CHARACTERIZATION OF CLAYEY SOIL USING VARIOUS ADDITIVES

Thesis submitted in fulfilment of the requirements for the Degree of

DOCTOR OF PHILOSOPHY

By

PREETPAL SINGH

Enrolment No. 176602

विद्या तत्व ज्योतिसमः

Under the supervision of

Dr.Amardeep
Assistant Professor (Sr. Grade)
and
Prof. (Dr.) Ashok Kumar Gupta
Professor and Dean (Academics & Research)

DEPARTMENT OF CIVIL ENGINEERING

JAYPEE UNIVERSITY OF INFORMATION TECHNOLOGY, WAKNAGHAT, SOLAN, INDIA

June, 2024

DECLARATION BY THE SCHOLAR

I hereby declare that the content in the PhD thesis entitled Characterization of Clayey Soil using Various Additives submitted at Jaypee University of Information Technology, Solan, India is an authentic record of my works carried out under the supervision of Dr. Amardeep, Assistant Professor (Sr. Grade) and Prof. (Dr.) Ashok Kumar Gupta, Professor and Dean (Academics & Research), Jaypee University of Information Technology.I have not submitted this work elsewhere for any other degree or diploma. I am fully responsible for the contents of my PHD thesis

Preetpal Singh
Enrolment Number: 176602
Department of Civil Engineering
Jaypee University of Information Technology
Solan-173234, Himachal Pradesh, India
Date: 11th June, 2024

JAYPEE UNIVERSITY OF INFORMATION TECHNOLOGY

(Established by H.P. State Legislative vide Act No. 14 of 2002)
P.O. Waknaghat, Teh. Kandaghat, Distt. Solan - 173234 (H.P.) INDIA
Website: www.juit.ac.in
Phone No. (91) 01792-257999
Fax: +91-01792-245362

SUPERVISOR'S CERTIFICATE

This is to certify that the work reported in the Ph.D. thesis entitled "Characterization of Clayey Soil using Various Additives", submitted by Preetpal Singh at Jaypee University of Information Technology, Solan, India, is an authentic record of his original work carried out under my supervision. This work has not been submitted elsewhere for any other degree or diploma.

Date:

Dr. Amardeep

Assistant Professor (Sr. grade)

Department of Civil Engineering

Jaypee University of Information
Technology, Solan, Himachal Pradesh, India

Dr. Ashok Kumar Gupta

Dean, Academics and Research, JUIT

and Professor,

Department of Civil Engineering

Jaypee University of Information
Technology, Solan, Himachal Pradesh, India

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Date:
(Preetpal Singh)
JUIT, Waknaghat

ABSTRACT

Expansive soils, commonly referred to as shrink-swell soils, are a type of soil that exhibits significant volume changes in response to variations in moisture content. These soils are characterized by their ability to undergo substantial expansion when they absorb water and, conversely, to contract or shrink when they lose moisture. This unique behavior is primarily attributed to the presence of certain clay minerals, particularly smectites, which have a high capacity to absorb water molecules and expand their crystal lattice structure. When expansive soils absorb water and expand, they exert pressure on surrounding structures, such as foundations, pavements, and retaining walls resulting in structural damage, cracking, and distortion, compromising the stability and durability of constructions.

The purpose of this research was to investigate the impact of using waste materials such municipal solid waste incineration ash (MSWIA), marble dust (MD) and polypropylene fiber (PPF) along with cement (C) on geotechnical properties of expansive soil. The effect of various admixtures mixed to clayey soil has been evaluated by conducting various laboratory tests as per suitable Indian Standards. The drainage behaviour of clayey soil alone and after adding various admixtures has been studied using constant head permeability test. In order to study the micro-structure of various additives alone and along with various admixtures, X-ray diffraction tests were performed. To check the practical applicability of various optimum combinations obtained from geotechnical testing, thickness of the sub-grade was evaluated using IITPAVE software for various CBR values. The unconfined compressive strength experimental tests results were validated using multiple linear regression analysis. Finally, the cost of subgrade for a flexible pavement having length 1000 metre for various optimum combinations was evaluated. It was observed that the addition of MSWIA, MD and cement decreases the differential free swell (DFS) of clayey soil by 72%, 75% and 64% at 20% MSWIA, 15% marble dust and 9% cement content respectively. Further, on adding various percentages of cement to clay: MSWIA: MD, the DFS value reduced to zero at 6% cement

content stating that the required cement content to reduce DFS value decreased by 3% leading to more economy. The results of consistency limit tests revealed that all the materials i.e., MSWIA, cement and marble dust are helpful in reducing plastic characteristics of clayey soil to a greater extent. However, cement being costlier material among all may not be cost-effective solution for reducing plasticity index in large scale projects. From the results of compaction test it was observed that maximum dry density decreased on adding MSWIA and PPF; however, maximum dry density (MDD) increased on adding MD and cement alone and combination to various admixtures; whereas the optimum moisture content decreased on adding MSWIA and MD but increased on adding cement and remained almost constant on adding PPF to clayey soil alone and to its various admixtures. The results obtained from modified Proctor test didn't provide any idea about the optimum percentage of various materials, but it is an important factor while using the soil for subgrade purpose and needs to be evaluated. The unconfined confined strength tests revealed that with the increase in curing period and adding optimum percentage of various additives alone and in combination to clayey soil progressed the strength value. The California bearing ratio value for various combinations was found to be satisfied for the materials to be used in sub-grade construction as per Indian Road Congress. The permeability tests conducted on various optimum samples demonstrated improvement in the drainage characteristics of clayey soil. The results obtained from X-ray diffraction tests revealed that the change in mineral composition reflects the filling of voids present in clayey soil thus leading to increase in the strength characteristics and reduction in swelling potential of clayey soil making it suitable for construction purposes. A reduction in pavement thickness was noticed when soil was stabilized using various admixtures alone and in combination to each other. The highest reduction in pavement thickness was observed at S:MSWIA:MD:C:PPF::61:20:15:3:1.A mixture of S:MSWIA:MD:C:PPF:: 61:20:15:3:1provided the highest economy giving around a benefit

of 25% cost saving. Based on cost analysis it was interpreted that any combination depending upon the availability of material in local area may be used as additive for increasing geotechnical properties of subgrade clay for design of flexible pavements. The multiple linear regression analysis performed on various combinations based on unconfined compressive strength values gave coefficient of determination, R^2= 0.984 and the percentage error for all the selected combinations was also <10%, stating the accuracy of results. Finally, the various tests results proved that the use of cement in small construction activities and low volume flexible pavements may not be a crucial choice. Instead, for more economy, clayey soil may be reinforced with polypropylene fiber (to lessen temperature stresses), marble dust, or municipal solid waste incinerator ash, or perhaps both, depending on availability. The current study not only offers a cost-effective and environmentally beneficial method for resolving the disposal problems associated with various types of waste from communities and enterprises, but it also advances sustainable goals.

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Chapter 1

INTRODUCTION

1.1 General

Expansive soils possess a unique characteristic of both swelling and shrinking, caused by significant changes in their volume due to variations in natural moisture levels. These soils are predominantly found in semi-arid and arid regions worldwide. Approximately 21% of India's topography is covered with black cotton soils. These soils are distributed across various regions including Western Madhya Pradesh (30.2%), Gujarat (7%), Andhra Pradesh (13.4%), Uttar Pradesh (1.6%), Karnataka (8%), and Maharashtra (34.3%), as illustrated in Figure 1.1 (Singh et al., 1992).

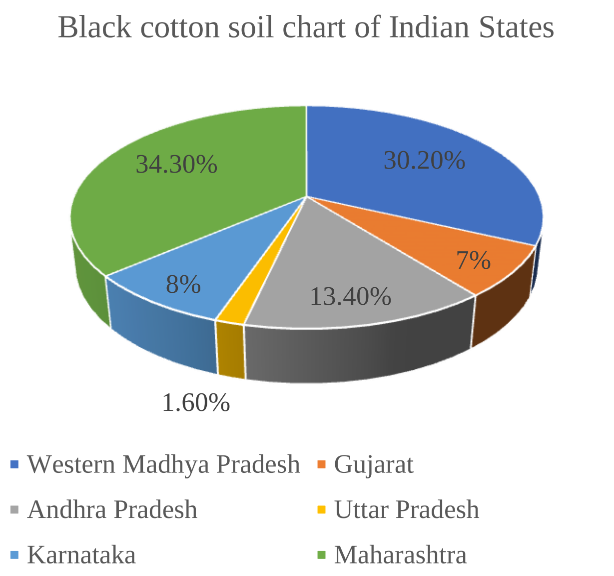


Figure 1.1: Black cotton soil chart of Indian States

The predominant component of these soils is montmorillonite, a mineral known for its high affinity for water, leading to the expansion and contraction observed with moisture changes. The fundamental structural arrangement of montmorillonite consists of an octahedral sheet of alumina sandwiched between two tetrahedral sheets of silica, with a thickness of roughly 10 Angstrom (Å), depicted in Figure 1.2. It takes a magnification of 25,000 to see the microstructure of a single mineral particle, which has a usually flattened shape. The granules of clay are not firmly connected, and the passage of water into the soil's void spaces causes the soil to swell, resulting in a loss of strength. During the monsoon season, when a large amount of water seeps into the soil's pores, these soils typically swell. In contrast, soil shrinkage occurs during the summer due to water evaporation (Singh and Agnihotri 2018; Sharma and Sharma 2020; Singh et al. 2022). Depending on its stress and suction history, the wetness of expansive soil during the monsoon period results in either swelling or collapse (Nelson and Miller 1992; Jha et al. 2008; Phanikumar 2009). The damage caused by swelling and shrinking of expansive soils as a result of moisture fluctuations costs billions of dollars worldwide. Structures with dynamic loads i.e. flexible and rigid pavements are particularly vulnerable to the deterioration caused by expanding soils with inferior characteristics.

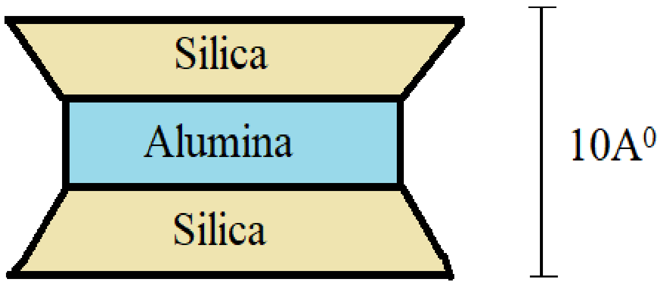


Figure 1.2: Montmorillonite mineral basic structural unit

1.2 Introduction

There are a number of alternatives that can be used in sites of poor soils, which include total soil replacement, stabilisation of soil, and improvement of soil properties through the introduction of stone columns or sand drains. Soil stabilisation is the most popular improvement technique. In regions with clayey soil, stabilization methods are often necessary to improve its subgrade characteristics and strength. This process involves employing compaction methods and adding specific substances in carefully measured amounts to enhance the mechanical and chemical attributes of the soil, ultimately bolstering its stability.

The stabilisation of the soil is attainable through one of the following two methods:

1. The alteration or improvement of the characteristics of the existing soil by the process of compaction and/or the addition of soil of a high quality sourced from other areas.
2. The alteration or enhancement of the characteristics of soil through the use of a number of different additives.

The first approach to soil stabilisation is an expensive one (Nelson and Miller 1992), while the second approach, in which waste products are employed as additives, is not only more cost-effective but also friendlier to the environment (Katti 1978; Sankar 1989). The stability of soil can be accomplished with either inert or chemical additives, both of which are considered to be types of additives. When inert additives are used, the only thing that changes about the soil is its physical characteristics. Conversely, the utilization of chemical additives prompts a chemical interaction between soil particles and the additive, leading to enhanced strength. Given the superiority of the second method—incorporating waste materials—it has been employed in this study. The research seeks to assess how waste materials like municipal solid waste incineration ash (MSWIA), marble powder (MP), and polypropylene fiber (PPF) combined with cement affect the geotechnical properties of expansive soil. By utilizing these materials for soil stabilization, the study aims to enhance the soil's geotechnical attributes while addressing waste disposal concerns, thereby promoting environmental preservation. Utilizing waste materials lowers construction costs because they are readily available for free and require little to no processing. Cement has additionally been employed as a stabilising substance in addition to these waste products to enhance the geotechnical properties of soil-waste material blends and to investigate the impact of chemical additives on soil stabilisation. In order to justify the same different soil stabilisation techniques utilized by the different researchers across the world will be discussed in detail in the next section.

1.3 Soil improvement techniques

The following are some of the soil stabilisation methods which have been used in the past as corrective measures to address the issues related to expansive soils:

1. Mechanical techniques,
2. Physical alterations and
3. Chemical alteration method

1.3.1 Mechanical techniques

I. Sand cushion method

The sand cushion method, also known as the sand drainage method, is a technique used in civil engineering and construction for stabilizing soft or loose ground. This method involves the installation of a layer of sand or other granular material beneath a structure's foundation to improve its load-bearing capacity and reduce settlement[7-8].

II. Cohesive non-swelling (CNS) layer technique

The Cohesive Non-Swelling (CNS) Layer Technique is a method used in geotechnical engineering to stabilize expansive clay soils. Expansive clay soils are prone to significant volume changes with changes in moisture content, leading to ground movement and potential damage to structures built upon them. The CNS layer technique aims to mitigate these issues by introducing a layer of non-swelling material into the soil profile [9]. Although this method is highly popular in India, the researchers had to reconsider its use due to the issue of CNS material availability.

III. Physical alternations

This method reduces the possibility of swelling by mixing the expansive soil with the appropriate proportion of granular particles [7]. However, because of the increased permeability of the end result, the approach is not appropriate.

1.3.2 Chemical alterations

Chemical stabilization refers to a process in which chemicals are added to a material or substance to improve its properties or performance. This process is commonly used in various industries, including construction, agriculture, environmental remediation, and manufacturing. Chemical soil stabilization, a technique of fortifying soil integrity, employs a variety of substances to alter soil properties. Through meticulous application of chemicals like lime, cement, or fly ash, this method aims to enhance soil stability, mitigate swelling tendencies, and fortify load-bearing capacities. By effectively modifying soil composition, chemical stabilization offers a sustainable solution for construction projects, ensuring long-term structural integrity and resilience against environmental factors[10-32].

1.4 Problem Identification

The above-mentioned physical techniques of soil stabilization are very costly and many of them cannot be used for subgrade of pavements. The above physical techniques use skilled workers and years of expertise into the field. The chemical alteration of soil with different chemicals leads to leaching issues thus degrading quality of groundwater and is a big concern. The waste materials such as municipal solid waste incineration ash and marble powder are produced in large amount and their disposal is a big concern to geoenvironmentalists and policy makers for building sustainable environment. Both the materials are rich in binder content and the polypropylene fiber is advantageous in terms of providing tensile strength. Keeping this in view this thesis is an attempt to utilize these materials in soil stabilization for subgrade pavements.

1.5Need of the Study

India being a developing country is already facing lot of environmental issues due to poor disposal of waste materials. The huge population of India has resulted in production of large amount of municipal solid waste leading to haphazard disposal thus polluting environment. Due to rapid growth of infrastructures and thinking towards better living standards of people in last two decades has resulted in tremendous amount of construction where marble is being used which produces lot of dust during its cutting thus polluting air and water both and giving rise to prolonged diseases. There is an urgent need of study towards finding a best possible solution to reduce the impact of both the wastes by using in soil stabilization so as to construct economic and environmental friendly subgrade for flexible pavements.

1.6 Research Significance

Massive amounts of waste materials are created, including marble powder and ash from municipal solid waste incineration. The details on these waste products' manufacture and usage, along with the significance of using cement as a stabiliser, are covered in the sections that follow.

1.6.1 Municipal solid waste incineration ash

Managing municipal solid waste in India has become a pressing concern due to the substantial quantities generated daily and associated environmental and aesthetic issues. According to the Central Pollution Control Board (CPCB) for the year 2020-21, despite only 36% of India's 493 million people residing in urban areas, they produce an astounding 1,60,038.9 metric tonnes of municipal solid waste per day, with these figures escalating alongside population growth. Compounding the challenge, the total number of towns in the country, including both statutory and census towns, increased from 5,161 in 2001 to 7,936 in 2011, resulting in a surge of 2,775 metric tonnes of municipal solid waste over a decade. Out of this huge production of municipal solid waste only 40% is being collected and surprisingly only 10% is being given treatment leaving behind the remaining to be disposed of either into landfills or road side or barrel land thus polluting soil and ground water. Municipal solid waste is frequently burned to minimise the volume before being dumped in landfills again leading to environmental effects and haphazard conditions. Keeping this in view, the municipal solid waste incineration ash has been selected as one of the materials for the current research.

1.6.2 Marble dust

When white marble is cut and polished, a solid waste material known as marble dust is produced as a by-product of the operation. The ground calcium carbonate is distinguished by the great brightness as well as the chemical purity it possesses. Marble dust holds versatile potential in various applications, serving as a natural mineral pigment or filler/texture enhancer. It can be transformed into casein paints or incorporated into lime, whitewash, coatings, stucco, and cement. In these applications, marble dust contributes to enhancing the visual appeal, texture, and durability of the final products, making it a valuable resource in both artistic and construction contexts.As the addition of marble dust to other substances does not change the colour of the material in its natural state, using marble dust as filler or to improve the appearance of the substance's texture does not have an effect on the substance's original colour. When marble is cut, a large quantity of powder in the form of waste that is referred to as marble dust is produced. This powder accounts for around 30 % quantity of marble. The disposal of marble dust is a difficult process since it increases the soil's alkalinity and also leads to air pollution which causes bad impact on human health, plant life, and other living things. Keeping this in view; the marble dust has been selected as second material for the current research.

1.6.3 Polypropylene fiber

A type of synthetic fibre made from a linear polymer called polypropylene is known as polypropylene fibre (PPF). Its advantages are its extremely lightweight, strength and stiffness, impact resistance, and good corrosion resistance. The PPF is commonly used in the construction sector, textile industry, energy industry, and chemical industry. Fiber made of polypropylene has been used to reinforce mortars and concrete made with cement for quite some time. The fibres prevent cracks from spreading and improve the quality of various concrete characteristics. Some researchers have proven polypropylene fibre to be excellent in enhancing the strength characteristics of soils also. Marble dust possesses hydrophobic properties and is chemically inert, meaning it does not absorb or react with soil moisture or leachate. (Shukla 2017). Keeping this in view, the polypropylene fibre has been selected as third material for the current research.

1.6.4 Cement

The mineral clinker that makes up cement is typically grey in colour and is ground to a very fine powder. Limestone, clay, and marl are the three primary raw materials that are utilised in the cement manufacturing process. Cement, when combined with water, acts as an adhesive that binds sand, gravel, and hard rock together to form concrete. Cement will harden in both air and water, and once it has reached this state, it will remain in this state permanently.

Cement is often offered for sale as a homogenous dry commodity that is sold in bulk quantities. Its properties have been standardised in order to ensure that the application can maintain the requisite level of stability and reliability and can be processed effectively. One of the first stabilisers, cement is still utilised today in many construction projects, including those involving roads, railroads, airports, embankments, and slope protection. Due to the chemical reaction between soil and cement particles, which occurs quickly and with a substantial strength gain, cement is recommended for use in soil stabilisation.

Despite its high cost, cement was included as an additive in the current study due to its capacity to yield high strength through chemical reactions and facilitate comparative analyses of its strength relative to other materials.

1.7 Organization of the Thesis

The thesis is addressed in seven chapters, each of which is briefly described below:

- Chapter 1: This chapter provides an overview of soil stabilisation before providing a brief explanation of the processes involved in producing municipal solid waste incineration ash, marble dust, polypropylene fiber and cement.
- Chapter 2: Discusses the in-depth literature review that was conducted in the past that's been related to the present study is discussed, and then a brief summary of the literature review is presented and deliberated. It has been determined, on the basis of the summary of the literature review, where the research is lacking, and the process of problem formulation has been carried out. The objectives of the study have been proposed on the basis of the problem formulation.
- Chapter 3: Following a brief explanation of the geotechnical properties of clay and additives (materials), this chapter moves on to discuss material combinations, methodology, and the steps involved in carrying out various tests.
- Chapter 4: This chapter contains a detailed presentation of the experiments' outcomes. There is also discussion of the effects of adding various additives both singly and in combination on differential free swell, pH, compaction, unconfined compressive strength, split tensile strength, California bearing ratio, and coefficient of permeability.
- Chapter 5: This chapter is focusing on the identification of most suitable mix design with respect to the stabilising characteristics and economical point of view. To determine the most stabilising composite material, the data from Chapter 4 are interpreted in this chapter. In this chapter, the effect of curing time periods on the compressive strength is discussed. The investigation aims to identify the most effective mixture for stabilization by evaluating changes in California bearing ratio and coefficient of permeability resulting from the addition of different additives, both individually and in combination. Subsequently, the optimal thickness for the subgrade is determined, followed by a cost analysis.

- Chapter 6: In this chapter, the conclusions of the experimental findings are provided, and significant findings on the ideal blend are discussed.
- Chapter 7: This chapter has addressed the scope of future work.

Lastly, a list of publications resulting from the present investigation is included in the thesis, along with pertinent references that were included in the current study.

1.8 Summary

The chapter provides an overview of the value of soil stabilisation and a brief description of the accessibility of various waste products. The rationale behind the selection of soil stabilising additives such municipal solid waste incineration ash, marble dust, polypropylene fiber and cement has been laid out. The discussion of the research project's goal is followed by a summary of the various chapters. The quick overview of the literature will be covered in chapter 2.

Chapter 2

LITERATURE REVIEW

2.1 General

For earthwork-related infrastructure projects, soils with significant stress-strain properties and load-bearing capacities are essential to withstand superstructure loads. However, soil conditions at many sites may lack the necessary load-bearing capacity, leading to potential deformations detrimental to structural safety and efficiency. In such instances, enhancing soil properties through various methods, including soil stabilization, becomes imperative. Soil stabilization encompasses techniques such as the addition of stabilizers, blending granular soil with clayey soil (or vice versa), or utilizing chemical stabilizing agents. Although initial soil stabilization experiments date back to 1904 in the United States, it wasn't until the 1960s and 1970s that soil stabilization gained widespread adoption.

Common methods of stabilization are:

1. Mechanical stabilization
2. Chemical stabilization

1. Mechanical stabilization

In order to increase soil's strength, volume stability, and permeability, mechanical stabilisation involves adding or removing certain constituents and densifying/compacting the soil. Mechanical stabilization techniques are commonly employed in various construction projects, including highway and pavement construction. Mechanical stabilization techniques are often combined with other methods, such as chemical stabilization or drainage measures, to achieve the desired stability and performance characteristics. The selection of the appropriate mechanical stabilization method depends on factors such as soil conditions, project requirements, and the expected traffic load on the stabilized material.

a. Compaction

In the process of compaction, a heavy weight is often utilised to raise the density of the soil by exerting pressure from above. In order to accomplish this task, it is common practise to make use of machinery such as big soil compactors that have steel drums that vibrate. Because excessive soil compaction results in the crushing of aggregates and a loss of the engineering qualities of the soil, its over-compaction should be avoided and given careful consideration in this context.

b. Soil Reinforcement

The use of engineered or non-engineered mechanical solutions can often be effective in resolving soil-related issues. Geo-textiles and engineered plastic mesh serve the common goal of capturing soils, aiding in erosion control, regulating moisture levels, and enhancing soil permeability. In scenarios requiring greater mass or stiffness to prevent soil displacement or enhance load-bearing capacity, larger aggregates such as gravel, stones, and boulders are often employed.

c. The Mixing of Differently Graded Aggregate Components

When trying to improve the engineering properties of a soil, one way that is frequently used is to add certain aggregates to the soil. These aggregates give the soil desirable traits such as enhanced strength or decreased flexibility. This technique results in a reduction in the amount of material required, enhances the bearing capacities of the subgrade, and offers a suitable working environment for the remaining building.

d. Remediation Through Mechanical Means

Dealing with contaminated soil has always been done in this manner, and it is still the standard protocol. This method involves physically removing contaminated soil and transporting it to a hazardous waste facility that is located in an area that is far from densely populated areas of the world. Recently, chemical and bioremediation techniques have emerged as superior solutions due to their cost-effectiveness and minimal environmental impact.

2. Chemical Stabilization

Chemical stabilisation is the process of adding a variety of admixtures that, when mixed with soil, chemically react to form stable compounds that enhance the qualities of the soil. Lime, cement, bitumen, industrial wastes like municipal solid waste incineration ash, fly ash, molasses, and water proofers including synthetic and natural resins are some of the admixtures. Waste products have been employed by numerous researchers to stabilise soil. Numerous researches have noted the large increases in soil deformation and strength caused by the addition of waste materials. The next paragraphs in this chapter will examine several well-known research studies on soil stabilisation using municipal solid waste incineration ash, marble dust, cement and polypropylene fiber that have been published in the literature.

2.2 Expansive soils

Due to their tendency to fluctuate in volume in response to changes in water content, expansive soils are troublesome in nature. The seasonal difference in water content in the bottom surface is what causes changes in volume of such soils (Chen 1975). Polygonal fissures appear on the soil's surface as a result of this volume change over the summer, and in most cases, these cracks are only present up to a depth of 2 m, indicating that the soil at this depth is very susceptible to elastic deformation (Ola 1978). The depth of the cracks indicates the depth of the active zone, where substantial volumetric shrinkage occurs as a result of the absence of water (Plait 1953). The depth of the active zone has been shown to be limited only to the top 1.0 to 1.2 metres in the instance of expansive soils found in India. Considerable ground motions have been seen in the past up to 3.5 m below the surface of the ground, far below the level of the active zone (Osinubi 2020). The depth of the active zone has indeed been discovered to go over 3.5 m in few specific locations (Gidigasu and Gawu 2013).

2.2.1 Problems with expansive soils

The projects constructed on expansive soils are frequently susceptible to differential settlements due to the shrinkage and swelling features of these soils. Due to the expanding soil's shrinkage, water pours out from the fractures in waterway beds and linings. If weep holes are not constructed, enormous swelling pressure on the back of the wall causes embankments and retaining structures to break. The middle layer of earthen dams made with impervious expanding clay may develop fissures. Gas, oil, water, and other pipelines built across expansive soil may sustain damage from major displacements, which could lead to serious accidents and have a negative impact on the environment. Transmission towers built on expansive soils may collapse as a result of foundation uplift brought on by the expanding pressure of the expansive soils.

2.3 Application of Municipal Solid Waste Incineration Ash in Soil Stabilisation

Over the past few decades, considerable research has focused on integrating Municipal Solid Waste Incineration Ash into construction projects. This has led to the formulation of strategies for waste recycling and management. Figure 2.1 illustrates the total volume of municipal solid waste generated in India in 2010.

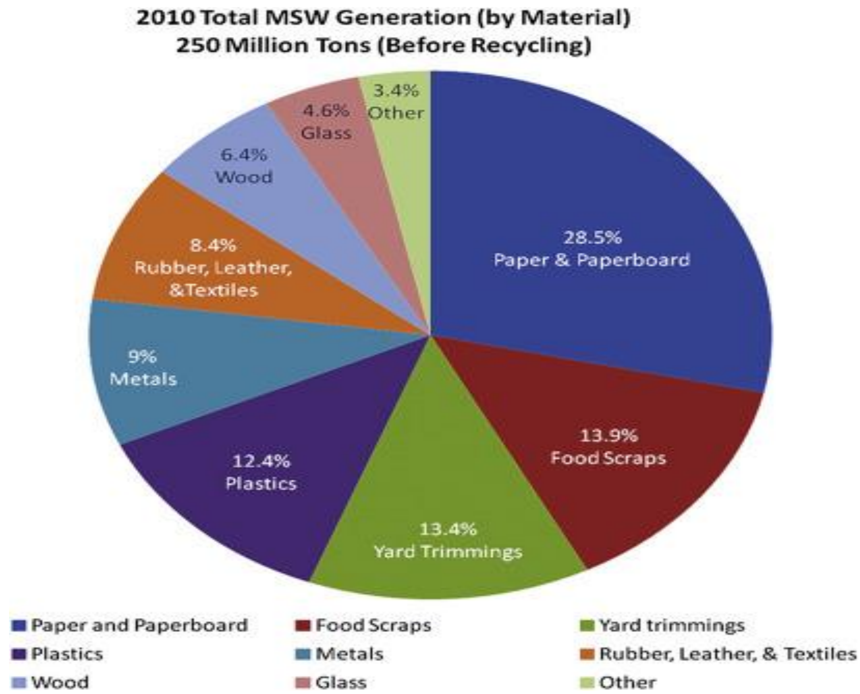


Figure 2.1: Breakdown of Municipal solid waste in India (Funk et al. 2020)

Despite extensive research and advancements in municipal solid waste incineration (MSWI) ash utilization, the recycling initiatives for MSWI ashes remain limited. When organic materials in municipal solid waste are incinerated at high temperatures, energy is generated in the form of gases and ashes. The utilization of MSWI ash is gradually gaining acceptance worldwide, with many countries incorporating it into diverse construction projects and programs. Incineration is a waste management method or waste-to-energy approach that converts the organic component of solid waste into carbon dioxide and water, along with residual byproducts such as bottom ash and fly ash (Lam et al. 2011).

Bresson et al. (2001) found that clayey soils typically exhibit unfavourable engineering properties, including low bearing capacity, pronounced shrinkage and swell tendencies, and heightened susceptibility to moisture variations. It is common practice to stabilise these soils in order to increase their strength. In order to stabilise the cohesive soil that is readily accessible in the area, this investigation adds 20% municipal solid waste (MSW) incinerator ash. It also assesses the impact of this addition on the soil's characteristics and shear strength when utilised in varying amounts.

Show et al. (2003) revealed that the properties of incinerator fly ash generated from MSW incineration, fly ash might be used as a jet-grouting additive for improving soil. Due to its chemical makeup and physical features, fly ash shows a potential of pozzolanic reaction. The stabilisation of a soft marine clay using fly ash as an admixture produced stabilised samples with increased strength greater than 75 times that of the untreated clay. Fly ash addition also resulted in a reduction of the plasticity and compression indices of roughly 69 and 23%, respectively, and an improvement of the drainage property of at least one order of magnitude. Leachate testing on the fly ash-stabilized soils revealed that nickel and lead levels were above the World Health Organization (WHO) drinking water guidelines whereas chromium levels were substantially below the limit. Over a period of around 130 and 110 days, respectively, the nickel and lead leachate concentrations decreased to below the permitted drinking water levels.

Mohamedzein et al. (2006) added incinerator ash in percentages of 2, 4, 8, 10, and 12 % to evaluate its effect on desert sand. To gauge the stabilised material's engineering properties, laboratory experiments like compaction, unconfined compression, shear boxes, and hydraulic conductivity were carried out. The parameters for unconfined compressive strength and shear strength significantly improved as a consequence of the study. As a result, it is possible to employ incinerator ash to enhance the shear strength properties of desert sands. The blend of sand and incinerator ash has a low degree of permeability.

Jadhav et al. (2010) investigated the potential utilization of different solid wastes in the production of construction materials. The basis of the investigation is an extensive analysis of research on building materials, including various types of solid wastes. Furthermore, solid waste is produced by industrial and urban management systems, which often dump them in open fields. The environment is seriously harmed by these actions. Many attempts are being made to recycle various solid waste kinds in order to use them in the manufacturing of different building materials, all with the goal of protecting the environment. This study examines the effects that different solid waste types have on the environment, emphasising how these wastes may be recycled and perhaps utilised to make building materials. **Mohamedzein and Mohammed (2012)** tested desert sand with 10-80% MSWIA. Various lab tests assessed the stabilized material's properties. Results showed stable maximum dry density up to 30% ash, with water content increasing. Unconfined compressive strength peaked at 30% ash, then declined, mirroring the angle of friction. Cohesiveness increased consistently. Hydraulic conductivity decreased as ash content rose.

Abdulfatah et al. (2013) investigated the compaction behavior of Lateritic soil stabilized with Municipal Solid Waste (MSW) Bottom Sediment. Their focus was on determining how the presence of MSW Bottom Sediments affects the results of the British Standard Compaction Test for Lateritic Soils.Different amounts of lateritic soils were combined with bottom sediments of MSW from specific dumping locations in Kano, Nigeria, and the mixes were subjected to a compaction test. The mixes were determined to have optimal moisture contents (OMC) of between 12% and 17% and maximum dry densities (MDD) ranging from 1.600 to 1.700 gm/cc. The findings were comparable to those of silty clay soils with OMC between 15% and 25% and MDD between 1.600 and 1.845 gm/cc. After being sorted, it was suggested that the bottom particles be utilised as building materials for roads or landfills.

Leong and Eriktius (2014) assessed the environmental effect of utilising fly ash derived from municipal solid waste and investigated whether or not it is possible to improve peaty soil by using fly ash derived from municipal solid waste. The findings of the tests revealed that the shear strength of peaty soil may be multiplied many times over by combining it with fly ash derived from municipal solid waste. Leaching tests conducted by the Environmental Protection Agency (EPA) show that effluent element concentrations in mixtures of peaty soil and municipal solid waste fly ash remain below permissible levels for trade effluent discharged into uncontrolled watercourses. However, they typically surpass limits set for drinking water and trade effluent discharged into controlled watercourses. Hence, it is not recommended to use combinations of peaty soil and municipal solid waste fly ash in regions where there's potential for effluent to enter restricted watercourses.

