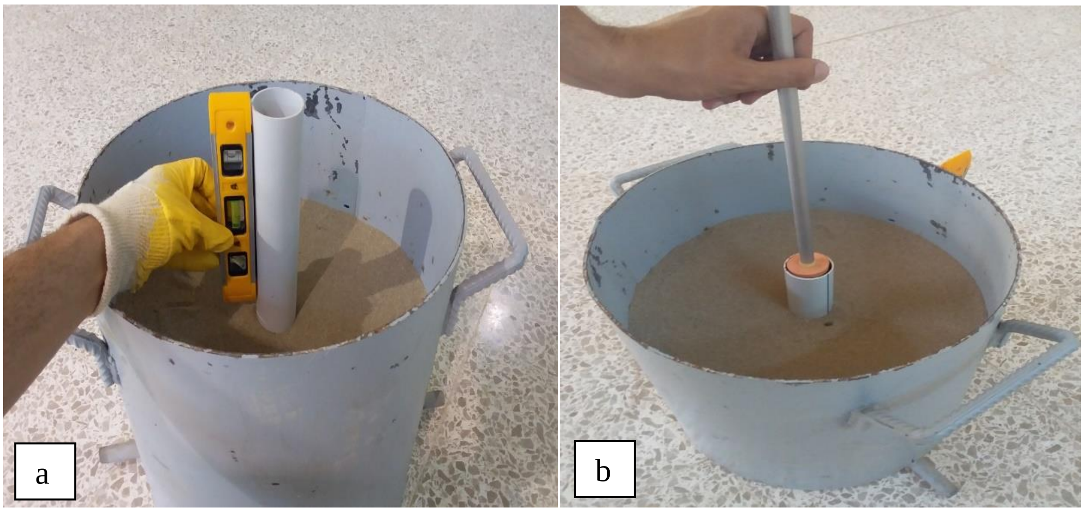

Figure 3.17: Preparation of DSM column in the test tank: (a) checking the verticality of PVC pipe (b) compacting the soil-binder mixture in the PVC pipe

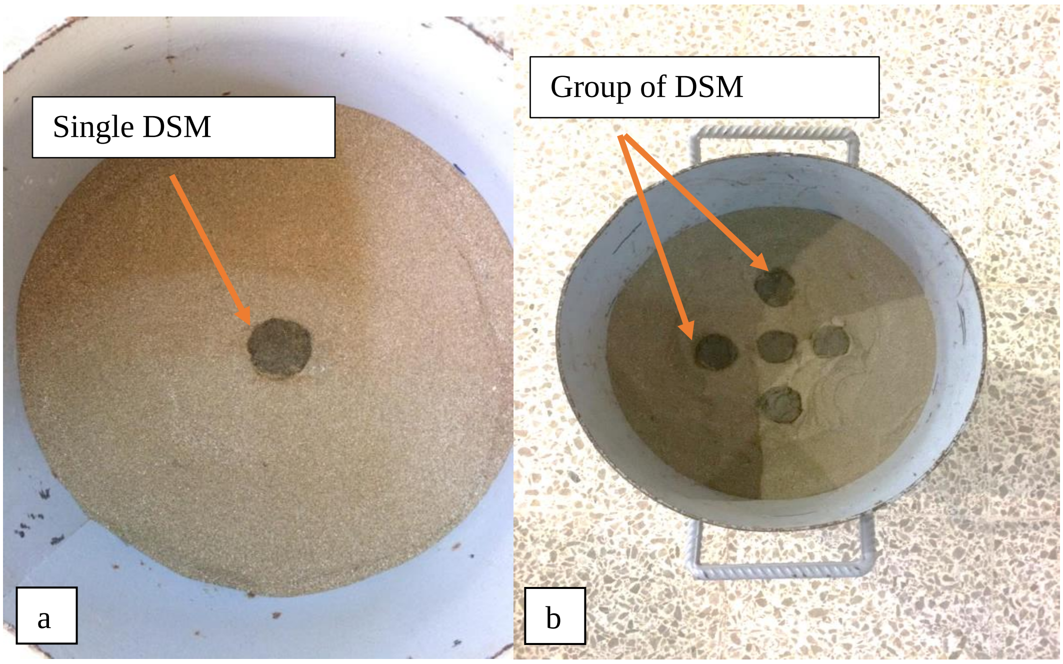

Figure 3.18: DSM column constructed in the test tank (a) single DSM column (b) group of DSM columns

3.9 Deep Soil Mixing Models: Single and Group of DSM Columns

Two different test models were studied in this study: single and group of DSM columns. The dimensions of DSM columns in both single and group columns were 5 cm in diameter and 20 cm in length. In real field applications, the diameter of DSM column varies from 0.5 to 2.1 m and center to center spacing ranges from 1 to 1.5 m

(Nissa Mat Said et al., 2019). The dimensions of the DSM columns used in the present study simulate a prototype laboratory model with a scale of 1:20. Whereas, the length of DSM column: 20 cm presents a length/diameter ratio of 4 which was the similar ratio used by Shah et al., (2019) who stated that the optimum L/D ratio was nearly 4 in DSM column simulation.

3.9.1 Single End-Bearing DSM Column Model

The first model performed in this study was the single DSM column. As aforementioned, DSM column with 5 cm diameter and 20 cm length was constructed in the sand bed sitting completely over a coarse aggregate (base layer) with thickness of 10 cm. Table 3.6 describes the cases of single end-bearing DSM column that were performed in this study.

Table 3.6: Model of single end-bearing DSM column

Sample	**Depth of sand bed, (*h*) cm**	**DSM column diameter, (*d*) cm**	**DSM column length, (*l*) cm**	**WMR**
1	20	--	--	No
2	20	5	20	No
3	20	5	20	Yes

DSM: Deep soil mixing
WMR: Waste material replacement
Yes: WBD and WMD are used
No: No waste materials were used

3.9.2 Single Floating DSM Column Model

To study the effect of soil depth on the bearing capacity and settlement behaviour of DSM column three different cases were chosen to be studied. As mentioned by (Dehghanbanadaki et al., 2014) the bearing capacity and settlement performance are considerably affected by the depth of soil bed in DSM application. Therefore, in the study, three different soil depths were chosen to be investigated. The ratio of length of DSM to the soil depth is expressed as (*l/h)* ratio. The (*l/h)* ratios that have been studied in this study are shown in Table 3.7.

Table 3.7: Model of single floating DSM column model

Sample	Depth of sand bed, (*h*) cm	DSM column diameter, (*d*) cm	DSM column length, (*l*) cm	*l/h* ratio	WMR
1	20	--	--	--	No
2	20	5	20	1	No
3	25	5	20	0.8	Yes
4	33	5	20	0.6	No
5	50	5	20	0.4	No

DSM: Deep soil mixing
WMR: Waste material replacement
Yes: WBD and WMD are used
No: No waste materials were used

3.9.3 Group of DSM Columns Model

Based on the results obtained from the first model (single DSM column), some cases of group of DSM columns were chosen to be studied in order to investigate the performance of group of DSM columns in the model tank. Table 3.8 shows the cases of group of DSM columns studied in this study.

Table 3.8: Model of group of DSM columns

Sample	Thickness of sand bed, (*h*) cm	DSM column diameter, (*d*) cm	DSM column length, (*l*) cm	*l/h* ratio	WMR
1	20	--	--	--	No

2	20	5	20	1	No
3	20	5	20	1	Yes
4	25	5	20	0.8	No
5	20	5	20	0.8	Yes

DSM: Deep soil mixing
WMR: Waste material replacement
Yes: WBD and WMD are used
No: No waste materials were used

3.10 Model Test Set-up and Load Application

After the preparation process of the sand bed and the construction of the DSM columns in the model test tank, the DSM columns were loaded by using the loading frame given in Figure 3.19. The load application was chosen to be applied over a circular rigid steel footing resting on the DSM columns in the test tank. The load was vertically applied at a constant rate of 1 mm/min up to 25 mm vertical settlement of the footing. The loading process and settlement limit were designed according to the specification suggested by (Farouk & Shahien, 2013). During the load application, two dial gauges which were fixed on the footing were used for recording the settlement of the footing sitting on the DSM columns. Those two dial gauges were connected to the data logger for recording the settlement. Figure 3.19 presents the loading frame and its parts. The footing was designed to simulate a circular rigid footing resting over the DSM columns with an area improvement ratio of 25%. The area improvement ratio was defined as the ratio of the area of the DSM columns to the total area of footing. As stated in the study of Bruce & Bruce, (2003), the most effective range of area improvement ratio for most soils was proposed to be between 10–30 %. Therefore, the area improvement ratio in this study was chosen to be 25% which was similar to the area improvement ratio used by Dehghanbanadaki et al., (2014).

1- Steel loading frame
2- Hydraulic jack
3- Proving ring
4- Test tank
5- Dial gauge (Data logger)
6- Footing model
7- DSM columns
8- Sand
L: Length of DSM
B: Width of footing

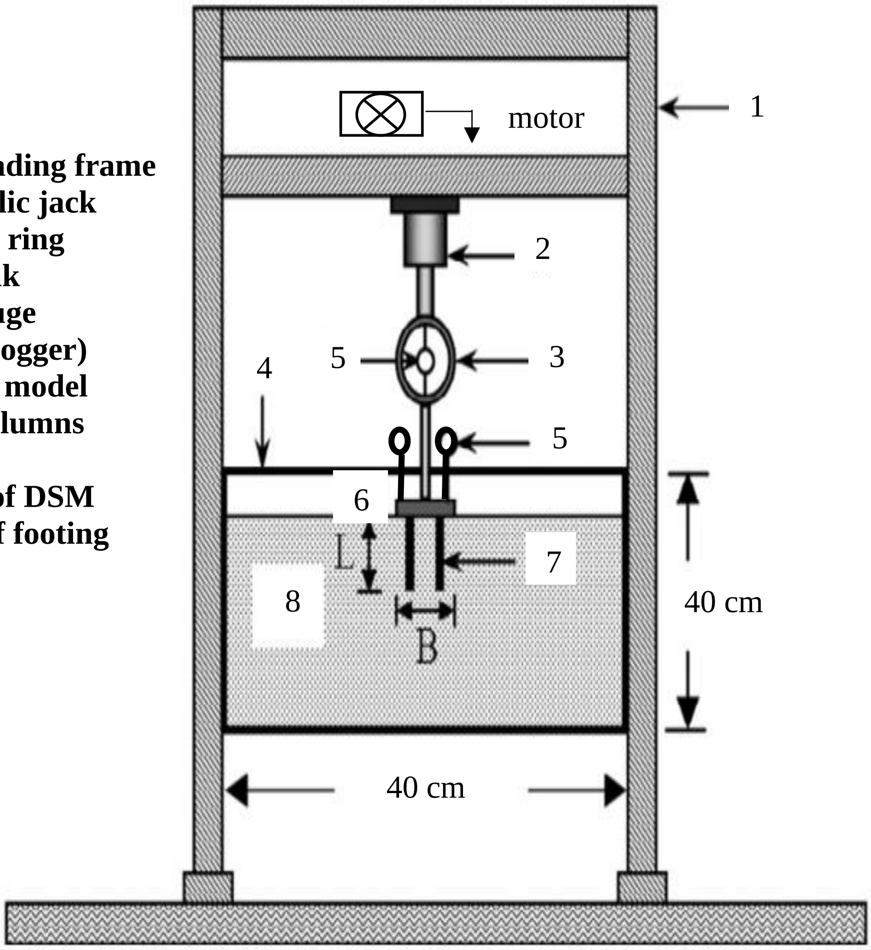

Figure 3.19: Schematic diagram of the loading

Chapter 4

RESULTS AND DISCUSSIONS

4.1 Introduction

The results of all the experiments conducted in this study are thoroughly examined and discussed in this chapter. These results are divided into two distinct sections for ease of understanding and analysis of the findings. The first section focuses on the behavior and quality of small specimens of the soil-binder mixtures, while the second section deals with the behavior of the soil-binder mixtures used in the construction of the DSM single and group of columns in the model test tank. The results obtained from these experiments provide valuable insight into the performance and effectiveness of the soil-binder mixture under different conditions and configurations. By thoroughly analyzing and discussing these results, a comprehensive understanding of the capabilities and limitations of the soil-binder mixtures as a DSM material will be obtained.

4.2 Effect of WMR on Setting Time

Determination of the setting time was first performed on the control sample (cement paste only) and then the cement paste was replaced by different percentages of waste brick dust, WBD and waste marble dust, WMD with the percentage of 10, 20 and 30. Figure 4.1 shows the effect of different percentages of WBD on the final setting time of cement paste. According to the WBD, it was observed that a reduction in the final setting time of cement-waste brick dust mixtures was obtained due to the increase in the waste brick dust content. The increasing replacement percentages: 10, 20 and 30%

of waste brick dust in cement paste decreased the final setting time of control sample by 4.8, 9.3 and 13.9%, respectively. The replacement of cement with waste brick dust in cement paste caused the cement-waste brick dust mixtures to absorb more water compared with the mixture of cement paste only and resulted in faster rate of hardening. This could be explained due to the faster rate of release of silica and alumina present in the waste brick dust which resulted in reduction in the final setting time of cement-waste brick dust mixtures. Moreover, the high-water absorption of waste brick dust in the cement-waste brick dust mixture was attained and this led to faster rate of hardening of cement-waste brick dust mixture. This finding was in good agreement with the findings of Rakhimova and Rakhimov (2015) who stated that the increase in the rate of geopolymerization reaction in cement paste replaced by brick dust resulted in the shortening of the final setting time of the mixture.

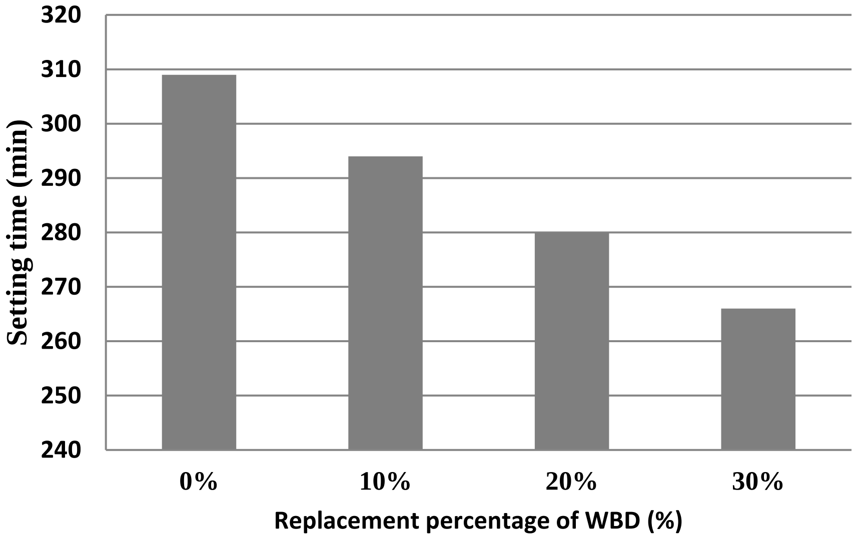

Figure 4.1: Effect of replacement percentages of waste marble dust on the setting time

It was observed that there was a significant reduction in the final setting time of cement with an increase in the replacement percentage of WMD. The increasing replacement percentages of WMD: 10, 20 and 30% decreased the final setting time of cement by

11, 23 and 35%, respectively. Test results indicated that due to the observed higher consistency of cement-WMD mixtures, higher water absorption compared with the mixture of cement paste only was attained and this led to faster rate of hardening of cement-WMD mixtures. The high calcium oxide, CaO content in WMD as presented in Table 3.3 influenced the setting time of cement and caused an increase in the acceleration of setting times which resulted in reduction in the final setting time of cement–WMD mixtures. Figure 4.2 shows the effect of different percentages of WMD on the initial and final setting time of cement.

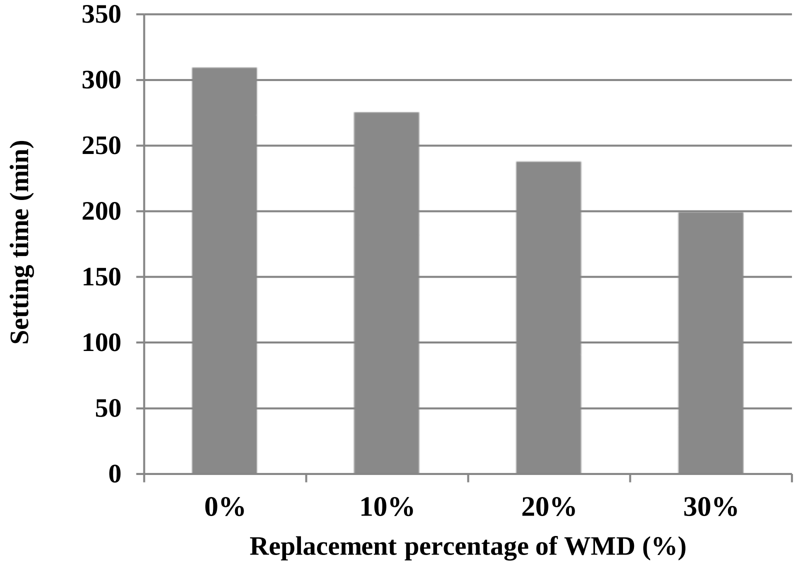

Figure 4.2: Effect of replacement percentages of waste marble dust on the setting time of cement

4.3 Effect of WMR on the Bulk Density

Figure 4.3 shows the bulk density of the soil cement mixture with the waste brick dust mixture at 28 curing days. The figure indicates that the B/S ratio: 10, 15 and 20% has a direct effect on the bulk density. The B/S ratio is directly proportional to the bulk densities. As the B/S ratio increases, there is a continuous increase in the bulk densities. The bulk density values were in the range of 2022 – 2113 kg/m3.