Vizcarra et al. (2014) investigated using municipal solid waste (MSW) incineration ash from an electric energy generation plant in base road pavement layers. They mixed it with non-lateritic regional clay soil and conducted tests on soil mixtures with 20% and 40% ash contents. Results showed increased California bearing ratio (CBR) and resilient modulus values due to reduced material expansion from fly ash presence. Overall, the study demonstrated the potential beneficial application of MSW fly ash in road pavement foundation layers.

Greenwood et al. (2015) conducted geotechnical characterization of municipal solid waste incinerator ash deposited at the Carleton Farms monofill in Michigan through both field and laboratory studies. Field characterization involved observations, collection of four bulk samples, and shear wave velocity measurement at two locations. Laboratory characterization included essential geotechnical tests such as grain size distribution, Atterberg limits, specific gravity, compaction, moisture and organic content analysis, as well as direct shear and triaxial shear testing. The results of these tests were compared with existing literature findings. While the grain size distribution of the samples closely matched data from the literature, significant differences were observed in compaction properties. Moreover, specific gravities were lower compared to those of silicic soils. Interestingly, even in loose conditions, shear strengths surpassed typical values for sandy soils in MSWI ash specimens. Notably, strain rate did not affect shear resistance. There were substantial differences in both the peak shear resistance and the stress-strain response between dry and saturated specimens in triaxial shear testing.

Kim et al. (2016) determined that how MSWIA can affect the properties of cement when added to it. Petrographic analyses were carried out to ascertain the chemical temperament of the ashes and to ascertain their contents. Ash and aluminium powder were immersed in a high pH solution to create a network of bubbles, which allowed researchers to quantify the evolution of hydrogen gas and assess the primary adverse effect of ashes when employed in cement. The strength and durability of cement paste cylinders that had different levels of mineral additives were studied. Analysis of the collected data showed that the filler effect and hydrogen gas formation, which were responsible for the strength and durability, had both positive and negative effects on the use of ashes as a substitute for cement.

Singh and Kumar (2017) explored the compaction and strength characteristics of composite samples containing both cement and MSWI ash. Parameters like pH value, unconfined compressive strength, split tensile strength, and California bearing ratio (CBR) were examined after aging the samples for 7, 14, and 28 days. The study found that adding cement decreased the maximum dry density (MDD) but increased the optimum moisture content (OMC). Additionally, cement improved the overall strength of the composite specimens. A blend of 15% MSWI ash and 10% cement emerged as a potential frivolous substantial material for applications like embankments and road construction.

Tang et al. (2017) investigated fly ash mixed with cement and a bonding agent for pavement use, considering mechanical and environmental factors. They found that solidified fly ash strength depended on cement/fly ash ratio and curing time. Fly ash reduced cement hydration product concentration, impacting structure. Compressive strength initially dropped from days 7 to 14 but increased from days 14 to 28. Finite element analysis suggested solidified fly ash could enhance asphalt pavement durability. Metal leachability decreased with higher cement/ash ratio, longer curing, and more chelating agent.

Wasim et al. (2017) investigated soil stabilization using municipal solid waste management techniques. They tested the soil strength with different ash replacement percentages (5%, 10%, 15%, and 20%), finding optimal improvement in soil index properties—such as shear, compaction, and permeability—at a 10% addition of MSWA. The study suggested that burning solid waste could reduce its volume by 80% and repurpose it effectively as a soil stabilizer.

Kumar and Mittal (2019)explored using municipal solid waste (MSW) ash to stabilize cohesive soils, mixing it in varied proportions. Laboratory experiments assessed the engineered properties of the stabilized material, focusing on the impact of MSW ash on parameters and unconfined compressive strength. Tests included geotechnical evaluations, with MSW ash additions ranging from 0 to 20% by dry weight. Results suggested that integrating waste materials like fly ash, rice husk ash, and cement, with or without lime, could enhance soil quality, with MSW playing a significant role in environmental waste.

Barua et al. (2020) carried out experimental study in order to gain a better understanding of the influence that various percentages of municipal solid trash have on the unconfined compression strength of clayey soil that has been combined with that waste. The study demonstrated that ash may be utilised as a soil stabilising material for ground improvement and details the impact that using varying quantities of ash has on the engineering qualities of soil as well as how soil behaves when it is engineered. The findings of the tests indicated a significant increase in the stability of the ground and that ash derived from municipal solid waste may be utilised for the purpose of ground improvement. When compared to pure soil, the increase in unconfined compressive strength was more than 50 % higher.

Liang et al. (2020) evaluated municipal solid waste incineration fly ash, to reinforce cement-stabilized soil. After water washing and addition of 4% ferrous sulphate, leaching concentrations of chromium and lead decreased significantly. Blending post-treated MSWIFA with cement-stabilized soil at 5% and 10% ratios, alongside 10%, 15%, and 20% ordinary Portland cement (OPC), led to improved UCS, internal friction angle, and cohesiveness. Substituting OPC with PFA showed similar UCS enhancements. The study demonstrated reduced heavy metal leaching in cement-stabilized soil, attributed to physical encapsulation and chemical stabilization. Incorporating PFA accelerated hydration product formation, offering sustainable foundation reinforcement options.

Sharma and Singh (2020) investigated the impact of bottom ash and fly ash addition on soil strength. They examined 21 samples with varying ash ratios using Atterberg's limits, Proctor, and California Bearing Ratio (CBR) tests. Optimal strength was achieved with a composition of 12% bottom ash, 18% fly ash, and 70% soil, yielding a CBR value of 13.7%. This proportion reduced soil plasticity by filling voids with fine ash particles, altering the soil's flocculated structure.

Gautam et al. (2021) conducted laboratory tests on black cotton soil and a blend of black cotton soil, incinerator ash, and lime. The results revealed that the addition of incinerator ash and lime, either individually or in combination, led to a decrease in the liquid limit and differential free swell of the black cotton soil, along with an increase in unconfined compressive strength. This study provided valuable insights into addressing challenges related to incinerator ash disposal and promoting environmental conservation efforts.

Kumar and Singh (2021) explored the potential benefits of MIBA (Municipal Incinerator Bottom Ash) in various construction and soil stabilization projects. They proposed that partial replacement of primary aggregates with MIBA could offer a cost-effective and durable solution while maintaining similar or improved strength. Additionally, MIBA contains various chemical compounds that could be utilized in cutting-edge industrial applications. The residue from MIBA could be repurposed as a key ingredient for synthesizing novel chemicals, land reclamation, and even hydrogen gas production. However, due to environmental and strength-related constraints, opinions on its utilization vary. The essay critically evaluates relevant research and underscores the potential advantages of utilizing waste byproducts as a valuable source of raw materials.

Chauhan and Deka (2022) examined the geotechnical properties of fine-grained soil mixed with lime (1%, 2%, and 3%) and MSWA (2%, 4%, 6%, 8%, and 10%). Curing durations of 0, 3, 7, and 28 days were assessed for soil plasticity, while curing durations of 0, 3, 7, and 14 days were examined for soil strength. Results revealed a significant influence on soil flexibility and strength due to the combined action of lime, municipal solid waste ash, and curing. Additionally, admixture addition altered compaction parameters, decreasing maximum dry density and increasing optimal moisture content.

Randhawa and Chauhan (2022) conducted a literature review on the enhancement of engineering properties of expansive soils, particularly black cotton soil (BCS), through the addition of MSWI ash at varying proportions. The review revealed that the optimal percentage of MSWI ash required to enhance the strength characteristics of expansive soils falls within the range of 10% to 30%, with the most effective proportion being 25%. This concentration of MSWI ash led to a notable increase in the unconfined compressive strength (UCS) of expansive black cotton soil, rising from 28.8 kPa to 53.4 kPa, while the CBR value increased from 3.38% to 9.38%. Consequently, the review recommends the utilization of MSWI ash, considering the substantial increase in municipal solid waste (MSW) volumes due to rapid urbanization in the country.

Singh et al. (2022) used MSWIA along with marble dust to evaluate its effect on the cost of subgrades for road construction and to solve the disposal issues associated with waste materials. To assess their impact on the geotechnical properties of clayey soils, substantial laboratory research was done on a variety of soil samples, both alone and in combination with waste products such municipal solid waste incinerator ash and marble dust by adding cement. The experimental study showed that the soil mixture: Ash from municipal solid waste incinerators: masonry and ground: (MD) Marble dust Low traffic volume roads can be successfully constructed using cement. When MSWIA: cement and MD: cement was added to clayey soil in the proper amounts, the differential free swell of the clayey soil is zero.

Tabyang et al. (2022) examined using municipal solid waste incineration fly ash (MSWI FA) as a geopolymer to stabilize recycled concrete aggregate (RCA) strength for pavement applications. Increasing MSWI FA replacement boosted the maximum dry unit weight of RCA-MSWI FA geopolymer specimens due to MSWI FA's filler effect. This suggests the geopolymer's suitability for low-traffic volume road pavement construction.

Zimar et al. (2022) explored the process of stabilisation as well as the hydro-mechanical performance of high plasticity expansive clays that were stabilised by MSWI fly ash. In order to better understand the efficacy of MSWI fly ash in treating high-plasticity expansive clay, a number of tests were conducted in this investigation, including compressive strength, X-ray diffraction (XRD), dynamic cone penetration, scanning electron microscopy (SEM), shrinkage and swelling, and X-ray micro-computed tomography (micro-CT). According to the findings of the study, the swelling potential of MSWI fly ash was reduced, and the ten-day soaking CBR was increased to around 80%. An investigation at the microscopic level revealed that the primary stages in the process of MSWI fly ash stabilisation include the hydration reaction, cationic exchange, flocculation, and agglomeration between clay sheets. In addition, the stabilisation of the clay with 20% MSWI fly ash resulted in a reduction in the porosity of the clay from 3.43% to 0.18%. The findings of the study offer recommendations for applying MSWI ash as a method for remediating damaged soils while also facilitating an effective method for the management of municipal solid waste.

Li et al. (2023) performed triaxial tests to examine the effects of polypropylene fibre concentration and length on the mechanical characteristics of bottom-ash-mixed (BA-mixed) clay soil produced by municipal solid waste incineration (MSWI). The stress-strain characteristics and mechanical properties of soil reinforced with polypropylene fibers were analyzed under different confining pressures through adjustments in fiber length and concentration. Discussions centered on the primary stress distribution and shear resistance observed in soil reinforced with polypropylene fibers combined with BA. The reinforcing mechanism of fibers during soil shear was investigated using principles of strength variation. Comparative analysis against unenhanced soil and soil mixed solely with BA revealed significant enhancements in strength and resistance to deformation in polypropylene fiber-reinforced soil. Notably, the cohesiveness of the reinforced soil increased substantially with higher fiber concentrations, while changes in the internal friction angle were minimal. Optimal reinforcement and maximum strength were observed with polypropylene fibers of 2.5 cm length and a concentration of 0.3%.

2.4Application of Marble Dust in Soil Stabilisation

Marble Dust Powder is a kind of metamorphic rock that is made up of recrystallized carbonate minerals, the majority of which are either calcite or dolomite. The process of cutting and polishing marble stone results in the production of marble dust. The quantity of marble slurry that is generated each year is somewhere in the region of five to six million metric tonnes. The country wise production of marble dust is shown in Figure 2.2 (as per Kore et al. 2019).

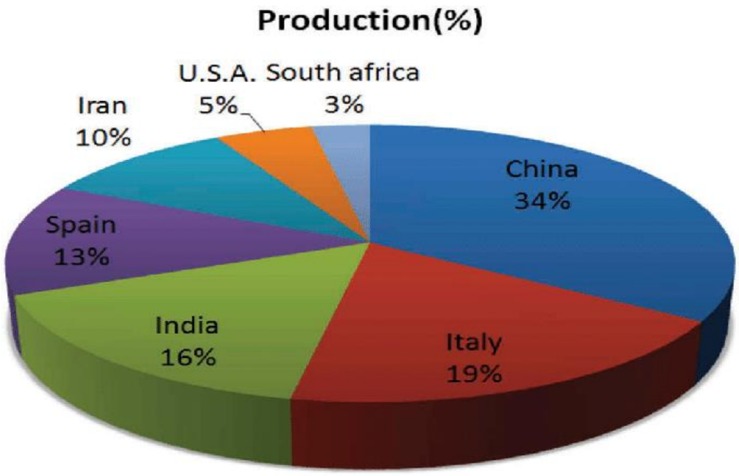


Figure 2.2: Breakdown of Marble Dust Country wise (Kore et al. 2019)

Many researches have noted that the lime content of the marble dust powder is rather high, and this is one factor that contributes to the stabilisation process.

Okagbue and Onyeobi (1999) determined whether marble dust has the ability to act as a stabilising component to red tropical soils. The evaluation consisted of determining the geotechnical parameters of three different red tropical soils in their original form as well as when combined with marble dust in variable quantities. The particle size distribution, specific gravity, Atterberg limits, standard compaction characteristics, compressive strength, and CBR were some of the metrics that were examined. The tests on the samples' strength were redone after a standard curing time of 28 days, as well as after an accelerated curing time of 24 hours at temperatures of 40 degrees Celsius, 60 degrees Celsius, and 80 degrees Celsius. The results showed that the addition of marble dust significantly enhanced the geotechnical parameters of red tropical soils. The plasticity of soil was decreased by 20 to 33%, while its strength and CBR increased by 30 to 46 % and 27 to 55 % correspondingly.

Chandra et al. (2002) investigated the impact of marble dust and lime on the stabilization of expansive soil. They observed that the incorporation of both marble dust and lime led to notable enhancements in the soil's unconfined compressive strength, California Bearing Ratio (CBR), and a reduction in its swell potential. The study proposed that the combined action of marble dust and lime can effectively improve the stability of expansive soils.

Sabat and Nanda (2011) conducted a study to explore the influence that marble dusts have on the strength and durability of expansive soil and was stabilised with the optimal percentage of rice husk ash (RHA). Based on the results of the Unconfined Compressive Strength (UCS) tests, it was determined that a percentage of RHA of 10 % was the ideal amount. Marble dust was mixed into RHA-stabilized expansive soil in increments of 5 %, bringing the total amount of marble dust to a maximum of 30 % of the soil's dry weight. After 7 days of curing, these samples were put through various geotechnical tests. The UCS and Soaked CBR of RHA-stabilized expansive soil increased by up to 20 % when marble dust was added to the mix. The continued introduction of marble dust brought to undesirable changes in these characteristics. Regardless of the percentage of marble dust that was added to RHA-stabilized expansive soil, both the MDD and the Swelling Pressure of expansive soil continued to decrease, while the OMC continued to increase. According to the findings of the durability test, the incorporation of marble dust into the RHA stabilised expansive soil contributed to the soil's increased durability.

Patel and Patel (2012) found the engineering properties of expansive soil stabilized with a combination of marble dust and bagasse ash. The study revealed that the addition of these materials improved the soil's strength parameters, such as increased CBR and reduced swelling potential, making it more suitable for construction purposes.

Ali et al. (2014) studied effect of marble dust on the strength and compaction characteristics of clayey soil. The study revealed that the inclusion of marble dust enhanced the soil's strength properties, such as increased unconfined compressive strength and California Bearing Ratio (CBR), and improves the compaction characteristics.

Gupta and Sharma (2014) conducted a study to assess the effects of marble dust and fly ash on the subgrade characteristics of black cotton soil. Through a series of laboratory tests on fly ash, sand, and stabilized black cotton soil blended with marble dust ranging from 0% to 20%, the researchers found that adding 15% marble dust resulted in a significant increase in the soaked California Bearing Ratio (CBR) value by approximately 200%.

Sharma and Gupta (2014) investigated the influence of marble dust on the stabilization of expansive soil. Their findings revealed that incorporating marble dust enhanced the geotechnical properties of expansive soil. Specifically, it reduced the plasticity index and swell potential while increasing the California Bearing Ratio (CBR) and shear strength.

Singh and Yadav (2014) conducted a study to check the suitability of marble dust as a primary material used for soil stabilisation. In order to explore the impact that marble dust has on the index qualities of black-cotton soil, a number of laboratory experiments were carried out on samples of black-cotton soil that were combined with 0 to 40 % marble dust based on the weight of the dry soil. The findings of the experiment revealed a discernible change in the consistency limits of the samples that contained marble dust. With the addition of marble dust ranging from 10- 40 %, the plasticity index dropped from 28.35 % to 16.67 %, and the shrinkage limit rose from 8.06 %to 18.39 %. Additionally, the differential free swell went from 66.6 % down to 20.0 %, which demonstrates a significant reduction in the swelling behaviour. This laboratory investigation came to the conclusion that waste material like marble dust generated by stone crushing has the capacity to affect the properties of expansive clay like black-cotton soil.

Saygili (2015) evaluated the feasibility of making use of waste marble dust in the process of stabilising problematic soils (especially swelling clays) in two different sections. In the first portion, the shear strength parameters and swelling characteristics were discussed, and in the second section, the microstructural analysis of the improved problematic soils was discussed. The addition ratios of marble dust that were investigated were 0- 30 % by weight respectively. According to the findings of the tests, the addition of marble dust enhanced the shear strength characteristics of the examined clay samples and decreased the possibility for the samples to swell. The results that were obtained revealed that adding marble dust to the clay samples would lower the cost of constructing structures on difficult soils. Additionally, the results showed that identifying new usage areas for waste marble dust would reduce the amount of environmental pollution. The utilisation of waste materials such as marble dust in problematic soils will make a significant contribution to the economy as well as the conservation of resources.

Minhas and Devi (2016) revealed the potential use of waste marble dust as an additive in cement-stabilized clayey soils and found that the addition of marble dust improved the strength and durability properties of the stabilized soil, such as increased compressive strength and reduced swelling potential.

Abdelkader et al. (2017) investigated the impact of marble dust on the compaction and shear strength properties of clayey soil. Their research revealed that incorporating marble dust led to an elevation in the maximum dry density while reducing the soil's optimal moisture content. Additionally, it bolstered the soil's shear strength characteristics, notably enhancing cohesion and the angle of internal friction.

Firat at al. (2017) investigated the effect of marble dust on the geotechnical properties of expansive clay soil and revealed that the inclusion of marble dust in the soil significantly reduced its plasticity index, swell potential, and consolidation characteristics, while enhancing its CBR value and shear strength.

Karthika et al. (2017) explored the influence of marble dust on the geotechnical characteristics of clayey soil. Their findings indicated that incorporating marble dust improved soil strength parameters like cohesion and angle of internal friction, while also diminishing plasticity and swelling potential, resulting in enhanced stability.

Prasad et al. (2017) investigated the engineering properties of expansive soil treated with marble dust. The study revealed that the addition of marble dust elevated compressive strength, California Bearing Ratio (CBR), and reduced swell potential of the soil. The results suggested that marble dust stabilization could effectively alleviate soil expansiveness.

Yilmaz and Yurdakul (2017) examined the use of marble dust in soil stabilization. Geotechnical parameters of the mixtures, such as compaction, Atterberg limits, and unconfined compressive strength, as well as changes in these properties brought about by the marble dust ratio were investigated. Based on the findings of the tests, it was clear that marble dust enhanced the mechanical characteristics of soil due to the inclusion of coarser particles of marble dust as compared to clayey soil, and it was also clear that the application of dust wastes for the purpose of soil stabilisation will be an effective practise in terms of the management of solid waste.

Shaikh et al. (2018) examined the effect of marble dust on the index and engineering properties of black cotton soil. The findings indicated that the incorporation of marble dust reduces the soil's plasticity index, improved its compaction characteristics, and increased the CBR value, thereby enhancing its strength and stability.

Sheikh et al. (2018) examined the stabilization of clayey soil using a combination of marble dust and fly ash and the results indicated that the addition of marble dust and fly ash improved the geotechnical properties of clayey soil, including reducing the plasticity index, increasing the CBR value, and enhancing the shear strength parameters.

Yada and Kumar (2019) investigated the combined effect of marble dust and bagasse ash on the stabilization of expansive clay and revealed that the addition of these materials improved the soil's geotechnical properties, such as swelling potential, plasticity, and shear strength. It suggested that the use of marble dust and bagasse ash can be an effective approach for stabilizing expansive clay soils.

Jain et al. (2020) investigated how marble dust influences expansive soil's geotechnical behavior. They conducted various tests, including geotechnical and physico-chemical analyses, as well as micro-analyses, using marble dust proportions up to 80%. Results indicated marble dust can enhance soil plasticity, reduce swelling, and notably, strengthen the soil, particularly at a 20% marble dust content during initial curing stages.

Waheed et al. (2021) conducted a number of laboratory experiments in order to investigate the degree to which waste marble dust (WMD) is successful as a stabiliser in elevating the physio-chemical characteristics of CL-ML soil. The characteristics of soil samples were analysed both without the addition of any WMD and after the addition of 5, 10, and 15 % of WMD. The MDD was reduced when the WMD was mixed with the collapsible soil, but the OMC was enhanced across the board for all WMD dosages. The addition of up to 10 % of WMD caused an increase in the UCS and CBR value of the soil. The stabilisation of collapsible soil by using a waste material (WMD) that is readily available in abundant quantities presents an environmentally benign technique from the biological, technological, and economic points of view. The key reason for the soil's improvement was the processes of a physiochemical nature, such as mixing, densification, and cation exchange reactions.

Özen et al. (2022) examined the utilization of waste marble dust as an additive in lime-stabilized clayey soil. The findings demonstrated that the incorporation of marble dust enhances the soil's strength and durability properties, including increased CBR, reduced plasticity index, and improved resistance against water erosion.

Rathore and Tiwari (2023) utilized marble dust in soil stabilization for road construction and found that incorporation of marble dust enhanced the strength characteristics of stabilized soil, such as increasing the CBR value and reducing the optimum moisture content. It also improved the stability and durability of the road pavement.

2.5Application of Cement in Soil Stabilisation

Mixing the subgrade soil with cement and water, which is referred to as soil cement stabilisation, is a construction procedure that is used to strengthen the strength of the subgrade soil. The cement becomes hydrated as a result of the water, which also triggers processes that produce a matrix that is formed between the soil particles. This matrix provides the soil its strength. The stabilisation of coarse-grained soils by the application of cement is very beneficial.

Tremblay (2002) investigated 13 different organic material one at a time to 2 distinct soils in a laboratory environment, followed by treating the soils with 10% cement. Undrained shear strength evaluations on several specimens and chemical analysis of the pore fluids were done to evaluate the cementing process. The findings showed that almost no strength enhancement was observed and that the growth of cementing products was highly influenced by the organic acids that produce a pH less than 9 in the pore fluid.

Chen and Wang (2006) stabilized soft soil with high organic content cement and other supplementary admixtures. The mechanical indices under various circumstances were acquired using direct shear and unconfined compression experiments. Every sample's total organic matter content and individual organic matter components were calculated as well. The findings demonstrated that different additional admixtures have distinct roles in improving the characteristics of soils stabilised by cement.

Otoko (2014) did laboratory testing of the mechanical characteristics of a lateritic soil-cement and a soil-cement-pozzolana manufactured from silty clay, respectively. The findings demonstrated that less than half of the Portland Cement Association's recommended cement amount is needed to effectively stabilise a lateritic soil, and that up to 30% of this cement amount can be replaced by calcined and ground Chikoko mud without negatively affecting the performance criteria and strength of the soil cement.

Jaffar et al. (2018) investigated the strength and microstructure characteristics of cement solidified cadmium contaminated expansive soil. Cement has been used to treat expansive soil that has been artificially polluted with cadmium nitrate in various concentrations, depending on the results of the laboratory test for consolidation of heavy metal Cd-polluted soil. The study examined the effects of heavy metal concentration, cement dose, and curing age on the expansive soil's unconfined compressive strength after it had been solidified and its microstructure properties had been examined. The study's findings indicated that unconfined compressive strength increased with cement curing time and cement concentration but decreased with heavy metal concentration; the effects of heavy metal concentration on strength were different, with high concentration having a greater impact than low concentration. The results of the micro-structure analysis demonstrated that the porosity reduced following the addition of cement, which is supported by the changing rules of the micro-structure features, as the cause of the strength increase.

Adeyanju and Okeke (2019) studied the effectiveness of cement kiln dust (CKD) in stabilizing clayey soil that was excavated from a portion of Sango, Ota, road that had been deteriorated. CKD is cheap since it doesn't need any extra processing or treatment because it is a byproduct of the cement industry and can be utilised in powder form. It was mixed with clayey soil in different ratios of 7.5, 10, 12.5, and 15% for this experiment. For each combination, several geotechnical experiments were carried out. The results indicated that the soil treated with 10% CKD had the greatest mechanical improvement after a 7-day curing period, with the clay soil's unsoaked CBR increasing from 1.49 to 28.6%. In addition to the CBR increase, further tests such as Atterberg limits, Proctor compaction, and free swell demonstrated that the addition of CKD had enhanced the geotechnical qualities of the stabilised soils.

Wibisono (2019) used the pozzolanic material in the form of hybrid geopolymers or geopolymers that have Ordinary Portland Cement added to them. Fly ash was activated using a solution of NaOH and sodium silicate to create geopolymer. At room temperature, OPC addition increased initial strength and promoted geopolymerization. Binder content, an OPC percentage, and a fly ash % were the variables that were examined. All specimens had their unconfined compressive stress (UCS) at 7 days measured. Fly ash geopolymer hybrid mass stabilisation could enhance peat soil's strength development.

Bandara et al. (2020) investigated the used of cement kiln dust and fly ash to improve weak pavement subgrades encountered in Michigan, USA. Findings suggested that FA and LKD can be utilised in some soil types as a short-term soil stabilizer, but cement kiln dust or a mixture of FA and LKD is recommended for the long-term stabilization of soil subgrade in all three soil types examined (for construction). At the conclusion, there is also a brief discussion of the sustainability benefits that could result from the upcycling of KD/LKD/FA.

Rivera et al. (2020) examined clayey soil treated with alkali activated cementitious materials (AAC) at 20% and 30%, classified as A-7-5 per ASTM D3282. They utilized granulated blast furnace slag, hydrated lime (L), and fly ash (F1, F2) with high unburned carbon content (up to 38.76%). The study assessed durability after 12 wetting and drying cycles and unrestricted compressive and flexural strengths at 28 days. AAC-F1L-treated soil experienced a 0.51% volume expansion and -0.57% contraction. Mass loss after wetting and drying was only 3.74%, notably below Colombian regulations (7%) and slightly less than soil stabilized with ordinary Portland cement (OPC) at 3.86%.

Yang et al. (2020) provided designers and practitioners with a better understanding of how cement stabilizations can affect the mechanical and soil index properties both before and after saturation. 28 cohesive and granular soil samples from nine building sites were examined in this study utilising a 4-12% type I/II Portland cement concentration. Two-inch-by-two-inch compaction equipment was used to create the specimens, which were then evaluated for 28-

day unconfined compressive strength (UCS) both with and without vacuum saturation. The findings showed that there are statistically significant correlations between cement content, UCS, and soil index characteristics. A laboratory evaluation approach for cement stabilisation mix design for both granular and cohesive soils is proposed based on the findings of the laboratory tests.

Arifin et al. (2021) investigated the use of additives in soil-cement mixtures that had gone through a cycle of soaking and drying. Granitic and lateritic soils, which are frequently utilized in the construction of road bases in the Katingan region of Central Kalimantan, Indonesia, were used in combination. The cement used was regular Portland type I cement, and the addition was primarily made for commercial use and contained $CaCl_2$. In order to evaluate the shear strength in accordance with Indonesian regulations (i.e., a minimum Unconfined Compressive Strength of 2400 kPa), the ideal cement concentration for each soil was tested. On a dry weight basis, it was determined that the ideal cement concentrations for granitic and lateritic soils were 5.5% and 5%, respectively. The 0.8% additive's use caused the ideal cement content of granite-like soil to be reduced by 0.5%. The findings showed that while there were no changes in lateritic soil, the optimum additive content for granitic soil was higher than that without supplementation. However, the benefit of utilising supplements was more obvious in the samples after they had gone through wetting-drying cycles. Additionally, the moisture content and soil-cement loss during wetting were always lower at the optimal additive amount than they would have been without it.

Bakaiyang et al. (2021) assessed the efficacy of a blend of lime and cement treatment. They employed microstructural and geotechnical examinations to describe the soil samples. Their results revealed that treating karal soils with a combination of 2% hydrated lime mixed with CaO or 3% low-carbonated hydrated lime along with 3%, 5%, or 7% cement notably decreased soil volume fluctuations with changing water content and improved the soil's physical and mechanical characteristics. Following treatment, the soils reached the minimum requirements necessary for use in road construction.

Chandra andNaidu (2021) studied the impact of curing method on CBR properties of gravel soil stabilized with cement OPC 53 grade by taking into account the moisture needed for cementation to form and pozzolanic activity throughout the curing time, the curing process effected CBR values. Compared to water curing, moist curing strengthened the development of gel components.

Etim et al. (2021) focused on efficient way to reduce, manage, and dispose of solid wastes produced by quarry activities by adding them as an additive to the protocol for cement amelioration of poor lateritic soil intended for durable sub grade. Twenty-five test specimens from an amelioration protocol were combined with cement that ranged from 0 to 8 % and 0 to 10 % quarry dust in step increments of 2 % by dry weight of the soil. Twenty-five test specimens from an amelioration protocol were combined with cement that ranged from 0 to 8 % and 0 to 10 % quarry dust in step increments of 2 % by dry weight of the soil. As per the test results, quarry dust admixture gradually increased improved the cement stabilized soil's plasticity index by lowering it. The highest dry density in the majority of the fields increased with an increase in stabilizer mix percentage for optimum water content of the soil amended. With an increase in the micro-sized quarry dust stabilizer, the mechanical characteristics such as UCS and CBR of cemented lateritic soil greatly improved. The durability values observed for the resistance to strength loss were greater than 80%. In contrast to untreated soil, the maximally stabilized specimen's SEM/EDS investigation revealed that calcite developed as C-S-H and C-(A)-S-H.

Ghadir et al. (2021) assessed the viability of adopting volcanic ash (VA)-based geopolymer as a substitute soil stabiliser to cement by comparing their shear strength behaviour and life cycle assessment (LCA). Investigations were conducted into the impacts of curing conditions, vertical confinements, binder components, and alkali activator characteristics. The findings showed that, regardless of the kind of binder, adding more binder to clayey soil alters its structure through aggregation and boosts shear resistance. At greater curing temperatures, inter-particle bonds formed more quickly, and at higher confining pressures, the particles' interlocking intensified.

James et al. (2021) used Portland pozzolana cement (PPC) rather than regular Portland cement (OPC) to stabilize an expansive soil that has been subjected to alternating cycles of wetting and drying. 38mm x 76mm unconfined compression strength (UCS) test specimens were cast, then allowed to cure for 7, 14, and 21 days. The UCS specimens were then calculated after the specimens had gone through 1, 2, and 3 cycles of wetting and drying. The investigation's findings revealed that OPC outperformed PPC under typical circumstances by a significant margin. However, when enough binder content was present, PPC stabilised soil outperformed OPC stabilised soil under wet and dry conditions.

Kulkarni and Mandal (2021) showed that different grades of soil treated with nano silica enhanced the strength of soil by significantly increasing the cement content. The soil amended with NS-40 and % cement produced the best results. In the case of optimised soil mixes, adding %, 4 %, or % cement increased the soaked CBR values of soil mixes by 240.76 %, 268.62 %, and 312.90 %, while the 7-day UCS values were found to be improved by

20.98 %, 43.93 %, and 80.19 %. Results from XRD and SEM revealed evidence of increased cementitious reactivity inside the soil matrix. Results showed that soil reinforced with nano silica cement met the requirements for chemically stabilised bound sub bases.

Mohanty et al. (2021) used cement clinker, ground granulated blast furnace slag (GGBS), and fly ash to stabilize the dispersive soil. The UCS findings were found to be greatly improved by combining additives in various ratios. According to the findings of the UCS testing, mixing dispersive soil with % fly ash, 15 % GGBS, and 30 % cement clinker produced the ideal mix percentage. To examine the impact of freezing-thawing and water immersion ageing on durability of mix ratio, a coefficient of strength loss/gain was also defined. Due to the reaction between the soil and the additives, the X-ray diffraction tests revealed that the production of hydrated particles plays a crucial role in enhancing strength.

MotahariTabari and Shooshpasha (2021) conducted laboratory tests, including Proctor compaction and direct shear tests (DSTs), considering different cement and zeolite contents. Results indicated that zeolite increased the optimal moisture content (OMC) but decreased the maximum dry density (MDD) of cemented sand. The DSTs revealed that substituting up to 30% of cement with zeolite led to higher shear strength parameters due to enhanced pozzolanic and chemical reactions, resulting in increased production of calcium aluminate and calcium silicate hydrates compared to zeolite-free samples.