Considering the effect of only waste brick dust on the bulk density, it has been observed that there was no significant effect on the bulk densities. Due to the light weight of waste brick dust and lower density, waste brick dust does not show any considerable effect on the density of the mixtures at the same B/S ratios which is considered to be an advantage in terms of obtaining a constant density without degradation in the structure of mixture.

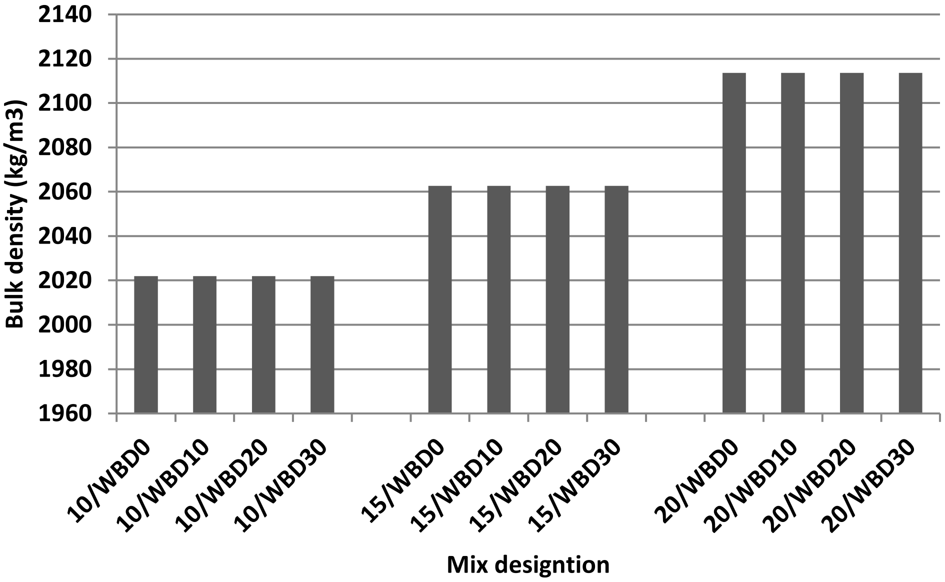

Figure 4.3: Effect of replacement percentages of waste brick dust on the bulk density

Considering only the effect of WMD on the bulk density, it was observed that the effect of WMD on the bulk density was significant. An increase of 0.3% and 0.17% in the bulk density of the soil–cement–WMD mixtures was achieved at B/S ratio of 20 with 10 and 20% WMD content, respectively. This enabled producing more dense specimens with strong strength characteristics, while at 30% of WMD, a reduction of 0.54% in the bulk density of the mixture was observed compared to the specimens with cement only. The reduction obtained with 30% of WMD could be explained due to the high amount of WMD which was more than needed for filling the pore space in soil–cement mixture. Increasing the percentage of WMD above 20% did not contribute to the improvement of the density of soil-cement mixtures. Instead, reduction in the density of the specimens was observed as shown in Figure 4.4.

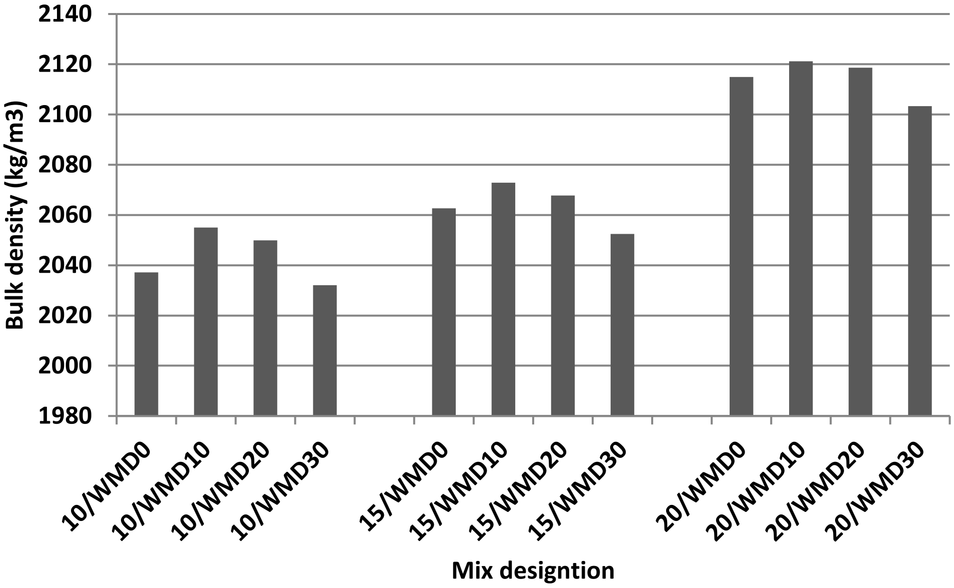

Figure 4.4: Effect of replacement percentages of waste marble dust on the bulk density

4.4 The Effect of WMR on the Unconfined Compressive Strength, UCS

The unconfined compressive strength of the soil-cement mixture with waste brick dust showed variation with changing B/S ratio and replacement percentages of waste brick dust as shown in Figure 4.5. The results showed that the optimum replacement percentage of waste brick dust was at 20% in all B/S ratios. At 28 curing days, the UCS values of the mixtures with 10/BD20, 15/BD20 and 20/BD20 ratios increased from 2374.35 kPa to 2509.73 kPa, 3769.80 kPa, and 5331.87 kPa, respectively. By increasing the percentage of waste brick dust to 30, a decrease in UCS was obtained. The UCS values of the mixture with 10/WBD30, 15/WBD30 and 20/WBD30 ratios were 2343.10 kPa, 3457.38 kPa and 4384.21 kPa, respectively. The most effective percentage of waste brick dust replacement in increasing UCS was 20 above which there was no further increase in UCS. This indicates that the presence of silicon dioxide, SiO2 in waste brick dust with a replacement percentage of 20 is sufficient for the completion of the pozzolanic reaction that will take place in the soil-cement-waste brick dust mixtures. Beyond this percentage, the waste brick dust acts as a filler and does not contribute to the strength.

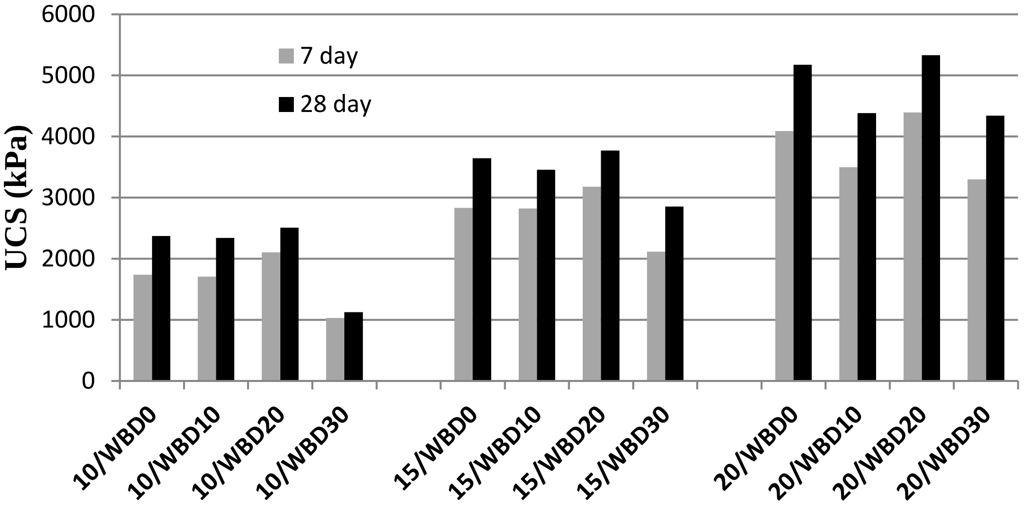

Figure 4.5: UCS of treated specimens with different replacement percentages of WBD

In order to investigate the effect of curing time on the compressive strength of the specimens, unconfined compression test was performed on the specimens after 7 and 28 curing days. The inclusion of WMD in all mixtures resulted in values above the UCS value of the control specimen (with cement only). The highest value of UCS was obtained with 10% WMD replacement at 20% B/S ratio. Figure 4.6 indicates that at all B/S ratios, replacement of WMD percentage higher than 10 caused reduction in UCS values compared to the UCS values obtained with 10% WMD replacement. At 7 day curing time, the UCS values of the specimens treated with cement only were 1739.10, 2832.55 and 4092.63 kPa in mix designations: 10/WMD0, 15/WMD0 and 20/WMD0, respectively. With the inclusion of 10% WMD in the mixtures, the UCS values of the specimens were increased to 3103.31, 4722.66 and 6852.29 kPa, in mix designations: 10/WMD10, 15/WMD10 and 20/WMD10, respectively. The figure indicated that at all B/S ratios, the obtained UCS values of the mixtures were below the value obtained at 10% WMD. The optimum percentage of WMD required to improve the compressive strength of the mixtures was 10% at 20% B/S ratio. This indicated that the optimum percentage of WMD needed for filling the pore space completely and generating effective soil–binder reactions is 10 at 20% B/S ratio. At the percentage above this value, the WMD fills all the pore spaces and the excess WMD accumulates on the grains in the soil–binder mixtures. Which resulted in reduction in the contact surface area needed for chemical reaction.

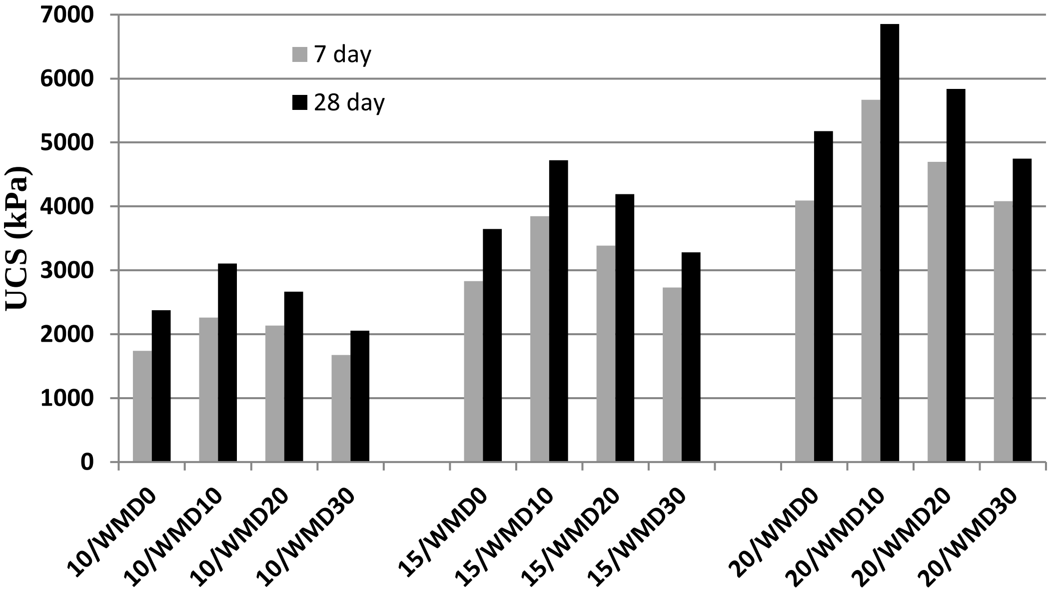

Figure 4.6: UCS of treated specimens with different replacement percentages of WMD

4.5 Stress–Strain Response Curves of Specimens Treated with WBD and WMD

Considering only the B/S ratio, it can be seen that, the strain values of the specimens obtained at failure increased with an increase in B/S ratio. This shows that at higher B/S ratios, the ability of the specimens to deform before failure increased and resulted in ductile behavior. Figure 4.7 indicates that the specimens with WBD exhibited a considerable ductility than the control specimen (cement only). All the specimens treated with WBD changed the behaviour of the specimens from brittle to ductile behavior.

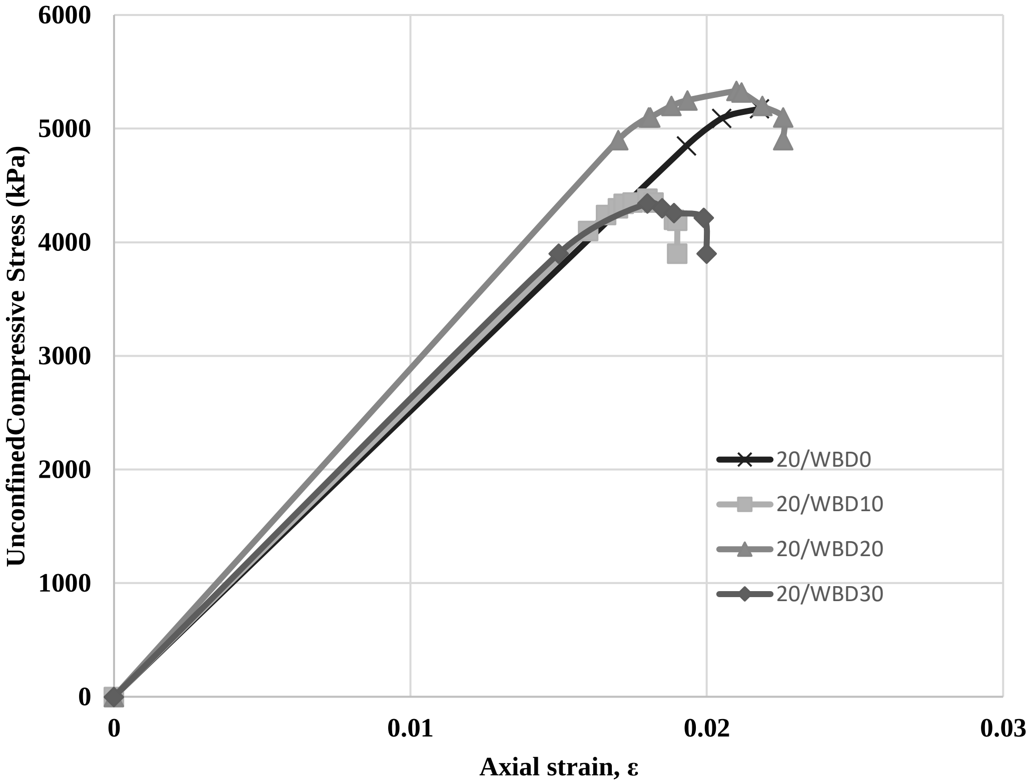

Figure 4.7: Stress–strain response curves of specimens with WBD at 20 % of B/S ratios

Figure 4.8 shows the stress–strain curves of the specimens with 20% of B/S ratios and different replacement percentages of WMD at curing time 28 days. For the specimens treated with cement only (20/WMD0) the failure of the specimens occurred suddenly at smaller strain levels indicating a brittle behavior. It was found that increased replacement percentage of WMD in the mixtures was effective in changing the soil's brittle behavior. Figure 4.8 indicates that the specimens with WMD exhibited much better ductility than the control specimen (cement only). All the specimens treated with WMD had a transitional response from the brittle to ductile behavior better than the specimens treated with WBD. The specimens with WMD absorbed more energy before failure and reached the peak stress without failure.

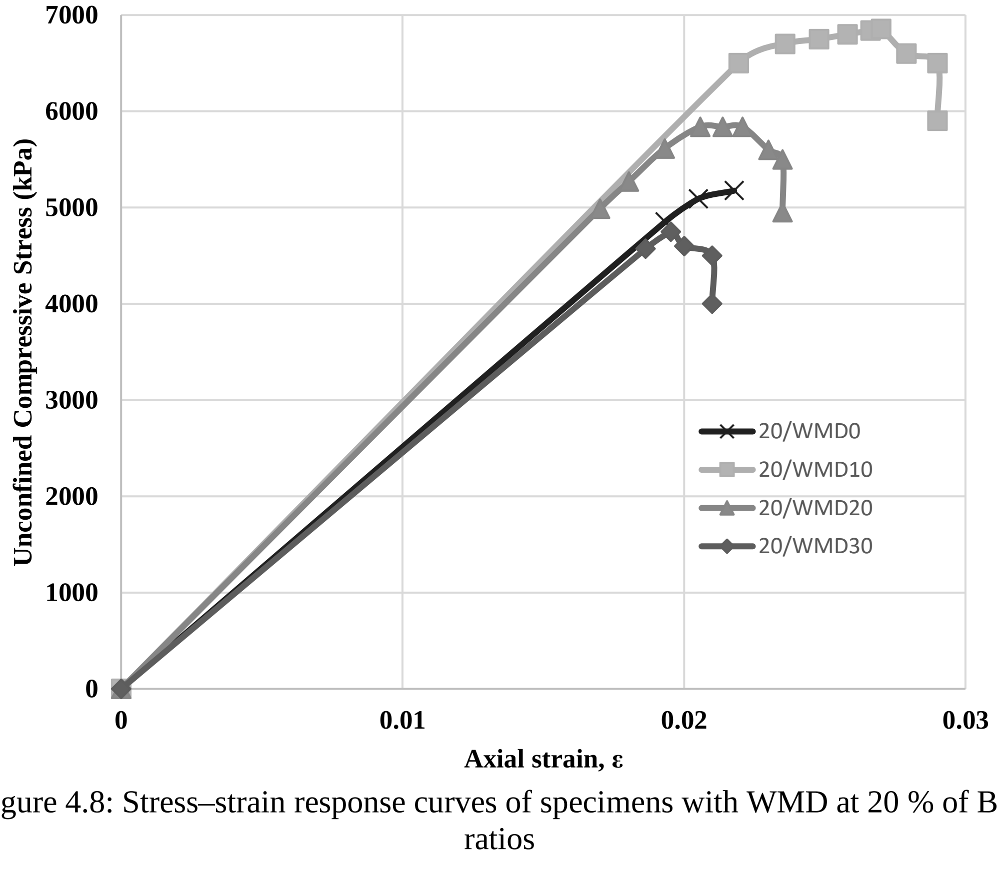

Figure 4.8: Stress–strain response curves of specimens with WMD at 20 % of B/S ratios

4.6 Effect of WMR on the Modulus of Elasticity, E_s

The modulus of elasticity, Es of the specimens with different WMR is shown in Figure 4.9. The E_s values were determined from the slope of the stress–strain curves given in Figure 4.9. The E_s value is a measure of stiffness of a given material. Greater values of modulus of elasticity means stronger resistance of the material to the applied loads before failure in which greater force is required to produce strain before failure. As shown in Figure 4.9, at (20) B/S ratios, the highest modulus of elasticity value was obtained with a 20% waste brick dust replacement. As Rosato (2003) stated, the increase in the modulus of elasticity of the mixtures is a good indication for the strength and the stiffness of the mixtures. On the other hand, the specimens that treated with WMD, the best improvement in Es of the specimens was obtained for the specimens with 10% WMD replacement. The same trend of increment in both Es and UCS values were obtained in the study. In addition, the increase in the Es values of the specimens with WMD substantiated the previous findings that the ductility of the specimens increased with the inclusion of WMD in the mixtures.

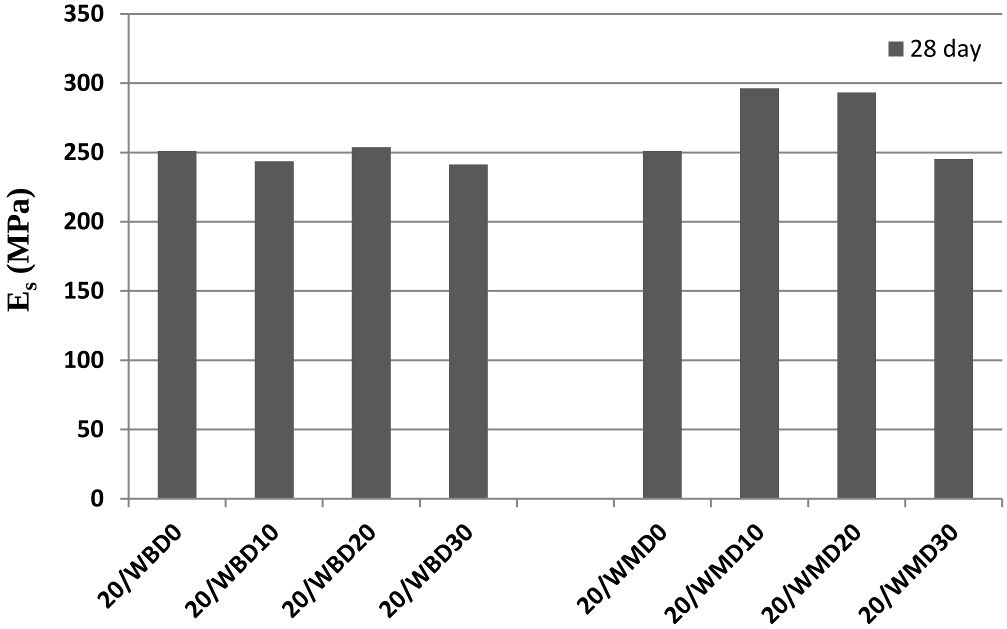

Figure 4.9: The effect of replacement percentages of WMR on the modulus of elasticity

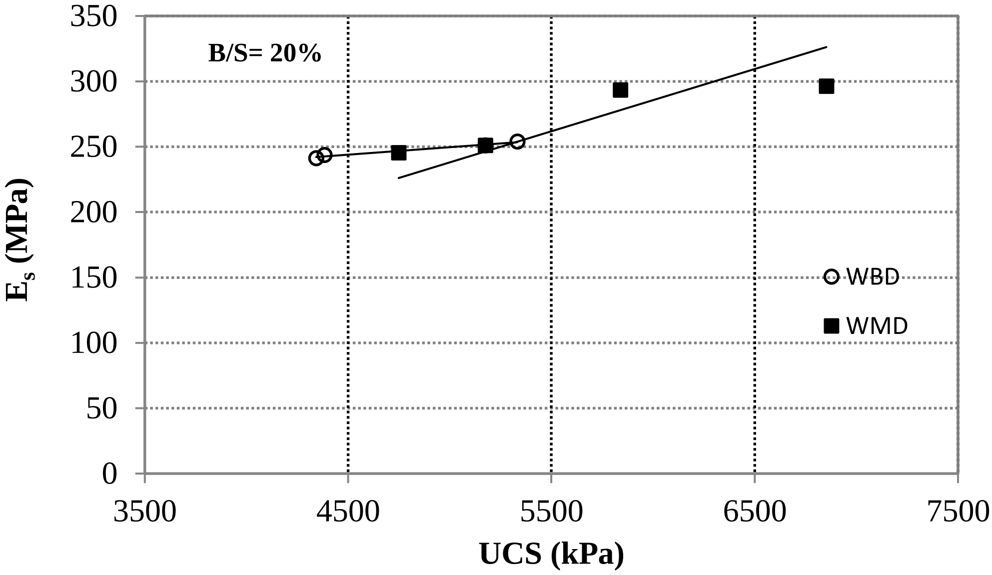

Figure 4.10: The effect of WMR on the modulus of elasticity and UCS

The results of the UCS and Es tests at a 20% B/S ratio with different percentages of waste materials are depicted in Figure 4.10. Upon the analysis of the data, it is clear that there is a strong dependency on the values obtained for E_s and UCS. An increase in the amount of waste materials used in the specimens has a similar effect on both the unconfined compressive strength, UCS and the modulus of elasticity, E_s.

4.7 Microscopic Study of the Binder-Soil Mixture

To better understand the behaviour of the binder-soil mixtures, the specimens were examined under a stereoscopic microscope and the resulting microscope images were analyzed. Figure 4.11 presents the microscope images of four specimens with 20% B/S ratio and 10%, 20%, and 30% replacement of waste brick dust after 28 curing days. Upon the comparison of the image of the specimen with cement only (20/WBD0) in Figure 4.11(a) with the other images obtained for the specimens with different percentages of waste brick dust replacement, it was observed that the specimens treated with 20% waste brick dust in Figure 4.11(c) had less pore spaces than the other specimens. The microscope images of the specimens with 10% and 30% waste brick dust showed larger sizes of pore spaces. The image of the optimal percentage of waste brick dust (20/WBD20) in Figure 4.11(c) demonstrated that this percentage of waste brick dust used in the sand-cement mixture filled all the pore spaces of the sand particles and lead to enhanced interlocking resulting in denser structures. The cementitious compounds formed in the optimal percentage of waste brick dust (20/WBD20) were found to contribute to the strength and stiffness of the specimens. However, in the specimens with 10% and 30% replacement of waste brick dust, the visible pore spaces and weak bonding between sand particles were observed as shown in Figures 4.11(b) and 4.11(d), and resulted in insufficient formation of cementitious compounds and reduced stiffness.

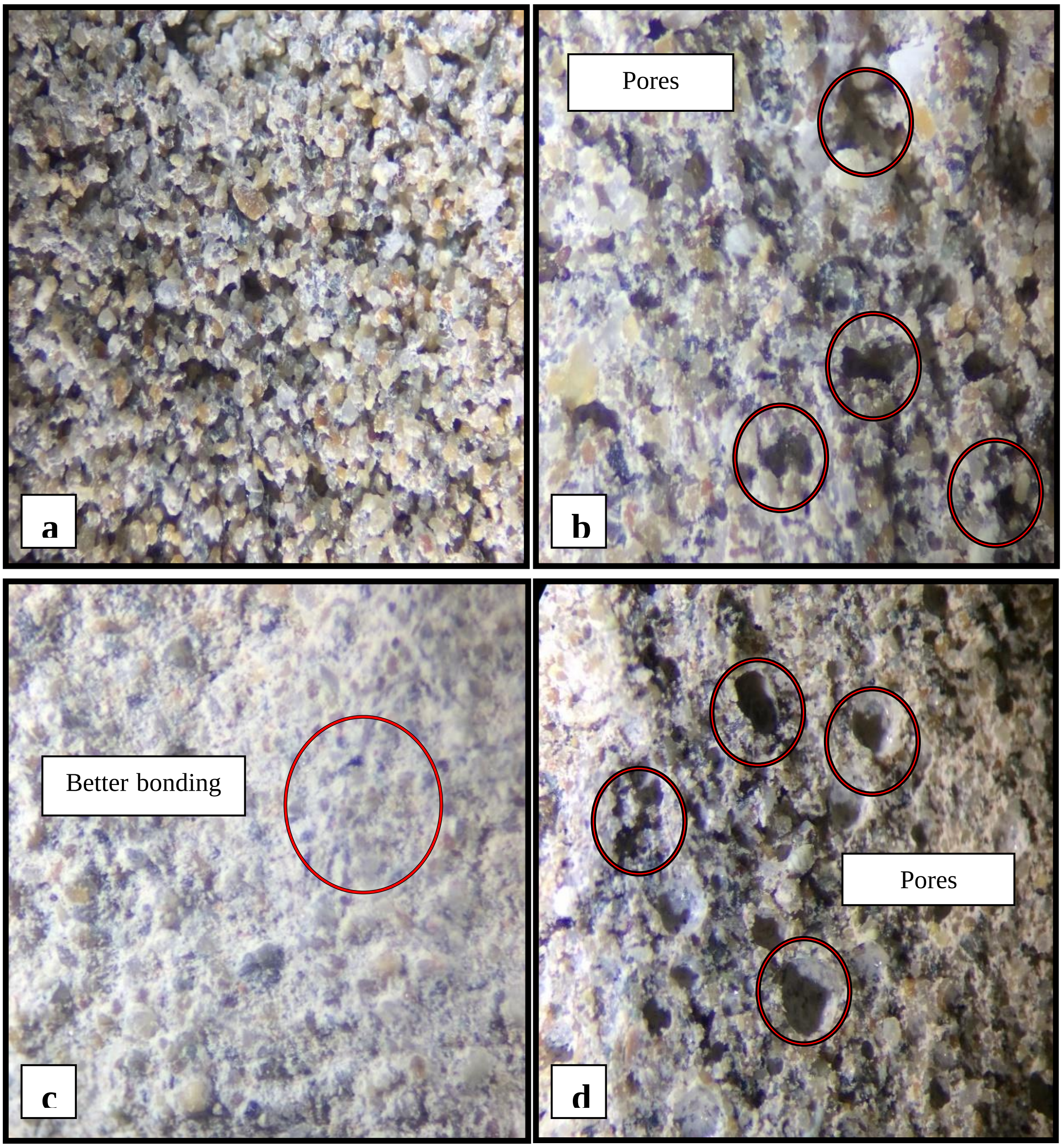

Figure 4.11: Microscopic images of the specimens with cement and waste brick dust (a) 20/WBD0; (b) 20/WBD10; (c) 20/WBD20; (d) 20/WBD30

From the microscopic image of the specimens with WMD given in Figure 4.12, it could be seen that the microscopic structure of the specimen with 10% WMD replacement had less pore spaces and better interlocking between the surface grains compared to the other replacement percentages of WMD. Figure 4.12 (c), and (d) show the microscopic images of the mixtures with 20% and 30% WMD, respectively. The WMD replacement above 10% resulted in the accumulation of the excess WMD on the surface of the mixtures [Figures 4.12(c) and (d)] and weakened the homogeneity of the mixtures compared to the microscopic image of the specimen with 10% WMD as shown in Figure 4.12(b). Increase in the replacement percentage of WMD above 10% resulted in more porous mixtures in Figures 4.12(c) and (d). The specimen with 30% WMD replacement [Figure 4.12(d)] resulted in larger pore spaces than the specimen with 20% as shown in Figure 4.12(c). The larger pore spaces of the specimen generated with 30% WMD replacement are highlighted in circles in Figure 4.12(d). As aforementioned, 10% WMD replacement with a B/S ratio of 20 formed the best structure of the mixture.

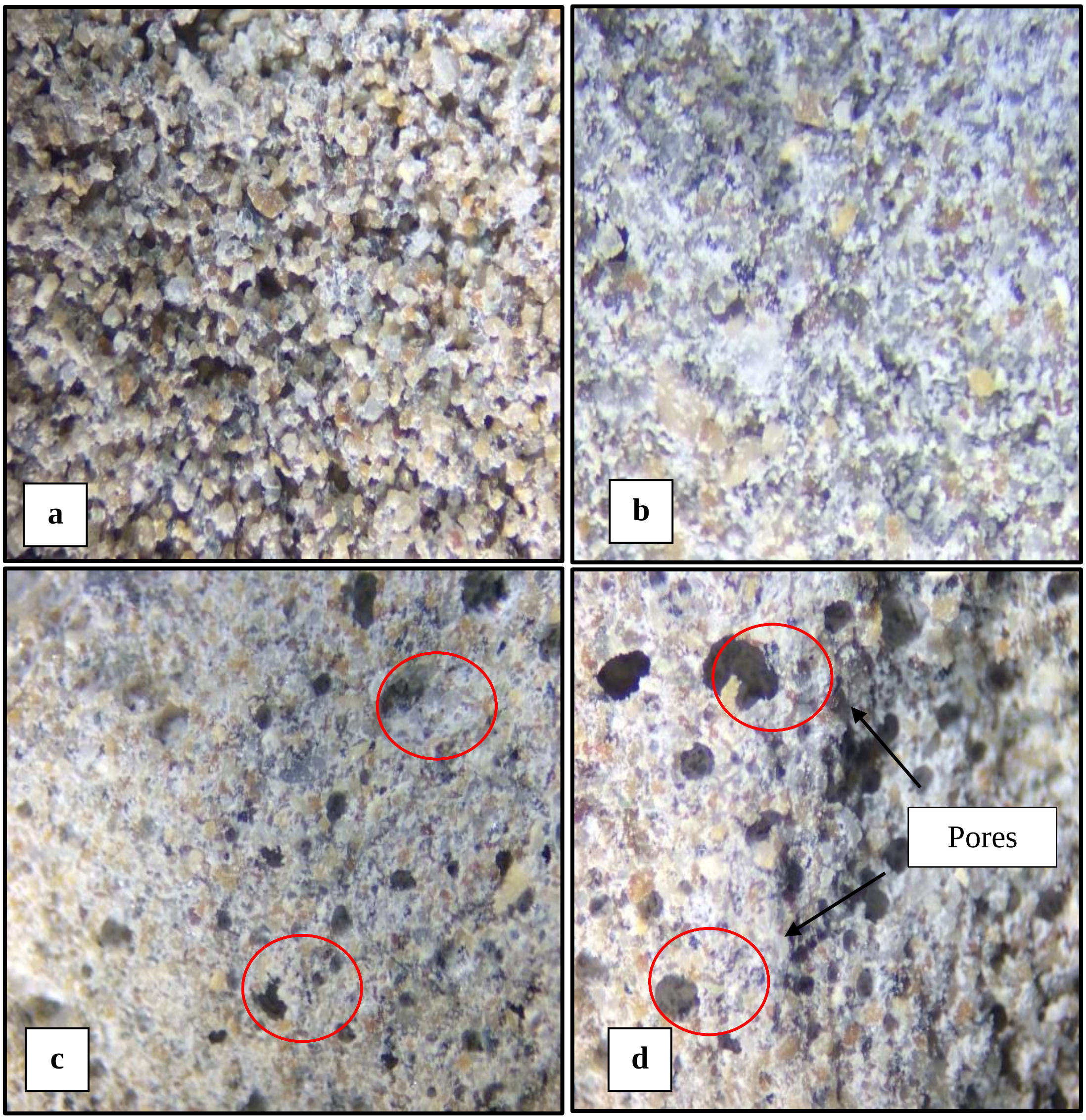

Figure 4.12: Microscopic images of the specimens with cement and waste marble dust (a) 20/WMD0; (b) 20/WMD10; (c) 20/WMD20; (d) 20/WMD30

4.8 Failure Modes in Binder-Soil Mixtures During UCS Tests

The deformation behaviour of the soil-cement mixture with different percentage of WMR was investigated by using the unconfined compression test specimens after failure. The unconfined compression test specimens were tested under uniaxial compression testing and the effect of WMR on the deformed shapes of the specimens and the cracking propagation of the specimens after failure were investigated. Figure 4.13 and Figure 4.14 illustrate the deformation behaviour of soil-cement mixture with different percentage of WBD and WMD, respectively. The figures illustrate the deformed shapes of the specimens at failure. Figure 4.13(a) and Figure 4.14(a) show the failure deformation of the specimen with 0% of WMR in mix designations 20/WBD0 and 20/WMD0, respectively. The obtained deformation type is a typical shear failure pattern obtained in UCS test. Whereases at 10% of waste brick dust in mix designation 20/WBD10 and 30% of waste marble dust in mix designation 20/WMD30, a fracture surface with small cracks were observed as shown in Figure 4.13(b) and Figure 4.14(c), respectively. At 20% replacement of waste brick dust in mix designation 20/WBD20 and at 10% of waste marble dust in mix designation 20/WMD10, it was found that the crack path was along the vertical direction of the axial stress, which was typically axial splitting tensile failure as shown in Figure 4.13(c) and Figure 4.14(b). On the other hand, at 30% replacement of waste brick dust in mix designation 20/WBD30, the deformation resulted in fracture surfaces with lots of cracks as shown in Figure 4.13(d). The increasing amount of WMR altered the deformation and cracking pattern of the binder-soil specimens as shown in Figure 4.13(d) and Figure 4.14(d). All the binder-soil specimens with different percentage of WMR yielded more crack surfaces than the only cement mixed specimen: 20/WBD0 and 20/WMD0. As previously reported by Yadav et al. (2019), the cracks formed on the surface of the specimens cause sudden failure of the specimens with less energy absorption before failure. The deformation and cracking pattern of the specimens with 10 and 30% WBD and with 30% WMD resulted in lower unconfined compressive strength and poorer strength and stiffness development. These findings are in harmony with the observations of Li et al. (2005), who linked the decrease in unconfined compressive strength of marble dust treated samples to cracks formed in the specimens.