Yu et al. (2021) recommended using cement to enhance the soil around the underground LNG system. In order to do this, the physical, mechanical, and thermal characteristics of soils stabilised with cement in subzero temperatures and F-T cycles were examined. The volumetric expansion of stabilised soils (1.3–1.7%) was much less than those of unprocessed soils (4.2–10%) at subfreezing temperatures, which is advantageous for reducing the risk of freezing expansion harm to nearby infrastructure. After one F-T cycle, untreated soils showed a sizable deformation, but stabilised soils showed no apparent cracks or deformations and only a minor drop in strength after 12 F-T cycles, showing strong resistance to F-T cycles. At both ambient and subzero temperatures, the thermal conductivity of stabilised soils was 19–36% less than those of unprocessed soils, which can reduce the rate of heat transmission between the internal and exterior environments. In general, stabilising the soil with cement helps the subsurface LNG storage system operate more effectively.

Zaika et al. (2021) studied the effect of addition of cement on grati soft soil. To ascertain the impacts of cement contents of 5%, 8%, 12%, and 15%, laboratory studies were conducted, including measurements of physical characteristics, compaction, and CBR. Additionally, triaxial and unconfined compressive tests were conducted to look into various factors of strength, such as curing time. Based on the triaxial test, the soil's shear strength and friction angle has been improved cohesion values have been decreased. The percentage of cement in the soil directly correlated to the shear strength and stiffness.

Beyene et al. (2022) carried out the finite element method to examine deformation properties of soft clay soil treated with cement. Using PLAXIS 2D finite element software, the deformation characteristics of soft clay soil treated with cement were examined. A constitutive soil model and a hardening soil model were both employed in the finite element analysis. On 9, 12, and 15 % of the stability of soil-cement, triaxial test and one-dimensional consolidation were undertaken. According to laboratory findings, pre-consolidation pressure increased as the stabiliser content increased. Soft clay had a pre-consolidation pressure of 190 kPa, 290 kPa, 320 kPa, and 340 kPa when soil was treated with 9%, 12%, and 15% of cement respectively. Thevertical deformation values of soft clay soil increased as the cement % increased, according to numerical study. The optimum percentage of cement was taken as 15% as this percentage yielded highest shear strength and least amount of deformation.

Ezreig et al. (2022) investigated the use of hydrophobic caltite (HC) in various amounts (ranging from 3%, 5%, to 7%) and 5% of cement to enhance laterite soils. The investigation included the assessment of soil characteristics such as California Bearing Ratio soaked and unsoaked, flexural strength, and unconfined compressive strength by curing in air and under water. When caltite was mixed with cement, the strength properties improved with UCS values ranging from 2078 to 2853 kPa on the seventh day of curing and 4688 to 4876 kPa on the 90th day. When compared to cement soil alone, the samples of cement soil with additional caltite demonstrated a reduced index of strength loss underwater with UCS values of 3196, 3334, and 3751 kPa. According to the FS results, adding caltite to cement may improve post-peak behaviour by lowering brittleness and raising ductility. The microstructural analysis findings indicated that HC combined with cement lessened the porosity, voids, and cracking of laterite soils. Additionally, as a result, fresh polymer globules were developed onclay particle surfaces,which decreased water absorption.

Ifediniru and Ekeocha (2022) examined the shear strength enhancement of weak subgrade soil of a highway embankment following mass stabilisation of soil with 6 and 10% Portland cement. Analysis of the cement-stabilized subgrade followed by an analysis of the unstabilized subgrade revealed the factor of safety against shear collapse of the embankment. The limit equilibrium approach was used to conduct the analysis for embankment heights of 4, 5, 6, and 7 metres. The embankment was built on top of thick, soft clayey silt with a Cu range of 9 to 15 kPa; after improvement, Cu values of 154 and 208 kPa were found at stabilization rates of 6 and 10% respectively. The strength of the improved soils, cement concentration, stabilisation depth, and the safety factor were all found to be linearly related.

Iyaruk et al. (2022) assessed the subbase material performance of lateritic soil (LS), stabilised with cement and biomass BA. Prior to invention of hydraulic cement stabilisation techniques, BA was thought of as a substitute material in LS. The modified Proctor test, the California Bearing Ratio (CBR) test, and the unconfined compression test were the geotechnical engineering tests. The mineralogical characteristics of the stabilised soil samples were examined using X-ray fluorescence (XRF) and X-ray diffraction (XRD) assays. To gauge the discharge of heavy metals, a permeability mould was used in the leachate test. Finally, using the mechanistic-empirical (M-E) pavement design approach, the advantages of adopting the stabilised subbase material were evaluated. Due to its excellent engineering and environmental features, the admixture of 80% BA and 5% cement is recommended for use as a soil-cement subbase material for flexible pavements.

Liu et al. (2022) combined experimental results with existing literature to study the impact of water content, sand/silt fraction, and size distribution on the cement based stabilized-soil (CBS) strength and to develop a generalised predictive strength equation for clays with various gradations, water contents, and cement contents. The results indicated that the addition of sand (about 80%) had no effect on the UCS at a fixed cement mass, initial dry clay, and water. However, the UCS drops with the substitution of sand since there was less water absorbed and more water that was available at the very same mass of cement, water content, and total soil. By using scanning electron microscopy (SEM), it was determined that sand behaves like solid intrusions within the CBS matrix.

Marik et al. (2022) examined the subgrade soil stabilisation potential of cement and StabilRoad. CBR and UCS increased by 72.413 (soaked) and 79.16 (28 days) with 1% StabilRoad in cement-modified soil. Quantile regression (QR), partial least square regression (PSL-R), and linear regression (LNR) models were developed to determine the link between UCS and CBR and subgrade soil parameters. This addition, which increased soil strength, increased the intensity of C-S-H peaks. This additive's subgrade stabilization reduced costs by lowering the pavement's crust thickness.

Minh and Nien (2022) experimented with a modifying agent for stabilizing expansive soil on a scaled rural road. Divided into four sections, each underwent different stabilization tests. Specimens treated with the modifying agent showed increased strength and water stability compared to those without. However, fly ash use may lead to pavement damage. Utilizing the constituent materials in specimen Q4 is recommended for improved soil stabilization.

Sadek et al. (2022) explored compaction energy effects on stabilized subgrade soil by adding regular Portland cement and sulfate-resistant cement. Increased compaction led to higher UCS values and increased maximum dry density (MDD), while optimum moisture content (OMC) decreased. This resulted in improved UCS and CBR, indicating better soil performance.**Sagidullina et al. (2022)** investigated soil remediation using Calcium Sulfoaluminate (CSA) cement, conducting UCS and ultrasonic pulse velocity tests on stabilized soil specimens. Results showed that higher cement content improved soil performance, especially in achieving sufficient subgrade strength despite freeze-thaw cycles.

Thanushan and Sathiparan (2022) studied soil blocks stabilized with cement and reinforced with banana fibre and coconut coir. Both fibres enhanced post-peak performance in compression and flexural strength, respectively. Additionally, both fibre additions increased resistance to various weathering conditions, with coconut coir reinforcement showing greater durability.

Wang et al. (2022) designed an empirical model to determine the ideal water-cement ratio of cement-stabilized soil with varying cement concentrations. The fluidity of the cement-stabilized soil was satisfied and bleeding prevented by the water-cement ratio was determined by this model. According to the test results, the ideal water-cement ratio varies with cement concentration and is well captured by the suggested model. Additionally, this model can forecast the appropriate water-cement ratios for cement-stabilized soil's 7-day UCS and stiffness. The consistency and strength may be ensured in cement-stabilized soil with the ideal water-cement ratio. The suggested model will be useful in solving technical issues with the choice of water-cement ratio in deep soil mixing construction.

Xiao et al. (2022) conducted compressive strength and splitting tensile strength tests on three types of cement-stabilized soils to assess the impact of rice husks and polypropylene fibers. Factors like fiber content, initial moisture, curing duration, and fiber type were evaluated. Results indicated a significant enhancement in both UCS and split tensile strength with the inclusion of rice husks and polypropylene fibers. The optimal range for fiber content was found to be between 0.3% and 0.5%.

Amiri et al. (2023) investigated cement's microstructural effects on hematite-rich red soil, focusing on C-S-H nanostructure changes. Different cement percentages and curing periods were used. Tests included particle size analysis, slake durability, water absorption, UCS, and UPV. pH, EC, XRD, EDX, and SEM imaging were employed to examine the stabilization process and hematite's impact on C-S-H microstructure. Addition of cement enhanced C-F-H and ilavite formation, boosting stability and compressive strength of the red soil, reaching

2.04 MPa in seven days with 6% cement and hematite.

2.6Application of Polypropylene Fibre in Soil Stabilisation

Polypropylene fibre (PPF) strands withstand stress by eliminating shrinkage fissures, which increase swelling by allowing moisture to infiltrate expansive soil. Randomly arranged fibres reduce the risk of failure plains. PPF strands give the soil mass ductility by holding the soils' particle. Design professionals have also begun to focus on improving the issue soil's tension, for which PPF has proven useful.These fibres can biodegrade or be eliminated chemically. Natural fibres aren't suggested for engineering problems. Chemically inert synthetic fibres last longer. Synthetic fibres are respected in engineering because of their great strength and shear.

Tang et al. (2007) conducted an experimental investigation to assess the impact of shorter polypropylene fiber (PP-fiber) on both uncemented and cemented clayey soil. They formulated 12 soil groups with varying PP-fiber contents (0.05%, 0.15%, and 0.25% by weight of soil) and two distinct cement contents (5% and 8% by weight of soil). Unconfined compressive strength (UCS) and direct shear tests were performed at intervals of 7, 14, and 28 days post-curing. The findings revealed that fiber reinforcement led to improvements in UCS, shear strength, and axial strain at failure while reducing soil stiffness and post-peak resilience. Moreover, it transitioned the behavior of cemented soil from brittle to ductile.

Kalantari and Huat (2008) did experiments on stabilising peat soil using polypropylene fibres as an addition and Ordinary Portland Cement (OPC) as a binding agent. The stabilised peat soil samples were maintained in normal air temperature and away from water invasions to drier condition throughout the curing time due to the high preliminary water content of the samples and to progressively lower their moisture content. UCS and CBR laboratory tests were used to assess the strength of stabilised peat soil. For the UCS testing, air curing times of 28, 90, and 180 days were employed, whereas 90 days were used for the CBR tests. The stabilised peat soil hardened and developed strength as the curing process goes on because as moisture content dropped, the weight of water relative to cement (W/C) also dropped.

Jiang et al. (2010) conducted a series of experiments to explore the enhanced engineering characteristics of soil through the incorporation of short polypropylene fibers. These investigations aimed to examine the influence of factors such as fiber content, length, aggregate size, and additives on soil properties. The results indicated a significant enhancement in the unconfined compressive strength (UCS) by 96%, and the internal frictionangle of the fiber-reinforced soil rose to 28º from an initial value of 16.5º, surpassing those of the untreated soil.

Malekzadeh and Bilsel (2012) did experimental examination of polypropylene fiber's influence on expansive soils. In the first phase of the experiment, polypropylene fiber's effect on dry density and moisture content was studied. Dynamic compaction experiments were done on an expansive soil sample with 0%, 0.5%, 0.75, and 1% PPF. Consequently, unreinforced and reinforced soil samples were examined in unconfined compression, tensile, and one-dimensional swell. On the basis of the findings, it was concluded that the use of PPF (1.5%) as the mitigation material in expansive soils may result in the improvement in the physico - mechanical features of roadways and light buildings.

Moghal et al. (2018) tested that the use of synthetic fibres as reinforcement in expansive soils in order to stabilise the soil is gaining popularity. In order to make a contribution to this expanding area of research, two distinct forms of synthetic fibres, namely Fiber Mesh® and Fiber Cast®, were investigated and tested for their potential use as an alternate method of stabilisation for expansive soils where lime was present. The CBR, was chosen to serve as a performance indicator since it is an excellent predictor of how effective a pavement is. A number of factors, including curing time, length of the fibres, and quantity of the fibres, were investigated. In this work, deterministic and probabilistic (or dependability) studies are offered. Although the probabilistic approach takes into consideration the experimental data's stochastic character and offers a stronger justification for the design choices, the deterministic analysis is useful in comprehending the observed experimental data. The deterministic approach showed that longer lengths and greater fibre contents improved CBR, with the impact being most noticeable when lime was employed as a stabiliser. Furthermore, the deterministic approach discovered that larger fibre lengths resulted in a greater improvement in CBR. Based on the results of the probabilistic research, the CBR strength is significantly impacted by both the total number of fibres and their lengths. It was also discovered that the degree of variation in the target CBR value had a significant impact on the degree to which the length and quantity of the fibres could be optimised.

Soltani et al. (2018) showed results of an experimental programme regarding the capacity of fibre to mitigate the swelling behaviour of expansive soil.As the reinforcements, they utilised two distinct kinds of tape-shaped fibresincorporated into the material at three different concentrations. It was shown that the improvement in swelling potential or pressure was a direct consequence of fc and fl (fibre length) or fAR, with the former playing a more significant influence than the latter. This was the case for a given fibre type with a constant fibre width. In addition, when the fc and fl were held constant, the wider fibre (with the lower fAR) was found to be more effective in preventing swelling. In order to determine the optimal stabilisation situations, the qualities of compression and the attributes of swelling were compared with one another. It was claimed that fc = 0.5% would be an optimal situation for both types of fibre. However, greater inclusions of up to 1% could potentially be an acceptable choice in situations where compressional deformations are not the primary concern.

Nitin and Neelima (2019) performed testing on mechanically reinforced expansive soil with randomly distributed polypropylene fibres of varying percentages (0.25 percent, 0.5 percent, and 1 percent), each of which was 12 millimetres in length. The subsequent phase of the study concentrated on exploring the synergistic effects of mechano-chemical stabilization on expansive soil, combining various proportions of silica (2%, 4%, and 8%) and polypropylene fibers (0.25%, 0.50%, and 1.00%). Previously, the experiment focused on This was evidenced by a reduction in the volume of expansive soil, with the extent of reduction directly correlated to the fiber content. Furthermore, the application of silica fume resulted in a notable decrease in the upward swelling potential of the material. Interestingly, the magnitude of this reduction was found to be considerably greater than the effects observed with polypropylene fibers.

Lui et al. (2020) investigated the effect of short fibres, including as polypropylene, basalt, and glass fibres, influence the mechanical performance of polyurethane (PU) polymer treated sand. The results of unconfined compressive and tensile tests were examined, and inferences were drawn on the degree to which various types of fibre reinforcements enhanced the material's strength. In addition, scanning electron microscopy was utilised in order to investigate the intrinsic process and the variations in the microstructure (SEM). In compared to using solely polymer reinforcement, the results demonstrated that fibre integration resulted in a significant improvement in both the brittle behaviours and the strength properties of the composite. In comparison to other fibres, polypropylene fiber's well-flexible structure and inherent strength made it possible for it to impart a larger degree of strength to the treated soil while maintaining the same level of content. According to what was found, the addition of 0.8% polypropylene fibre led to an increase in compressive and tensile strength by 108.07% and 295.42% respectively. Comparatively, the addition of 0.8% basalt fibre imparted 63.91% and 147.06%, and the addition of fibreglass imparted 47.92% and 253.08% respectively with the same content. In addition, the shift in the stress-strain curves as well as the failure mode, as well as the increased value of the brittleness index (by approximately two to four times), all pointed to an increase in ductility. The presence of polymer resulted in the cementation of the soil matrix, which also led to a large binding strength in the contacts between the grains and the fibres that make up the grains. During the process of failure, the fibres stretched and broke rather than moving through the soil like monofilament polypropylene fibre reinforcement is known to do. This was a common observation. The dry density of the soil had an effect on the mechanical properties of the soil as well. The brittleness of the material worsened with increasing dry density, which was caused by increased interfacial friction at the fiber-sand and sand-sand interfaces. However, the strength characteristics improved with increasing dry density and soil reinforcement with polymer and fibre demonstrated high strength and modulus for its efficient use. This was discovered to be influenced by the softness, strength characteristics, density, and size of various types of fibres.

Radwan et al. (2021) investigated the effects of reducing the amount of cement used in peat soil stabilisation projects by utilising fly ash waste and polypropylene fibre (PPF). The unconfined compressive strength (UCS) and California bearing ratio (CBR) tests were performed to compare the mechanical properties of the cements, with the primary focus being on soil mechanical mediation for the stabilisation of peat with fly ash cement and PPF cement. The specimens of peat that were evaluated included the control (untreated) peat specimen, as well as specimens that had either fly ash (10%, 20%, or 30%) or PPF (0.1%, 0.15%, or 0.2%) added to them. According to the findings of the tests, a content of 30% fly ash and cement demonstrates the greatest UCS and CBR values, and it also delivers the most dependable compressibility qualities. On the other hand, the results of the UCS and CBR tests show that the specimen should have an optimal value of 0.15% PPF and 30% cement for the content of the PPF–cement stabilising agent. PPF threads were found to be well enclosed by cement-stabilized peat matrix after being examined using scanning electron microscopy (SEM) on a selection of specimens. When compared to the specimen that was composed entirely of cement, the one that contained fly ash at a percentage of thirty percent developed a greater number of hydration products. It has been determined that the utilisation of fly ash cement and PPF cement as stabilising agents in peat soil treatment has the potential to be viable. This will reduce the amount of cement that is utilised.

Syed and GuhaRay (2020) explored the effectiveness of using polypropylene (PF) and glass fiber (GF) in stabilizing black cotton soil (BCS) with an envirosafe alkali-activated binder (AAB) comprising different proportions of fly ash and slag. AAB, created by mixing an alkali-activator solution with aluminosilicate precursors at a 0.4 water-to-solid ratio, was combined with PF and GF concentrations ranging from 0% to 0.4% in BCS, alongside 5%

AAB. Tests for UCS, ITS, and CBR assessed the geomechanically strength of fiber-reinforced AAB-treated BCS, aiming to ascertain optimal fly ash to slag ratios and fiber content using Monte Carlo Simulation. The results exhibited substantial enhancements in both shear and tensile properties of BCS with varying fiber doses and fly ash to slag ratios, emphasizing the pivotal role of fiber quantity and ash-slag proportion in determining the strengths of PF and GF reinforcement in UCS, ITS, and CBR.

Sujatha et al. (2021) investigated the use of two distinct varieties of glass fibres, namely alkali resistant (AR) glass fibre and electronic grade (E) glass fibre, as reinforcement in soils in an effort to increase their levels of strength. The plastic character and compaction behaviour of the reinforced soil are only slightly altered as a result of the addition of glass fibre reinforcement. Additionally, the incorporation of fibres into the soil makes it less reactive to shifting moisture levels. The incorporation of fibres in reinforced soil makes it more ductile in its behaviour. Unreinforced soil collapses with a clear shear plane, but reinforced soil fails with several shears, bulging, and a network of tiny cracks that are bridged by fibres. According to the findings of this research project, the random inclusion of fibres leads in an increase in both the unconfined compressive strength of the reinforced soil and its capacity to absorb energy. For both AR glass fibre and E glass fibre, it has been determined that a content of 0.75 percent glass fibre is ideal. When compared across all tested percent of fibre inclusion, the performance of AR glass fibre is superior to that of E glass fibre.

Suriya et al. (2021) investigated the effectiveness of red soil by adding polypropylene fibre in various ratios of (1-3%) on its geotechnical properties. The primary engineering properties, such as shear strength from UCS and CBR, as well as the index properties, such as sieve analysis, consistency limit, and compaction characteristics, were discovered. The outcome showed that red soil's properties were strengthened by PPF reinforcement.

Ashiq et al. (2022) modified the qualities of Siwalik clay, which were to be used as the basis soil, by adding marble and glass powders (up to five percent) and polypropylene fibres (up to one point and a quarter of one percent). On the control and modified clay samples, laboratory tests were carried out. At a pressure of 1.57 kPa, the unconfined compressive strength (UCS) and swelling strains (SS) were found to have increased by 43 and 8 percentage points, respectively, when marble powder made up 15% of the replacement material. In contrast, the incorporation of 20% glass powder and 0.5% polypropylene fibres not only resulted in an increase in UCS of 110% and 39%, but also brought about a reduction in SS of 27% and 86%, respectively. If 15% glass powder was used instead of marble powder or polypropylene fibres, the capital construction cost of a one-kilometre-long road with a modified subgrade was 16% less expensive. On the other hand, the cost increased by 22% and 17%, respectively, when using polypropylene fibres and marble powder. Each of the modifiers posed a very modest risk to the watery environment that was adjacent to them. In conclusion, glass powder and polypropylene fibres can both be utilised as earth-friendly soil improvement modifiers, which can ultimately lead to the development of sustainable solutions for the serviceability issues.

Behera (2022) evaluated the viability of using polyvinyl chloride (PVC) fibre reinforced-fly ash stabilised black cotton (BC) soil as a long-term subgrade material. Fly ash was utilised as an admixture for the purpose of stabilising the BC soil, and PVC fibre was employed as a reinforcing element. According to the findings, there was an increase in the UCS and CBR values of the soil amended. Also, the optimal value of fly ash was 30 %, and the optimal value of PVC fibre was to be added to BC soils 1.5%.

Chowdary and Pillai (2022) studied that the ways that are commonly employed in the stabilisation of soft and weak soils is called Deep Soil Mixing, or DSM for short. As a more environmentally friendly alternative to cement, a geopolymer binder was suggested to be used in DSM applications. The prevention of crack propagation that results from the addition of fibres to treated soil contributes to the overall enhancement of both its strength and its ductility. In the current experiment, a geopolymer (GP) binder made from ground granulated blast furnace slag (GGBS) that had been reacting with 8 M sodium hydroxide was utilised to treat soft clay that included a high amount of water. Reinforcement was accomplished through the utilisation of polypropylene (PP) fibres of 12 millimetres in length, with percentages ranging from 0.25% to 1.0%. The prepared specimens were put through tests to determine their UCS as well as their durability (wetting – drying).Specifically, soil mixes treated with GP, comprising a binder content of 30% and an Activator/Binder (A/B) ratio of 0.75, and reinforced with 1% PP fibers by weight, demonstrated exceptional strength and durability attributes. Consequently, they represent an environmentally sustainable substitute for traditional binders in deep soil mixing applications.

Meddah et al. (2022) investigated the synergistic effect of dune sand, lime, and polypropylene (PP) fibers on enhancing the geotechnical properties of highly plastic clay (LL = 86%). Plasticity, compaction characteristics, UCS, and CBR were analyzed for samples incorporating these additives. Results demonstrated significant improvements in soil strength and ductility, even with minimal lime addition. A mixture comprising 20% sand, 3.4% lime, and 0.9% fibers yielded the most substantial enhancement, with a 12.75-fold increase in strength compared to untreated clay.

Uday et al. (2022) revealed that discrete, randomly-placed polypropylene fibres are effective in reducing expansive soils' susceptibility to swell. The swelling features of expansive soil specimens that had been remoulded and reinforced with varied fibre contents (0.2, 0.3, 0.4, and 0.5 %) and aspect ratios (15, 30, and 45) were examined. On consolidometer test specimens, one-dimensional swell-consolidation experiments were performed. At low aspect ratios and both the fibre concentrations of 0.2-0.5 %, the drop in heave and swelling pressure was at peak. Finally, the interaction between the soil and the fibres was used to describe the method through which discrete and randomly positioned polypropylene fibre prevent expansive soil from swelling.

Xiao et al. (2022) compared rice husks and polypropylene fibers' effects on mechanical parameters in cement-stabilized soils. Both additives improved UCS and STS values, with the most effective fiber content range being 0.3–0.5%. Rice husks had a stronger influence on UCS in cement-stabilized clayey sand and sandy clay with low liquid limit.

Karboua et al. (2023) investigated the strength of soil mixtures with varying proportions of bentonite clay and silt, with and without reinforcement. Optimal strength was observed with up to 20% silt in clay, although no distinct threshold was identified. Adding synthetic fibers, such as polypropylene and nylon, to silt-containing soil led to comparable strength and consistency improvements.

2.7Summary of review of literature

On the basis of findings of literature review, adding marble dust and ash from the burning of municipal solid waste to clayey soil found to improve its strength characteristics while significantly reducing its swelling properties. When cement is added to clayey soil, the soil's strength increases significantly, but the substance loses its ability to expand and becomes brittle. The strength improves higher when the right amount of cement and municipal solid waste incineration ash are used together to stabilise soil than when cement and municipal solid waste incineration ash are used separately, but it decreases when cement is used alone as a stabiliser (but costlier in nature). Few researches have been conducted on the combination of marble dust and municipal solid waste incinerator ash, according to the literature, although it may be used as an alternative to natural aggregates. Several studies noticed the improvement in strength when polypropylene fibre was added.

2.8 Research Gap

It is clear from the available research that a significant amount of study has been conducted on the use of cement and ash from municipal solid waste incineration for the purpose of soil stabilisation, both on their own and in combination with one another. On the other hand, the comparative efficacy of marble dust, municipal solid waste incineration ash, and cement as soil reinforcement materials has not been studied to the same extent by a great number of researchers. According to the research that was done on municipal solid waste, one of the most comprehensive disposal methods involves collecting the waste, sorting it into its many component forms, and then burning it to generate municipal solid waste incineration ash. The utilisation of polypropylene fibre combined with other additives such as municipal solid waste incineration ash, marble dust, and cement has not been investigated, despite the fact that there is a significant amount of research work available in the literature on the use of polypropylene fibre alone and with other waste materials in soil stabilisation.

2.9Objectives

The prime focus of the present study is to utilize different additives i.e., waste materials in the stabilization of sub-grade which may enhance the soil characteristics and overcome on the dumping issue of different waste materials. Besides this, present study is aiming to suggest most cost-effective mix design i.e., having waste materials by doing a comparison analysis among different mixes. The planned study aims to enhance the geotechnical qualities of clayey soil by incorporating additives such as municipal solid waste incineration ash, marble dust, cement, and polypropylene fiber. The primary goals of this research include reducing the differential free swell and enhancing the strength and sub-grade characteristics of the soil. The detailed objectives are as follows:

1. To study the effect of addition of additives individually and in combination with each other on the differential free swell and consistency limits of clayey soil.
2. To study the effect of addition of municipal solid waste incineration ash, marble dust, cement and polypropylene fiber individually and in combination with each other on the compaction characteristics of the clayey soil.
3. To check the influence of different additives on the UCS of clayey soil individually and in combination with each other and to identify the possible way to use the same to improve the requisite soil properties.
4. To examine the variation in CBR and resilient modulus of the clayey soil due to the incorporation of different additives individually and in a combined manner.
5. To identify the most suitable way for utilisation of different additives i.e., individually or in combined way in order to design the thickness of subgrade layer of a pavement structure with the help of IITPAVE software.
6. To analyse the cost of various pavements designed and compare the cost.

Chapter 3

Materials and methodology

3.1 General

As discussed in previous chapters, there are numerous problems associated with clayey soils. In order to check the application of different additives, i.e., procured from different regions and industry several tests have been conducted. The detailed procedure of each test has been be discussed in the next sections. In this study, municipal solid waste incineration ash, marble dust, cement and polypropylene fibre were used to stabilise clayey soil. The basic properties of various materials used in the study are described in the chapter, along with their source from which they were obtained. Furthermore, material manufacturing and generation have been discussed. This chapter's subsequent sections have discussed the methodology and codal provisions used, as well as a brief procedure for each experiment. The evaluations were carried out to determine the soil's swelling, plasticity, and strength as well as the modification in parameters brought on by the addition of potential stabilising components.

3.2 Materials

3.2.1 Soil Sample

In the present study, soil (Figure 3.1) was brought from Majra village, nearby PGI Chandigarh- Kurali road, Punjab, India. The soil was sieved using 4.75 mm sieve and oven dried for 1 day to perform experiments in the laboratory was conducted to determine the various properties of soil. In order to find the type of soil, wet sieve analysis and hydrometer analysis was performed and found that soil has a high plasticity and lying in range of CH as per unified soil classification system. The physical and chemical characteristics of soil are shown in (Tables 3.1 and 3.2**)** respectively.

Figure 3.1: Clayey Soil

Table 3.1: Physical properties of clayey soil

Property	Value/type
Specific gravity (ASTM D 854-14, 2000)	2.30
Physical appearance	Light brown
Liquid limit (%) (ASTM D4318-10, 2000)	62.2
Plastic limit (%) (ASTM D4318-10, 2000)	34.3
Plasticity Index (%) (ASTM D4318-10, 2000)	27.9
Optimum moisture content (%) (ASTM D698-07e1, 2000)	22.2
Maximum dry density (g/cc) (ASTM D698-07e1, 2000)	1.74
pH (ASTM D4972-18)	6.7
Differential free swell (%) (IS 2720-1977)	55

Table 3.2: Chemical properties of clayey soil

Minerals	Type/Value
Calcium oxide (CaO)	1.00
Silicon dioxide (SiO_2)	76.9
Aluminium oxide (Al_2O_3)	12.50
Magnesium oxide (MgO)	2.10
Sodium oxide (Na_2O)	0.53
Potassium oxide (K_2O)	1.20
Titanium dioxide (TiO_2)	0.54
Others	2.36
LOI (Loss on Ignition)	2.87

3.2.2 Municipal Solid Waste Incineration Ash

The municipal solid waste incineration ash (MSWIA) (Figure 3.2) was obtained from Municipal Solid Waste Incineration Plant, Chandigarh. The incineration ash was hermetically sealed in airtight bags to prevent moisture ingress and subsequently transported to the geotechnical laboratory. Wet sieve analysis was employed to sieve out the heavy metals, after which the municipal solid waste incineration ash (MSWIA) (Figure 3.5)underwent further drying for gradation purposes. The gradation curve of MSWIA, derived from both dry and wet sieve analyses, depicted that approximately 97% of particles fell within the size range of 1.18-0.075 mm, suggesting a poorly graded sand composition. Geotechnical characteristics and chemical properties of MSWIA were evaluated and given in Tables 3.3 and 3.4, respectively.

Figure 3.2: Municipal solid waste incineration ash

Table 3.3: Physical properties of municipal solid waste incineration ash

Property	Value/type
Specific gravity (ASTM D 854-14, 2000)	2.06
Physical appearance	Dark grey
Optimum moisture content (%) (ASTM D698-07e1, 2000)	12.3
Maximum dry density (g/cc) (ASTM D698-07e1, 2000)	1.65
Coefficient of uniformity, C_u	2.53
Coefficient of curvature, C_c	0.70
pH (ASTM D4972-18)	7.8

Table 3.4: Chemical properties of municipal solid waste incineration ash

Minerals	Value
Calcium oxide (CaO)	21.36%
Silicon dioxide (SiO_2)	55.24%
Aluminium oxide (Al_2O_3)	10.70%
Magnesium oxide (MgO)	0.35%
Ferric oxide (Fe_2O_3)	7.23%
Lead (Pb)	0.04%
Zinc (Zn)	0.03%
Others	5.05%

3.2.3 Marble Dust

The marble dust (MD), as depicted in Figure 3.3, was sourced from Chandigarh Marbles, Chandigarh, India, and subsequently transported to the laboratory in securely sealed air-bags for subsequent testing. The gradation curve derived from dry sieve analysis, as illustrated in Figure 3.5, indicated the presence of uniform particles within the marble dust. Various chemical properties of the marble dust were documented and presented in Table 3.5 and 3.6, respectively.