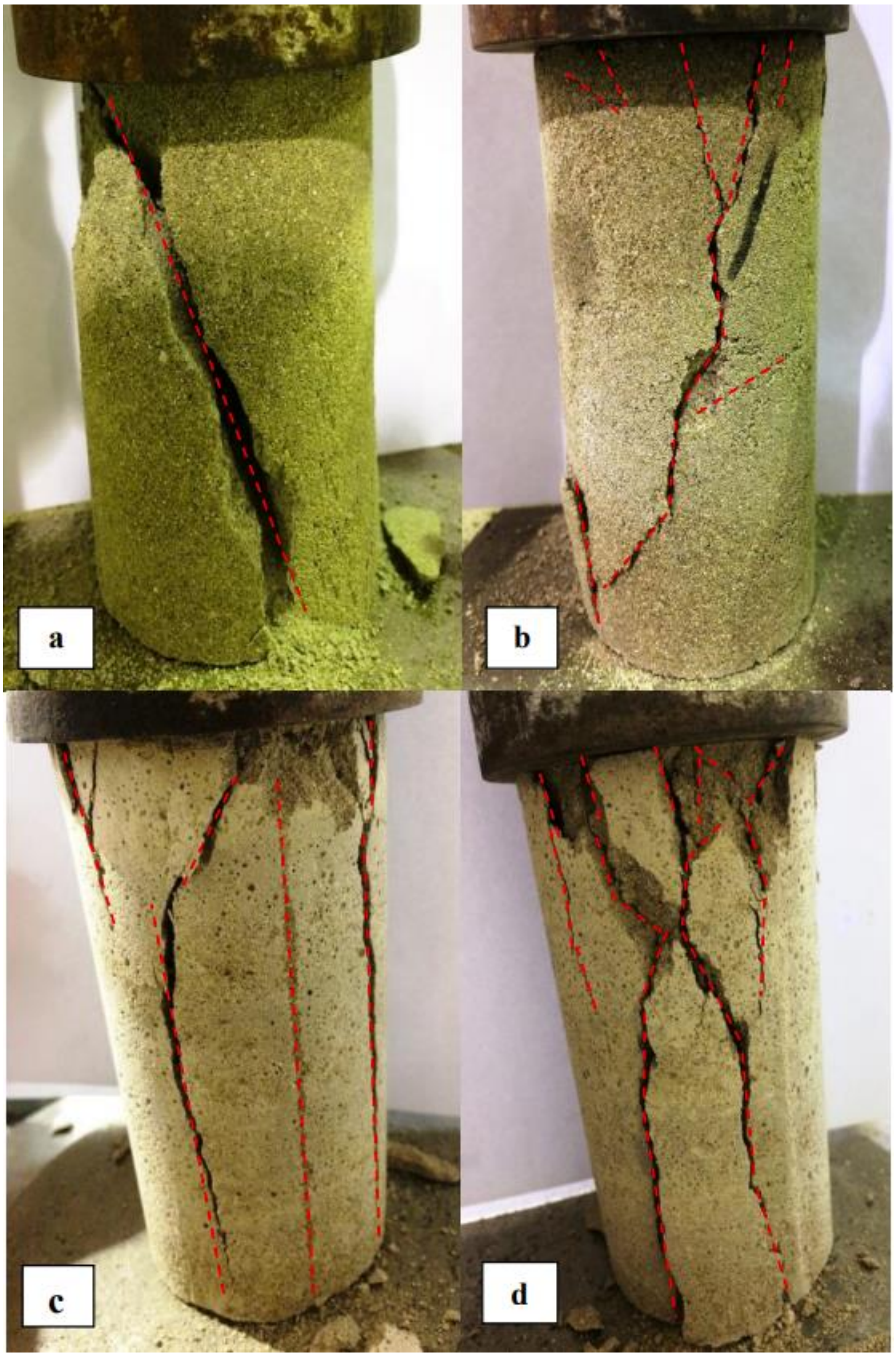

Figure 4.13: Deformation behaviour of binder-soil mixture with waste brick dust (a) 20/WBD0, (b) 20/WBD10, (c) 20/WBD20 and (d) 20/WBD30

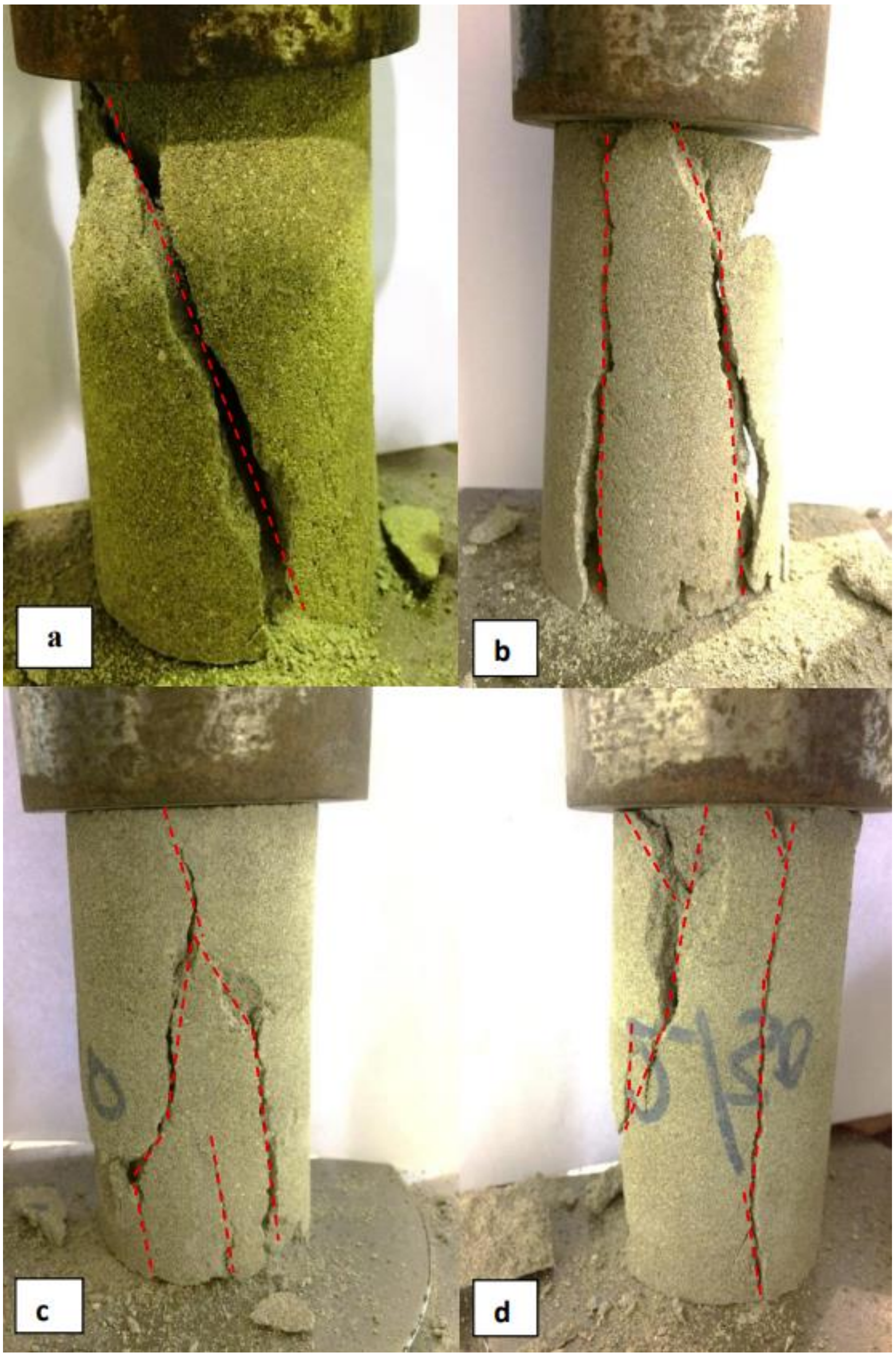

Figure 4.14: Deformation behaviour of binder-soil mixture with waste marble dust (a) 20/WMD0, (b) 20/WMD10, (c) 20/WMD20 and (d) 20/WMD30

4.9 DSM Columns Constructed in The Model Test Tank: Single End-Bearing, Single Floating, Group of End-Bearing and Group of Floating

4.9.1 Introduction

Based on the optimal results of the control small binder-soil specimens discussed in the previous sections in this chapter, WBD at 20% replacement and WMD at 10% replacement, with 20% binder-soil were chosen to be utilized in the soil-cement mixtures in the construction of the DSM columns in the model test tank.

The vertical stress-settlement behavior of a soil refers to the relationship between the vertical stress applied to the soil and the amount of settlement that occurs under that stress. Modulus of subgrade reaction or also named as subgrade modulus, k is defined as the stress per unit deformation of the subgrade. It is the ratio of the stress applied to the soil to the deformation under that stress. The subgrade modulus of a soil is a measure of the stiffness parameter of the soil. It is often used to predict the amount of settlement that will occur when a load is applied to the soil. In some studies, the degree of improvement of a soil was measured in terms of how much the subgrade modulus of a soil has been increased by some forms of treatment applied onto the soil (Alonso et al., 2015; Dash et al., 2008; Moghaddas Tafreshi et al., 2016).

Some studies in the literature indicated that understanding the vertical stress-settlement behavior of a soil, subgrade modulus and the improvement ratio which was defined as the ratio between the bearing capacity of the treated soil to the bearing capacity of the untreated soil is important parameters in the design of structures (Jenck et al., 2007; Massarsch, 2004; Rui et al., 2020; Sakr et al., 2019; Youssef & Moftah, 2007).

In DSM studies, in the literature (Dehghanbanadaki et al., 2014; Esmaeili & Khajehei, 2016), various displacement percentages were used to determine the ultimate vertical stress of DSM columns. In the present study, for comparison purpose according to (Sakr et al., 2019). The vertical stress value corresponding to 10 mm settlement was taken to be the ultimate bearing capacity of the DSM columns. The normalized stress-settlement curves were drawn and the subgrade modulus values were calculated. For normalizing the stress-settlement curves, the obtained settlement values, S were divided by the width of the footing, D (100 mm) and the applied vertical stress vertical stress values were plotted against S/D ratio as shown in Figures 4.15-4.19.

4.9.2 Behaviour of Single End-bearing DSM Column

The vertical stress-settlement behaviour, the ultimate bearing capacity, the percent of improvement achieved and also the subgrade modulus (*k*) of single end-bearing DSM column with different waste replacement materials are investigated in this section. Figure 4.5 shows the normalized vertical stress-settlement curves of the untreated soil and the soil treated with single end-bearing DSM column constructed with cement, WBD and WMD.

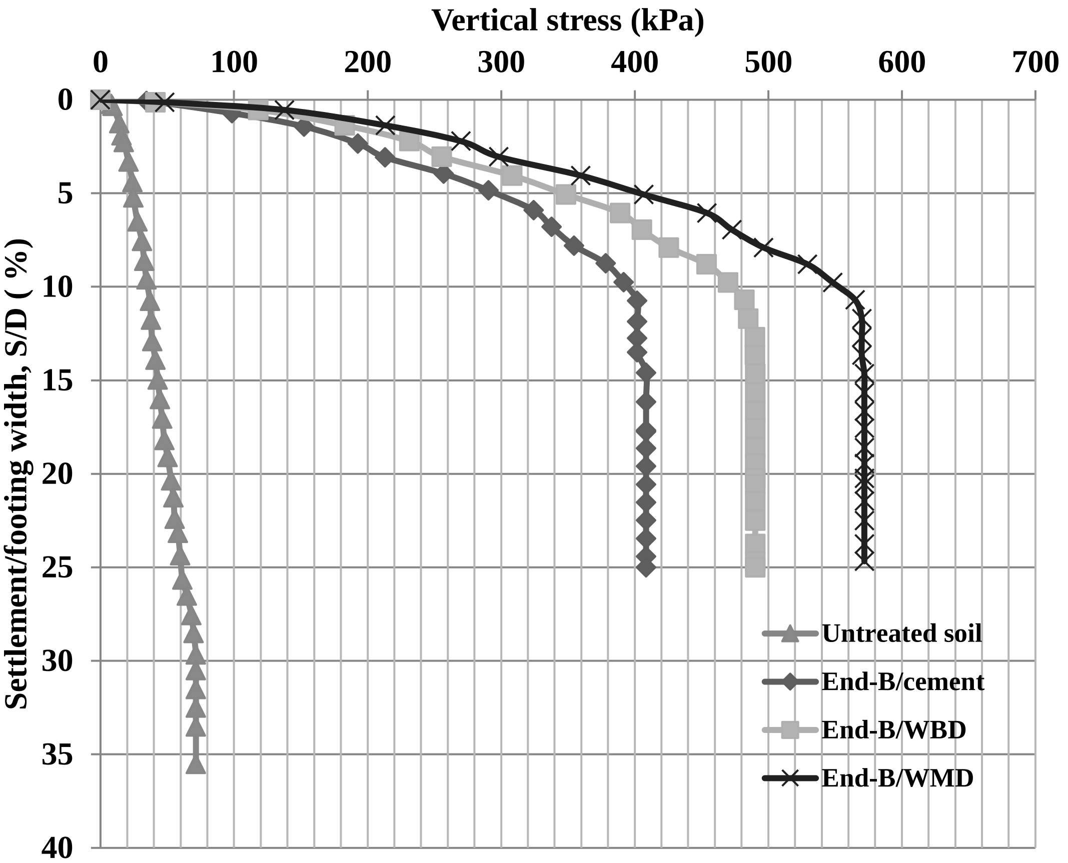

Figure 4.15: Normalized vertical stress-settlement behaviour of single end-bearing DSM columns

The stress-settlement response of loose sand reinforced with a single end-bearing DSM column with and without the use of waste materials as a replacement of cement is shown in Figure 4.15. From this figure, it can be seen that the presence of DSM column in loose sand significantly improves and modifies the stress-settlement response. The ultimate bearing capacity of the loose sand without the DSM column was found to be 18 kPa, while the ultimate bearing capacity of the reinforced sand with an end-bearing DSM column using cement only (End-B/cement) was 410 kPa. The ultimate bearing capacity of DSM columns with WBD (End-B/WBD) and WMD (End-B/WMD) was found to be 480 and 570, respectively. The obtained stress-settlement curves confirm that the construction of the DSM columns in loose sand increase the load carrying capacity, and enable the sand to experience more settlement under the same loading before failure. In the obtained normalized stress-settlement curves of the sand with end-bearing DSM columns, the stress-settlement relationship before failure was almost linear. It can be seen that beyond the peak points, where the entire composite failed around 10% vertical displacement, the surrounding soil around the DSM column began to take part in load carrying until failure.

Using the test results obtained in Figure 4.15, the subgrade modulus, (k) of the soils were calculated at 0.01 mm settlement. Table 4.2 gives the subgrade modulus, *k* of the untreated and treated sand with single end-bear DSM column.

Table 4.1: Subgrade modulus of single end-bearing DSM column at S/D ratio of 10

Model type	Settlement, (m)	Ultimate vertical stress, (kPa)	Subgrade modulus, k (kN/m^3)
Untreated soil	0.01	18	1800
End-B/cement		395	39500
End-B/WBD		480	48000
End-B/WMD		559.4	55940

From Table 4.2, it can be seen that in all single end-bearing DSM column application, a markable amendment of the subgrade modulus values was achieved. In the case of (End-B/WBD), the obtained subgrade modulus was 4800 kN/m^3. Whereas, the (End-B/WMD) case had the most significant improvement of subgrade modulus (55940 kN/m^3) among all the other DSM columns. This is attributed to the results obtained from the small control specimens which was discussed in the previous chapter 3. The existence of waste marble dust in the soil-cement mixture at 10 percent replacement in DSM column significantly modify the stress-settlement behaviour and result in an increase in the subgrade modulus. Compared to End-B/cement application, the ultimate bearing capacity, UBC of sand-DSM column composite increased up to 21.5 and 41.6 % in case of (End-B/WBD) and (End-B/WMD), respectively.

4.9.3 Behaviour of Single Floating DSM Column with Cement Only

In section, the vertical stress-settlement behaviour of single floating DSM column and the subgrade modulus (*k*) will be discussed. First, the behaviour of single end-bearing DSM column (with cement only) at different length/depth, (*l/d*) ratio: 0.4, 0.6 and 0.8 will be studied. In the length/depth ratio, l is the length of DSM column and d is the total depth of soil in the model test tank (Dehghanbanadaki et al., 2014). With these *l/d* ratios, the behaviour of DSM column with different waste replacement materials (WBD and WMD) is investigated and the ultimate bearing capacity and the subgrade modulus of the sand-DSM column composites are discussed. Figure 4.16 shows the normalized stress-settlement curves of single floating DSM column with cement only.

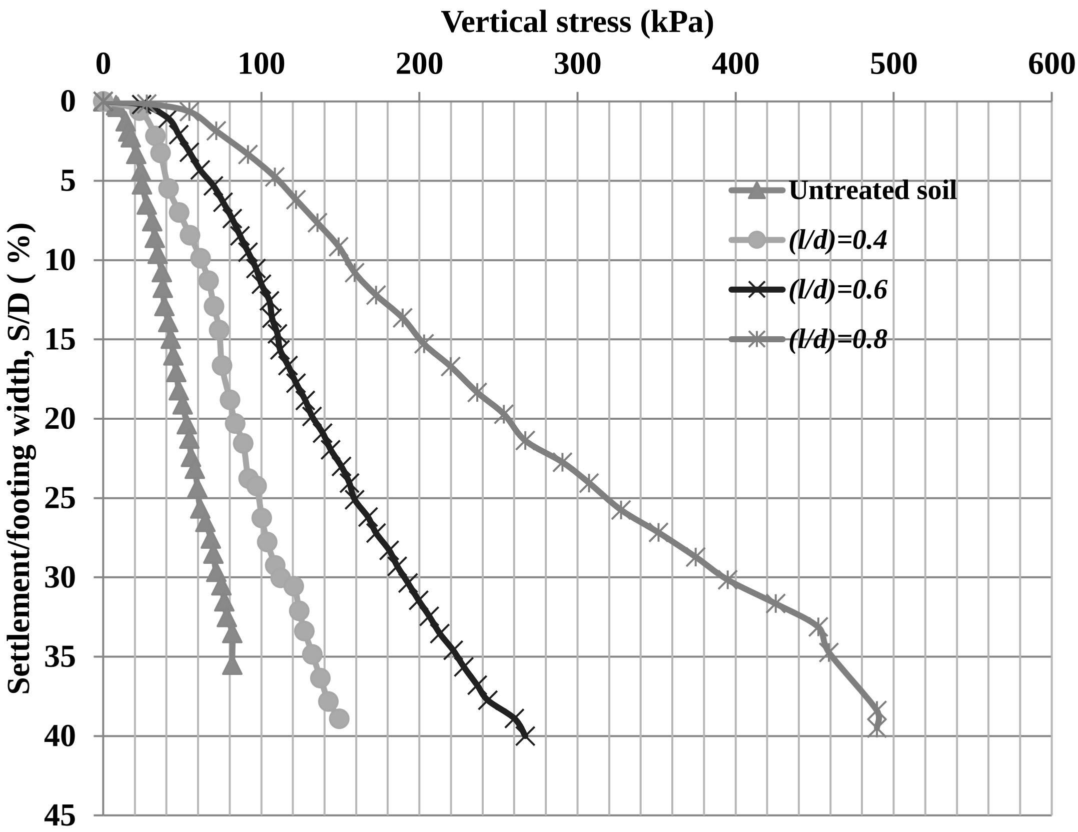

Figure 4.16: Normalized vertical stress-settlement behaviour of single floating DSM column with cement only and with different (l/d) ratio

The figure shows the comparison between the stress–strain responses of the sand reinforced with/without single floating DSM column at different length/depth ratios. As it can be seen from the figure, the sand reinforced with single floating DSM column with cement only, showed a ductile behavior unlike the behaviour obtained in the case of end-bearing DSM column in Section 4.9.2. In the case of end-bearing DSM column, the relationship between the normalized vertical stress and displacement before failure was almost linear. But this behaviour was completely different in the case of the floating DSM columns.

Considering only the *l/d* ratio, it was found that by increasing the *l/d* ratio, the obtained ultimate vertical stress of the sand-DSM columns became greater as shown in Table 4.3. Compared to the untreated sand, the improvement of the ultimate vertical stress of sand with single floating DSM column increased 230.5, 430 and 752.7% for length/depth, *l/d* ratios: 0.4, 0.6 and 0.8, respectively. In the following section, the maximum *l/d* ratio: 0.8 was selected to be used in the case of single DSM column with waste replacement materials.

Table 4.2: Subgrade modulus of single floating DSM model at S/D ratio of 10

Model type	(*l/d*), ratio	Settlement, (m)	Ultimate vertical stress, (kPa)	Subgrade modulus, *k* (kN/m^3)
Untreated soil	--	0.01	18	1800
DSMc/cement	0.4	0.01	59.5	5950
DSMc/cement	0.6	0.01	95.4	9540
DSMc/cement	0.8	0.01	153.5	15350

4.9.4 Behaviour of Single Floating DSM Column with Waste Replacement Material at l/d ratio of 0.8

Figure 4.17 shows the normalized vertical stress-settlement behaviour of single floating DSM column with waste replacement materials. This figure shows the behaviour of single floating DSM column with and without waste materials as a substitute for cement in the construction of DSM columns.

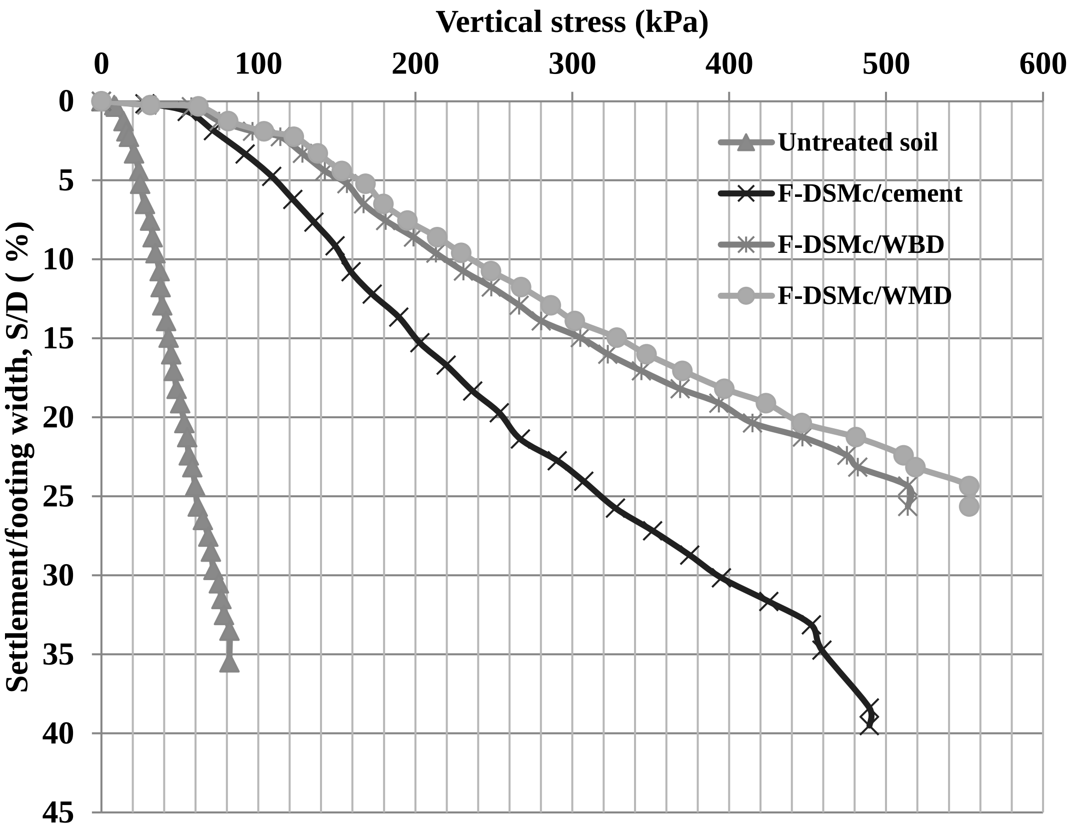

Figure 4.18: The normalized vertical stress-settlement behaviour of single floating DSM column with different waste replacement materials at *l/d* ratio of 0.8

It can be observed that the inclusion of the floating DSM column in loose sand significantly enhanced the stress-settlement response behavior. From the figure, it can be seen that, using WBD and WMD in the single floating DSM column resulted in more ductile behaviour in the stress-settlement curves compared to the floating DSM column with cement only. Compared to F-DSMc/cement and F-DSMc/WBD cases, the WMD in the floating DSM column was able to carry the highest vertical loads at 25 S/D ratio. However, the DSM columns with F-DSMc/WBD and F-DSMc/WMD tended to fail at 25 S/D ratio; earlier than the DSM column with F-DSMc/cement. The ultimate vertical stress of the DSM column with F-DSMc/cement was obtained at a higher value of S/D ratio (approximately S/D ratio of 40). The ultimate bearing capacity of F-DSMc/WBD and F-DSMc/WMD at 25 S/D ratio was obtained to be 519 and 558 kPa, respectively. It can be observed that the used WBD and WMD in DSM columns enhanced the load bearing capacity and resulted in an increase in the bearing capacity of the sand-DSM column. Table 4.4 gives the subgrade modulus, *k* of the DSM columns with F-DSMc/WBD and F-DSMc/WMD. The higher value of *k* indicates a stiffer soil, with less settlement of the DSM columns. When a single floating DSM column with cement only was compared to a single floating DSM column with WBD or WMD, it was found that the ultimate bearing capacity of a single floating DSM column with WBD or WMD increased by 42.8% and 55.9%, respectively, at the length/depth ratio of 0.8. Again, this finding indicates that using WBD or WMD as replacement materials in DSM columns results in a significant increase in bearing capacity.

Table 4.3: Subgrade modulus (k) of single floating DSM column at S/D ratio of 10

Model type	(*l*/*d*), ratio	Settlement, (m)	Ultimate vertical stress, (kPa)	Subgrade modulus, *k* (kN/m^3)
Untreated soil	0.8	0.01	18	1800
F-DSMc/cement		0.01	153.5	15350
F-DSMc /WBD		0.01	219.3	21930
F-DSMc /WMD		0.01	239.4	23940

4.9.5 Behaviour of Group of End-bearing DSM Columns

In this section, the vertical stress-settlement behavior of a group of end-bearing DSM columns and subgrade modulus of these columns will be studied. The behavior of the group of columns will be examined using cement and different waste replacement materials: WBD and WMD, and the ultimate bearing capacity of the columns will be determined.

Figure 4.18 gives the normalized vertical stress-settlement behaviour of group of end-bearing DSM columns constructed with cement only and with WBD and WMD. From the figure, it can be seen that the incorporation of these group of end-bearing DSM columns in loose sand significantly modifies the stress-settlement response of the sand. The ultimate bearing capacity of the reinforced sand with a group of end-bearing DSM columns made with cement alone (E-G/cement) was found to be 1280 kPa. The ultimate bearing capacity of DSM columns with WBD (E-G/WBD) and WMD (E-G/WMD) was found to be 1535 and 1840, respectively.

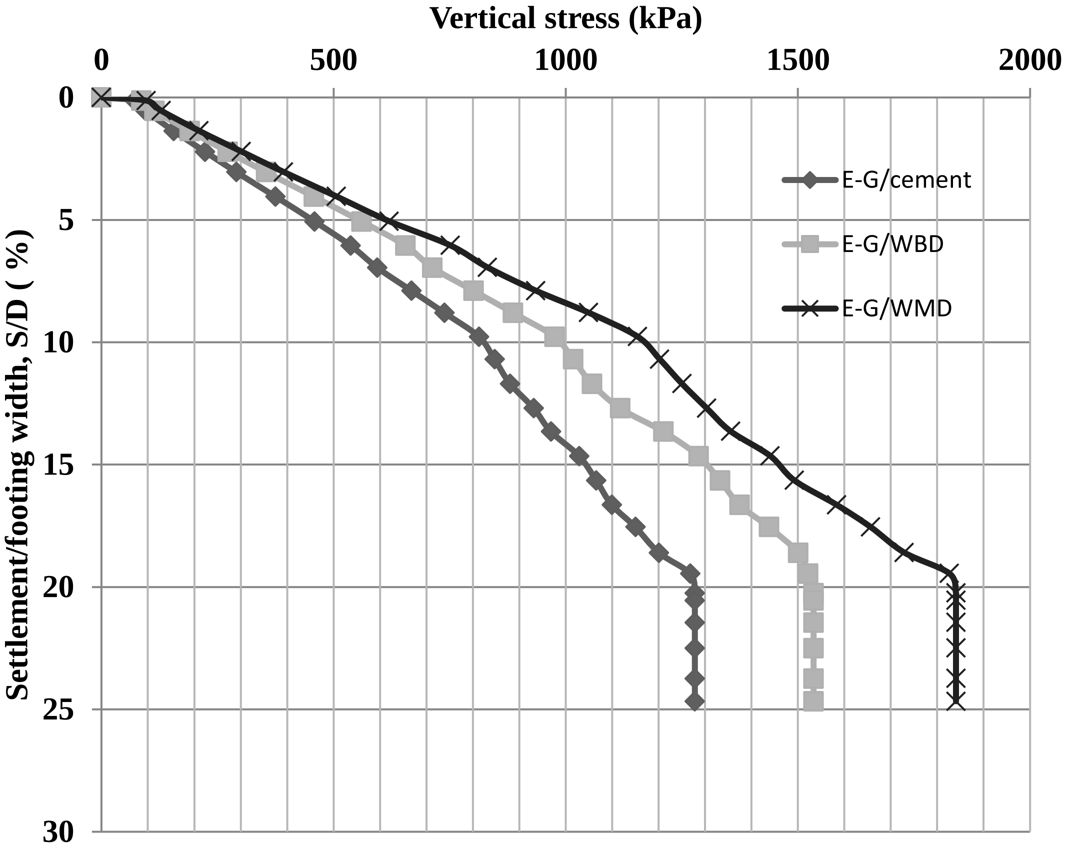

Figure 4.19: Normalized vertical stress-settlement behaviour of group of end-bearing DSM columns with different waste replacement materials

The stress-settlement curves obtained in Figure 4.18 indicates that the existence of the group of end-bearing DSM columns in loose sand increased the load carrying capacity, and enabled the sand to experience more settlement before failure. Each stress-settlement curve obtained in Figure 4.18 can be evaluated in two different stages. In the first stage, the relationship between the applied vertical stress and the settlement was relatively linear up to a S/D value of 10. Beyond this point, the load currying transferred from the DSM column to the surrounding soil around the DSM column and this resulted in a decrease in the load carrying capacity to the applied vertical stress and resulted in a more rapid increase in settlement up to a S/D value of 20. This behavior was observed just before the occurrence of failure as shown in Figure 4.18.

At the first stage of the loading of the footing, the loads were first transferred to DSM columns and this was accompanied by a sharp increase in the vertical stress and a small amount of settlement up to a S/D value of 10. As the loading continued, the soil surrounding the DSM column weas gradually densified and its capability to resist the applied vertical loads was increased.

The UBC of the group of end-bearing DSM columns in case of (E-G/cement) was around 1280 kPa, while the UBC of the single end-bearing DSM column (End-B/cement) was around 410 kPa. The group of end-bearing DSM columns demonstrated better performance compared to a single end-bearing DSM column, potentially due to the confinement of the surrounding soil between the central DSM column and the other DSM columns, which resulted in an increase in the ultimate bearing capacity of the DSM reinforced sand.

In comparison to the soil reinforced with E-G/cement, the soil reinforced with E-G/WBD and E-G/WMD had higher ultimate bearing capacities of 1535 and 1840 kPa, respectively. However, the (E-G/cement), (E-G/WBD) and (E-G/WMD) cases had similar responses in the stress-settlement curves, The WBD and WMD had ability to absorb more energy during loading and attained higher peak stress before failure.

Table 4.4 gives the subgrade modulus, *k* of the end-bearing DSM columns. Overall, the addition of WBD and WMD to the soil-cement mixture in DSM columns significantly strengthens the DSM columns and the surrounding soil and improves the subgrade modulus of the reinforced sand as shown in Table 4.5.

When compared to the End-B/cement case, it was found that the ultimate bearing capacity of sand with group of end-bearing DSM columns increased by 23.2% and 44.9% in the E-G/WBD and E-G/WMD cases, respectively.