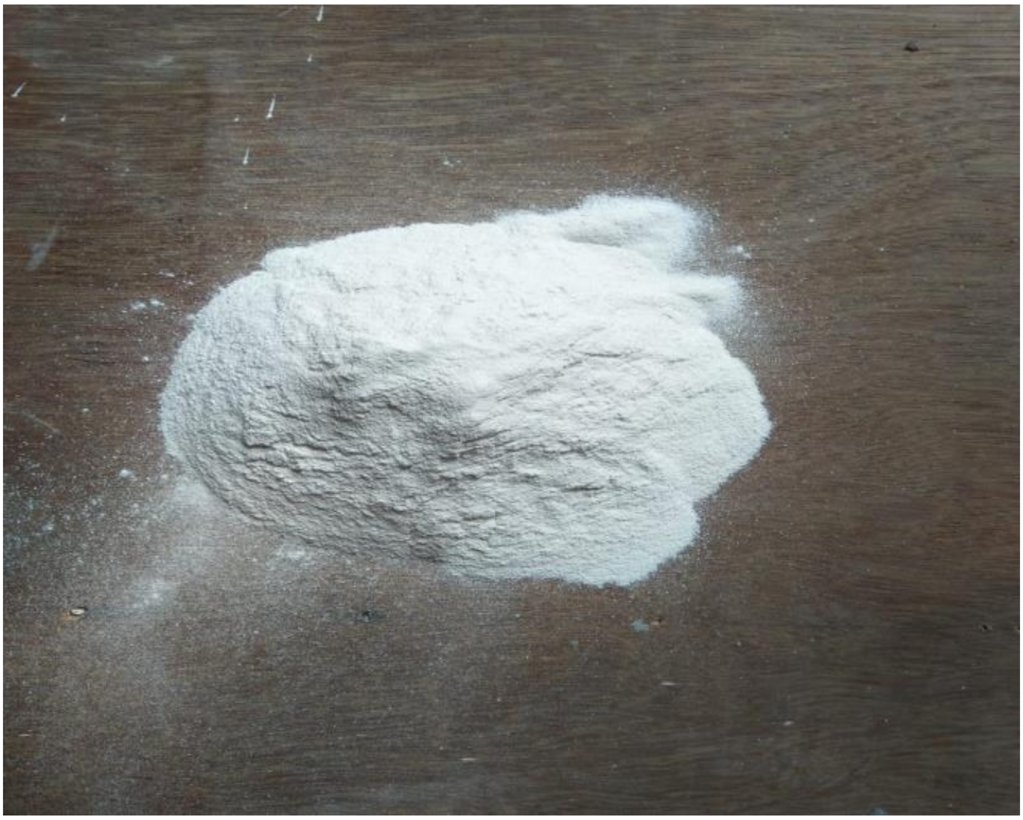


Figure 3.3: Marble dust

Table 3.5: Physical properties of marble dust

Property	Value/type
Specific gravity (ASTM D 854-14, 2000)	2.64
Physical appearance	White
Optimum moisture content (%) (ASTM D698-07e1, 2000)	14.2
Maximum dry density (g/cc) (ASTM D698-07e1, 2000)	1.62
Coefficient of uniformity, C_u	3.88
Coefficient of curvature, C_c	1.46
pH (ASTM D4972-18)	8.1

Table 3.6: Chemical properties of marble dust

Mineral	Value
Calcium oxide (CaO)	55.60%
Magnesium oxide (MgO)	1.62%
Aluminum oxide (Al_2O_3)	0.65%
Ferric oxide (Fe_2O_3)	0.23%
Sulfur Trioxide (SO_3)	0.13%
Sodium Oxide (Na_2O)	0.14%
Potassium Oxide (K_2O)	0.13%
Loss of ignition	42.36%

3.2.4 Cement

Cement stands as the predominant substance employed for clayey soil stabilization. The particular type of cement utilized in this investigation, as depicted in Figure 3.4, was OPC 43, procured from a local hardware vendor situated in Chandigarh, India. The cement was stored in a dry location to shield it from direct atmospheric exposure and prevent moisture infiltration. Various physical and chemical properties of the cement were cataloged and presented in Tables 3.7 and 3.8, respectively.

Figure 3.4: OPC 43 grade cement

Table 3.7: Physical properties of cement

Property	Value/type
Specific gravity (ASTM D 854-14, 2000)	3.12
Physical appearance	Grey
Optimum moisture content (%) (ASTM D698-07e1, 2000)	20.2
Maximum dry density (g/cc) (ASTM D698-07e1, 2000)	1.71
pH (ASTM D4972-18)	11.2

Table 3.8: Chemical properties of cement

Chemical constituent	Content
Calcium oxide (CaO)	46.12%
Silicon dioxide (SiO_2)	30.24%
Aluminum oxide (Al_2O_3)	6.75%
Ferric oxide (Fe_2O_3)	3.68%
Magnesium oxide (MgO)	1.67%
Sulfur Trioxide (SO_3)	1.98%
Chlorine (Cl)	0.01%
Loss of ignition	7.72%

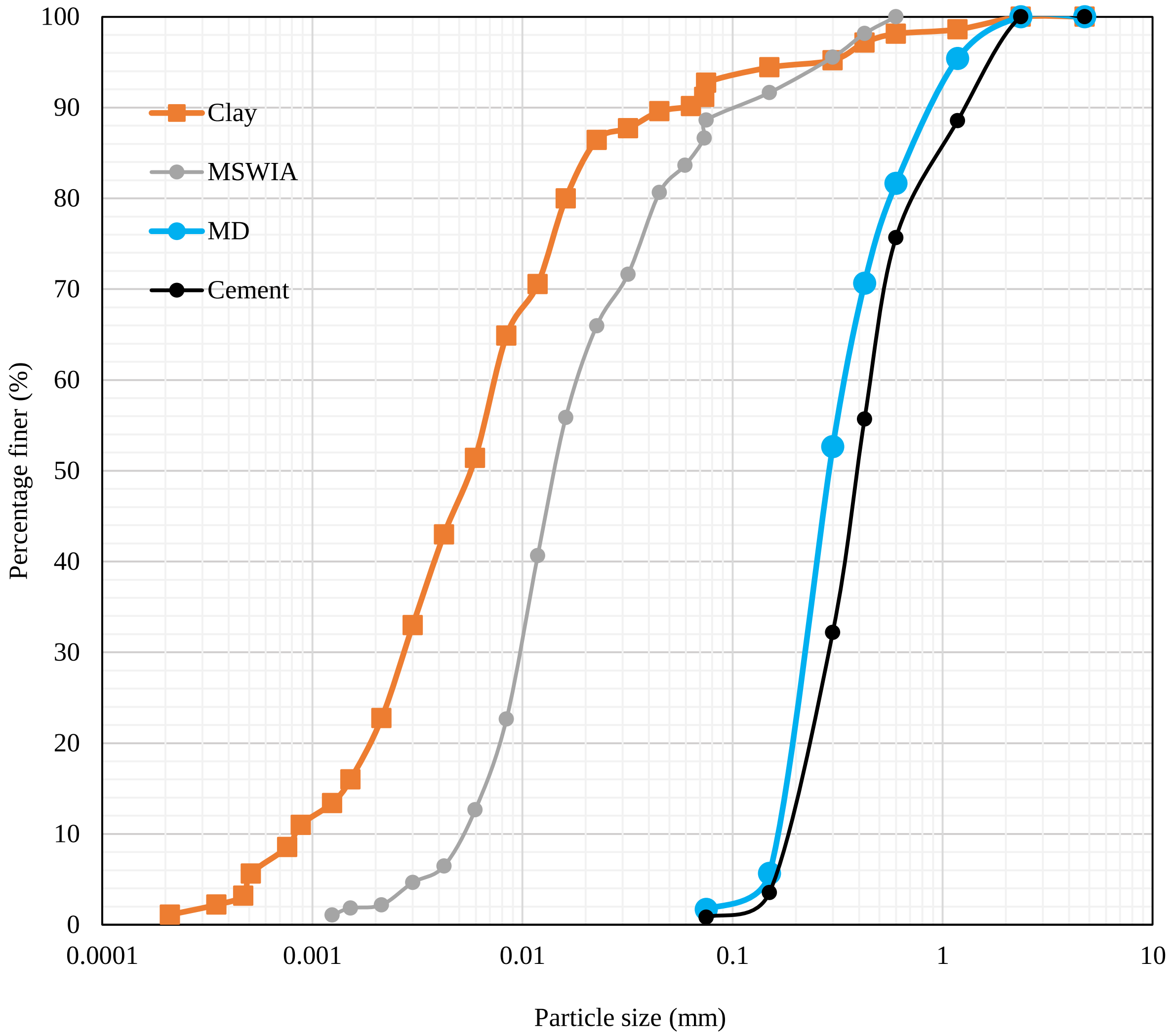


Figure 3.5: Gradation curves of various materials

3.2.5 Polypropylene fiber

The polypropylene fiber (PPF) (Figure 3.6) used in the study was synthetic fiber and was obtained from Vardhman Yarns & Threads Ltd., Ludhiana, Punjab, India. The aspect ratio (length to diameter) of PPF was kept constant as 75 throughout the test. The various properties of PPF are tabulated in Table 3.9.

Figure 3.6: Polypropylene fiber

Table 3.9: Properties of polypropylene fiber

Property	Value
Type of fiber	Polypropylene
Length (mm)	12
Diameter (mm)	0.05
Specific gravity	0.92
Tensile strength (MPa)	455
Elongation at break (%)	18.25
Melting point (°C)	170
Heating resistance (°C)	130

3.3 Testing Procedures

Extensive laboratory research has been conducted using various combinations of materials, as shown in Table 3.10, including clay, Municipal Solid Waste Incineration Ash (MSWIA), cement (C), marble dust (MD), and polypropylene fibers (PPF). These materials were systematically combined in different proportions to assess their impact on the geotechnical properties of soil, particularly to reduce differential free swell (DFS) and increase the pH value of the clay. The experiments were designed to evaluate how the addition of these materials could improve the stability and performance of expansive soils. The goal was to mitigate the swelling potential by reducing DFS, a crucial factor in controlling soil volume changes, and to enhance the chemical reactivity of the soil through an increase in pH, which plays a key role in the stabilization process. The choice of materials like MSWIA and cement was based on their potential to raise the pH, while additives such as marble dust and polypropylene fibers were included to contribute to mechanical stability and reduce swelling. The envisaged experiments aim to optimize these combinations to improve soil behavior, making it more suitable for construction and engineering applications.

Table 3.10: Material combinations used in the research

Sr. No.	Material combinations	Sieve analysis	Specific gravity	Differential free swell	Liquid Limit/ Plastic limit	Compaction (MPT)	Unconfined compressive strength	CBR	Permeability
1	S: 100	✓	✓	✓	✓	✓	✓	✓	✓
2	MSWIA:: 100	✓	✓	×	×	✓	×	×	✓
3	MD:: 100	✓	✓	×	×	✓	×	×	✓
4	C :: 100	×	✓	×	×	×	×	×	×
5	PPF :: 100	×	×	×	×	×	×	×	×
6	S: MSWIA :: 95: 5	×	×	✓	✓	✓	✓	✓	×
7	S: MSWIA :: 90: 10	×	×	✓	✓	✓	✓	✓	×
8	S: MSWIA :: 85: 15	×	×	✓	✓	✓	✓	✓	×
9	S: MSWIA :: 80: 20	×	×	✓	✓	✓	✓	✓	✓
10	S: MSWIA :: 75: 25	×	×	✓	✓	✓	✓	✓	×
11	S: MSWIA :: 70: 30	×	×	✓	✓	✓	✓	✓	×
12	S: MD :: 95: 5	×	×	✓	✓	✓	✓	✓	×
13	S: MD :: 90: 10	×	×	✓	✓	✓	✓	✓	×
14	S: MD :: 85: 15	×	×	✓	✓	✓	✓	✓	✓
15	S: MD :: 80: 20	×	×	✓	✓	✓	✓	✓	×
16	S: C::97: 3	×	×	✓	✓	✓	✓	✓	×
17	S: C::94: 6	×	×	✓	✓	✓	✓	✓	×
18	S: C::91: 9	×	×	✓	✓	✓	✓	✓	✓
19	S: C::88: 12	×	×	✓	✓	✓	✓	✓	×
20	S: PPF::99.5: 0.5	×	×	×	×	✓	✓	✓	×
21	S: PPF:: 99: 1	×	×	×	×	✓	✓	✓	✓
22	S: PPF:: 98.5: 1.5	×	×	×	×	✓	✓	✓	×
23	S: MSWIA: PPF:: 79.5: 20: 0.5	×	×	×	×	✓	✓	✓	×
24	S: MSWIA: PPF :: 79: 20: 1	×	×	×	×	✓	✓	✓	✓
25	S: MSWIA: PPF :: 78.5: 20: 1.5	×	×	×	×	✓	✓	✓	×
26	S: MD: PPF :: 84.5: 15: 0.5	×	×	×	×	✓	✓	✓	×
27	S: MD: PPF :: 84: 15: 1	×	×	×	×	✓	✓	✓	✓
28	S: MD: PPF :: 83.5: 15: 1.5	×	×	×	×	✓	✓	✓	×
29	S: C: PPF :: 82: 15: 3	×	×	×	×	✓	✓	✓	×

30	S: C: PPF :: 79: 15: 6	×	×	×	×	✓	✓	✓	×
31	S: C: PPF :: 76: 15: 9	×	×	×	×	✓	✓	✓	✓
32	S: C: PPF :: 73: 15: 12	×	×	×	×	✓	✓	✓	×
33	S: MSWIA: C :: 77: 20: 3	×	×	✓	✓	✓	✓	✓	×
34	S: MSWIA: C :: 74: 20: 6	×	×	✓	✓	✓	✓	✓	✓
35	S: MSWIA: C :: 71: 20: 9	×	×	✓	✓	✓	✓	✓	×
36	S: MSWIA: C :: 68: 20: 12	×	×	✓	✓	✓	✓	✓	×
37	S: MD: C :: 82: 15: 3	×	×	✓	✓	✓	✓	✓	×
38	S: MD: C :: 79: 15: 6	×	×	✓	✓	✓	✓	✓	✓
39	S: MD: C :: 76: 15: 9	×	×	✓	✓	✓	✓	✓	×
40	S: MD: C :: 73: 15: 12	×	×	✓	✓	✓	✓	✓	×
41	S: MSWIA: MD :: 75: 20: 5	×	×	✓	✓	✓	✓	✓	×
42	S: MSWIA: MD :: 70: 20: 10	×	×	✓	✓	✓	✓	✓	×
43	S: MSWIA: MD :: 65: 20: 15	×	×	✓	✓	✓	✓	✓	✓
44	S: MSWIA: MD :: 60: 20: 20	×	×	✓	✓	✓	✓	✓	×
45	S: MSWIA: MD :: 80: 5: 15	×	×	✓	✓	✓	✓	✓	×
46	S: MSWIA: MD :: 75: 10: 15	×	×	✓	✓	✓	✓	✓	×
47	S: MSWIA: MD :: 70: 15: 15	×	×	✓	✓	✓	✓	✓	×
48	S: MSWIA: MD :: 65: 20: 15	×	×	✓	✓	✓	✓	✓	✓
49	S: MSWIA: MD :: 60: 25: 15	×	×	✓	✓	✓	✓	✓	×
50	S: MSWIA: MD :: 55: 30: 15	×	×	✓	✓	✓	✓	✓	×
51	S: MSWIA: MD: C :: 62: 20: 15: 3	×	×	×	✓	✓	✓	✓	✓
52	S: MSWIA: MD: C :: 59: 20: 15: 6	×	×	×	✓	✓	✓	✓	✓
53	S: MSWIA: MD: C :: 56: 20: 15: 9	×	×	×	✓	✓	✓	✓	✓
54	S: MSWIA: MD: PPF :: 64: 20: 15: 1	×	×	×	×	✓	✓	✓	✓
55	S: MSWIA: C: PPF::73: 20: 6: 1	×	×	×	×	✓	✓	✓	✓
56	S: MD: C: PPF::78: 15: 6: 1	×	×	×	×	✓	✓	✓	✓
57	S: MSWIA: MD: C: PPF :: 61: 20: 15: 3: 1	×	×	×	×	✓	✓	✓	✓

Where,

S- Clayey soil, MSWIA- Municipal solid waste incineration ash, MD- Marble dust, C- Cement, PPF- Polypropylene fiber

3.4 Experiments and procedure

3.4.1 Determination of Specific Gravity

Specific gravity of a material represents the average specific gravity of all its particles. It is determined by dividing the weight of the material in a given volume by the weight of a standard liquid occupying the same volume at the same temperature. The specific gravity values of clay, municipal solid waste incineration ash, marble dust, and cement were determined using the density bottle method, while the specific gravity of polypropylene fiber was determined using a Pycnometer, as per the ASTM code listed in Table 3.8. Only the portion of clay, municipal solid waste incineration ash, marble dust, and cement that passed through the 425 µm sieve after being oven-dried to 105°C was used in the experiment. A 50 ml density bottle (Figure 3.7) was cleaned, dried, and filled with distilled water before each test. The specific gravity was calculated for multiple specimens, and the results were reported for each test using 5-10 grams of soil sample (equation 3.1).

$$G_s = \frac{W_2 - W_1}{(W_4 - W_1) - (W_3 - W_2)} [3.1]$$

Figure 3.7: Density bottle

Figure 3.8: Pycnometer

3.4.2 Particle size distribution analysis

A study was conducted to assess the distribution of fine particles in the clayey soil through a particle size analysis. While definitions of clay particle size may vary globally, particles smaller than 2µm are generally classified as clay. Distinguishing between clay and silt particles can sometimes pose a challenge, underscoring the importance of understanding their origins and morphology. Clay-sized aggregates typically result from chemical weathering, whereas silt-sized particles form due to mechanical erosion. Hence, their compositions and sheet structures serve as distinguishing factors between clay and silt. The chapter includes an examination of the gradation curves of clay, municipal solid waste incineration ash, marble dust, and cement particles. The gradation curve of the clayey soil was analyzed using wet-sieve analysis and hydrometer analysis, depicted in Figures 3.9 and 3.10, respectively. For municipal solid waste incineration ash, marble dust, and cement, dry-sieve analysis was conducted after subjecting them to 105℃ for 24 hours, and the resulting curves are illustrated in Figure 3.11.

(a). Sample just after wetting with water

(b) Wet sieve sample after oven drying for 24 hours

Figure 3.9: Wet sieve analysis for particle size analysis of clayey soil

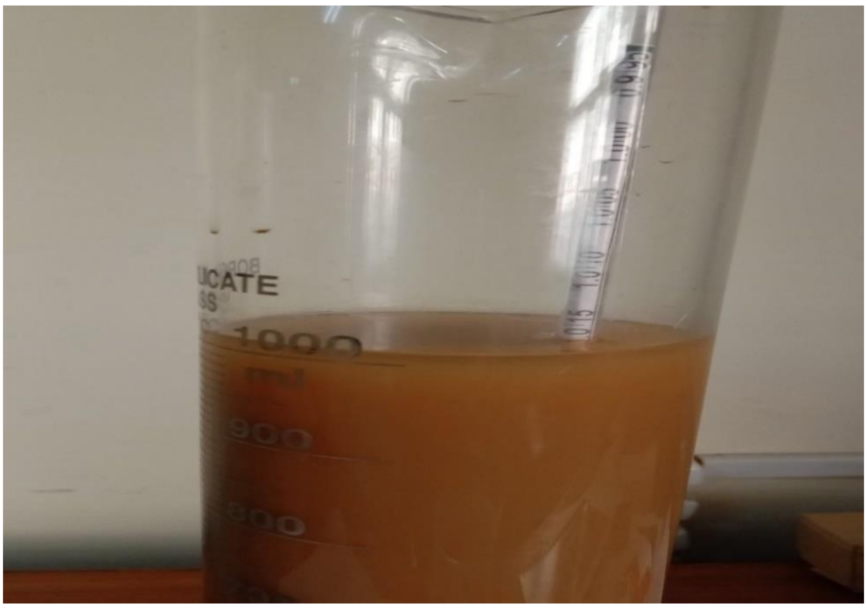


Figure 3.10: Hydrometer analysis for particle size analysis of soil

Figure 3.11: Sieve sets used for particle size analysis of admixtures

3.4.3 Differential free swell index test

The DFS test was conducted following the guidelines outlined in the IS standard. It quantifies the percentage of soil swell after immersion in distilled water without applying any external forces. Given the propensity of clayey soils to expand upon water absorption, it is imperative to assess the risk of soil swell prior to commencing construction activities. Preparing for the experiment involved cleaning all necessary equipment, and obtaining oven-dried soil that had passed through a 425µ sieve. Subsequently, 10 grams of soil sample mixes were distributed into two cylinders, each equipped with visible graduations (depicted in Figure 3.12). One cylinder was filled with water, while the other was filled with a non-polar liquid up to the 100 ml mark, chosen to serve as a benchmark for DFS calculations. In this instance, kerosene was selected as the non-polar fluid due to its non-absorbent nature, making it suitable for DFS determination. After thorough mixing of the liquid in both cylinders using a glass rod to expel any trapped air, the mixture was left undisturbed for 24 hours before conducting the final DFS measurements, as per equation 3.2.

$$\mathrm{DFS} = \frac{V_d - V_k}{V_k} \times 100\% \qquad [3.2]$$

Figure 3.12: DFS tests of admixtures and their combinations

3.4.4 Atterberg's Limit Test

The Atterberg's limit test was conducted to ascertain the water content and establish distinct boundaries between the liquid limit (LL), plastic limit (PL), and plasticity index (Ip) consistency states of clayey soil, both independently and when combined with different admixtures at varying proportions (Figure 3.13). The study encompassed clayey soil and its assorted combinations with municipal solid waste incineration ash, marble dust, and cement. In each instance, the soil, which had been oven-dried and sieved through a 425µm sieve, was utilized. The testing protocol for LL, PL, and Ip adhered to the specifications outlined in ASTM standards.

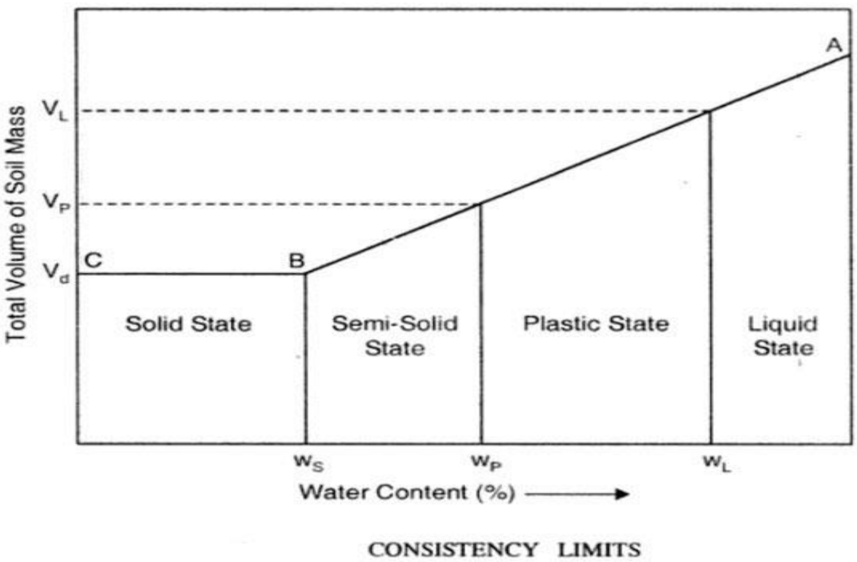


Figure 3.13: Consistency states of soil on variation in water content

3.4.4.1 Liquid Limit

The liquid limit serves as a crucial parameter in soil mechanics, offering insights into the behavior of fine-grained soils, particularly those with a high clay content. It denotes the moisture level at which the soil transforms from a plastic to a liquid state under incremental mechanical stress. To conduct the test, the drop cup was positioned 1 cm above the base following thorough cleaning and verification of functionality. Each test utilized 120 g of the sample comprising various blends. The admixtures were meticulously mixed with distilled water on a glass plate until achieving uniform consistency (Figure 3.14). Subsequently, a portion of the mixture was placed into the cup, and a symmetrical groove was created along the cup's centerline using a spatula. As the composite mixture's two segments met with a 12mm gap, the knob of the Casagrande apparatus was rotated at a predetermined rate specified in the protocol. The liquid limit of the composite specimen mix was determined by the water content corresponding to 25 blows (N). A semi-log graph was then plotted to accurately ascertain the water content corresponding to precisely 25 blows.

Figure 3.14: Liquid limit test on soil composite using Casagrande's apparatus

3.4.4.2 Plastic limit test

The plastic limit (PL) of clayey soil is determined by the percentage of water content, indicating the boundary between the plastic and semi-solid states of consistency. At this stage, the soil becomes plastic, retaining its shape upon drying. To achieve the desired consistency allowing the soil specimen to be rolled without adhering to the glass plate, 50g of soil specimen was placed on the plate, and water was added in smaller quantities compared to the liquid limit test. Within less than 2 minutes of applying strokes, the rolled specimen composite was further manipulated by applying palm or finger pressure, resulting in a diameter of 3.2 mm.

3.4.4.3 Plasticity Index

The numerical difference between a composite's LL and PL is known as its I_p (Equation 3.3). When any external force is applied, the composite materials respond plastically over the I_p-defined domain of water, showing no signs of rupture or breaking. High plasticity blends have the potential to distort in a variety of ways at a given load.

$$I_p = LL - PL \qquad [3.3]$$

3.4.5 Standard Proctor Test

This test was carried out in accordance with ASTM code. The test was carried out in a 100 mm diameter mould (d_m). In order to test different combinations of clayey soil and its various combinations with municipal solid waste incineration ash, marble dust, cement and polypropylene fiber, the weight of the mould (W_m) was obtained using a weighing machine, and its volume (V_m) was computed using Equation 3.4. For each test, a graduated cylinder was used to add a predetermined volume of distilled water to a container containing 2.5 kg of dry soil mixture. The prepared specimen was placed in the mould after it had been properly lubricated, in three layers to prevent lumps from forming, and each layer was tamped with 25 blows from a height of 12 inches using a hammer weighing 24.5 N. Before applying the subsequent 25 tamping, friction was generated by scratching the surface of the compacted soil in order to produce a monolithic soil specimen in the mould. The mould surface was cleaned of excess soil mixture, and the weight of the compacted soil mound was taken (W) (Figure 3.15). The final value of unit weight and dry unit weight was calculated using equations 3.5 and 3.6 respectively.

$$V_m = \pi \times d_m^2 \times h_m [3.4]$$

$$\gamma = \frac{W - W_m}{V_m} [3.5]$$

$$\gamma_d = \frac{\gamma}{1 + w} [3.6]$$

(a) Sieving sample from 4.75 mm sieve

(b) Mixing water to soil sample

(c) Cut on soil sample for proper bond with next layer

(d) Smoothening top surface before final weight

(e) Weighing compacted sample

Figure 3.15: Compaction tests procedure

Unit weight of the soil (γ) was computed (Equation 3.5), and from the sufficient number of tests carried out for a per set of soil and its combination mixes, a curvilinear graph was obtained by plotting moulding moisture content (w) against dry unit weight (γ_d). The value of γ_d was calculated from Equation 3.6.

3.4.6 Unconfined Compressive Strength Test

The Unconfined Compression Strength (UCS) test is a crucial laboratory procedure for determining the compressive strength of cohesive soils, particularly useful when cohesive properties dominate. To conduct the test, cylindrical soil samples are prepared, typically either from undisturbed soil cores or remolded soil. These samples are carefully trimmed to ensure flat and parallel ends, with accurate measurements of their dimensions recorded. Saturation of the samples may be necessary, achieved by submerging them completely in water for an appropriate duration (Figure 3.16). Once prepared, the samples are placed on the base plate of a compression testing machine, with porous stones or filter papers installed at both ends to facilitate water drainage during compression without allowing soil particles to escape. Initial measurements of sample height and diameter are recorded, along with the initial cross-sectional area. Axial loading is then applied at a constant rate until failure occurs, during which axial stress and strain are continuously monitored. The resulting stress-strain curve provides insights into the material's behavior under compression. After failure, the maximum axial stress reached before failure is noted as the unconfined compression strength. It's essential to ensure axial loading is centered to prevent eccentric loading, and multiple tests on different samples are performed to validate the results' reliability and repeatability. The axial strain was computed using equation 3. 7.

$$\varepsilon_1 = \frac{\Delta L}{L_o} \times 100 \qquad [3.7]$$

Calculations can be made to determine the average cross-sectional area (A) for the imposed maximum load (P_{max}) at failure using equation 3.8.

$$A = \frac{A_0}{(1-\frac{\varepsilon_1}{100})} [3.8]$$

Compressive stress (σ_c) was calculated as per equation 3.9.

$$\sigma_c = \left({P_{max}}/{A} \right) [3.9]$$

(a) Mould for preparation of UCS specimen

(b) Prepared soil + MSWIA mixed specimen

(c) Specimen after failure

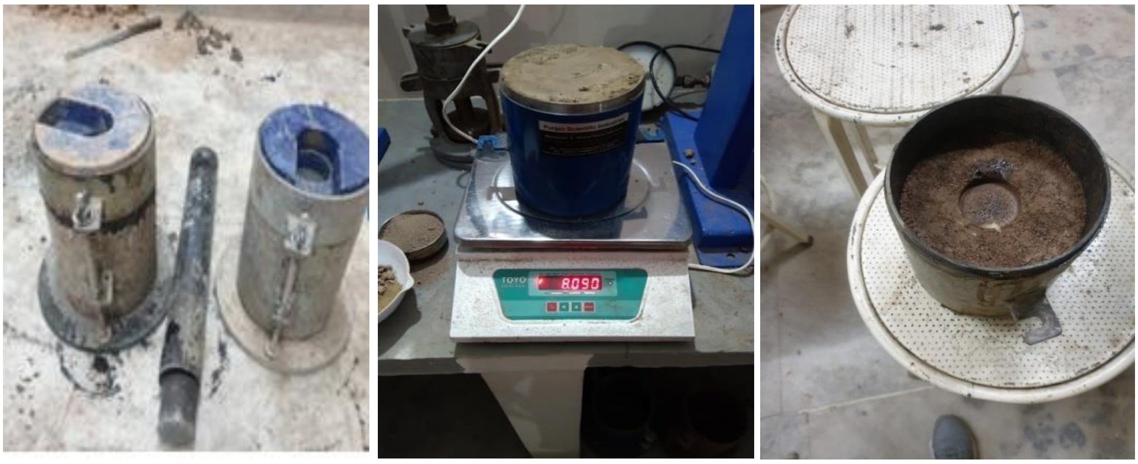
Figure 3.16: Various UCS specimen

3.4.7 California Bearing Ratio Test (CBR)

The California Bearing Ratio (CBR) test is a vital laboratory procedure extensively used in civil engineering to assess the strength and load-bearing capacity of subgrade soils and base course materials, particularly for road pavement design. The test begins with the preparation of a representative soil sample, typically obtained from the field or through laboratory compaction methods (Figure 3.17). The sample is carefully prepared and compacted into a standard cylindrical mold with specified dimensions using a mechanical compactor or manual rammer. Various moisture contents and densities may be tested to simulate different field conditions. Once the sample is compacted to the desired density, a plunger is positioned on top of the specimen, and a standard load is applied through the plunger at a controlled rate, typically 1.25 mm/min. This load causes the plunger to penetrate into the soil specimen, and the penetration depth is continuously measured. The load versus penetration curve is recorded throughout the test. The test continues until the penetration reaches a specified depth, commonly (equation 3.10) and 5 mm (equation 3.11) respectively. At this point, the applied load and penetration depth are recorded, and the CBR value is calculated using the following formula: CBR = (Test Load / Standard Load) × 100. The standard load refers to the load required to achieve the same penetration in a standard material, typically crushed rock or a well-graded aggregate. The CBR value provides a relative measure of the soil's strength and load-bearing capacity compared to this standard material. The CBR test is crucial for pavement design as it helps engineers determine the suitability of soils and base materials for supporting road pavements under varying traffic loads. It allows them to assess the soil's ability to withstand deformation and support the pavement structure without excessive settlement or rutting.

$$\text{CBR calculation for 2.5mm} = \frac{Load\ at\ 2.5mm\ penetration}{Standard\ Load} * 100 \qquad [3.10]$$

$$\text{CBR calculation for 5mm} = \frac{Load\ at\ 5mm\ penetration}{Standard\ Load} * 100 \qquad [3.11]$$



(a) CBR mould and rammer (b) Weighing CBR mould filled with sample before final testing (c) CBR specimen after failure

Figure 3.17: CBR tests procedure

3.4.8 Permeability test

The variable head permeability test is a standard laboratory procedure utilized to determine the hydraulic conductivity or permeability of soil samples, particularly granular soils like sands and gravels. The test begins with the preparation of a representative soil sample, ensuring it fits the dimensions of the permeameter apparatus and is devoid of any extraneous material (Figure 3.18). Following sample preparation, the permeameter apparatus is assembled, with porous stones or filter papers placed at both ends of the sample to prevent soil particles from escaping. Saturation of the soil sample is crucial, achieved by fully submerging it in water or gradually adding water until saturation is attained, ensuring the removal of all air bubbles. Initial measurements of the sample dimensions and water level in the reservoir are recorded to establish baseline parameters. Water flow through the sample is initiated by connecting the reservoir to the permeameter apparatus, and measurements of water level changes at regular intervals are recorded. These measurements, along with time intervals, are used to calculate hydraulic conductivity using Darcy's law. Data analysis involves plotting a graph of head loss versus time to determine the coefficient of permeability.The coefficient of permeability can be calculated by the equation 3.12:

$$k = 2.303\,\frac{(al)}{(At)}\log_{10}\frac{h_1}{h_2} \qquad [3.12]$$

where,

k = coefficient of permeability in cm/sec,

a = area of stand pipe in cm^2,

l = length of sample in cm,

A = area of sample in cm^2,

t = time required for headdrop in seconds,

h_1 = initial head, and

h_2 = final head.

Figure 3.18: Falling head permeability test

3.5 Design of pavement using IIT-PAVE

3.5.1 Determination of resilient modulus of subgrade

Resilient modulus, which is calculated from CBR data, is the measure of its elastic performance. According to IRC 37: 2012, it is computed as per equations 3.13 and 3.14 and is a key factor in the design of pavements:

$$MR\ (MPa) = 10.0 * (CBR)\ \text{for}\ CBR \leq 5 \qquad [3.13]$$

$$M_R\ (MPa) = 17.6 * (CBR)^{0.64}\ \text{for}\ CBR > 5 \qquad [3.14]$$

3.5.2 Thickness of flexible pavement

Table 3.11: Input values assumed for flexible pavements

Input Name	Value
Carriageway width after construction	Single lane
Classification of Road	Major District Road (MDR)
Design Life (n)	15
Growth Rate (t)	5%
Terrain	Hilly
Construction Period	1 year
Length of flexible pavement to be constructed in one year	38 km

3.5.3 Design Approach and Criteria

The three types of pavement distress caused by repeated traffic application are considered:

- Horizontal tensile strain at the bituminous layer's base.
- Vertical compressive strain at the subgrade's top.
- Pavement deformation within the bituminous layer.
- It is assumed that the deformation within the bituminous layer is controlled by meeting the mix design requirements.

3.5.4 Design Approach and Criteria according to IRC

- The pavement was modelled as a three-layer structure, and stresses and strains were computed at critical locations using the linear elastic structural model.

3.5.5 Failure Criteria

Tensile tension that has accumulated at the base of the asphaltic concrete layer is what causes fatigue cracking. If 20% of a pavement's surface is damaged, the pavement is deemed to have failed. Rutting failure results from a development of too much compressive strain at the top of the subgrade layer.

3.6 X-Ray diffraction test

Conducting X-ray tests on clay involves meticulous procedures to analyze its mineral composition and structure. X-ray diffraction (XRD) and X-ray fluorescence (XRF) are primary techniques used for this purpose. For XRD, a representative clay sample is first prepared by grinding it into a fine powder, which is then evenly spread onto a sample holder. This holder is then placed in the X-ray diffractometer where X-rays interact with the clay's crystal lattice, producing a diffraction pattern. Analysis of this pattern helps identify specific clay minerals and quantify their relative abundances. In contrast, XRF analysis requires calibration of the instrument using reference materials before loading the powdered clay sample (Figure 3.19). X-rays excite the sample, causing it to emit characteristic fluorescent X-rays, which are then detected and measured to determine elemental concentrations. Both techniques offer insights into the mineralogical and chemical composition of clay, aiding in various applications from geotechnical engineering to material science research. Careful adherence to procedures and interpretation of results ensures accurate and reliable analysis of clay samples using X-ray methods.

Figure 3.19: X'Pert Pro XRD testing machine

3.7 Summary

The chapter comprises briefing of the materials used, i.e., clay, municipal solid waste incineration ash, marble dust, cement and polypropylene fiber which were procured from various regions and industries. The chapter discusses many experiments that were used to carry out the stabilization studies by using standard codes in order to improve the strength characteristics of clayey soils. This chapter is composed of a number of related formulas that were used to compute the final outcome. The materials figures and the results of many experiments have also been provided. The next chapter deals with the result analysis of all the experiments.

Chapter 4

Result Analysis

4.1 Introduction

The previous chapter detailed the index and engineering properties of clay, municipal solid waste incineration ash, marble dust, cement, and polypropylene fiber. It also outlined the methodology for achieving optimal mixes and conducting tests such as specific gravity, grain size distribution curve, liquid limit, plastic limit, differential free swell, compaction, unconfined compressive strength, split tensile strength, California bearing ratio, permeability, and X-ray diffraction. The subsequent paragraphs will delve into the experimental findings and the impact of incorporating additives like municipal solid waste incineration ash, marble dust, cement, and polypropylene fiber on the engineering characteristics of clay.

4.2 Particle size distribution analysis

Figure 4.1 displays a comparison of particle size distribution curves for clay, municipal solid waste incineration ash, and marble dust. These curves indicate that both municipal solid waste incineration ash and marble dust contain larger particles compared to clayey soil. Marble dust particles are categorized as fine sand, while clayey soil primarily consists of clay-sized particles. The particle size distribution curve for municipal solid waste incineration ash demonstrates uniform grading, while marble dust exhibits poor grading. Clayey soil's particle size distribution highlights a significant presence of clay-sized particles.

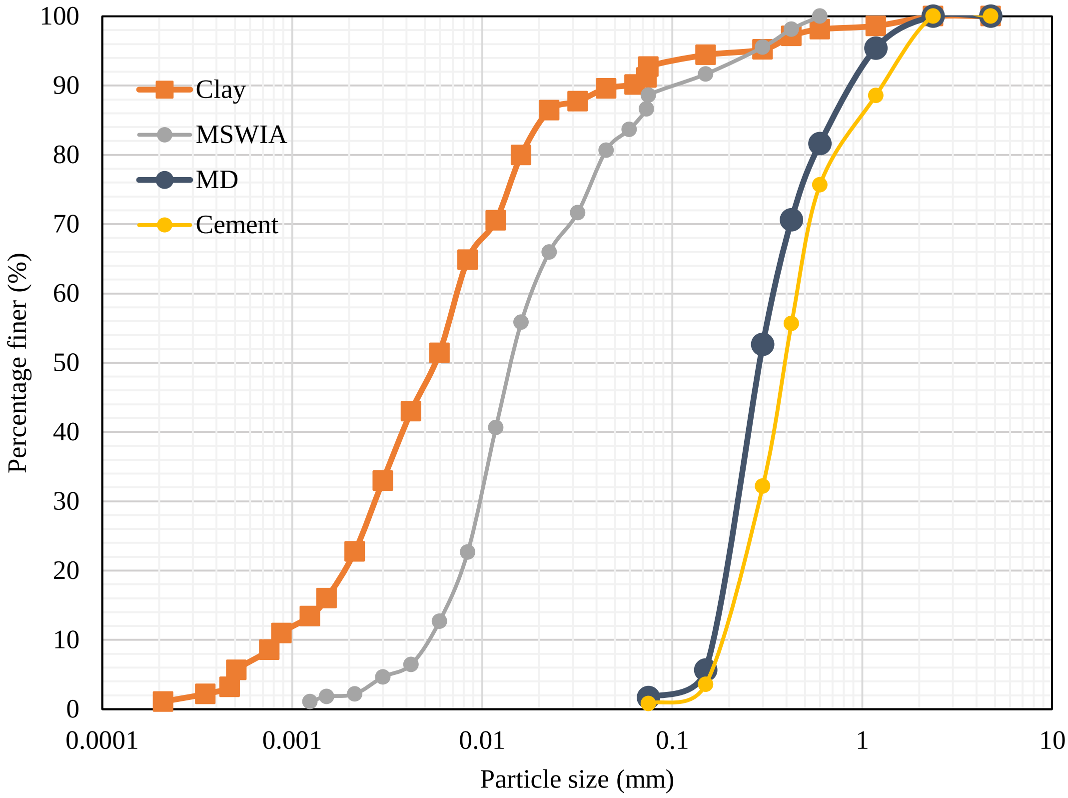


Figure 4.1: Comparison of particle size distribution curve of clay, municipal solid waste incineration ash and marble dust

4.3 Differential free swell

The subsequent sections describe the impact of adding various admixtures, including clay, municipal solid waste incineration ash, marble dust, and cement, both individually and in combination with each other, on the differential free swell of clay.

4.3.1 Clay-municipal solid waste incineration ash mix

To assess the differential free swell of the composite, municipal solid waste incineration ash is mixed with clayey soil at varying percentages: 5%, 10%, 15%, 20%, 25%, and 30%. Figure 4.2 illustrates the relationship between the percentage of municipal solid waste incineration ash and the resulting differential free swell, depicted graphically.

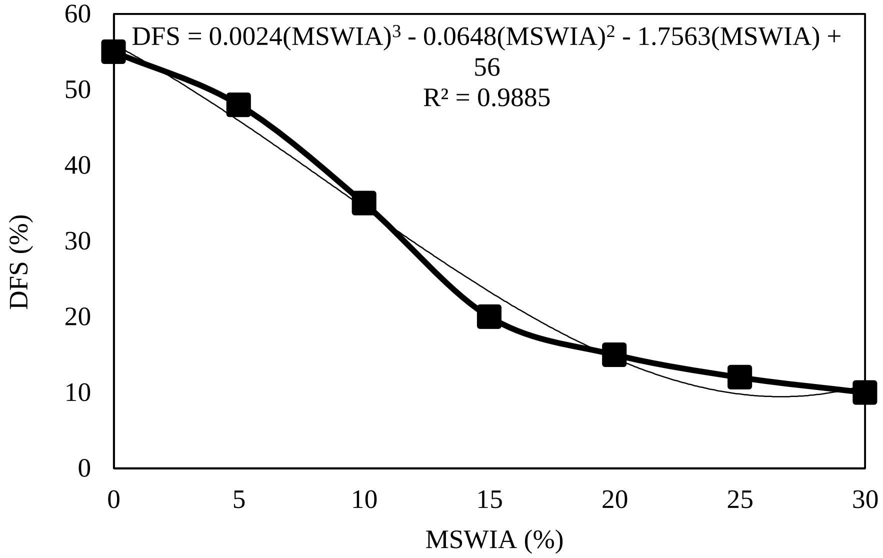


Figure 4.2: Variation in DFS of clay with addition of municipal solid waste incineration ash

The soil's initial differential free swell of 55% decreases to 15% with the addition of municipal solid waste incineration ash at a content of 20%. Beyond this concentration, further increases in municipal solid waste incineration ash content have minimal impact on clayey soil swelling. These findings align well with previous conclusions (Baruah et al., 2020), suggesting that the reduction in differential free swell is likely due to decreased specific surface area and the replacement of swelling clay with non-swelling, pozzolanic material. This reduction could also be attributed to the higher silica content in municipal solid waste incineration ash and the replacement of monovalent clay cations with multivalent cations from the ash. The relationship between municipal solid waste incineration ash content and clay-MSWIA mix differential free swell is modeled polynomially, with 'DFS' representing differential free swell and 'MSWIA' representing municipal solid waste incineration ash percentage, as:

$$DFS = 0.0024(MSWIA)^3-0.0648(MSWIA)^2-1.7563(MSWIA)+56\ [R^2 = 0.9885] \quad [4.1]$$

4.3.2 Clay-marble dust mix

Marble dust is introduced to clayey soil at proportions of 5%, 10%, 15%, and 20%, and the resulting differential free swell is measured. Figure 4.3 illustrates the impact of marble dust addition on the differential free swell of clayey soil. The differential free swell decreases with increasing marble dust content, reaching a plateau at 15% marble dust. Therefore, 15% marble dust content could be identified as the point of marble dust stabilization.

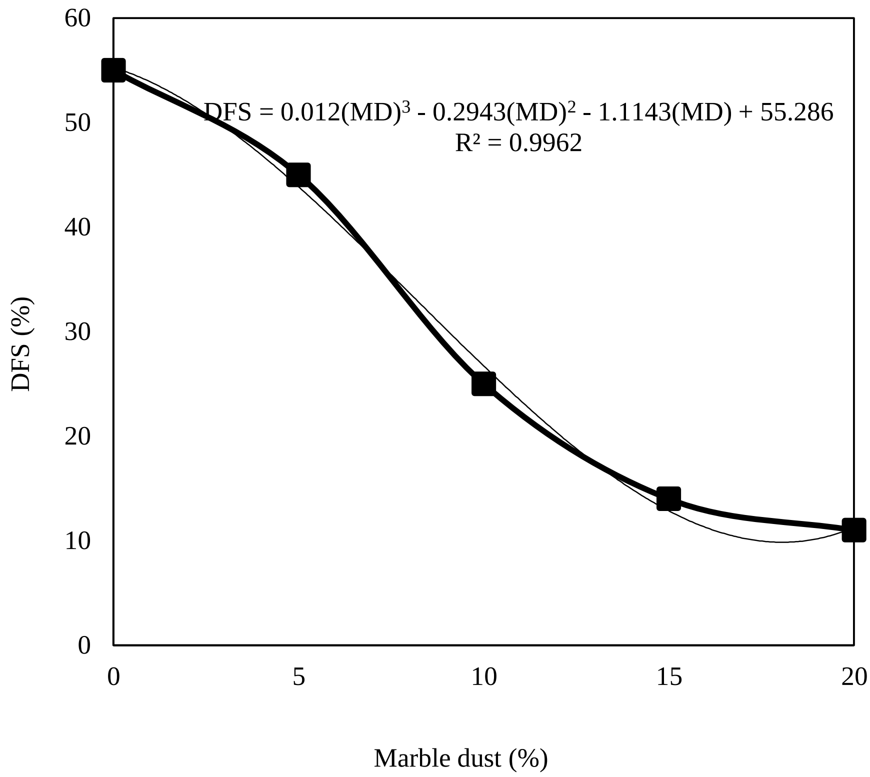


Figure 4.3: Variation in DFS of clay with addition of marble dust

The reduction in DFS value on adding MD may be due to the replacement of finer particles of clayey soil with coarser particles of MD leading to the decrease in surface activity and may also be due to the non-swelling nature of MD. These results are in agreement with the conclusions of many researchers (Phanikumar 2009, Dash and Husssain 2012, Panjaitan 2014). A polynomial regression model is employed to depict the correlation between the percentage of marble dust in the clay-marble dust mixture and the resulting differential free swell. In this model, the differential free swell is denoted by 'DFS', while the percentage of marble dust is represented by 'MD'.

$DFS = 0.012(MD)^3 - 0.2943(MD)^2 - 1.1143(MD) + 55.28$ [$R^2 = 0.9962$] [4.2]

4.3.3 Clay-cement mix

To assess the influence of cement on soil free swell, different proportions of cement, namely 3%, 6%, 9%, and 12%, are incorporated. Figure 4.4 illustrates the impact of cement addition on the differential free swell of soil. As cement content increases, the soil's differential free swell decreases, reaching a value of 20% at 9% cement content. However, beyond this point, the differential free swell of the clay-cement mixture begins to increase again. Therefore, 9% cement content could be identified as the cement stabilization threshold.

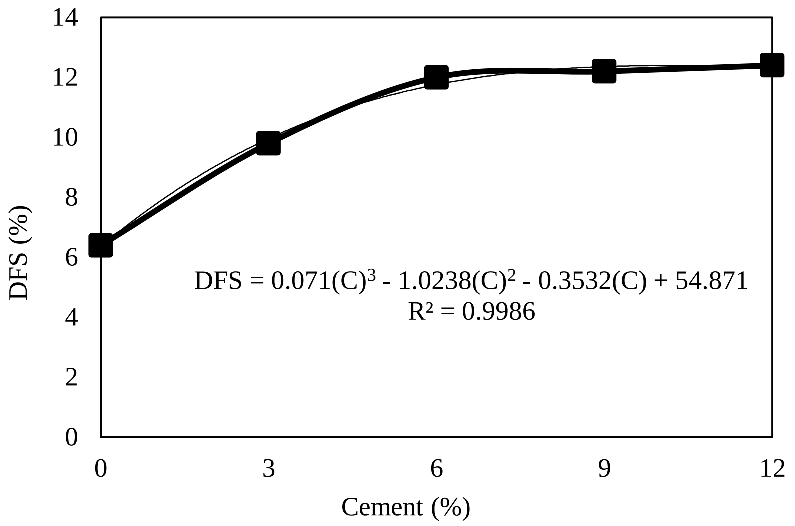


Figure 4.4: Variation in DFS of clay with addition of cement

The decrease in differential free swell upon addition of cement is due to flocculation of clay particles causing increase in particle size and the resulting decrease in specific surface. These results are in agreement with the conclusions of past research (Bhardwaj and Sharma 2020). The increase in the differential free swell with further addition of cement content occurs because of the presence of quick lime (Table 3.8) in the soil-cement mix. The variation of differential free swell on addition of cement in various percentages is represented by polynomial equation in which differential free swell is represented by 'DFS' and cement percentage are represented by 'C' as:

$$DFS = 0.071(C)^3 - 1.0238(C)^2 - 0.3532(C) + 54.871 \ [R^2 = 0.9986] \quad [4.3]$$

4.3.4 Clay-municipal solid waste incineration ash-cement mix

Cement is added to 80% clay: 20% cement mix in percentages of 3, 6, 9 and 12% and the differential free swell is determined. A graph is plotted between the differential free swell and percentage of cement in clay-municipal solid waste incineration ash mix as shown in Figure 4.5. The differential free swell is zero for 80% clay: 20% municipal solid waste incineration ash on adding 9% cement. Afterwards the differential free swell increases to 4% at 12% cement. These results are in agreement with the conclusions of many researchers (Zhang 2002, Phanikumar 2009, Athanasopoulou 2014). The reduction in differential free swell up to 9% cement is due to the reaction occurring between the cement and clay- municipal solid waste incineration ash which results in formation of granular particles free from swelling whereas, increase in differential free swell beyond 9% occurs due to presence of quick lime reacting with water resulting in increase in differential free swell.

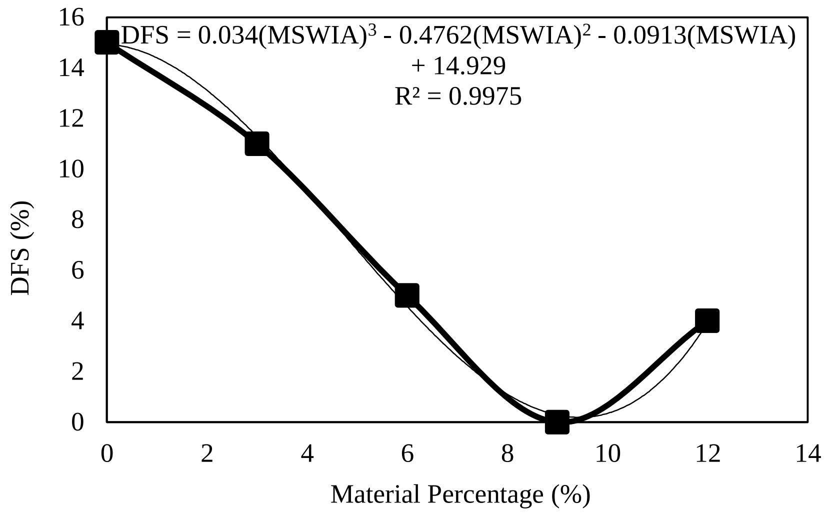


Figure 4.5: Variation in DFS of clay-MSWIA mix with addition of cement

4.3.5 Clay-marble dust-cement mix

Cement is added to 85% clay: 15% marble dust mix in percentages of 3, 6, 9 and 12% and the differential free swell is determined. A graph is plotted between differential free swell and percentage of cement added to clay-marble dust mix as shown in Figure 4.6. The differential free swell of 85% clay: 15% marble dust is zero at 9% cement content after which it starts increasing upon addition of more cement. The increase in differential free swell with addition of cement more than 9% occurs due to presence of quick lime. Quick lime present in the mix reacts with water forming the hydroxides which results in increase in volume of clay thereby increasing differential free swell. The similar results have been present in the past on adding marble dust to clayey soil by various researchers (Baig et al. 2014; Singh and Yadav 2014).

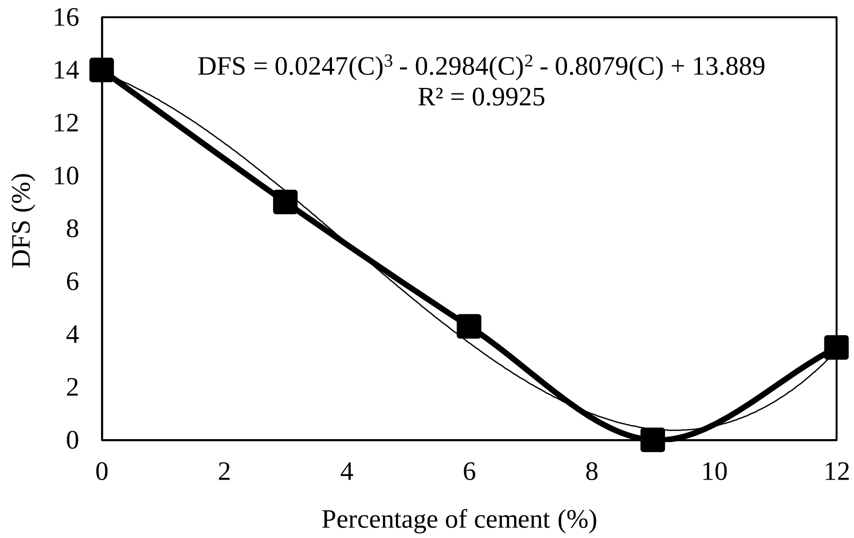


Figure 4.6: Variation in DFS of clay-Marble dust mix with addition of cement

The variation of differential free swell of clay-marble dust-cement mix with percentage of cement is represented by a polynomial given below in which differential free swell is represented by ‘DFS’ and percentage of cement by ‘C’.

$$DFS = 0.0247(C)^3 - 0.2984(C)^2 - 0.8079(C) + 13.889 \; [R^2 = 0.9925] \qquad [4.4]$$

4.3.6 Clay-municipal solid waste incineration ash-marble dust-cement mix

The differential free swell tests are conducted with addition of cement to clay-municipal solid waste incineration ash-marble dust mix; 59% clay: 20% municipal solid waste incineration ash: 15% marble dust composite. A graph is plotted between the percentage of cement and differential free swell as shown in Figure 4.7.

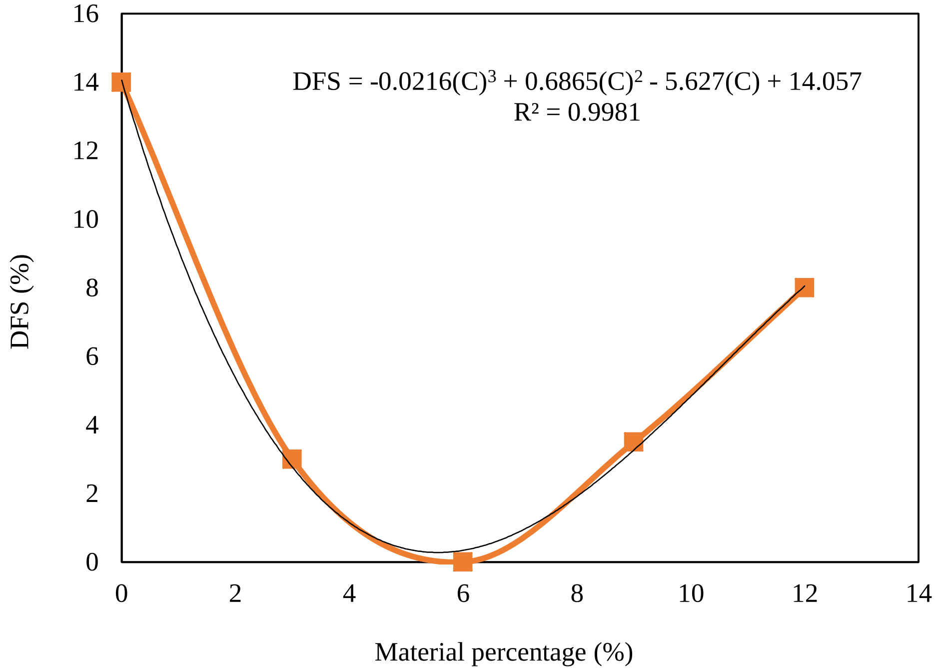


Figure 4.7: Variation in DFS of clay-municipal solid waste incineration ash-marble dust mix with addition of cement

The differential free swell is zero up to 6% cement content after which it increases with further addition of cement. The increase in differential free swell is due to presence of quick lime reacting with water causing increase in the volume of soil. Thus, 6% cement is required to be added to soil-municipal solid waste incineration ash-marble dust mix whereas addition of cement more than this percentage remains as free cement. The variation of differential free swell of clay-municipal solid waste incineration ash-marble dust mix with addition of cement can be represented by a polynomial, in which differential free swell is represented as ‘DFS’ and percentage of cement as ‘C’:

$$DFS = -0.0216(C)^3 + 0.6865(C)^2 - 5.627(C) + 14.057 \; [R^2 = 0.9981] \qquad [4.5]$$

4.4 Impact of different additives on pH value of Soil

The effect of addition of municipal solid waste incineration ash, marble dust and cement on pH of clay is described in subsequent sections.

4.4.1 Clay-municipal solid waste incineration ash mix

pH tests are conducted on clayey soil mixed with 5, 10, 15, 20, 25 and 30% of municipal solid waste incineration ash. The variation of pH of clay with addition of municipal solid waste incineration ash is plotted as shown in Figure 4.8. pH of clayey soil is 6.4 which is slightly acidic and pH of municipal solid waste incineration ash is 8.9 being slightly alkaline. When municipal solid waste incineration ash is added to clay, pH of the composite increases and becomes neutral (pH = 7) at 20% municipal solid waste incineration ash content and increases with further increase in municipal solid waste incineration ash content. The results showing the increase in pH of soil with addition of municipal solid waste incineration ash are in good agreement with the conclusions drawn by a few researchers (Cetin and Pehlivan 2007).

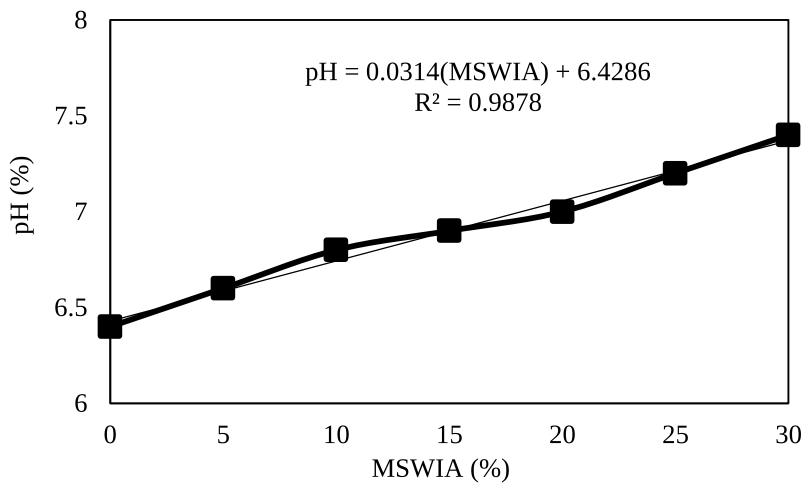


Figure 4.8: pH of clay-municipal solid waste incineration ash mixes

For the purpose of fixation in clay-municipal solid waste incineration ash mix, 20% municipal solid waste incineration ash content may be selected. The increase in pH of the mix upon addition of municipal solid waste incineration ash is due to the higher pH of municipal solid waste incineration ash compared to that of soil. The variation of pH of clay with addition of municipal solid waste incineration ash is represented by a polynomial given below in which percentage of municipal solid waste incineration ash is represented by 'MSWIA':

$$pH = 0.0314(MSWIA) + 6.4286 \quad [R^2 = 0.9878] \qquad [4.6]$$

4.4.2 Clay-marble dust mix

Marble dust is added to clayey soil in various percentages such as 5, 10, 15 and 20% and its pH is determined. The graph is plotted between pH and percentage of marble dust as shown in Figure 4.9. The addition of marble dust to clay tends to increase pH of the composite with increasing marble dust content. The pH of the composite is neutral (i.e. 7) for 15% marble dust content and therefore this may be selected as the fixation point. The increase in pH of the mix with addition of marble dust is due to higher pH of marble dust (pH = 8.4) as compared to that of clay.

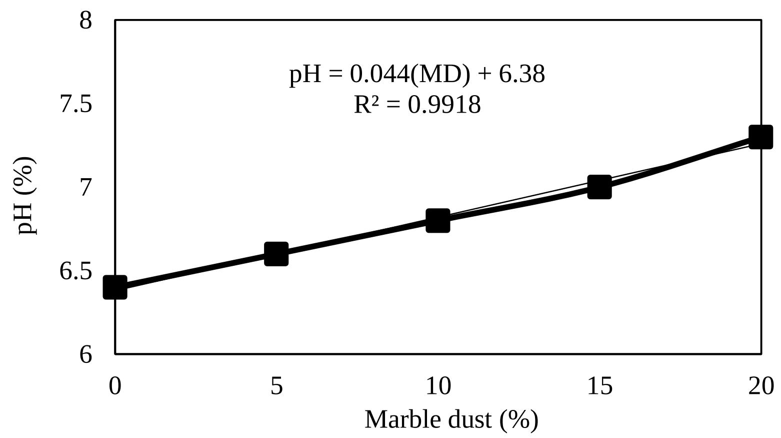


Figure 4.9: pH of clay-marble dust mixes

The effect of addition of marble dust on the pH of clay-marble dust mix is represented by the equation given below in which marble dust content is represented as 'MD':

$$pH = 0.044(MD) + 6.38 \quad [R^2 = 0.9918] \qquad [4.7]$$

4.4.3 Clay-cement mix

pH of clay-cement mixes increases with increase in cement content as shown in Figure 4.10. The increase in pH with addition of cement occurs due to the alkaline nature of cement. The maximum pH of 12 (pH of commercial cement used in this study, which contains some impurities) was achieved at 6% cement content in clay-cement mixture and hence this may be used for fixation in soil stabilization. ASTM-C977 (1992) indicates that in soil stabilization using cement, if the pH is 12.40 or higher, the lowest percentage that gives a pH of 12.40 is the optimum cement content. As the cement is added to clay, reaction takes place between cement and soil particles resulting in cation exchange up to certain cement content and the pH attains maximum value after which further dosage of cement does not cause any increase in pH (Davidson 1965; Yong and Ouhadi 2007; Sharma et al 2012). Thus 6% cement content may be fixed as optimum cement content for soil stabilization.

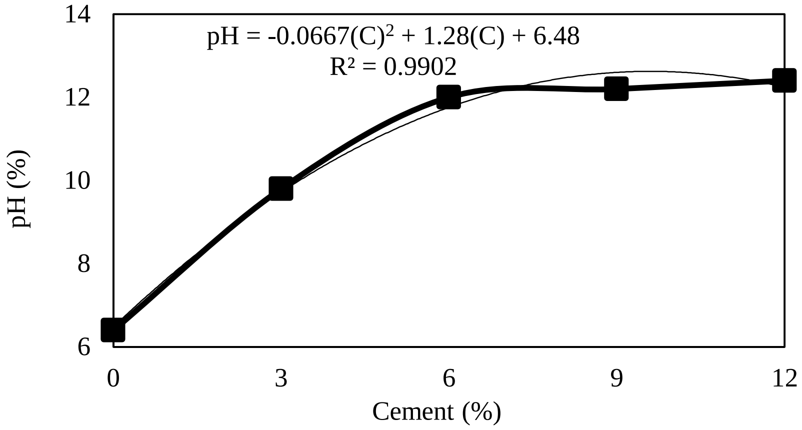


Figure 4.10: pH of clay-cement mixes

4.5 Compaction characteristics

The effect of addition of different additives such as municipal solid waste incineration ash, marble dust and cement individually and in combination with each other on compaction characteristics of clay is discussed in subsequent sections.

4.5.1 Clay-municipal solid waste incineration ash mix

The optimum moisture content and maximum dry density of clay used in this study are 22.2% and 1.74 g/cc respectively. The compaction tests are conducted on clay mixed with various percentages of municipal solid waste incineration ash to determine the optimum mix for stabilization of clayey soil. Municipal solid waste incineration ash is added to clay in 5, 10, 15, 20, 25 and 30% and the compaction tests were carried out. The compaction characteristics of the composites are shown in Figure 4.11.A comparison of the compaction characteristics of different composites with that of clay reveals that the maximum dry density as well as optimum moisture content decreases with increase in municipal solid waste incineration ash content. It can be seen from Figure 4.11 that on adding 20% MSWIA to clayey soil, the MDD value reduced from 1.74g/cc to 1.662g/cc, and the OMC value decreased from 22.2% to 16.5%. The further addition of MSWIA up to 30% showed a very little decrease in MDD value though OMC value reduced considerably to 15.8% at 30% MSWIA content. The reduction in MDD value on adding MSWIA may be due to the lower specific gravity of MSWIA to that of clayey soil and may also be due to the agglomeration of clay particles due to cation exchange thus increasing the volume. The reduction in OMC value may be attributed to the very lower OMC value of MSWIA (12.3%) to that of clayey soil. The results are in good agreement with the observations reported by several researchers (Sezer et al 2006, Chauhan et al 2008, Eskioglou and Oikonomou 2008).