Table 4.4: Subgrade modulus (*k*) of group of end-bearing DSM columns at S/D ratio of 10

Model type	Settlement, (m)	Ultimate vertical stress, (kPa)	Subgrade modulus, *k* (kN/m^3)
Untreated soil	0.01	18	1800
E-G/cement	0.01	810.5	81050
E-G/WBD	0.01	998.6	99860
E-G/WMD	0.01	1175	117500

4.9.6 Behaviour of Group of Floating DSM Columns

Figure 4.19 gives the normalized vertical stress-settlement behaviour of group of floating DSM columns. The figure shows the effect of a group of floating DSM columns with and without waste replacement materials for cement on the stress-settlement behavior of loose sand.

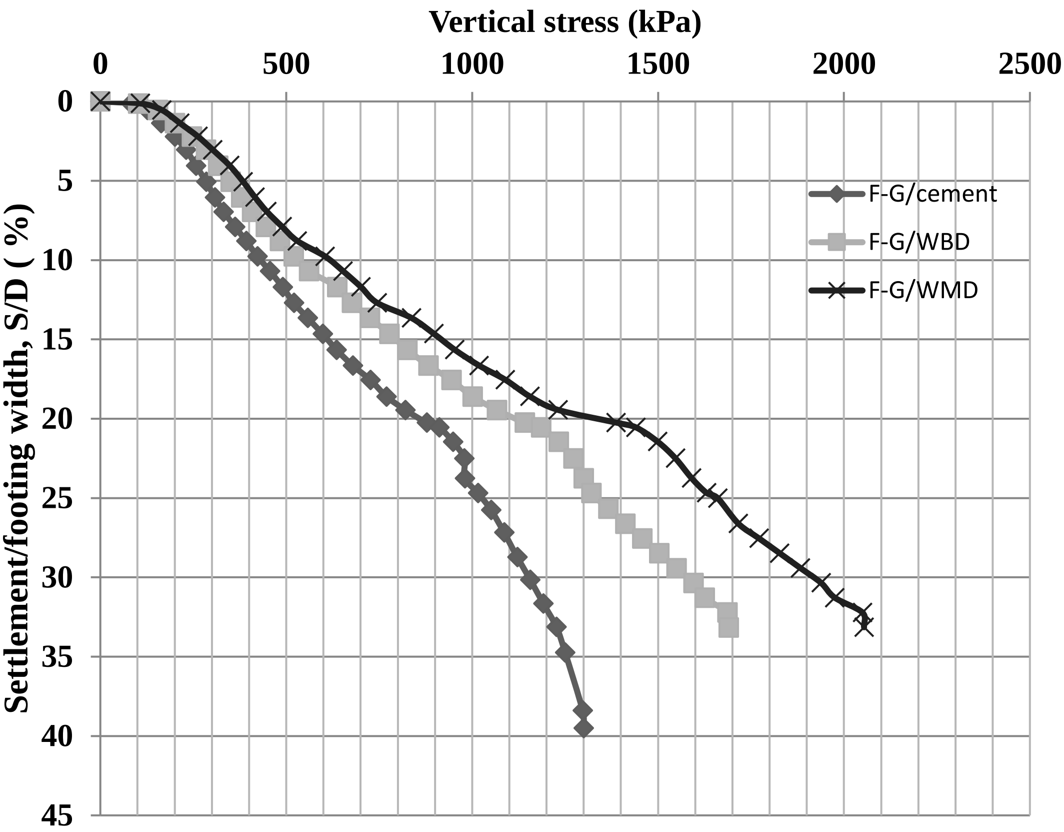

Figure 4.20: Normalized vertical stress-settlement behaviour of group of floating DSM columns with different waste replacement materials at l/d of 0.8

The figure indicates that the inclusion of the group of floating DSM columns can significantly modify and enhance the stress-settlement response of loose sand. Using WBD and WMD in the group of floating DSM columns results in better stress-settlement curves in comparison to the case of group of floating DSM columns with cement only (F-G/cement). It should be noticed that the stress-settlement curves of F-G/WBD and F-G/WMD exhibited a tendency towards failure at around 25 S/D ratio, but simultaneously reached higher ultimate vertical stress values at this value. The ultimate bearing capacities of F-G/WBD and F-G/WMD were found to be 1300 and 1650, respectively. These findings suggest that the incorporation of WBD and WMD in the group of floating DSM columns enhances the surrounding soil and leads to an increase in soil strength. This increase in soil strength and the improvement in bearing capacity can be attributed to the support and densification of DSM columns and also the densification of the surrounding soil around the DSM columns. The densification of the surrounding soil leads to an increase in the frictional resistance along the surface of the DSM columns and results in higher bearing capacity value. Furthermore, the subgrade modulus, *k* values of F-DSMc/WBD and F-DSMc/WMD, are presented in Table 4.6. The values in the table indicates that the subgrade modulus of the DSM columns increase with waste material replacement and result in the highest subgrade modulus of 60500 kN/m^3 with WMD replacement, leading to lesser settlement of the DSM columns.

A comparison of a group of floating DSM columns with WBD or WMD reveals that the ultimate bearing capacity of the soil increases by 42.8% and 55.9%, respectively. This demonstrates that the use of WBD or WMD as a replacement material in DSM columns can significantly enhance the bearing capacity of loose sand. The UBC of sand with group of floating DSM columns increased up to 25% and 44 % in case of F-G/WBD and F-G/WMD, respectively.

Table 4.5: Subgrade modulus (k) of group of floating DSM columns at S/D ratio of 10

Model type	(*l/d*), ratio	Settlement, (m)	Ultimate vertical stress, (kPa)	Subgrade modulus, *k* (kN/m^3)
Untreated soil	0.8	0.01	18	1800
F-G/cement		0.01	420	42000
F-G/WBD		0.01	525	52500
F-G/WMD		0.01	605	60500

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

A laboratory study was conducted to evaluate the effectiveness of using waste materials WBD and WMD in deep soil mixing (DSM) in order to improve the strength and the bearing capacity of loose sand. According to the results obtained from the preliminary experiments performed on the small size specimens, the DSM columns were modeled in a test tank by using an ex-situ replacement method. The following conclusions were drawn based on the results obtained:

- In terms of recycling materials, it was found that waste replacement materials WBD and WMD have good potential to be used as a cement replacement material in deep soil mixing (DSM).
- In terms of setting time, it was found that increasing the percentage of waste brick dust (WBD) replacement in the mixture, reduction in the final setting time due to the high water absorption of WBD was obtained. However, the final setting time decreased continuously with an increase in the percentage of waste marble dust (WMD) due to the high calcium oxide (CaO) content present in WMD, which influenced the setting time of cement and accelerated the setting process, resulting in a reduction in the final setting time.
- I Increasing the B/S ratio in the binder-soil mixtures resulted in an increase in the bulk density of all mixtures and resulted in more dense specimens.

Increasing the replacement percentage of waste brick dust (WBD) alone did not significantly affect the bulk density. However, an increase in the bulk density of the specimens was observed with 10% and 20% replacement of WMD in the mixture.

- The effective silicon dioxide content required for the pozzolanic reaction in soil-cement-WBD mixtures was achieved at a brick dust replacement of 20%. This percentage of WBD also resulted in the highest unconfined compressive strength among all the other mixtures.
- The optimal percentage of waste marble dust (WMD) replacement for improving the unconfined compressive strength and toughness of the specimens was 10% at a B/S ratio of 20%.
- The highest modulus of elasticity of soil-cement with waste brick dust (WBD) mixtures was observed at a WBD replacement of 20%. The obtained trend in the modulus of elasticity values was consistent with the values obtained for unconfined compressive strength. This finding suggests that increasing the WBD replacement to 20% in the DSM columns, can effectively enhance the stability and strength of the loose sand.
- The inclusion of both waste marble dust (WMD) and waste brick dust (WBD) in the binder-soil mixtures resulted in a transition from brittle to ductile behavior, which enabled the specimens to absorb more energy during loading and reach peak stress without failure.
- The cementitious compounds produced in the soil-cement with waste brick dust (WBD) mixtures at an optimal percentage of 20% contributed to the development of strength and stiffness in the specimens. However, in the specimens with 10% and 30% WBD replacement, the presence of visible pore

spaces and weak bonding between the sand particles resulted in insufficient cementitious compounds, leading to lower strength.

- The microscopic images of the specimens showed that the specimen with 10% waste marble dust (WMD) replacement at a B/S ratio of 20% had less porous structures and better contact surface areas. These characteristics are important for facilitating the chemical reactions between the grains and contributing to the stability and strength of the specimen.
- When the deformation behaviour of the soil-cement mixture with waste material replacement was investigated, it was found that at 10% and 30% of waste brick dust and also at 30% of waste marble dust replacement in UCS test specimens, some fractures and cracks were generated on the surface of the UCS specimens and resulted in lower strength.
- The vertical stress-settlement curves of the single end-bearing DSM columns in model test tank indicated that the failure of the entire composite took place around 10% vertical displacement value and the relationship between the vertical stress and settlement before failure was almost linear.
- Compared to (End-B/cement), it was observed that the ultimate bearing capacity of sand with single end-bearing DSM column increased up to 21.5 and 41.6 % in case of (End-B/WBD) and (End-B/WMD), respectively.
- Compared to untreated loose sand case, it was found that the UBC of sand with single floating DSM column increased up to 230.5, 430.0 and 752.7% for length/depth, (*l/d*) ratios of 0.4, 0.6 and 0.8, respectively.
- Using WBD and WMD in the group of floating DSM columns results in better stress-settlement curves in comparison to the case of group of floating DSM columns with cement only (F-G/cement).

- The ultimate bearing capacity of the reinforced sand with a group of end-bearing DSM columns made with cement alone (E-G/cement) was found to be 1280 kPa whereas the ultimate bearing capacity of DSM columns with WBD (E-G/WBD) and WMD (E-G/WMD) was 1535 and 1840 kPa, respectively.
- The findings indicated that the group of end-bearing DSM columns resulted in better performance compared to a single end-bearing DSM columns, due to more reinforcement and confinement generated in the loose sand surrounding the DSM columns resulting in higher ultimate bearing capacity and strength.
- Using WBD and WMD in the group of floating DSM columns resulted in better stress-settlement curves in comparison to the case of group of floating DSM columns with cement alone (F-G/cement).

The overall findings in the study indicate that waste material replacement such as WBD and WMD in the construction of DSM columns could be a promising option for obtaining better performance and strength in loose sand stabilization.

Deep soil mixing is a promising application for improving the mechanical and engineering properties of problematic loose sands, however, it has some limitations. Firstly, it is a time-consuming and labor-intensive process that requires specialized equipment and trained personnel. This may result in higher costs compared to other soil improvement techniques such as stone columns, etc. Secondly, the method may not be suitable for all areas where there is limited access to that area. Due to the dense population in that area and the building foundations which are very sensitive to ground shaking, may make the excavation needed for DSM application not possible. Furthermore, the effectiveness of the deep soil mixing technique can be affected by the existing soil type, the ground water level, and the presence of obstacles such as rocks or utility lines in that area. Furthermore, in the literature, there is limited data on the long-term performance and durability of deep soil mixing, and further research is needed to fully understand its limitations and performance of DSM. Despite these limitations, deep soil mixing can still be a valuable tool for improving the stability and safety of problematic soils, and it may be useful in certain situations where other methods are not feasible or effective.

5.2 Recommendations

- In the present study, WBD and WMD were used as cement replacement material in DSM columns but there are other types of waste materials that can be utilized in the DSM application. In the construction of the DSM columns, some other waste materials can be tested.
- Some microscopic studies using the scanning electron micrographs can be performed in order to follow the changes in the particle interaction with the addition of the waste materials.
- In this study, only one type of soil layering system was tested to evaluate the performance of single and group of DSM columns. However, for more comprehensive research, it would be beneficial to test different soil layering conditions with varying layer thicknesses. This would allow for a more thorough understanding of how the soil layering affects the performance of the DSM columns, and could provide insight into the optimal layering conditions for achieving desired outcomes.
- In the current study, a single diameter and length were selected to investigate the performance of a single DSM column in single-layered soil. However, to further expand on these findings, it would be useful to examine the effect of

varying DSM column diameter and length on the performance of DSM columns. Such research would provide a more comprehensive understanding of how column size affects the performance of DSM columns.

REFERENCES

A Rashid, A. S., Bunawan, A. R., & Mat Said, K. N. (2017). The Deep Mixing Method: Bearing Capacity Studies. *Geotechnical and Geological Engineering*, *35*(4), 1271–1298. https://doi.org/10.1007/S10706-017-0196-X

Abe, M. I. & T., Abe, M. I. & T., Yamamoto, M., Nozu, M., Yanagawa, Y., & Li, L. (2022). Behavior of cement deep mixing columns under road embankment. *Physical Modelling in Geotechnics*, 967–972. https://doi.org/10.1201/9780203743362-175

Abiodun, A. A., & Nalbantoglu, Z. (2015). Lime pile techniques for the improvement of clay soils. *Canadian Geotechnical Journal*, *52*(6), 760–768. https://doi.org/10.1139/CGJ-2014-0073

Ahmad, A. S., Black, J. A., Mohamad, H., & Mohd Noor, N. (2015). Behavior of Weak Soils Reinforced with End-Bearing Soil-Cement Columns Formed by the Deep Mixing Method. *Http://Dx.Doi.Org/10.1080/1064119X.2014.954174*, *33*(6), 473–486. https://doi.org/10.1080/1064119X.2014.954174

Ajorloo, A. (2010). *Characterization of the mechanical behavior of improved loose sand for application in soil-cement deep mixing* [The Lille University of Science and Technology]. https://www.semanticscholar.org/paper/Characterization-of-the-mechanical-behavior-of-sand-Ajorloo/55b5d45e5b10247624e8007d405427b17f48e227

Akrouch, G., Gillis, M. E., Hatch, D. A., & Cook, C. R. (2018). *Wet mass soil mixing applications in geotechnical engineering*. 249–261. https://doi.org/10.1061/9780784481639.017

Ali, M., Abdullah, M. S., & Saad, S. A. (2015). Effect of calcium carbonate replacement on workability and mechanical strength of Portland cement concrete. *Advanced Materials Research*, *1115*, 137–141. https://doi.org/10.4028/www.scientific.net/amr.1115.137

Alnunu, M. Z., & Nalbantoglu, Z. (2020). Performance of loose sand with different waste materials in stone columns in North Cyprus. *Environmental Geotechnics*, 1–6. https://doi.org/10.1680/jenge.18.00079

Alnunu, M. Z., & Nalbantoglu, Z. (2022a). Laboratory analysis of loose sand mixed with construction waste material in deep soil mixing. *Geomechanics and Engineering*, *28*(6), 559–571. https://doi.org/10.12989/GAE.2022.28.6.559

Alnunu, M. Z., & Nalbantoglu, Z. (2022b). Performance of Using Waste Marble Dust for the Improvement of Loose Sand in Deep Soil Mixing. *Arabian Journal for Science and Engineering*, *47*(4), 4681–4694. https://doi.org/10.1007/S13369-021-06252-9/METRICS

Alonso, E. E., Gens, A., & Lloret, A. (2015). Precompression design for secondary settlement reduction. *Https://Doi.Org/10.1680/Geot.2000.50.6.645*, *50*(6), 645–656. https://doi.org/10.1680/GEOT.2000.50.6.645

Al-Tabba, A., Ayotamuno, M. J., & Martin, R. J. (2000). Soil mixing of stratified contaminated sands. *Journal of Hazardous Materials*, *72*(1), 53–75. https://doi.org/10.1016/S0304-3894(99)00158-2

Archeewa, E., Puppala, A. J., Saride, S., & Kalla, S. (2011). Numerical Model Studies of Deep Soil Mixing (DSM) Column to Mitigate Bridge Approach Settlements. *In Geo-Frontiers 2011: Advances in Geotechnical Engineering (Pp. 3286-3295).*, 3286–3295. https://doi.org/10.1061/41165(397)336

Arel, H. S. (2016). Recyclability of waste marble in concrete production. *Journal of Cleaner Production*, *131*, 179–188. https://doi.org/10.1016/J.JCLEPRO.2016.05.052

Arulrajah, A., Yaghoubi, M., Disfani, M. M., Horpibulsuk, S., Bo, M. W., & Leong, M. (2018). Evaluation of fly ash- and slag-based geopolymers for the improvement of a soft marine clay by deep soil mixing. *Soils and Foundations*, *58*(6), 1358–1370. https://doi.org/10.1016/j.sandf.2018.07.005

Atalar, C., & Das, B. M. (2009). Geotechnical properties of Nicosia soils, Cyprus. *2nd International Conference on New Developments in Soil Mechanics and Geotechnical Engineering*.