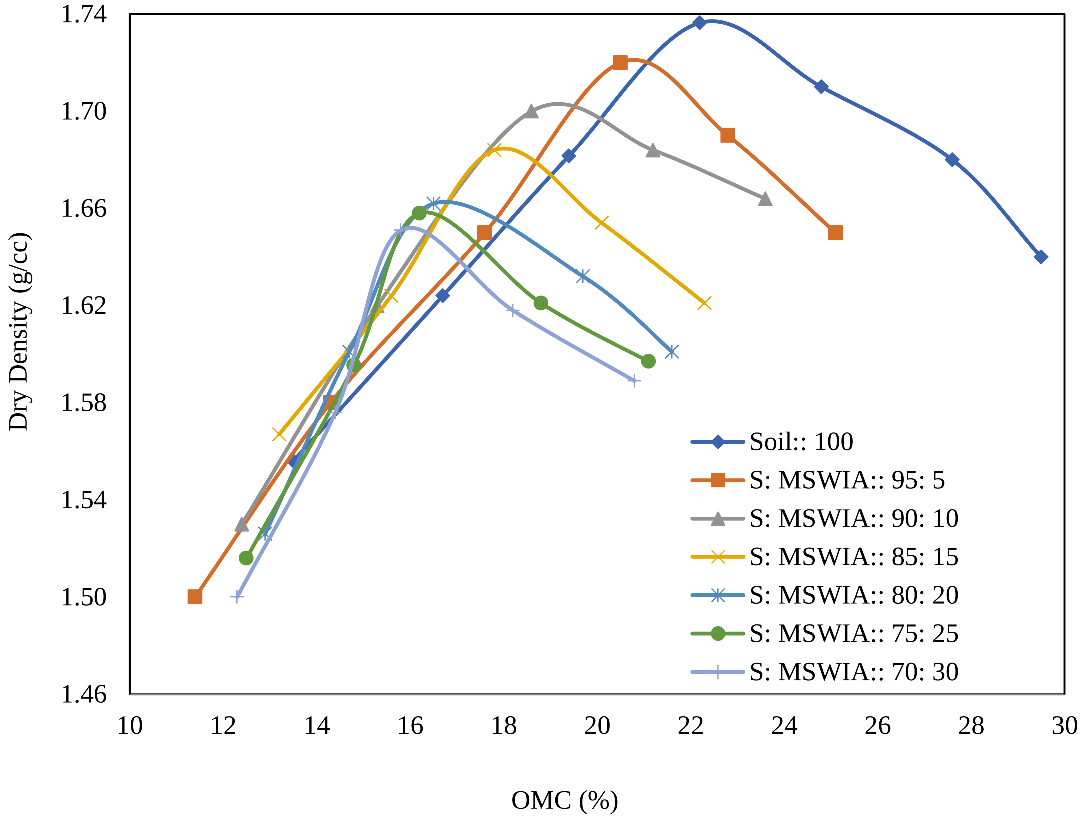


Figure 4.11: Compaction curves of clay and clay-municipal solid waste incineration ash mixes

4.5.2 Clay-marble dust mix

Compaction tests were conducted on clayey soil added with marble dust in percentages of 5, 10, 15 and 20% and compaction characteristics are compared as shown in Figure 4.12. On adding marble dust content in varying amounts from 5-20% in clayey soil, the MDD value increased from 1.74g/cc to 1.86g/cc and OMC value reduced from 22.2% to 17.8% at 15% marble dust content (Figure 4.12). On further increasing marble dust content to 20%, the same trend of variation was observed but the rate of increment of MDD value and rate of decrement of OMC value was very less. The increase in MDD value on increasing marble dust content may be due to the higher specific gravity of marble dust than that of clay; whereas, the reduction in OMC with increased marble dust content may be due the lesser OMC value of marble dust thus requiring less water. The decrease in optimum moisture content is due to the presence of fine sand particles in marble dust which possess lower specific surface area compared to that of clay particles. The decrease in maximum dry density is due to less specific gravity of marble dust compared to that of clay and also due to flocculation/ aggregation of un-reacted cement as flocculation/aggregation provides resistance to densification.

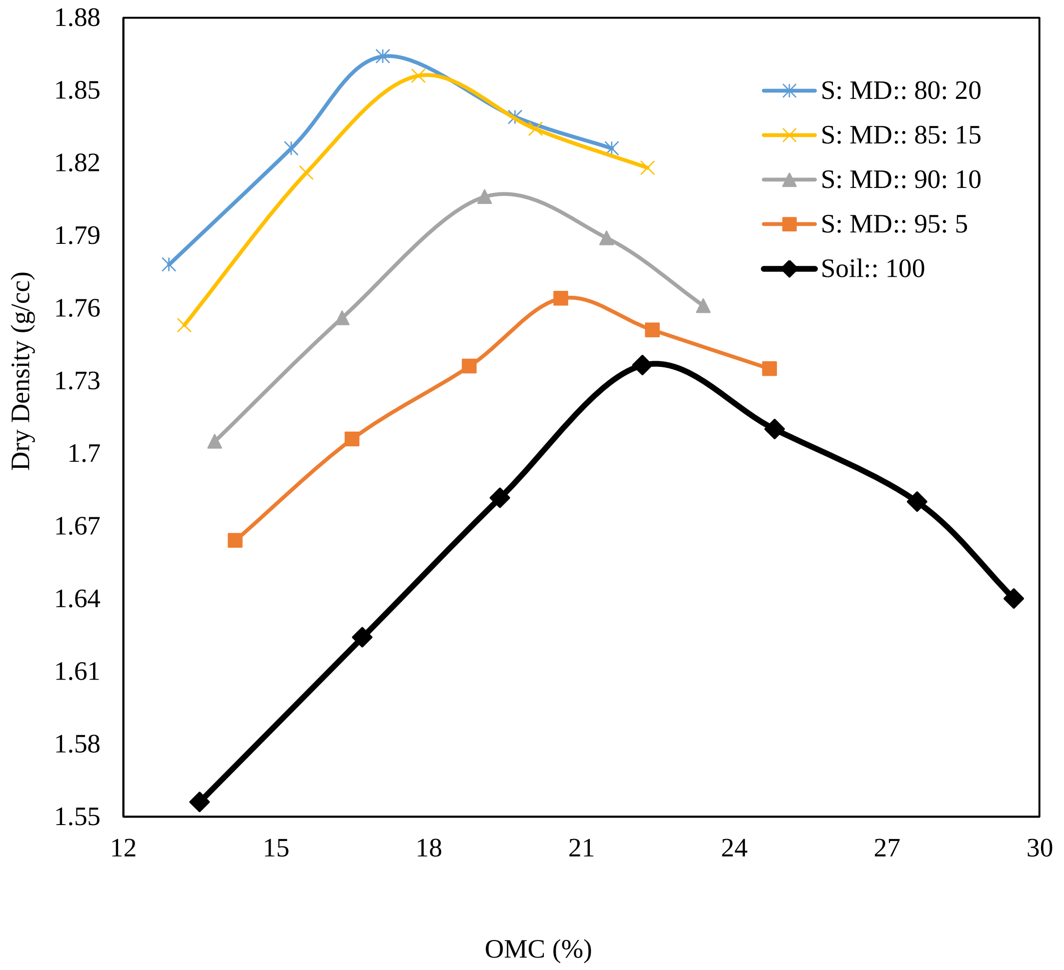


Figure 4.12: Variation of OMC and MDD with varying marble dust content in clayey soil

.4.5.3 Clay-cement mix

Cement is added to clayey soil in percentages of 3, 6, 9 and 12% and the compaction tests are conducted. The effect of addition of cement on compaction characteristics of clayey soil is shown in Figure 4.13. The addition of cement to clayey soil in varying amounts from 3-12% increased the OMC from 22.2% to 24.2% and increased MDD from 1.74g/cc to 1.82g/cc on adding 9% cement (Figure 4.13). The further addition of cement to in clayey soil up to 12% decreased the MDD value to 1.80g/cc. The increase in OMC value on adding cement may be due to the pozzolanic reaction occurring between cement and clay particles. The increase in optimum moisture content may also be due to water affinity upon addition of cement and also due to the pozzolanic reaction between clay particles and the cement. The improvement in MDD value may be due to the higher specific gravity of cement compared to that of clay. The results are in good agreement with the past few research works (Kavak and Akyarli 2007; Harichane et al. 2012; Bhardwaj and Sharma 2020).

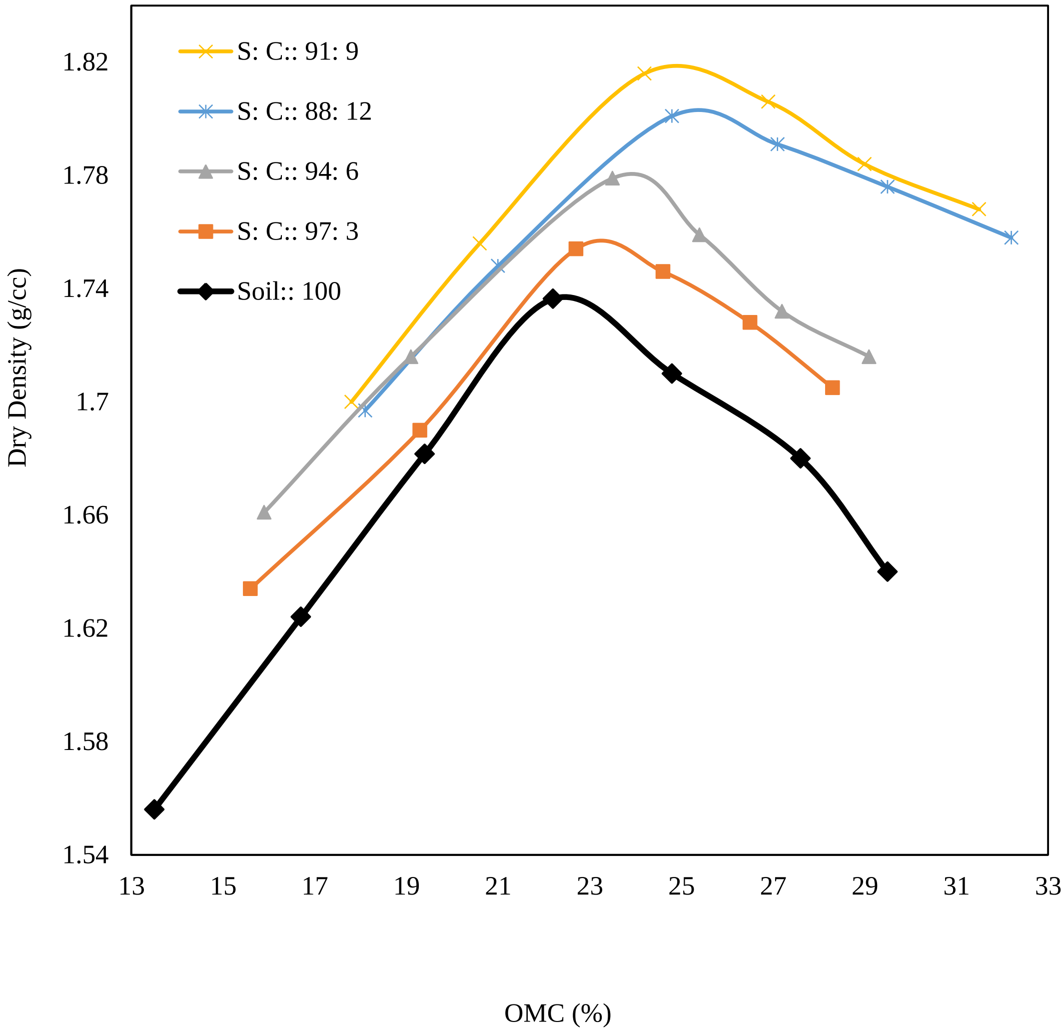


Figure 4.13: Compaction curves of clay and clay-cement mixes

4.5.4 Clay-polypropylene mix

Figure 4.14 shows the effect of fiber inclusion on compaction characteristics of soil in terms of compaction curves under standard compaction effort. Based on standard Proctor test results, the MDD of unreinforced soil was marginally decreased to 1.691g/cc from 1.74g/cc with an increase in PP fiber content from 0–1.5%. The slight reduction in MDD with some variation in OMC could be attributed to the low specific gravity of PP fiber, coupled with PP fiber and soil particles' physical interaction which might lead to different micro-structural arrangements. On the other hand, the OMC value of fiber-reinforced soil samples does not show a significant change with fiber addition (falling in the range of (22.2-21%) due to the inert nature of PP fiber with no water absorption ability of fiber particles. Researchers observed similar trends in MDD and OMC values of soil samples reinforced with various percentages of PP fiber (Ramasamy &Arumairaj, 2013; Soğancı, 2015; Viswanadham et al., 2009).

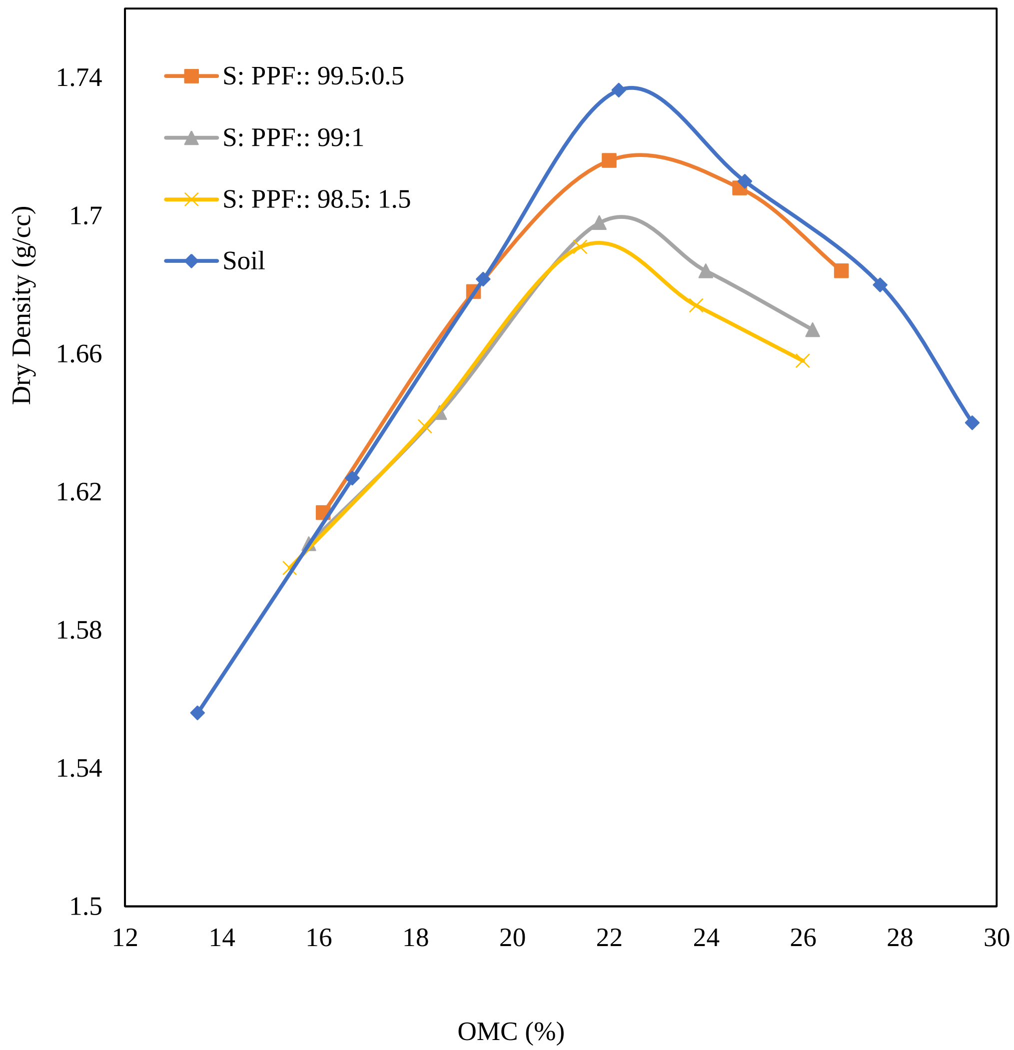


Figure 4.14: Compaction curves of clay and clay-PPF mixes

4.5.5 Clay-municipal solid waste incineration ash-cement mix

The addition of cement in varying amount from 3-12% in an optimized mix of clay and MSWIA (20%) shown in Figure 4.15 revealed that the MDD value increased from 1.662 g/cc to 1.796 g/cc and the OMC value increased from 16.5% to 18.4% at 6% cement content. The further addition of cement (9% and 12%) showed same results but the increase in both the values was very less. The increase in MDD value on adding cement may be due to the higher specific gravity of cement compared to clay and MSWIA particles both. The little increase in OMC value may be due to the pozzolanic reaction occurring between cement and clay particles and also due to the very higher OMC of cement compared to that of MSWIA. Researchers observed similar trends in MDD and OMC values of soil samples reinforced with various percentages of MSWIA (Liang et al. 2020).

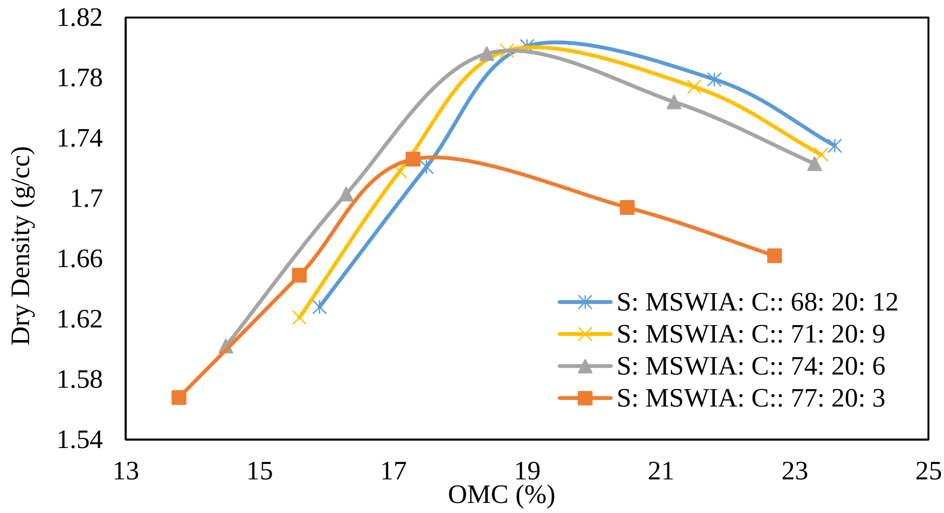


Figure 4.15: Variation of OMC and MDD with varying cement content in Clay: MSWIA mixture

4.5.6 Clay-marble dust-cement mix

The addition of cement in varying amount from 3-12% in an optimized mix of clay and MD (15%) shown in Figure 4.16 revealed that the MDD value increased from 1.856 g/cc to 1.924 g/cc and the OMC value increased from 17.8% to 19.5% at 6% cement content. The further addition of cement (9% and 12%) showed same results but the increase in both the values was very less. The increase in MDD value on adding cement to soil and marble dust mixture may be due to the higher specific gravity of both cement and marble dust compared to clay. The little increase in OMC value may be due to the pozzolanic reaction occurring between cement and soil: marble dust mixtures and also due to the very higher OMC of cement compared to that of marble dust.

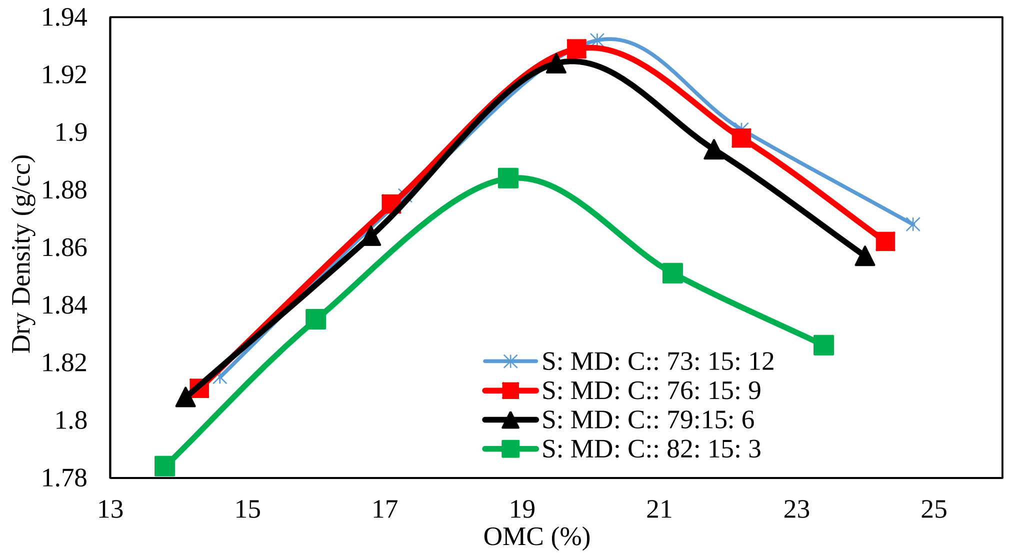


Figure 4.16: Variation of OMC and MDD with varying cement content in Clay: CDW mixture

The addition of higher cement content (3-12%) in the optimized mix of clay with 20% MSWIA and 15% MD, as shown in Figures 4.15 and 4.16 respectively, is necessary due to the complexity of soil-additive interactions and the need for enhanced performance. While 2-3% cement may suffice for simpler stabilization scenarios, the presence of MSWIA and marble dust requires more cement to ensure proper binding and effective pozzolanic reactions, leading to improved strength, compaction, and reduced swelling. The higher cement content also supports the creation of cementitious compounds necessary for long-term stability, especially in subgrades exposed to heavy loads, moisture fluctuations, and severe environmental conditions. In cases where the clay has high plasticity (PI = 28%) and a high free swelling index (FSI = 55%), a greater proportion of cement ensures further reduction of plasticity and swelling potential, converting expansive clay minerals into stable forms. This results in a more durable, stronger, and less permeable soil matrix, capable of maintaining its improved properties over time, ensuring long-term subgrade performance.

4.5.7 Clay-municipal solid waste incineration ash-polypropylene fiber mix

The addition of polypropylene fiber in varying amount from 0.5-1.5% in an optimized mix of clay and municipal solid waste incineration ash (20%) shown in Figure 4.17 revealed that the MDD value decreased from 1.662 g/cc to 1.646 g/cc and the OMC value reduced from 16.5% to 15.8% at 1% polypropylene fiber content but the reduction in OMC is very less. The further addition of polypropylene fiber (1.5%) showed same results but the decrease in both the values was very less. The minor reduction in MDD including some fluctuation in OMC might be due to the low specific gravity of PP fiber, along with the physical interaction of PP fiber and soil particles, which could result in various micro-structural arrangements. The OMC value of fiber-reinforced soil samples, on the other hand, did not exhibit a significant change with fiber inclusion (lying in the band of (16.5-15.7%) owing to the inert nature of PPF with no water absorption ability of fiber particles. Researchers discovered comparable patterns in MDD and OMC values of soil samples enhanced with varying percentages of PP fiber (Ramasamy &Arumairaj, 2013; Soanc, 2015; Viswanadham et al., 2009).

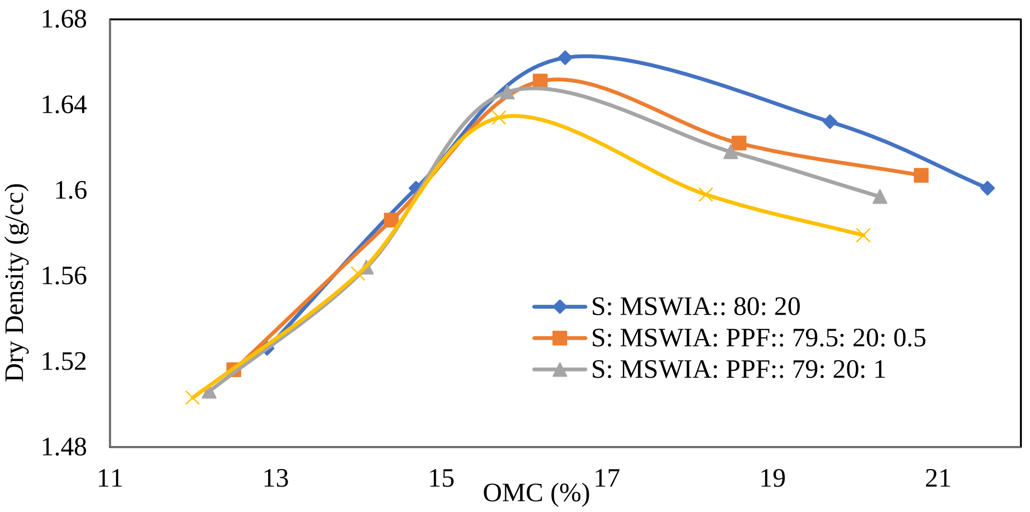


Figure 4.17: Variation of OMC and MDD with varying polypropylene fibre content in clay-MSWIA mixture

4.5.8 Clay-marble dust-polypropylene fiber mix

The addition of polypropylene fiber in varying amount from 0.5-1.5% in an optimized mix of clay and MD (15%) shown in Figure 4.18 revealed that the MDD value decreased from 1.856 g/cc to 1.812 g/cc and the OMC value showed a minor change from 17.8% to 17.5% at 1% polypropylene fiber content. The further addition of polypropylene fiber (1.5%) showed same results but the decrease in both the values was very less. The decrease in MDD, as well as some variability in OMC, might be related to the low specific gravity of PP fibre, as well as the physical contact between PPfiber and soil particles, which could lead in a variety of micro-structural formations. Due to the inert nature of PPF and the lack of water absorption ability of fibre particles, the OMC value of fibre mixed soil samples did not change much with fibre inclusion (lying in the range of (17.8-17.3%). The researchers identified identical patterns in the MDD and OMC values of soil samples that had been improved with varied amounts of Polypropylene fibers (Ramasamy &Arumairaj, 2013; Soanc, 2015; Viswanadham et al., 2009).

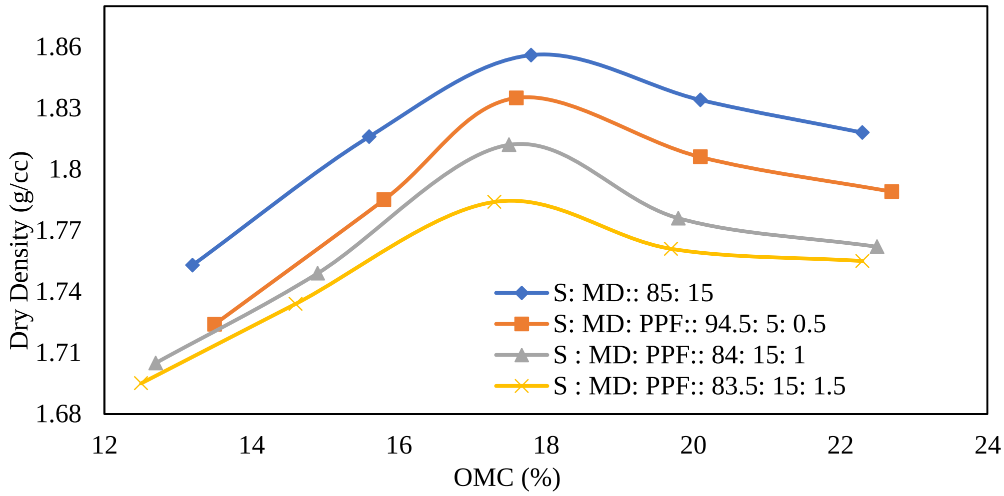


Figure 4.18: Variation of OMC and MDD with varying polypropylene fiber content in Clay: marble dust mixture

4.5.9 Clay-cement-polypropylene fiber mix

The addition of polypropylene fiber in varying amount from 0.5-1.5% in an optimized mix of clay and cement (6%) shown in Figure 4.19 revealed that the MDD value decreased from 1.779 g/cc to 1.735 g/cc and the OMC value showed a minor increment from 23.5% to 23.9% at 1% polypropylene fiber content. The further addition of polypropylene fiber (1.5%) showed same results but the decrease in both the values was very less. The decrease in MDD along with some variability in OMC might be attributed to PP fiber's low specific gravity, as well as physical interaction between PP fiber and soil particles, which could result in a range of micro-structural compositions. The OMC value of fiber mixed soil samples did not change greatly with fiber inclusion (lying in the range of (23.5-24.2%) due to the inert nature of PPF and the lack of water absorption capacity of fiber particles). The researchers discovered similar trends in the MDD and OMC values of soils improved with varying concentrations of polypropylene fibers (Ramasamy &Arumairaj, 2013; Soanc, 2015; Viswanadham et al., 2009).

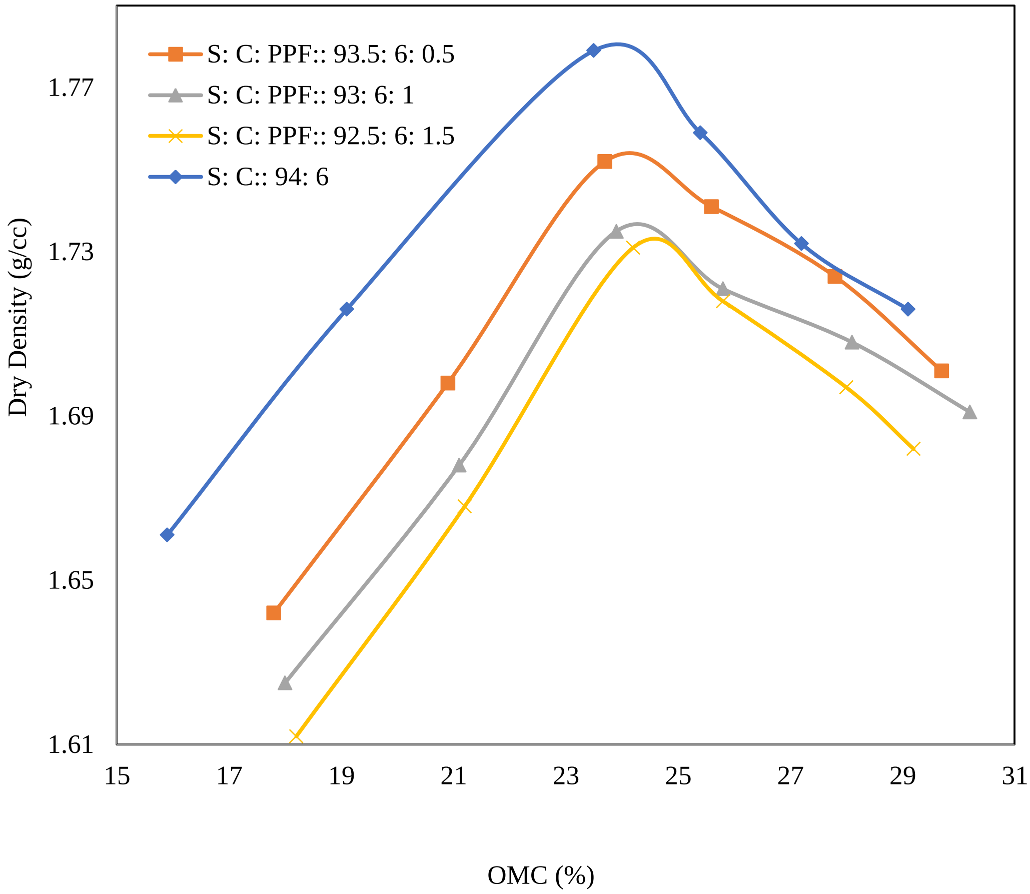


Figure 4.19: Variation of OMC and MDD with varying polypropylene fiber content in clay: cement mixture

4.5.10 Clay-municipal solid waste incineration ash-marble dust mix

The addition of marble dust in varying amount from 5-20% in an optimized mix of clay and MSWIA (20%) shown in Figure 4.20 revealed that the MDD value increased from 1.662 g/cc to 1.898 g/cc and the OMC value decreased from 16.5% to 14% at 15% marble dust content. The further addition of marble dust (20%) showed a minor increment in MDD value and very low reduction in OMC value. The rise in MDD value with rising marble dust percentage may be owing to marble dust's greater specific gravity than clay, whilst the decrease in OMC with increasing marble dust percentage may be related to marble dust's lower OMC value, needing less water. The inclusion of tiny sand particles in marble dust, which have a smaller specific surface area than clay particles, contributes to the drop in optimal moisture content.