Bagherinia, M., & Lu, A. S. Z. (2021). Effect of deep chemical mixing columns on properties of surrounding soft clay. *Https://Doi.Org/10.1680/Jgrim.18.00108*, *174*(2), 95–104. https://doi.org/10.1680/JGRIM.18.00108

Bahraq, A. A., Maslehuddin, M., & Al-Dulaijan, S. U. (2020). Macro- and Micro-Properties of Engineered Cementitious Composites (ECCs) Incorporating Industrial Waste Materials: A Review. *Arabian Journal for Science and Engineering*, *45*(10), 7869–7895. https://doi.org/10.1007/S13369-020-04729-7

Bergado, D. T., & Lorenzo, G. A. (2005). Economical Mixing Method for Cement Deep Mixing. *Innovations in Grouting and Soil Improvement*, 1–10. https://doi.org/10.1061/40783(162)12

Bhadriraju, V., Puppala, A. J., Madhyannapu, R. S., & Williammee, R. (2008). Laboratory procedure to obtain well-mixed soil binder samples of medium stiff to stiff expansive clayey soil for deep soil mixing simulation. *Geotechnical Testing Journal*, *31*(3), 225–238. https://doi.org/10.1520/GTJ100936

Borhan, T. M., Abo Dhaheer, M. S., & Mahdi, Z. A. (2020). Characteristics of Sustainable Self-compacting Concrete Reinforced by Fibres from Waste Materials. *Arabian Journal for Science and Engineering*, *45*(5), 4359–4367. https://doi.org/10.1007/S13369-020-04460-3

Bouassida, M., Fattah, M. Y., & Mezni, N. (2020). Bearing capacity of foundation on soil reinforced by deep mixing columns. *Https://Doi.Org/10.1080/17486025.2020.1755458*, *17*(1), 309–320. https://doi.org/10.1080/17486025.2020.1755458

Brasse, K., Tracz, T., Zdeb, T., & Rychlewski, P. (2018). Influence of soil-cement composition on its selected properties. *Matec-Conferences.Org*. https://doi.org/10.1051/matecconf/201816306006

Bruce, D. A., & Bruce, M. E. C. (2003). The Practitioner's Guide to Deep Mixing. *Grouting and Ground Treatment,* 474–488. https://doi.org/10.1061/40663(2003)22

Bruce, M., Berg, R., Collin, J., Filz, G., & Terashi, M. (2013). *Federal highway administration design manual: Deep mixing for embankment and foundation support*.

Caraşca, O. (2016). Soil Improvement by Mixing: Techniques and Performances. *Energy Procedia*, *85*, 85–92. https://doi.org/10.1016/J.EGYPRO.2015.12.277

Carvalho, J. M. F. de, Campos, P. A. M., Defáveri, K., Brigolini, G. J., Pedroti, L. G., & Peixoto, R. A. F. (2018). Low environmental impact cement produced entirely from industrial and mining waste. *Journal of Materials in Civil Engineering*, *31*(2), 04018391. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002617

Cement Deep Mixing Method Association. (1999). *Cement Deep Mixing Method (CDM), Design and Construction... - Google Scholar*. Cement Deep Mixing Method Association. https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=Cement+Deep+Mixing+Method+%28CDM%29%2C+Design+and+Construction+Manual&btnG=

Chen, J.-J., Zhang, L., Zhang, J.-F., Zhu, Y.-F., & Wang, J.-H. (2013). Field tests, modification, and application of deep soil mixing method in soft clay. *Journal of Geotechnical and Geoenvironmental Engineering*, *139*(1), 24–34. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000746

Chenari, R. J., Fatahi, B., Ghorbani, A., & Alamoti, M. N. (2018). Evaluation of strength properties of cement stabilized sand mixed with EPS beads and fly ash. *Geomechanics and Engineering*, *14*(6), 533–544. https://doi.org/10.12989/GAE.2018.14.6.533

Dash, S. K., Reddy, P. D. T., & Raghukanth, S. T. G. (2008). Subgrade modulus of geocell-reinforced sand foundations. *Proceedings of the Institution of Civil Engineers: Ground Improvement*, *161*(2), 79–87. https://doi.org/10.1680/GRIM.2008.161.2.79

Dehghanbanadaki, A., Ahmad, K., & Ali, N. (2014). Experimental investigations on ultimate bearing capacity of peat stabilized by a group of soil–cement column: a comparative study. *Acta Geotechnica 2014 11:2*, *11*(2), 295–307. https://doi.org/10.1007/S11440-014-0328-X

Demir, I., Yaprak, H., & Simsek, O. (2011). Performance Of Cement Mortars Replaced By Ground Waste Brick In Different Aggressive Conditions. *Ceramics-Silikáty*, *55*(3), 268–275.

Demirel, B. (2010). The effect of the using waste marble dust as fine sand on the mechanical properties of the concrete. *International Journal of the Physical Sciences*, *5*(9), 1372–1380. http://www.academicjournals.org/IJPS

Deshmukh, R., Iyer, S., & Bhangare, P. (2021). Geotechnical characterization of expanded polystyrene (EPS) beads with industrial waste and its utilization in flexible pavement. *Materials Today: Proceedings*. https://doi.org/10.1016/J.MATPR.2021.07.462

Dhar, S., & Hussain, M. (2018). The strength behaviour of lime-stabilised plastic fibre-reinforced clayey soil. *Road Materials and Pavement Design*, *20*(8), 1757–1778. https://doi.org/10.1080/14680629.2018.1468803

Dong, Y. P., & Whittle, A. J. (2018). Effects of deep soil mixing and jet grouting on adjacent retaining walls and ground. *Geotechnical Aspects of Underground Construction in Soft Ground - Proceedings of the 9th International Symposium on Geotechnical Aspects of Underground Construction in Soft Ground, IS &Amp;Amp;Amp;Amp;Amp;Amp;Amp;Amp;Ndash; SAO PAULO 2017*, 91–96. https://doi.org/10.1201/9781315099507-9/effects-deep-soil-mixing-jet-grouting-adjacent-retaining-walls-ground-dong-whittle

Dry Jet Mixing Method Association. (2006). Dry Jet Mixing (DJM) Method Technical Manual (in Japanese). *Dry Jet Mixing Method Association*. https://doi.org/10.1201/9781315141466-2/dry-mix-methods-bruce-bruce-dimillio

Egorova, A. A., Rybak, J., Stefaniuk, D., & Zajączkowski, P. (2017). Basic Aspects of Deep Soil Mixing Technology Control. *IOP Conference Series: Materials Science and Engineering*, *245*(2), 022019. https://doi.org/10.1088/1757-899X/245/2/022019

El-Bondkly, A. A. M., El-Gendy, M. M. A. A., & El-Bondkly, A. M. A. (2021). Construction of Efficient Recombinant Strain Through Genome Shuffling in Marine Endophytic Fusarium sp. ALAA-20 for Improvement Lovastatin Production Using Agro-Industrial Wastes. *Arabian Journal for Science and Engineering*, *46*(1), 175–190. https://doi.org/10.1007/S13369-020-04925-5

Esmaeili, M., Astaraki, F., Yaghouti, H., & Rad, M. M. (2021). Laboratory Investigation on the Effect of Microsilica Additive on the Mechanical Behavior of Deep Soil Mixing Columns in Saline Dry Sand. *Periodica Polytechnica Civil Engineering*, *65*(4), 1080–1091. https://doi.org/10.3311/PPCI.18126

Esmaeili, M., Gharouni-Nik, M., & Khajehei, H. (2014). Evaluation of deep soil mixing efficiency in stabilizing loose sandy soils using laboratory tests. *Geotechnical Testing Journal*, *37*(5). https://doi.org/10.1520/GTJ20130099

Esmaeili, M., & Khajehei, H. (2016). Mechanical behavior of embankments overlying on loose subgrade stabilized by deep mixed columns. *Journal of Rock Mechanics and Geotechnical Engineering*, *8*(5), 651–659. https://doi.org/10.1016/j.jrmge.2016.02.006

Farah, R. E., & Nalbantoglu, Z. (2019). Performance of plastic waste for soil improvement. *SN Applied Sciences*, *1*(11). https://doi.org/10.1007/S42452-019-1395-2

Farouk, A., & Shahien, M. M. (2013). Ground improvement using soil–cement columns: Experimental investigation. *Alexandria Engineering Journal*, *52*(4), 733–740. https://doi.org/10.1016/J.AEJ.2013.08.009

Filz, G. M., Hodges, D. K., Weatherby, D. E., & Marr, W. A. (2005). Standardized Definitions and Laboratory Procedures for Soil-Cement Specimens Applicable to the Wet Method of Deep Mixing. *Innovations in Grouting and Soil Improvement*, 1–13. https://doi.org/10.1061/40783(162)1

Forsman, J., Winqvist, F., & Korkiala-Tanttu, L. (2017). *Mass stabilization quality control methods Méthodes de contrôle de la qualité de masse stabilization Fin-C2M micropiles View project THEBES-THMC Behaviour of the Swelling Clay Barriers View project*. https://www.researchgate.net/publication/322078156

Foy, H. (2017). *In situ ground evaluation by deep soil mixing* [Doctoral dissertation, University of Canterbury]. https://oatd.org/oatd/record?record=oai\:ir.canterbury.ac.nz\:10092\%2F14407

Frikha, W., Zargayouna, H., Boussetta, S., & Bouassida, M. (2017). Experimental study of tunis soft soil improved by deep mixing column. *Geotechnical and Geological Engineering*, *35*(5), 931–947. https://doi.org/10.1007/s10706-016-0151-2

Ge, Z., Wang, Y., Sun, R., Wu, X., & Guan, Y. (2015). Influence of ground waste clay brick on properties of fresh and hardened concrete. *Construction and Building Materials*, *98*, 128–136. https://doi.org/10.1016/J.CONBUILDMAT.2015.08.100

Golhashem, M. R., & Uygar, E. (2019). Improvement of Internal Stability of Alluvial Clay from Famagusta Bay, Cyprus, Using Copolymer of Butyl Acrylate and Styrene. *Environmental and Engineering Geoscience*, *25*(4), 289–300. https://doi.org/10.2113/EEG-2205

Gullu, H., Canakci, H., & al Zangana, I. F. (2017). Use of cement based grout with glass powder for deep mixing. *Construction and Building Materials*, *137*, 12–20. https://doi.org/10.1016/j.conbuildmat.2017.01.070

Guo, X., Shi, H., Wu, K., Ju, Z., & Dick, W. A. (2016). Performance and risk assessment of alinite cement-based materials from municipal solid waste incineration fly ash (MSWIFA). *Materials and Structures/Materiaux et Constructions*, *49*(6), 2383–2391. https://doi.org/10.1617/s11527-015-0655-x

Harrison, R. W., Newell, W. L., Batihanli, H., Panayides, I., McGeehin, J. P., Mahan, S. A., Özhür, A., Tsiolakis, E., & Necdet, M. (2004). Tectonic framework and Late Cenozoic tectonic history of the northern part of Cyprus: implications for earthquake hazards and regional tectonics. *Journal of Asian Earth Sciences*, *23*(2), 191–210. https://doi.org/10.1016/S1367-9120(03)00095-6

Hasheminezhad, A., & Bahadori, H. (2020). On the deep soil mixing method in the mitigation of liquefaction-induced bearing capacity degradation of shallow foundations. *Geomechanics and Geoengineering*, 1–13. https://doi.org/10.1080/17486025.2020.1755460

Horpibulsuk, S., Miura, N., & Nagaraj, T. S. (2005). Clay–Water⁄Cement Ratio Identity for Cement Admixed Soft Clays. *Journal of Geotechnical and Geoenvironmental Engineering*, *131*(2), 187–192. https://doi.org/10.1061/(ASCE)1090-0241(2005)131:2(187)

Jain, A. K., Gupta, M., & Jha, A. K. (2021). Soil amendment using marble waste for road construction. *Problematic Soils and Geoenvironmental Concerns*, *88*, 245–256. https://doi.org/10.1007/978-981-15-6237-2_21

Jain, A. K., Jha, A. K., & Shivanshi. (2020). Geotechnical behaviour and micro-analyses of expansive soil amended with marble dust. *Soils and Foundations*, *60*(4), 737–751. https://doi.org/10.1016/J.SANDF.2020.02.013

Jain, N., & Garg, M. (2008). Effect of Cr(VI) on the hydration behavior of marble dust blended cement: Solidification, leachability and XRD analyses. *Construction and Building Materials*, *22*(8), 1851–1856. https://doi.org/10.1016/j.conbuildmat.2007.04.022

Jenck, O., Dias, D., and, R. K.-J. of G., & 2007, undefined. (2007). Two-dimensional physical and numerical modeling of a pile-supported earth platform over soft soil. *Academia.Edu*.

Jendrysik, K., Kiecana, M., & Szabowicz, H. (2018). Preliminary results of dry Deep Soil Mixing soil-cement composite testing. *MATEC Web of Conferences*, *251*, 01025. https://doi.org/10.1051/MATECCONF/201825101025

Ju, H., Filz, G. M., Green, R. A., & Mauldon, M. (2019). *Influence of Curing Temperature on Strength of Cement-treated Soil and Investigation of Optimum Mix Design for the Wet Method of Deep Mixing*. https://vtechworks.lib.vt.edu/handle/10919/86723

Juha, F., Leena, K., Peat, P. P.-, IntechOpen, undefined, & 2018, undefined. (2018). Mass stabilization as a ground improvement method for soft peaty. *IntechOpen, 107-139*. https://books.google.com/books?hl=en&lr=&id=9GiQDwAAQBAJ&oi=fnd&pg=PA107&dq=Mass+stabilization+as+a+ground+improvement+method+for+soft+peaty&ots=Oaigk1Ccib&sig=CHsf_pbfqQj6YO-McyZFajinpO4

Jung, C., Ceglarek, R., Clauvelin, T., Ayeldeen, M., & Kim, D. (2020). Deep soil mixing in sabkha soils for foundation support in United Arab Emirates. *International Journal of Geosynthetics and Ground Engineering*, *6*(1), 3. https://doi.org/10.1007/s40891-020-0188-4

Kacar, O., & Ho, C. E. (2019). Numerical Analysis of a TBM Retrieval Shaft Construction Using Deep Soil Mixing. *In Geo-Congress 2019: Earth Retaining Structures and Geosynthetics (Pp. 1-12). Reston, VA: American Society of Civil Engineers*, 1–12. https://doi.org/10.1061/9780784482087.001

Kazemian, S., & Huat, B. B. K. (2009). Assessment and Comparison of Grouting and Injection Methods in Geotechnical Engineering. *European Journal of Scientific Research*, *27*(2), 234–247. http://www.eurojournals.com/ejsr.htm

Kelly Costello, by M., Professor, M., Gray Mullins, A., Sen, R., & Stokes, M. J. (2016). *Full Scale Evaluation of Organic Soil Mixing*.

Khalili, H. D., Ghalandarzadeh, A., Moradi, M., & Karimzadeh, R. (2020). Effect of distribution patterns of DSM columns on the efficiency of liquefaction mitigation. *Scientia Iranica*, *27*(5), 2198–2208. https://doi.org/10.24200/SCI.2019.21647

Khan, M. N. A., Liaqat, N., Ahmed, I., Basit, A., Umar, M., & Khan, M. A. (2018). Effect of Brick Dust on Strength and Workability of Concrete. *IOP Conference Series: Materials Science and Engineering*, *414*(1). https://doi.org/10.1088/1757-899X/414/1/012005

Khazaei, J., & Moayedi, H. (2017). Soft Expansive Soil Improvement by Eco-Friendly Waste and Quick Lime. *Arabian Journal for Science and Engineering* , *44*(10), 8337–8346. https://doi.org/10.1007/S13369-017-2590-3

Khurshid, M. B., Qureshi, N. A., Hussain, A., & Iqbal, M. J. (2019). Enhancement of Hot Mix Asphalt (HMA) Properties Using Waste Polymers. *Arabian Journal for Science and Engineering*, *44*(10), 8239–8248. https://doi.org/10.1007/S13369-019-03748-3

Kinuthia, J. M., & Nidzam, R. M. (2011). Towards zero industrial waste: Utilisation of brick dust waste in sustainable construction. *Waste Management*, *31*(8), 1867–1878. https://doi.org/10.1016/J.WASMAN.2011.03.020

Kishore, K., & Gupta, N. (2020). Application of domestic & industrial waste materials in concrete: A review. *Materials Today: Proceedings*, *26*, 2926–2931. https://doi.org/10.1016/J.MATPR.2020.02.604

Kitazume, M. (2020). Keynote Lecture: Recent development of quality control and assurance of deep mixing method. *Lecture Notes in Civil Engineering*, *62*, 525–540. https://doi.org/10.1007/978-981-15-2184-3_69

Kitazume, Masaki., & Terashi, Masaaki. (2013). *The deep mixing method* (Vol. 21). CRC Press/Balkema. https://books.google.com/books/about/The_Deep_Mixing_Method.html?id=mXzMBQAAQBAJ

Knapen, E., & van Gemert, D. (2009). Cement hydration and microstructure formation in the presence of water-soluble polymers. *Cement and Concrete Research*, *39*(1), 6–13. https://doi.org/10.1016/J.CEMCONRES.2008.10.003

Kouakou, C. H., & Morel, J. C. (2009a). Strength and elasto-plastic properties of non-industrial building materials manufactured with clay as a natural binder. *Applied Clay Science*, *44*(1–2), 27–34. https://doi.org/10.1016/J.CLAY.2008.12.019

Kouakou, C. H., & Morel, J. C. (2009b). Strength and elasto-plastic properties of non-industrial building materials manufactured with clay as a natural binder. *Applied Clay Science*, *44*(1–2), 27–34. https://doi.org/10.1016/J.CLAY.2008.12.019