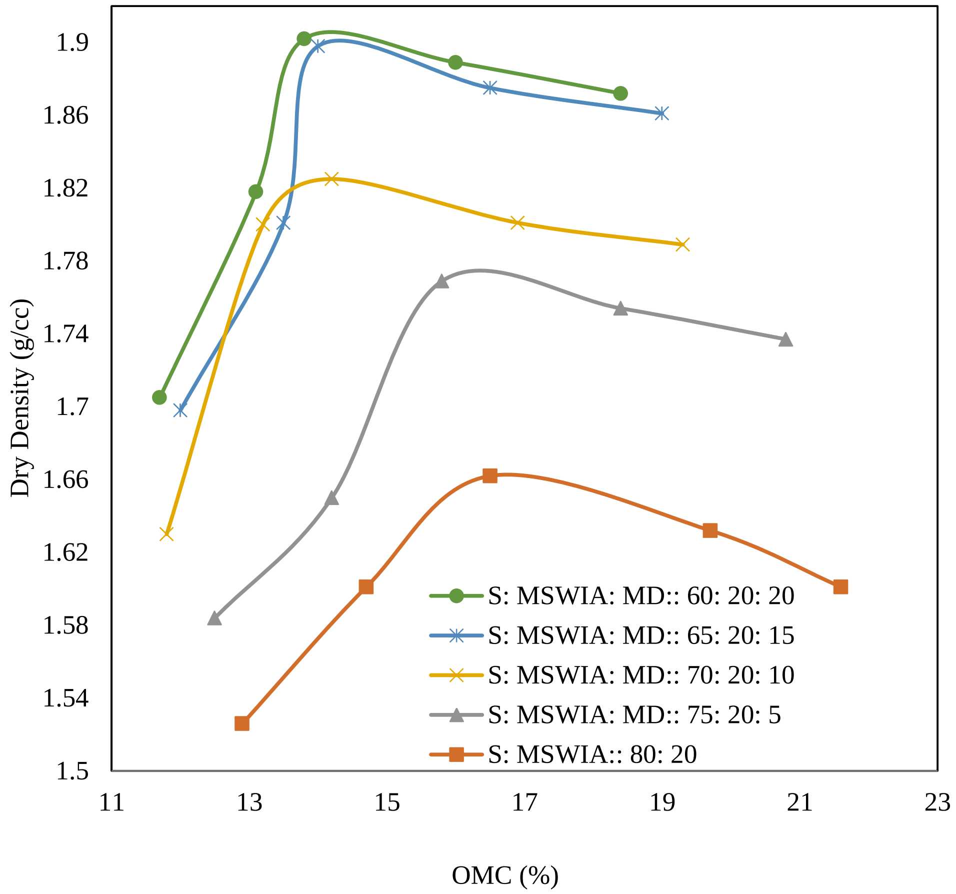


Figure 4.20: Variation of OMC and MDD with varying marble dust content in clay: municipal solid waste incineration ash mixture

4.5.11 Clay-municipal solid waste incineration ash-marble dust-cement mix

The addition of cement in varying amount from 3-9% in an optimized mix of clay, municipal solid waste incineration ash (20%) and marble dust (15%) shown in Figure 4.21 revealed that the MDD value increased from 1.898 g/cc to 1.978 g/cc and the OMC value increased from 14% to 17.1% at 6% cement content. The further addition of cement (9%) showed very minute change in OMC and MDD value. The increase in MDD value on adding cement to soil, municipal solid waste incineration ash and marble dust mixture may be due to the higher specific gravity of all cement, municipal solid waste incineration ash and marble dust compared to clay. The increase in OMC value may be due to the pozzolanic reaction occurring between cement and soil: municipal solid waste incineration ash: marble dust mixtures and also due to the very higher OMC of cement compared to that of municipal solid waste incineration ash and marble dust.

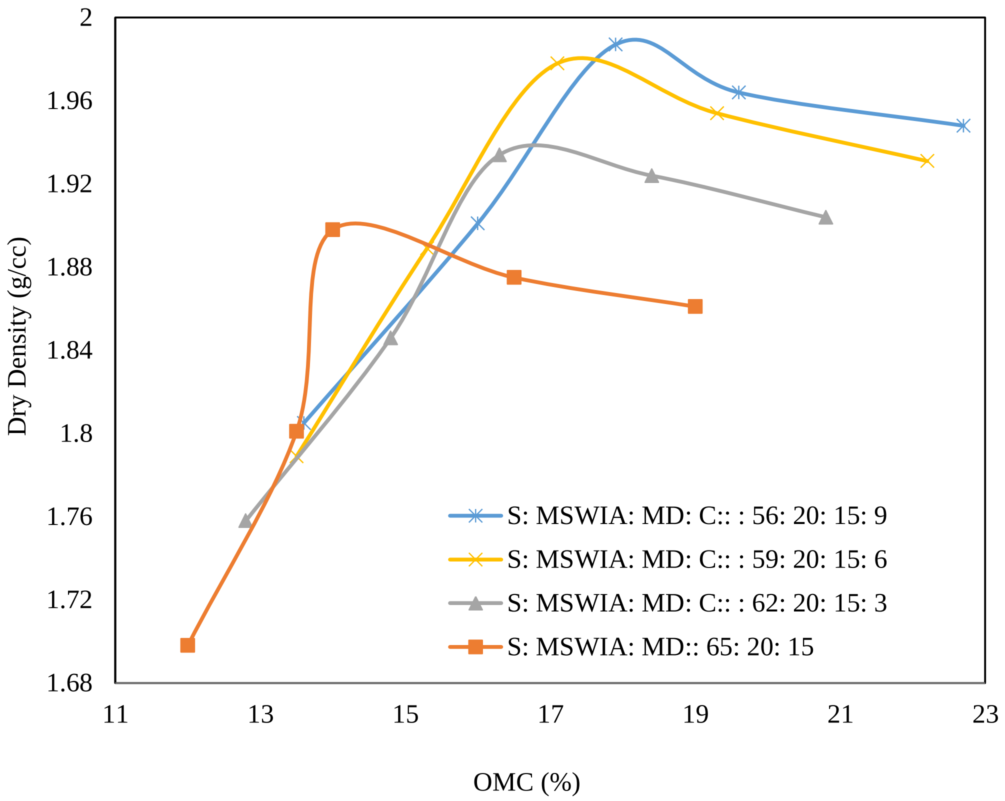


Figure 4.21: Variation of OMC and MDD with varying cement content in clay: municipal solid waste incineration ash: marble dust mixture

4.5.12 Clay-municipal solid waste incineration ash-marble dust-cement-polypropylene fiber mix

The addition of polypropylene fiber in varying amount from 0.5- 1.5% in an optimized mix of clay, municipal solid waste incineration ash (20%), marble dust (15%) and cement (3%) shown in Figure 4.22 revealed that the MDD value decreased from 1.934 g/cc to 1.918 g/cc and the OMC value increased very little from 16.3% to 16.8% at 1% polypropylene fiber content. The further addition of polypropylene fiber (1.5%) showed a comparable reduction in MDD value though OMC remained almost same. The decrease in MDD along with some variability in OMC might be attributed to PP fiber's low specific gravity, as well as physical interaction between PP fiber and soil particles, which could result in a range of micro-structural compositions. The OMC value of fiber mixed soil samples did not change greatly with fiber inclusion (lying in the range of (16.3-17.1%) due to the inert nature of PPF and the lack of water absorption capacity of fiber particles). The researchers discovered similar trends in the MDD and OMC values of soils improved with varying concentrations of polypropylene fibers (Ramasamy &Arumairaj, 2013; Soanc, 2015; Viswanadham et al., 2009).

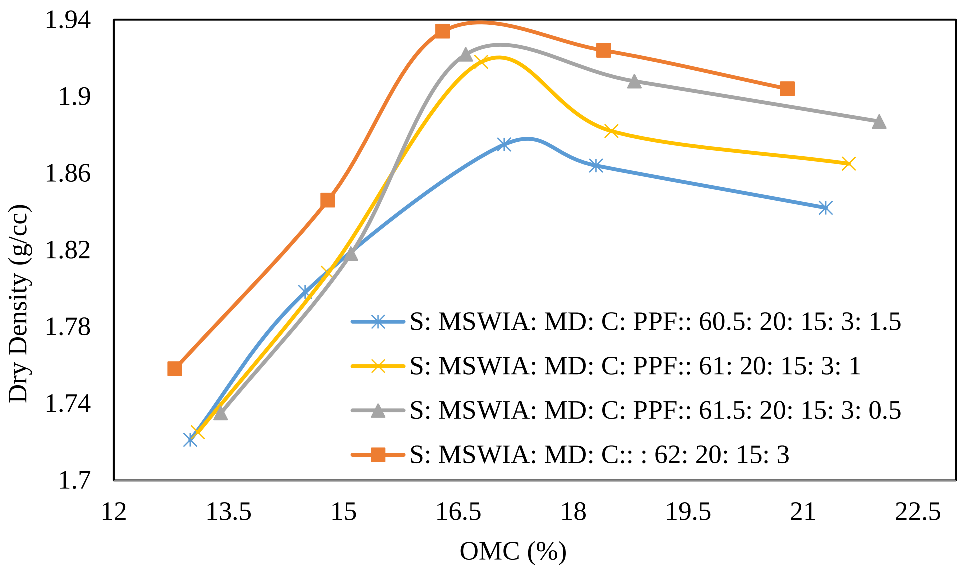


Figure 4.22: Variation of OMC and MDD with varying polypropylene fiber content in clay: municipal solid waste incineration ash: marble dust: cement mixture

The use of additives like MSWI ash, marble dust, cement, and polypropylene fiber is essential for improving clayey soil with a plasticity index (PI) of 28%, optimum moisture content (OMC) of 22%, and a free swelling index (FSI) of 55%. High PI indicates significant plasticity, leading to instability. MSWI ash reduces plasticity and increases strength through pozzolanic reactions, while marble dust acts as a filler, further lowering plasticity. Both additives also reduce OMC by improving compaction. Cement enhances strength and reduces moisture demand through hydration and pozzolanic reactions. A high FSI indicates expansive behavior, which MSWI ash and cement mitigate by altering mineralogy and reducing swelling potential. Marble dust further reduces swelling by diluting expansive minerals. Polypropylene fibers reinforce the soil, limiting deformation during swelling and shrinkage, enhancing stability and load-bearing capacity. Together, these additives address plasticity, moisture sensitivity, and expansive behavior, making the soil more suitable for construction.

4.6 Unconfined compressive strength tests

Unconfined compressive strength tests were conducted on clayey soil at different curing periods. The effect of curing period on the unconfined compressive strength of soil is shown in Figure 4.23. The 3 days unconfined compressive strength is 84kN/m^2 which increases to 175kN/m^2 for 7 days curing, further increases to 302kN/m^2 at 28 days of curing and further more increases to 350 kN/m^2 at 56 days of curing period. The strength is increasing with curing period but the material tends to be brittle.

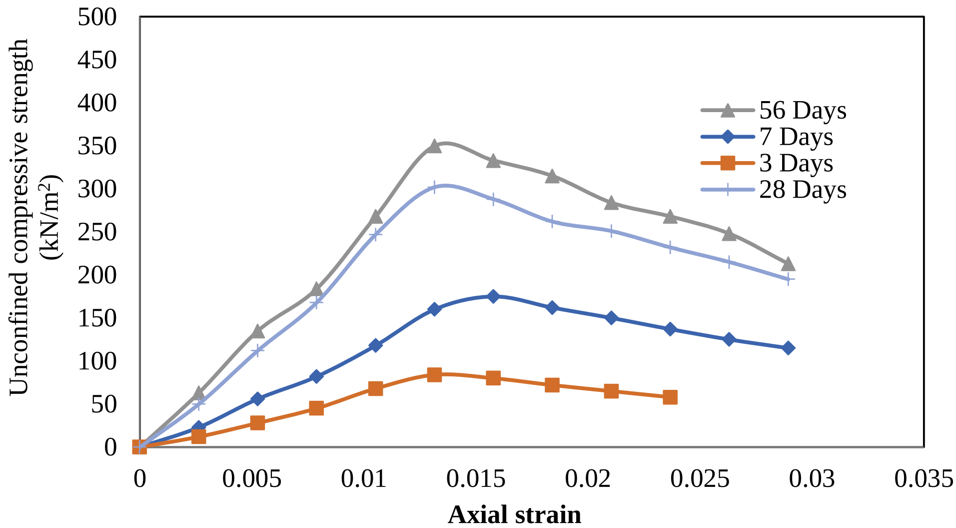


Figure 4.23: Variation in UCS of clay with curing period

In the following sub-sections, the stress- strain curves for a curing period of 28 days for various material combinations are presented from Figures 4.24- 4.35.

4.6.1 Clay-municipal solid waste incineration ash mix

Municipal solid waste incineration ash is added in 5, 10, 15, 20, 25, 30% to the clayey soil and unconfined compressive strength tests are conducted after 28 days to obtain the optimum mix for soil stabilization. The effect of municipal solid waste incineration ash on unconfined compressive strength is shown in Figure 4.24. The 28 days unconfined compressive strength of soil is 302kN/m^2 which on addition of municipal solid waste incineration ash increases to 415kN/m^2 for 5% municipal solid waste incineration ash, 522kN/m^2 for 10% municipal solid waste incineration ash,660kN/m^2 for 15% municipal solid waste incineration ash, 815 kN/m^2 for 20% municipal solid waste incineration ash, 874 kN/m^2 for 25% municipal solid waste incineration ash and 890 kN/m^2 for 30% municipal solid waste incineration ash content. Although, the strength is more in case of 30% municipal solid waste incineration ash content the rate of increase in strength from 20% to 30% municipal solid waste incineration ash content is less compared to the increase in strength from 15% to 20% municipal solid waste incineration ash content. Hence, 20% municipal solid waste incineration ash may be considered as the optimum municipal solid waste incineration ash content for stabilization of clayey soil. The increase in UCS value on adding MSWIA may be due to the pozzolanic reaction between MSWIA and clay particles and also may be due to the frictional resistance offered by MSWIA particles. A similar increase in UCS value on adding MSWIA has been reported earlier (Ashango and Patra 2016; Liu et al. 2019; Kolias et al 2005; Sezer et al 2006).

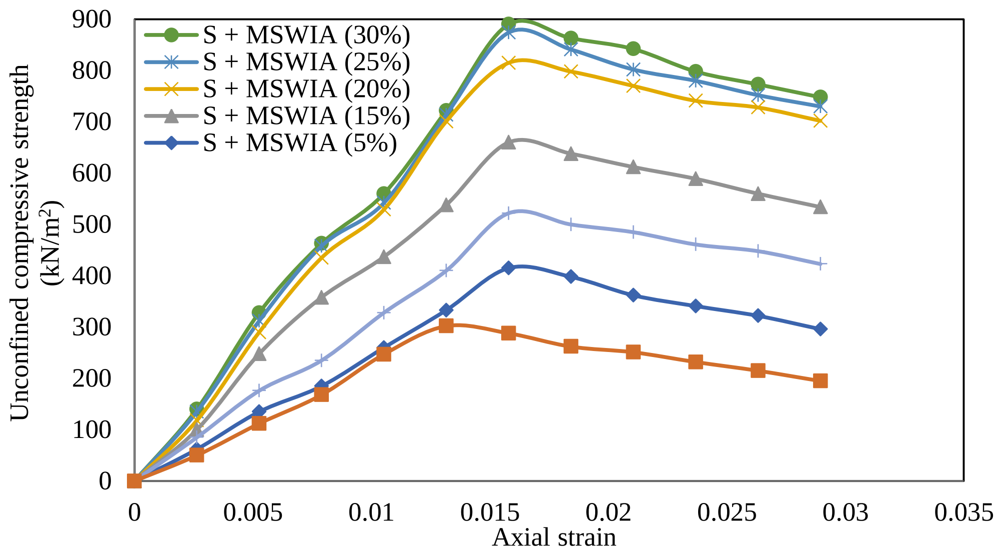


Figure 4.24: UCS of clay and clay-municipal solid waste incineration ash mixes after 28 days curing period

4.6.2 Clay-marble dust mix

The unconfined compressive strength tests are conducted after 28 days on clayey soil stabilized with marble dust in percentages of 5, 10, 15, 20and graph is plotted as shown in Figure 4.25. The addition of marble dust increases the strength of clayey soil from 302kN/m^2 to 452kN/m^2 on addition of 5% marble dust, 534kN/m^{2}for10% marble dust, 690 kN/m^2 for 15% marble dust and to 712kN/m^{2}for 20% marble dust content. Although, the strength is more in case of 20% marble dust content the rate of increase in strength from 15% to 20% marble dust content is less compared to the increase in strength from 10% to 25% marble dust content. Hence, 15% marble dust is considered as the optimum cement content for stabilization of clayey soil. Similar results indicating the increase in UCS have been reported by (Ola 1977; Attoh-Okine 1995; Bell 1996; Manasseh and Olufemi 2008; Sakr et al. 2009; Dash and Hussain 2012). The increase in UCS value by addition of marble dust is due to the pozzolanic reaction between soil particles and marble dust.

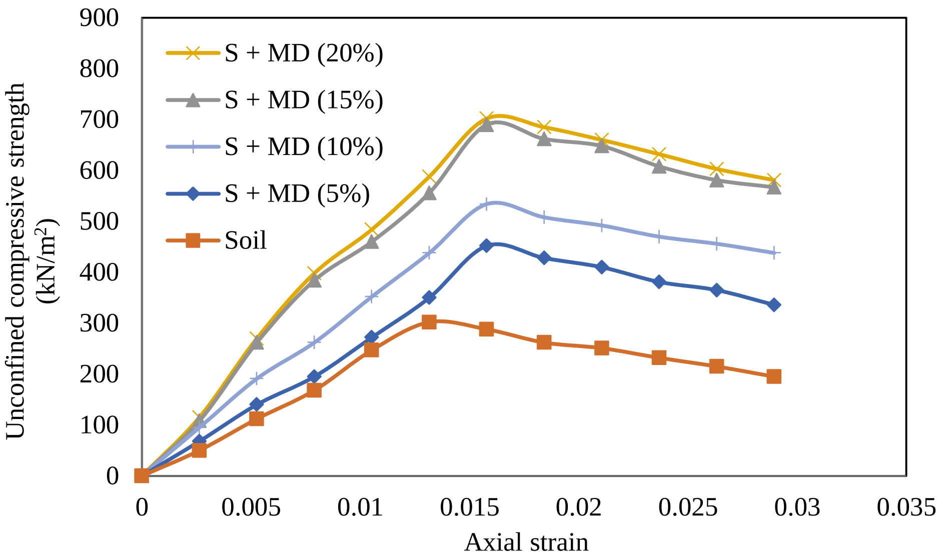


Figure 4.25: UCS of clay and clay-marble dust mixes after 28 days curing period

4.6.3 Clay-cement mix

The effect of addition of cement on unconfined compressive strength of clayey soil is shown in Figure 4.26. Cement is added in percentages of 3, 6, 9 and 12 to clayey soil for determining the optimum cement content based upon unconfined compressive strength. The 28 days unconfined compressive strength values of soil stabilized with cement are: 502kN/m^2 for 3% cement, 666kN/m^2 for 6% cement, 825kN/m^2 for 9% cement and 880 kN/m^2 for 12% cement. Thus, the addition of cement to the soil increases the unconfined compressive strength of the mix. This increase is due to the pozzolanic reaction between soil and cement. Similar behavior was reported by (Ransinchung et al. 2012; Bekhiti et al. 2019; Yao et al. 2020). The increase in strength is more in case of 12% cement but the percentage increase is higher for 9% cement content and hence9% cement is considered as optimum content for stabilization of clayey soilasbeyond 9% cement, the strength gains diminish, meaning the additional cement contributes less to the overall improvement. From a cost-efficiency perspective, 9% cement offers a better balance between material use and strength enhancement, as increasing cement content beyond this point leads to diminishing returns and higher costs. Furthermore, at 9%, the soil mix remains workable and easier to compact, which is essential for field applications. Higher cement contents can make the mix too stiff, complicating compaction efforts. Therefore, 9% cement achieves the desired strength, durability, and long-term stability while being more practical and cost-effective, meeting the necessary engineering standards without requiring excessive cement.

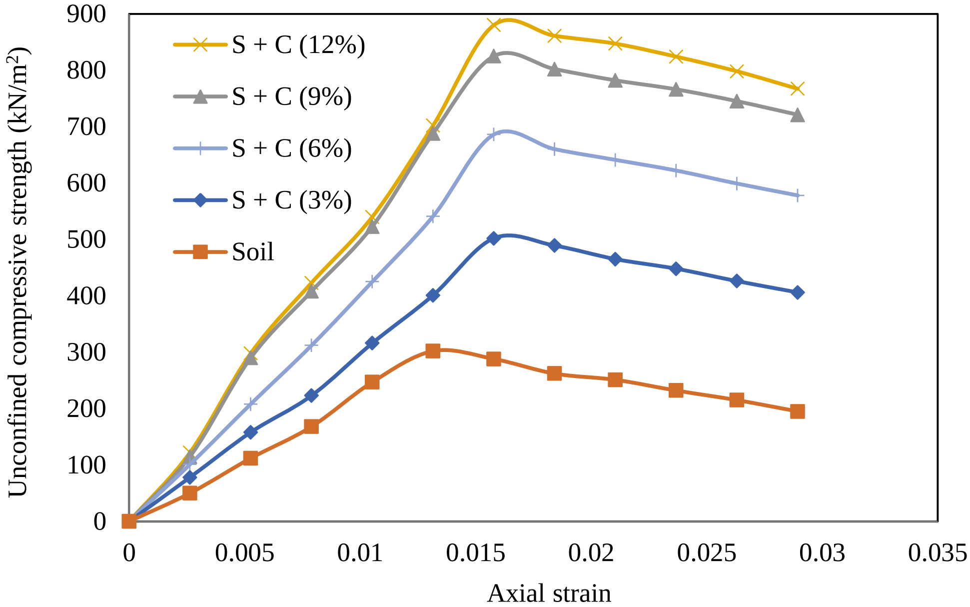


Figure 4.26: UCS of clay and clay-cement mixes after 28 days curing period

4.6.4 Clay-polypropylene fiber mix

The effect of addition of polypropylene fiber on unconfined compressive strength of clayey soil is shown in Figure 4.27. polypropylene fiber is added in percentages of 3, 6, 9 and 12 to clayey soil for determining the optimum cement content based upon unconfined compressive strength. The 28 days unconfined compressive strength values of soil stabilized with polypropylene fiber are: 412 kN/m^2 for 0.5% polypropylene fiber, 526 kN/m^2 for 1% polypropylene fiber and 539 kN/m^2 for 1.5% polypropylene fiber content. Thus, the addition of polypropylene fiber to the soil increases the unconfined compressive strength of the mix. This reveals that on adding polypropylene fiber in increasing amount, the UCS value increases constantly but the rate of increase is very less beyond 1.5% fiber content and hence 1.5% polypropylene fiber may be chosen as optimum content. The increase in UCS value on adding fiber may be due proper bond between all materials due to fiber content. A similar increase in UCS value on adding polypropylene fiber to clay has been reported earlier (Kumar et al. 2006; Puppala and 2000).

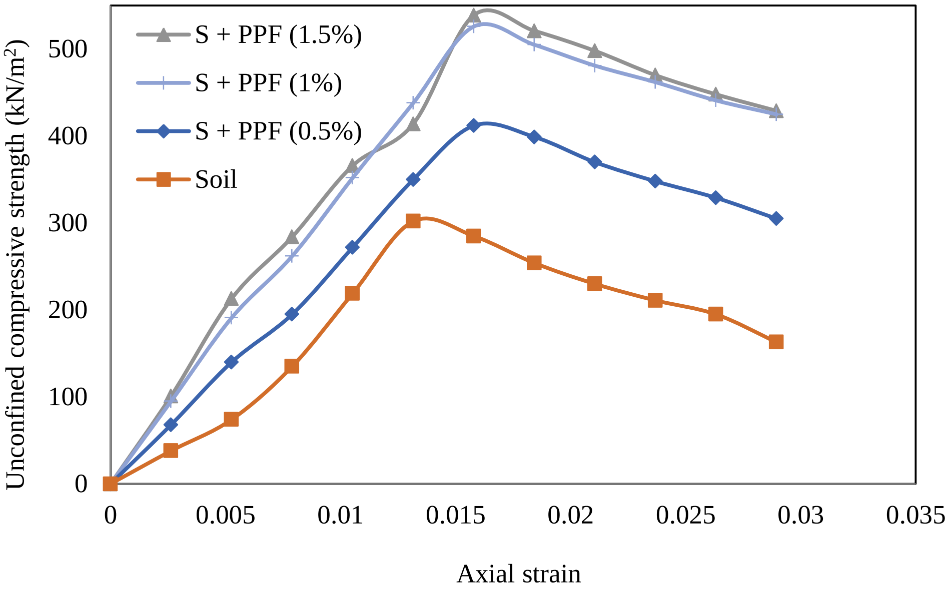


Figure 4.27: UCS of clay and clay- polypropylene fiber mixesafter28 days curing period

4.6.5 Clay-municipal solid waste incineration ash-cement mix

Cement is added to the optimum clay- municipal solid waste incineration ash (80%: 20%) mix obtained on the basis of 28 days unconfined compressive strength. A percentage of 3, 6 and 9 % cement is added to clay- municipal solid waste incineration ash mixes and unconfined compressive strength was determined and the results are shown in Figure 4.28.

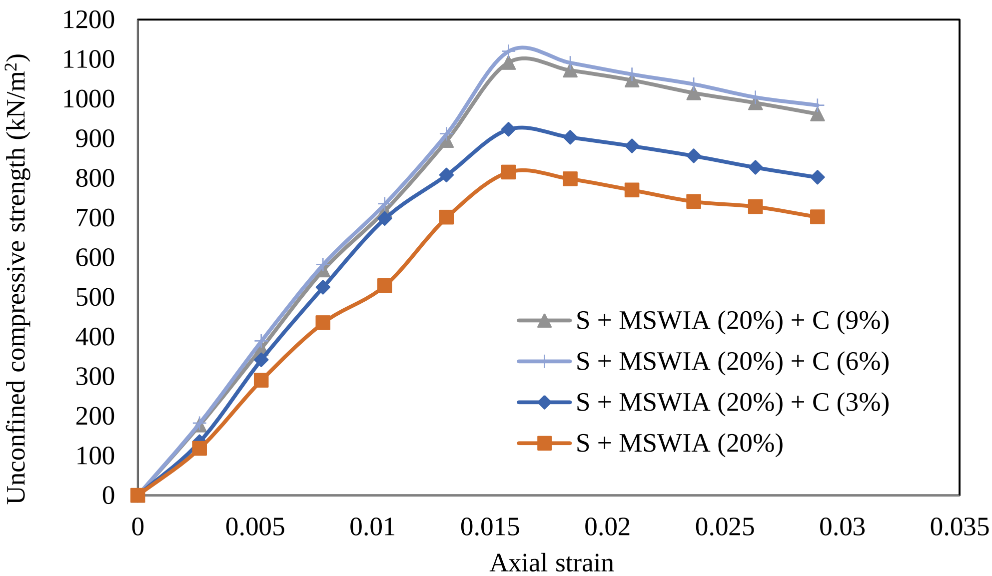


Figure 4.28: UCS of clay, clay- municipal solid waste incineration ash mixes and clay- municipal solid waste incineration ash -cement mixes after 28 days curing period

Addition of 3% cement increases the unconfined compressive strength from 815 kN/m^2 to 923 kN/m^2 whereas further addition of cement increases the unconfined compressive strength to 1120 kN/m^2 at 6% cement but the UCS value decreases to 1092 kN/m^2 at 9% cement. Thus, based on the results, 6% cement can be fixed as the optimum cement content for stabilization of clay- municipal solid waste incineration ash mix. The increase in strength up to 6% cement is due chemical reaction between cement and soil- municipal solid waste incineration ash mix.

4.6.6 Clay-marble dust-cement mix

Cement is added to the optimum clay-marble dust (85%: 15%) mix obtained on the basis of 28 days unconfined compressive strength.

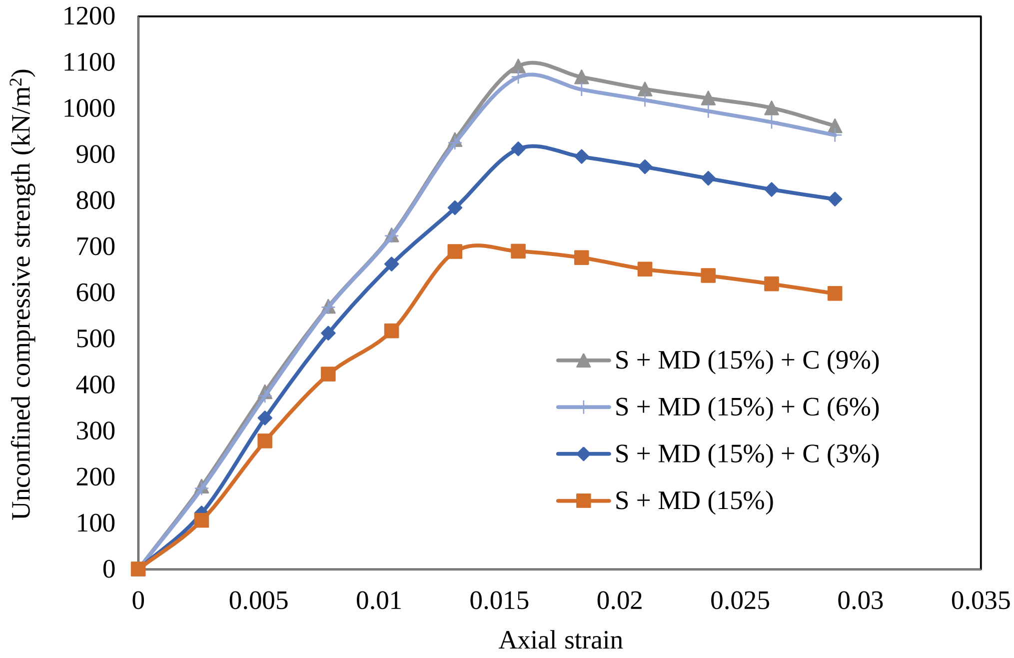


Figure 4.29: UCS of clay, clay-marble dust mix and clay-marble dust-cement mixes after 28 days curing period

A parentage of 3, 6 and 9 percent cement is added to clay-marble dust mix and unconfined compressive strength was determined and the results are shown in Figure 4.29. Addition of 3% cement increases the unconfined compressive strength from 690kN/m^2 to 912kN/m^2 whereas further addition of cement increases the unconfined compressive strength to 1068kN/m^2 at 6% cement and to 1092kN/m^2 at 9% cement but the rate of increase beyond 6% is very less Thus, based on the results, 6% cement can be fixed as the optimum cement content for stabilization of clay-marble dust mix as it will lead to economy also. The increase in strength on adding cement is due chemical reaction between cement and soil-marble dust mix.

4.6.7 Clay-municipal solid waste incineration ash-polypropylene fiber mix

The unconfined compressive strength tests are conducted on 79.5%clay: 20% municipal solid waste incineration ash: 0.5% polypropylene fiber mix, 79% clay: 20% municipal solid waste incineration ash: 1% polypropylene fiber mix and 78.5%clay: 20% municipal solid waste incineration ash: 1.5% polypropylene fiber mix. The effect of addition of municipal solid waste incineration ash and polypropylene fiber on unconfined compressive strength of clayey soil is shown in Figure 4.30.

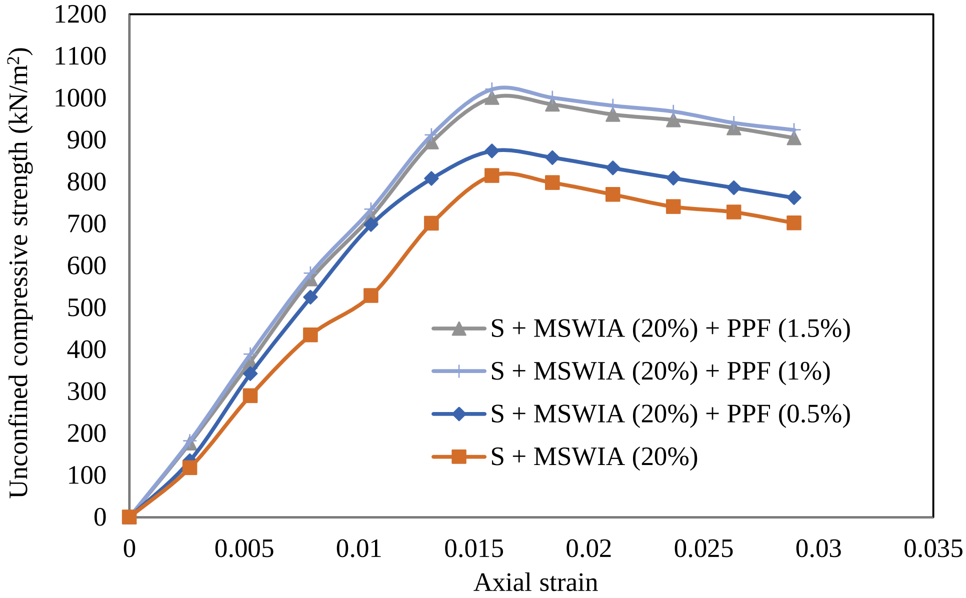


Figure 4.30: UCS of clay-municipal solid waste incineration ash and clay-municipal solid waste incineration ash-polypropylene fiber mixes after 28 days curing period

The addition of municipal solid waste incineration ash and polypropylene fiber increases 28 days unconfined compressive strength of clay to 874 kN/m^2 at 20% municipal solid waste incineration ash and 0.5% polypropylene fiber whereas addition of 20% municipal solid waste incineration ash and 1% polypropylene fiber increases it to 1021 kN/m^2 which is more than the unconfined compressive strength of 80% clay: 20% municipal solid waste incineration ash. The 28 days unconfined compressive strength of 78.5% clay: 20% municipal solid waste incineration ash: 1.5% polypropylene fiber is 1001 kN/m^{2}which is less than 79% clay: 20% municipal solid waste incineration ash: 1% polypropylene fiber mix. Thus, based upon results,79%clay:20% municipal solid waste incineration ash:1% polypropylene fiber may be considered as the optimum mix. The increase in UCS value on adding fiber may be due proper bond between all materials due to fiber content. A similar increase in UCS value on adding polypropylene fiber to clay has been reported earlier (Kumar et al. 2006; Puppala and 2000).

4.6.8 Clay-marble dust-polypropylene fiber mix

The unconfined compressive strength tests are conducted on 84.5% clay: 15% marble dust: 0.5% polypropylene fiber mix, 84% clay: 15% marble dust: 1% polypropylene fiber mix and 83.5% clay: 15% marble dust: 1.5% polypropylene fiber mix. The effect of addition of marble dust and polypropylene fiber on unconfined compressive strength of clayey soil is shown in Figure 4.31.