Larsson, S., 05, M. K.-D. M., & 2005, undefined. (2005). A laboratory study on the transition zone around lime-cement columns. *Diva-Portal.Org*. https://www.diva-portal.org/smash/record.jsf?pid=diva2:488560

Lee, F.-H., Lee, Y., Chew, S.-H., & Yong, K.-Y. (2005). Strength and modulus of marine clay-cement mixes. *Journal of Geotechnical and Geoenvironmental Engineering*, *131*(2), 178–186. https://doi.org/10.1061/(ASCE)1090-0241(2005)131:2(178)

Li, L. G., Huang, Z. H., Tan, Y. P., Kwan, A. K. H., & Liu, F. (2018). Use of marble dust as paste replacement for recycling waste and improving durability and dimensional stability of mortar. *Construction and Building Materials*, *166*, 423–432. https://doi.org/10.1016/j.conbuildmat.2018.01.154

Liu, S., & Hryciw, R. D. (2003). Evaluation and Quality Control of Dry-Jet-Mixed Clay Soil-Cement Columns by Standard Penetration Test: *Transportation Research Record*, *1849*, 47–52. https://doi.org/10.3141/1849-06

Liu, S., Zhang, D., Song, T., Zhang, G., & Fan, L. (2022). A Method of Settlement Calculation of Ground Improved by Floating Deep Mixed Columns Based on Laboratory Model Tests and Finite Element Analysis. *International Journal of*

Civil Engineering, *20*(2), 207–222. https://doi.org/10.1007/S40999-021-00662-4/METRICS

Lorenzo, G. A., & Bergado, D. T. (2006). Fundamental characteristics of cement-admixed clay in deep mixing. *Journal of Materials in Civil Engineering*, *18*(2), 161–174. https://doi.org/10.1061/(asce)0899-1561(2006)18:2(161)

Luo, Y., Meng, J., Wang, D., Jiao, L., & Xue, G. (2022). Experimental study on mechanical properties and microstructure of metakaolin based geopolymer stabilized silty clay. *Construction and Building Materials*, *316*, 125662. https://doi.org/10.1016/J.CONBUILDMAT.2021.125662

Madhyannapu, R. S., Puppala, A. J., Nazarian, S., & Yuan, D. (2010). Quality assessment and quality control of deep soil mixing construction for stabilizing expansive subsoils. *Journal of Geotechnical and Geoenvironmental Engineering*, *136*(1), 119–128. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000188

Majik, R. K., & Savoikar, P. P. (2022). Ground Modification Techniques for Deep Soft Soils Sites in Goa Region. *Lecture Notes in Civil Engineering*, *152*, 409–421. https://doi.org/10.1007/978-981-16-1831-4_38/COVER

Massarsch, K. (2004). Deformation properties of fine-grained soils from seismic tests. *International Conference on Site Characterization*. https://www.academia.edu/download/36122923/2004_Deformation_properties_of_fine-grained_1.pdf

McLaughlin, J. (2017). *Evaluation of Methods to Assess the Strength of Soil Cement Base*. https://etd.auburn.edu/handle/10415/5914

Moghaddas Tafreshi, S. N., Sharifi, P., & Dawson, A. R. (2016). Performance of circular footings on sand by use of multiple-geocell or -planar geotextile reinforcing layers. *Soils and Foundations*, *56*(6), 984–997. https://doi.org/10.1016/J.SANDF.2016.11.004

Mohammadhosseini, H., Lim, N. H. A. S., Tahir, M. Md., Alyousef, R., Samadi, M., Alabduljabbar, H., & Mohamed, A. M. (2019). Effects of Waste Ceramic as Cement and Fine Aggregate on Durability Performance of Sustainable Mortar. *Arabian Journal for Science and Engineering*, *45*(5), 3623–3634. https://doi.org/10.1007/S13369-019-04198-7

Mohammadinia, A., Disfani, M. M., Conomy, D., Arulrajah, A., Horpibulsuk, S., & Darmawan, S. (2019). Utilization of alkali-activated fly ash for construction of deep mixed columns in loose sands. *Journal of Materials in Civil Engineering*, *31*(10), 04019233. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002878

Mokrousova, D. (2010). *Ground improvement, practices in Russia, and Finland. Possibilities of cooperation*. https://www.theseus.fi/bitstream/handle/10024/17393/Mokrousova_Darya.pdf?sequence=1

Nadu, T. (2015). Study on the properties of concrete incorporated with various mineral admixtures-limestone powder and marble powder (review paper). *International*

Journal of Innovative Research in Science, Engineering and Technology (An ISO), *4*(1). https://doi.org/10.15680/IJIRSET.2015.0401014

Nalbantoglu, Z., & Gucbilmez, E. (2001). Improvement of calcareous expansive soils in semi-arid environments. *Journal of Arid Environments*, *47*(4), 453–463. https://doi.org/10.1006/JARE.2000.0726

Nalbantoglu, Z., & Tawfiq, S. (2006). Evaluation of the effectiveness of olive cake residue as an expansive soil stabilizer. *Environmental Geology 2006 50:6*, *50*(6), 803–807. https://doi.org/10.1007/S00254-006-0252-Y

Nissa Mat Said, K., Safuan A Rashid, A., Osouli, A., Latifi, N., Zurairahetty Mohd Yunus, N., & Adekunle Ganiyu, A. (2019). Settlement Evaluation of Soft Soil Improved by Floating Soil Cement Column. *International Journal of Geomechanics*, *19*(1), 04018183. https://doi.org/10.1061/(ASCE)GM.1943-5622.0001323

Oliaei, M., Heidarzadeh, H., & Mansouri, S. (2021). 3D Numerical Analyses for Optimization of Deep-Mixing Columns Combined by Raft Foundations. *Indian Geotechnical Journal 2021 51:6*, *51*(6), 1338–1348. https://doi.org/10.1007/S40098-021-00541-8

O’Sullivan, Quickfall, & Terzaghi. (2009). *Stabilisation of landslides using DSM columns in New Zealand - Google Scholar*. In Proceedings International Symposium on Deep Mixing and Admixture Stabilization.

https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=Stabilisation+of+landslides+using+DSM+columns+in+New+Zealand&btnG=

Ozbafli, A., & Jenkins, G. P. (2016). Estimating the willingness to pay for reliable electricity supply: A choice experiment study. *Energy Economics*, *56*, 443–452. https://doi.org/10.1016/J.ENECO.2016.03.025

Pan, Y., Liu, Y., & Chen, E. J. (2019). Probabilistic investigation on defective jet-grouted cut-off wall with random geometric imperfections. *Geotechnique*, *69*(5), 420–433. https://doi.org/10.1680/JGEOT.17.P.254

Peixoto, J., Carvalho, E. A. S., Gomes, M. L. P. M., da Silva Guimarães, R., Monteiro, S. N., de Azevedo, A. R. G., & Vieira, C. M. F. (2021). Incorporation of Industrial Glass Waste into Polymeric Resin to Develop Artificial Stones for Civil Construction. *Arabian Journal for Science and Engineering*. https://doi.org/10.1007/S13369-021-06071-Y

Pittaro. (2019). Tensile strength behaviour of ground improvement and its importance on deep excavations using deep soil mixing. *Ecsmge-2019.Com*. https://doi.org/10.32075/17ECSMGE-2019-0085

Porbaha, A., Shibuya, S., & Kishida, T. (2015). State of the art in deep mixing technology. Part III:geomaterial characterization. *Proceedings of the Institution of Civil Engineers - Ground Improvement*, *4*(3), 91–110. https://doi.org/10.1680/GRIM.2000.4.3.91

Prokopowicz. (2019). Strength testing of soil-cement composites used for improving mechanical properties of organic soil. *In Construction-the Formation of Living Environment: XXII International Scientific Conference on Advanced Civil Engineering,.*

Puppala, A. J. (2005). *Quality assurance practices and protocols for in-situ... - Google Scholar*. Int. Conf. on Deep Mixing: Best Practice And Recent Advances (Pp. 613-619). Stockholm, Sweden: Swedish Deep Stabilization Research Centre.

Puppala, A., Madhyannapu, R., Nazarian, S., & Yuan, D. (2008). *Deep soil mixing technology for mitigation of pavement roughness*. https://trid.trb.org/view/875415

Rabbani, P., Tolooiyan, A., Lajevardi, S. H., Daghigh, Y., & Falah, M. (2019). The Effect of the Depth of Cutter Soil Mixing on the Compressive Behavior of Soft Clay Treated by Alkali-Activated Slag. *KSCE Journal of Civil Engineering 2019 23:10*, *23*(10), 4237–4249. https://doi.org/10.1007/S12205-019-0335-4

Rashid, A. S. A., Black, J. A., Kueh, A. B. H., Mohamad, H., & Noor, N. M. (2017). Bearing capacity charts of soft soil reinforced by deep mixing. *Https://Doi.Org/10.1680/Jgrim.15.00008*, *170*(1), 12–25. https://doi.org/10.1680/JGRIM.15.00008

Rogers, C. D. F., & Glendinning, S. (1996). The role of lime migration in lime pile stabilization of slopes. *Quarterly Journal of Engineering Geology*, *29*(4), 273–284. https://doi.org/10.1144/GSL.QJEGH.1996.029.P4.02

Rogers, S. (2011). Evaluation and Testing of Brick Dust as a Pozzolanic Additive to Lime Mortars for Architectural Conservation [University of Pennsylvania]. In *Theses (Historic Preservation)*. https://repository.upenn.edu/hp_theses/162

Rui, R., Han, J., Zhang, L., Zhai, Y., Cheng, Z., & Chen, C. (2020). Simplified method for estimating vertical stress-settlement responses of piled embankments on soft soils. *Computers and Geotechnics*, *119*, 103365. https://doi.org/10.1016/J.COMPGEO.2019.103365

Ruiz-Sanchez, A., Sanchez-Polo, M., & Rozalen, M. (2019). Waste marble dust: An interesting residue to produce cement. *Construction and Building Materials*, *224*, 99–108. https://doi.org/10.1016/J.CONBUILDMAT.2019.07.031

Saeed, K. A., Kassim, K. A., & Nur, H. (2014). Fizikalno-kemijska karakterizacija kaolinske gline s dodatkom cementa. *Gradjevinar*, *66*(6), 513–521. https://doi.org/10.14256/JCE.976.2013

Sakr, M., Nazir, A., Abdelgawad Aamer, F., Azzam, W., & Aamer, F. A. (2019). *Model study of deep soil mixing in loose sand*. https://doi.org/10.13140/RG.2.2.14054.68161

Saygili, A. (2015). Use of waste marble dust for stabilization of clayey soil. *Materials Science* , *21*(4), 601–606. https://doi.org/10.5755/J01.MS.21.4.11966

Shah, M. v, Shah, P., & Gandhi, A. R. (2019). Effect of Cement Deep Mixing Technique on Strength and Settlement Characteristics of Low Plastic Soils.

Geotechnical Engineering Foundation of the Future. https://doi.org/10.32075/17ECSMGE-2019-1041

Shen, S.-L., Han, J., & Hong, Z.-S. (2005). Installation Effects on Properties of Surrounding Clays by Different Deep Mixing Methods. *Innovations in Grouting and Soil Improvement*, 1–12. https://doi.org/10.1061/40783(162)13

Shi, W., Chen, Q., Nimbalkar, S., & Liu, W. (2016). A new mixing technique for solidifier and dredged fill in coastal area. *Http://Dx.Doi.Org/10.1080/1064119X.2015.1102183*, *35*(1), 52–61. https://doi.org/10.1080/1064119X.2015.1102183

Singh, M., Srivastava, A., & Bhunia, D. (2019). Long term strength and durability parameters of hardened concrete on partially replacing cement by dried waste marble powder slurry. *Construction and Building Materials*, *198*, 553–569. https://doi.org/10.1016/j.conbuildmat.2018.12.005

Spross, J., Bergman, N., and, S. L.-J. of G., & 2021, undefined. (2021). Reliability-based verification of serviceability limit states of dry deep mixing columns. *Journal of Geotechnical and Geoenvironmental Engineering*, *147*(3). https://doi.org/10.1061/(ASCE)GT.1943-5606.0002458

T. Muttuvel, & S. Iyathurai. (1999). Deep soil mixing. In *Ground Engineering* (Vol. 32, Issue 9). CRC Press. https://doi.org/10.1201/9780429455544-13/deep-soil-mixing-muttuvel-iyathurai-ameratunga

Tatarniuk, C. (20104). Deep soil mixing as a slope stabilization technique in Northland Allochthon residual clay soil. *University of Canterbury. Civil and Natural Resources Engineering*. https://ir.canterbury.ac.nz/handle/10092/9648

Thomas, A., Tripathi, R. K., & Yadu, L. K. (2018). A Laboratory Investigation of Soil Stabilization Using Enzyme and Alkali-Activated Ground Granulated Blast-Furnace Slag. *Arabian Journal for Science and Engineering*, *43*(10), 5193–5202. https://doi.org/10.1007/S13369-017-3033-X

Topolnicki, M. (2009). *Design and execution practice of wet Soil Mixing in Poland. - Google Scholar*. In International Symposium on Deep Mixing & Admixture Stabilization. https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=Design+and+execution+practice+of+wet+Soil+Mixing+in+Poland.+&btnG=

Topolnicki, M. (2016). General overview and advances in Deep Soil Mixing. *XXIV Geotechnical Conference of Torino Design, Construction and Controls of Soil Improvement Systems*. https://www.researchgate.net/publication/337801273

Tremblay, H., Duchesne, J., Locat, J., & Leroueil, S. (2011). Influence of the nature of organic compounds on fine soil stabilization with cement. *Canadian Geotechnical Journal*, *39*(3), 535–546. https://doi.org/10.1139/T02-002

Tugrul Tunc, E. (2019). Recycling of marble waste: A review based on strength of concrete containing marble waste. *Journal of Environmental Management*, *231*, 86–97. https://doi.org/10.1016/J.JENVMAN.2018.10.034

Tyagi, A., Xiao, H. W., Chin, K. G., & Lee, F. H. (2019). Model for predicting the unit weight of cement-treated soils. *Soils and Foundations, 59*(6), 1921–1932. https://doi.org/10.1016/J.SANDF.2019.09.002

Venkatarama Reddy, B. v., & Prasanna Kumar, P. (2011). Cement stabilised rammed earth. Part A: Compaction characteristics and physical properties of compacted cement stabilised soils. *Materials and Structures/Materiaux et Constructions*, *44*(3), 681–693. https://doi.org/10.1617/s11527-010-9658-9

Vervoorn, R. R. E., & Barros, A. A. S. (2021). Deep soil mixing for stabilising deep excavations. *IOP Conference Series: Earth and Environmental Science*, *710*(1), 012060. https://doi.org/10.1088/1755-1315/710/1/012060

Wang, D., Gao, Z., Lee, J. L., & Gao, W. (2014). Assessment and optimization of soil mixing and umbrella vault applied to a cross-passage excavation in soft soils. *International Journal of Geomechanics*, *14*(6), 04014027. https://doi.org/10.1061/(ASCE)GM.1943-5622.0000374

Wong, J., Wong, S. Y., Kok, J., Wong, H., & Kok, S. T. (2020). Cementitious, pozzolanic and filler materials for DSM binders. *Researchgate.Net*, *6*(2). https://doi.org/10.28991/cej-2020-03091479

Yohannes, M., & Daramalinggam, J. (2019). Specifying Strength Properties of Soil Mixing and Jet Grouting in Malaysia: A Statistical Approach. *1 St Malaysian Geotechnical Society (MGS) and Geotechnical Society of Singapore (GeoSS) Conference*, 24–26.

Youssef, M. A., & Moftah, M. (2007). General stress–strain relationship for concrete at elevated temperatures. *Engineering Structures*, *29*(10), 2618–2634. https://doi.org/10.1016/J.ENGSTRUCT.2007.01.002

Youventharan, D., Arif, S. M., & Rokiah, O. (2020). Ultimate bearing capacity of peat treated with cement columns in physical model. *IOP Conference Series: Materials Science and Engineering*, *712*(1), 012043. https://doi.org/10.1088/1757-899X/712/1/012043

Zaika, Y., Journal, A. R.-G., & 2017, undefined. (2017). The estimation of bearing capacity and swell potential of deep soil mixing on expansive soil by small scale model test. *Geomate Journal*. https://doi.org/10.21660/2017.38.6527

Zakaria, M. M., Mohamed Hafez, K., Hamdy, W., Kamash, E., Mohamed, Zakaria, M., Kamal, M., Hafez, W., Hamdy, E., Kamash, A., & Hassan, M. (2020). Stabilization of soft clay soil by deep mixing. *Life Science Journal*, *17*(3), 1–15. https://doi.org/10.7537/marslsj170320.01

Zhao, Y., Gao, J., Xu, Z., Li, S., Luo, X., & Chen, G. (2021). Long-term hydration and microstructure evolution of blended cement containing ground granulated blast furnace slag and waste clay brick. *Cement and Concrete Composites*, *118*, 103982. https://doi.org/10.1016/J.CEMCONCOMP.2021.103982

Zorluer, I., & Gucek, S. (2014). The effects of marble dust and fly ash on clay soil. *Science and Engineering of Composite Materials*, *21*(1), 59–67. https://doi.org/10.1515/SECM-2012-0100