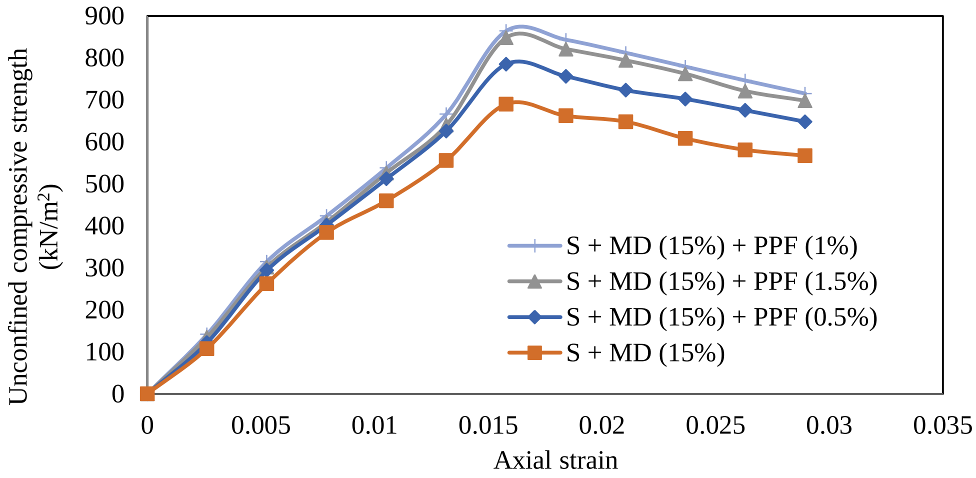


Figure 4.31: UCS of clay-marble dust mix and clay-marble dust-polypropylene fiber mixesafter28 days curing period

The addition of marble dust and polypropylene fiber increases 28 days unconfined compressive strength of clay to 785 kN/m^2 at 15% marble dust and 0.5% polypropylene fiber whereas addition of 15% marble dust and 1% polypropylene fiber increases it to 864 kN/m^2 which is more than the unconfined compressive strength of 85% clay: 15% marble dust. The 28 days unconfined compressive strength of 83.5% clay: 15% marble dust: 1.5% polypropylene fiber is 848 kN/m^2 which is less than 84% clay: 15% marble dust: 1% polypropylene fiber mix. Thus, based upon results, 83.5% clay: 15% marble dust: 1.5% polypropylene fiber may be considered as the optimum mix. The increase in UCS value on adding fiber may be due proper bond between all materials due to fiber content. A similar increase in UCS value on adding polypropylene fiber to clay has been reported earlier (Kumar et al. 2006; Puppala and 2000).

4.6.9 Clay-cement-polypropylene fiber mix

The unconfined compressive strength tests are conducted on 93.5% clay: 6% cement: 0.5% polypropylene fiber mix, 93% clay: 6% cement: 1% polypropylene fiber mix and 92.5% clay: 6% cement: 1.5% polypropylene fiber mix. The effect of addition of cement and polypropylene fiber on unconfined compressive strength of clayey soil is shown in Figure 4.32.

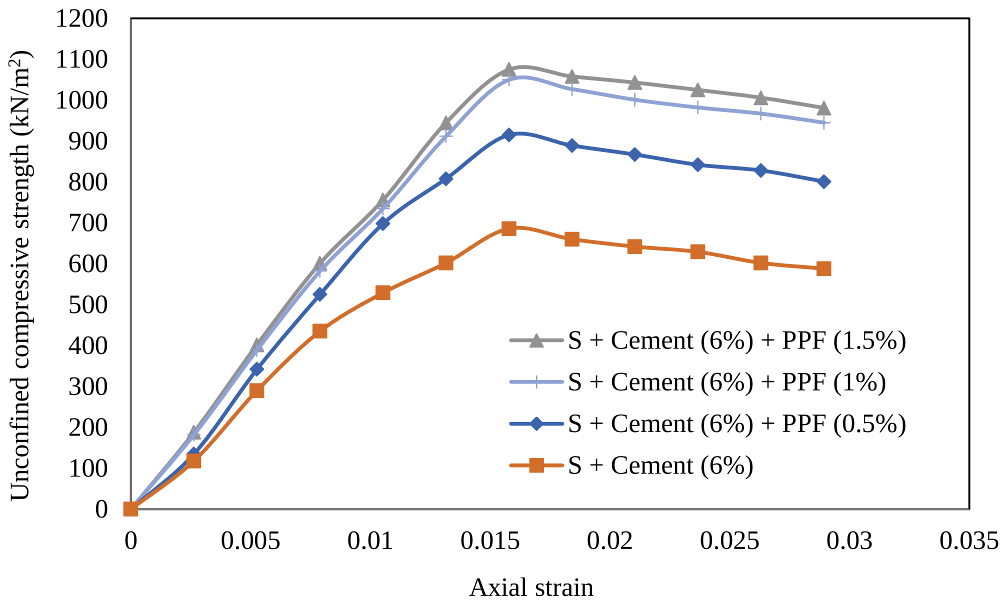


Figure 4.32: UCS of clay- cement mix and clay- cement -polypropylene fiber mixes after 28 days curing period

The addition of cement and polypropylene fiber increases 28 days unconfined compressive strength of clay to 915 kN/m^2 at 6% cement and 0.5% polypropylene fiber whereas addition of 6% cement and 1% polypropylene fiber increases it to 1050 kN/m^2 which is more than the unconfined compressive strength of 94% clay: 6% cement. The 28 days unconfined compressive strength of 92.5% clay: 6% cement: 1.5% polypropylene fiber is 1075 kN/m^2 which is slightly higher than 93% clay: 6% cement: 1% polypropylene fiber mix. Thus, based upon results, 93% clay: 6% cement: 1.5% polypropylene fiber may be considered as the optimum mix. The increase in UCS value on adding fiber may be due proper bond between all materials due to fiber content. A similar increase in UCS value on adding polypropylene fiber to clay has been reported earlier (Kumar et al. 2006; Puppala and 2000).The incorporation of polypropylene fiber into subgrade soil stabilization, particularly at a dosage of 0.5% alongside 6% cement, which results in a remarkable 28-day unconfined compressive strength (UCS) of 915 kN/m^2, presents several compelling techno-economic benefits that justify its use despite its higher cost. Firstly, polypropylene fiber significantly enhances the mechanical properties of clayey soils by improving tensile strength and ductility, leading to a more resilient subgrade that effectively distributes loads and minimizes cracking and deformation under stress. This enhanced structural integrity not only prolongs the lifespan of the pavement but also reduces the frequency and costs associated with maintenance and repairs over time. Additionally, the improved load-bearing capacity of the stabilized soil allows for the potential use of thinner pavement sections, which can translate into material savings and lower overall project costs. Moreover, the quicker setting times associated with the combination of cement and polypropylene fiber expedite construction processes, thereby reducing labor and equipment expenses while minimizing traffic disruptions during roadwork. From an environmental perspective, using recycled polypropylene fibers aligns with sustainable construction practices by decreasing the need for virgin materials and mitigating soil erosion and runoff issues related to pavement failures. Overall, the strategic use of polypropylene fiber in subgrade stabilization not only enhances performance but also proves economically advantageous in the long-term lifecycle of infrastructure projects, making it a worthwhile investment in modern civil engineering practices.

4.6.10 Clay-municipal solid waste incineration ash-marble dust mix

Marble dust is added in percentages of 5, 10, 15 and 20 % to the optimum clay-municipal solid waste incineration ash mix and unconfined compressive strength tests were conducted. The results shown in Figure 4.33 indicate that unconfined compressive strength increases with addition of marble dust. Addition of 5%, 10%, and 15%marble dust increases the UCS to 940kN/m^2, 1084kN/m^2 and 1324kN/m^2 respectively, however the addition of 20% marble dust decreases the UCS value to 1294 kN/m^2. Hence 15 % marble dust along with 20 % municipal solid waste incineration ash may be chosen as optimum content for increasing UCS value. The similar results indicating the increase in UCS have been reported by (Ola 1977; Attoh-Okine 1995; Bell 1996; Manasseh and Olufemi 2008; Sakr et al 2009; Dash and Hussain 2012). The increase in UCS value by addition of marble dust is due to the pozzolanic reaction between soil particles and marble dust.

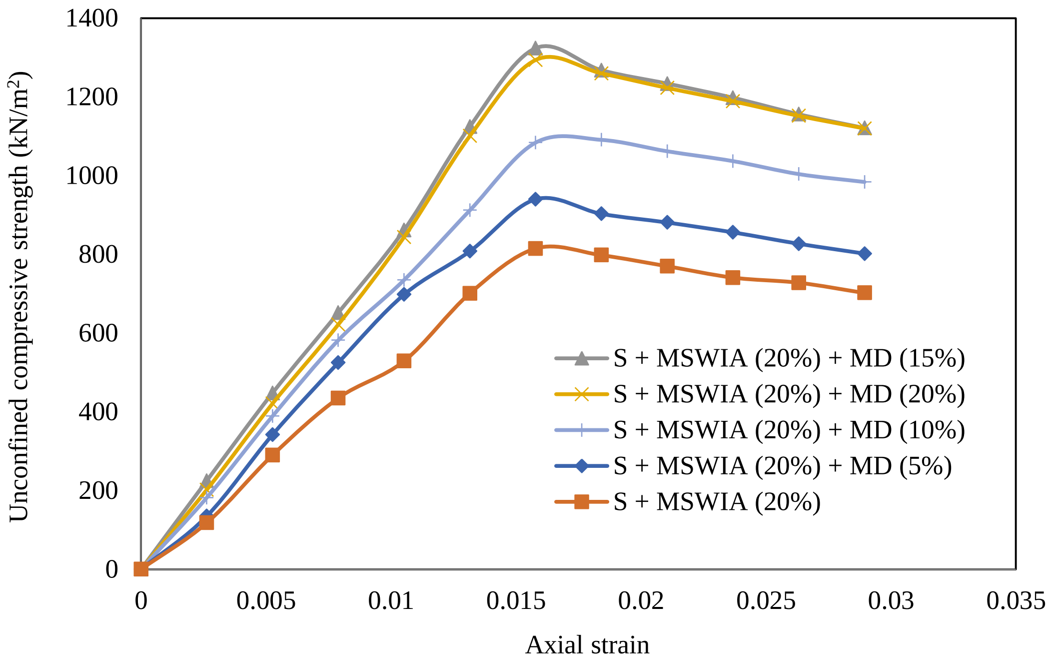


Figure 4.33: UCS of clay-municipal solid waste incineration ash mix and clay-municipal solid waste incineration ash-marble dust mixes after 28 days curing period

4.6.11 Clay-municipal solid waste incineration ash-marble dust-cement mix

Cement is added in percentages of 3, 6 and 9% to the optimum clay-municipal solid waste incineration ash-marble dust mix and unconfined compressive strength tests were conducted. The results shown in Figure 4.34 indicate that unconfined compressive strength increases with addition of cement. Addition of 3%, 6% and 9% cement increases the UCS to 1486kN/m^2, 1566kN/m^2 and 1602kN/m^2 respectively; however, the rate of increase in UCS value is very low beyond 6% cement content. Hence 6 % cement along with 20 % municipal solid waste incineration ash and 15% marble dust may be chosen as optimum content for increasing UCS value. The increase in strength on adding cement is due chemical reaction between cement and soil-municipal solid waste incineration ash-marble dust mix.

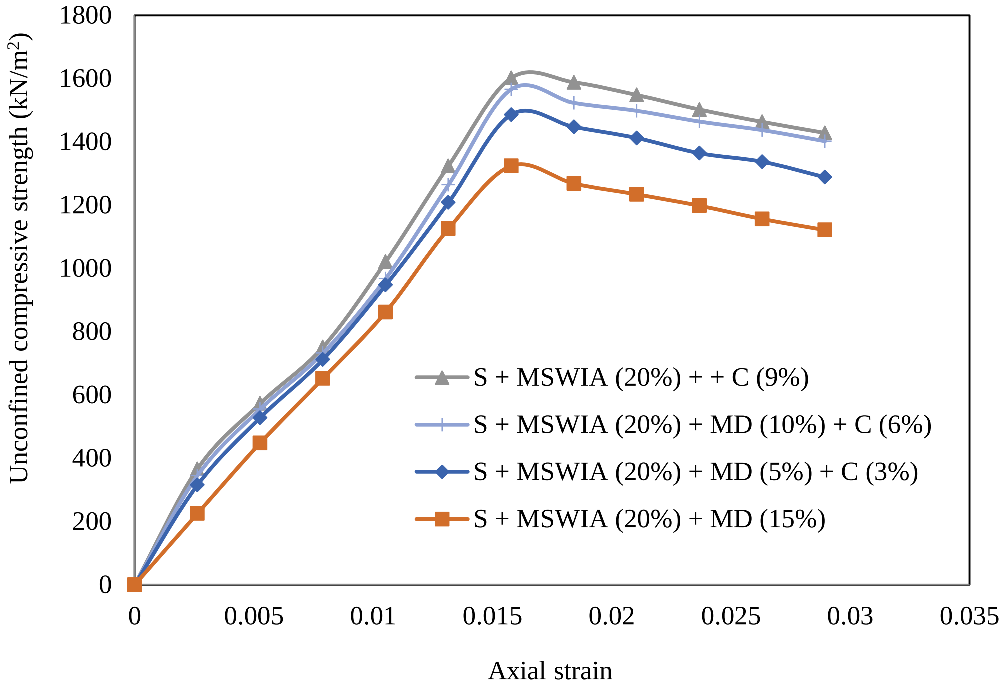


Figure 4.34: UCS of clay-municipal solid waste incineration ash-marble dust mix and clay-municipal solid waste incineration ash-marble dust-cement mixes after 28 days curing period

4.6.12 Clay-municipal solid waste incineration ash-marble dust-cement-polypropylene fiber mix

Polypropylene fiber is added in percentages of 0.5, 1 and 1.5% to the optimum clay-municipal solid waste incineration ash-marble dust-cement mix and unconfined compressive strength tests were conducted. The results shown in Figure 4.35 indicate that unconfined compressive strength increases with addition of PPF. Addition of 0.5% and1% polypropylene fiber increases the UCS to 1698 kN/m^2, and 1798kN/m^2 respectively; however, 1.5% polypropylene fiber decreases the UCS value to 1764 kN/m^2 and hence 1% polypropylene fiber along with 20% municipal solid waste incineration ash, 15% marble dust and 6% cement may be chosen as optimum content for increasing UCS value. The increase in UCS value on adding fiber may be due proper bond between all materials due to fiber content. A similar increase in UCS value on adding polypropylene fiber to clay has been reported earlier (Kumar et al. 2006; Puppala and 2000).

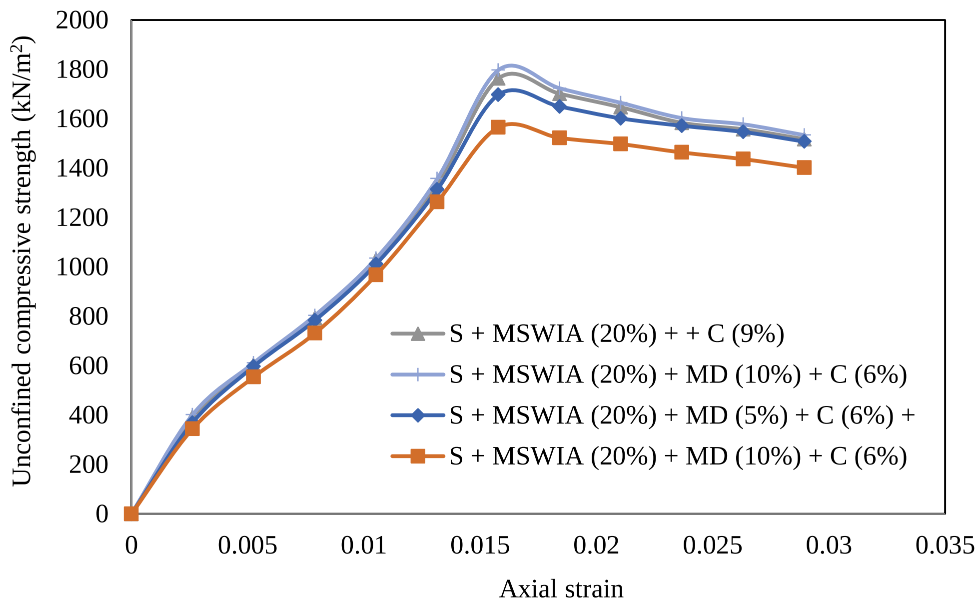


Figure 4.35: UCS of clay-municipal solid waste incineration ash-marble dust-cement mix and clay-municipal solid waste incineration ash-marble dust-cement-polypropylene fiber mixes after 28 days curing period

4.7 California bearing ratio tests

Soaked CBR tests were conducted on all the optimum mixes obtained on the basis of unconfined compressive strength and split tensile strength test results. The corresponding load-penetration graph for all optimum mixes are presented in Figure 4.36- 4.38. The results reveal that addition of admixtures such as municipal solid waste incineration ash, marble dust and cement individually and in combination with each other increases the CBR value significantly.

The soaked CBR value of clayey soil was 1.90% and thus cannot be utilized in sub-grade of pavements (5% CBR value is necessary for designing low traffic roads as per IRC: SP: 77-2008). On adding 20% MSWIA to clayey soil, the soaked CBR value increased from 1.90% to 3.80% showing an increase of 100% which may be due to the interlocking of the coarser particles. Similar behavior of increase in CBR value due to addition of municipal solid waste incineration ash has been reported by some researchers (Prabakar et al. 2004; Edil et al. 2006; Bose 2012; Firat et al. 2012). On adding 15% MD to clayey soil, the soaked CBR value of the composite increased from 1.90% to 4.10% showing an increase of about 115% and may be attributed to the coarser particles of very coarser nature of MD compared to that of clay thus mobilizing friction which leads to increase in the strength.These results are in good agreement with those reported in literature by (Ransinchung et al. 2012). On adding 1% PPF to clayey soil, the soaked CBR value of the composite increased from 1.90%

to 2.80% showing an increase of about 50%. All CBR values obtained on adding optimum amount of MSWIA, MD and PPF are not enough to be used as sub-grade material. The addition of 9% cement to clayey soil improved the CBR value (9.42%) drastically and showing a percentage increase of about 395% which may be due to the binding and hardening property of cement. A similar behaviour showing an increase in CBR on the addition of cement to clay was observed by several researchers (Kavak and Akyarli 2007; Panjaitan 2014). The obtained CBR value is quite higher and the material can be easily used in the construction of sub-grade, but the cost of cement is quite high and the overall cost of sub-grade will be quite high and thus cement alone cannot be used in construction of low volume roads.

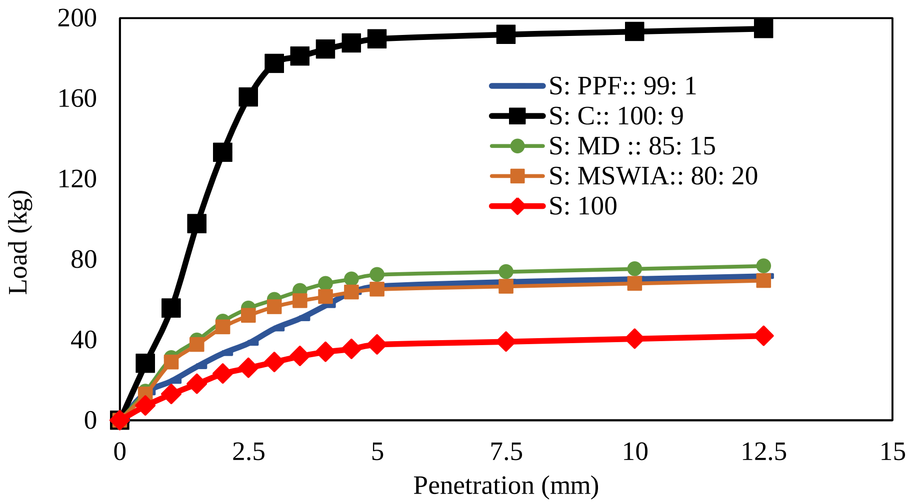


Figure 4.36: Load-penetration curves for the clay and various mixes (2 mixes)

The further testing was carried out by adding three materials together as S: MSWIA: MD:: 65: 20: 15, S: MSWIA: C:: 74: 20: 6, S: MD: C:: 79: 15: 6, S: MSWIA: PPF:: 79: 20: 1, S: MD: PPF:: 84: 15: 1, S: C: PPF:: 93: 6: 1. The addition of 15% MD to optimum soil: MSWIA mixture increased the CBR value from 3.80% to 6.50%; the addition of 6% cement to optimum soil: MSWIA mixture increased the CBR value from 3.80% to 10.50%; the addition of 6% cement to optimum soil: MD mixture increased the CBR value from 4.10% to 10.83%; the addition of 1% PPF to optimum soil: MSWIA mixture increased the CBR value from 3.80% to 5.81%; the addition of 1% PPF to optimum soil: MD mixture increased the CBR value from 4.1% to 6.3%; the addition of 1% PPF to optimum soil: cement mixture increased the CBR value to 11.41%.

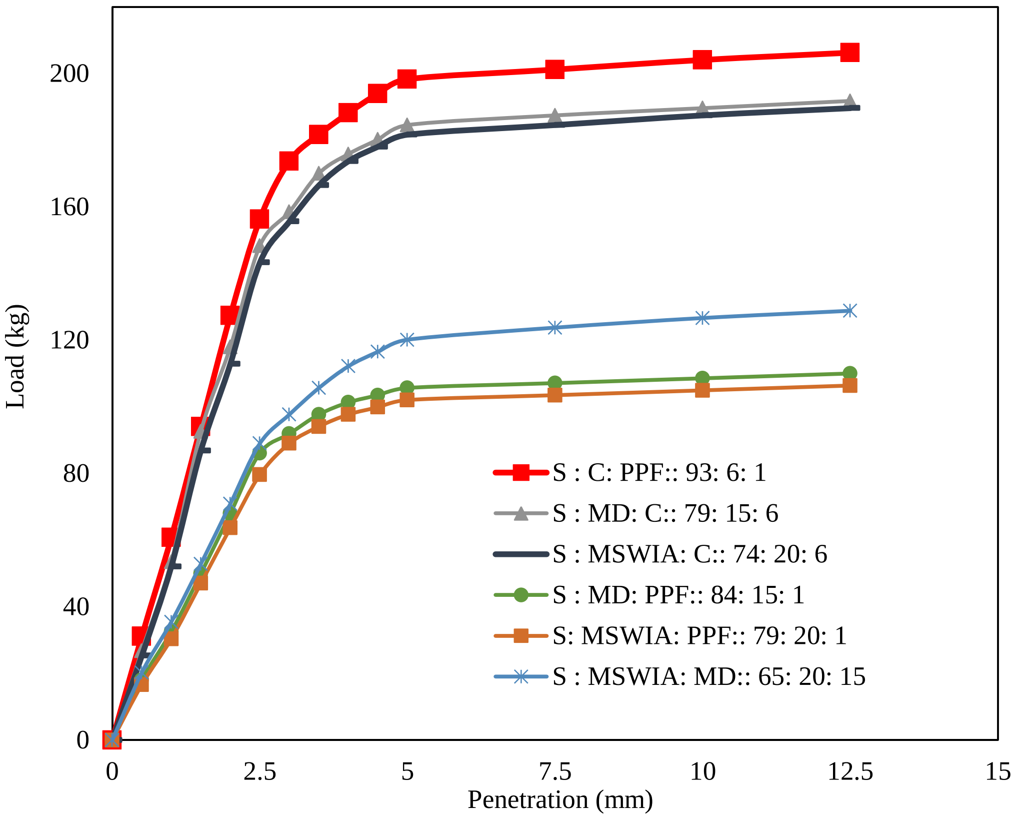


Figure 4.37: Load-penetration curves for various mixes (3 mixes)

Finally, the testing was carried out by adding four materials together as S: MSWIA: MD: C:: 62: 20: 15: 3, S: MSWIA: C: PPF:: 73: 20: 6: 1, S: MD: C: PPF:: 78: 15: 6: 1, S: MSWIA: MD: PPF:: 64: 20: 15: 1, S: MSWIA: MD: C: PPF:: 61: 20: 15: 3: 1. The addition of 3% cement to optimum soil: MSWIA: MD mixture increased the CBR value from 6.50% to 10.62%; the addition of 1% PPF to optimum soil: MSWIA: C mixture increased the CBR value from 10.50% to 11.83; the addition of 1% PPF to optimum S: MD: C mixture increased the CBR value from 10.83% to 12.5%; the addition of 1% PPF to optimum soil: MSWIA: MD mixture increased the CBR value from 6.50% to 7.8%; the addition of 1% PPF to optimum soil: MSWIA: MD: C mixture increased the CBR value from 10.62% to 14.84%.

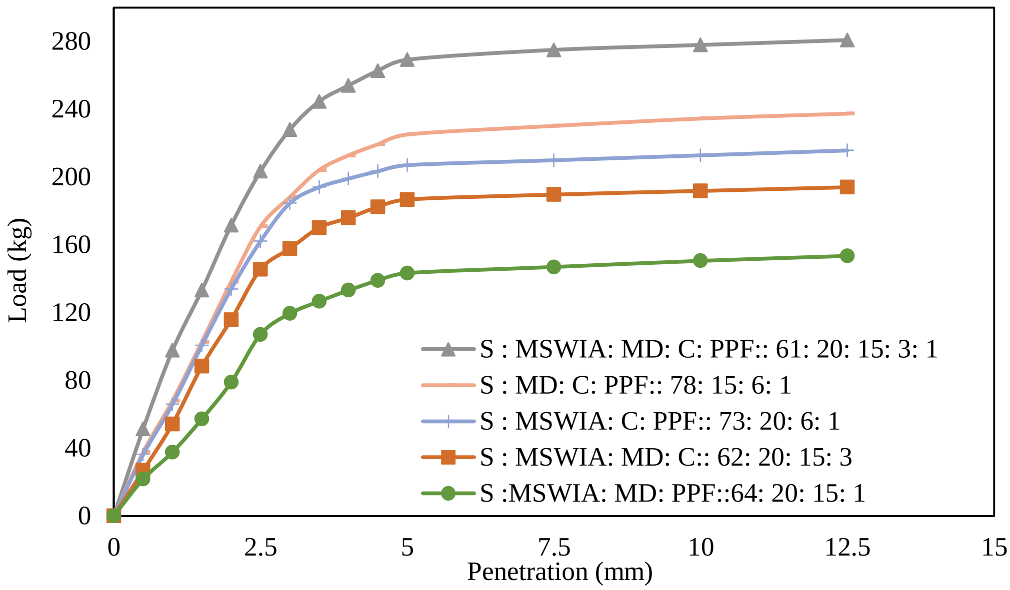


Figure 4.38: Load-penetration curves for various mixes (4 mixes)

4.8 Permeability tests

The permeability tests for subgrade soil stabilized with MSWIA, marble dust, cement, and polypropylene fiberis crucial for evaluating the drainage characteristics and overall performance of the stabilized mixtures. This test provides insights into how effectively water can move through the soil, which is essential for preventing water accumulation that can weaken the soil structure and lead to pavement failure. By understanding the permeability of different combinations of these stabilizing materials, engineers can assess their impact on the mechanical properties of the soil, optimize the mixture design for effective drainage, and ensure long-term durability of the pavement. Additionally, the permeability results help in predicting how the stabilized subgrade will respond to varying moisture conditions, thereby enabling better design decisions that enhance the resilience and reliability of the infrastructure.The permeability tests were conducted to assess the drainage characteristics of soil and composite mixes. Figure 4.39 and Table 4.1 shows the coefficient of permeability of soil and various optimum mixes. The coefficient of permeability of clay is 3.26×10^{-8} cm/sec which on addition of 20% municipal solid waste incineration ash decreases to 1.63×10^{-8} cm/sec. Similar behavior of decrease in coefficient of permeability of clay with addition of municipal solid waste incineration ash has been reported by a few researchers (Phanikumar and Sharma 2004).The decrease in coefficient of permeability of soil- municipal solid waste incineration ash is due to the pozzolanic reaction between the municipal solid waste incineration ash particles and soil which reduces the pore size. The coefficient of permeability increases to 7.67x10^{-8} cm/sec on addition of marble dust to clayey soil. The increase in coefficient of permeability on addition of marble dust is due to coarser particles of marble dust and its higher coefficient of permeability compared to that of soil. The addition of cement to clay increases the coefficient of permeability to 6.48x10^{-8} cm/s. This increase in coefficient of permeability on addition of cement is due to aggregation of clay particles with cement. Similar behavior of increase in coefficient of permeability of clay with addition of cement has been reported by some researchers (Locat et al 1996; Galvao 2004; Khattab et al 2007). Addition of municipal solid waste incineration ash and cement together to clay increases the coefficient of permeability to 6.88 x10^{-8} cm/sec which is more than that due to addition of cement and municipal solid waste incineration ash alone. The coefficient of permeability of clay-marble dust-cement mix is 6.75x10^{-8} cm/sec which is less than that of the clay-marble dust mix. The addition of municipal solid waste incineration ash and marble dust together to the clay increases the coefficient of permeability slightly i.e. 3.988x10^{-8} cm/sec which is more than that of clay- municipal solid waste incineration ash mix but less than the clay-marble dust mix.

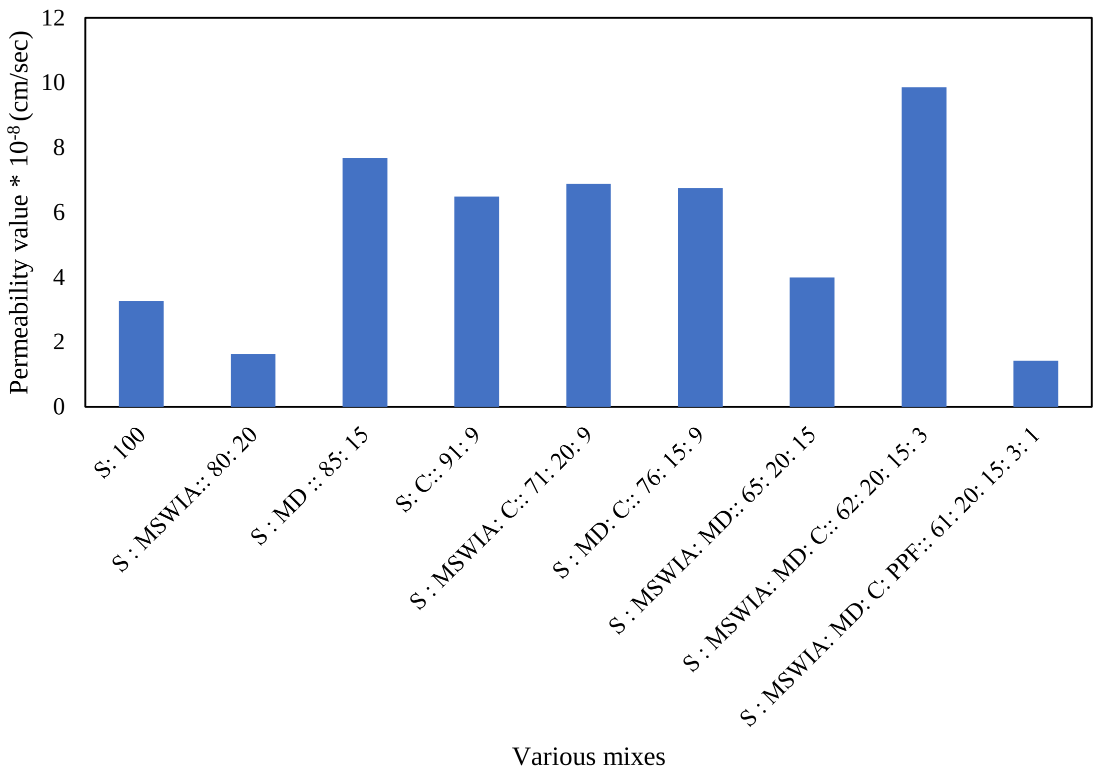


Figure 4.39: Coefficient of permeability of various optimum mixes

Table 4.1: Coefficient of permeability of clay and different optimum mixes

Sr. No.	Material	Coefficient of permeability, (cm/sec)
1	S: 100	3.26×10^{-8}
2	S : MSWIA:: 80: 20	1.63×10^{-8}
3	S : MD :: 85: 15	7.67×10^{-8}
4	S: C:: 91: 9	6.48×10^{-8}
5	S : MSWIA: C:: 71: 20: 9	6.88×10^{-8}
6	S : MD: C:: 76: 15: 9	6.75×10^{-8}
7	S : MSWIA: MD:: 65: 20: 15	3.988×10^{-8}
8	S : MSWIA: MD: C:: 62: 20: 15: 3	9.85×10^{-8}
9	S : MSWIA: MD: C: PPF:: 61: 20: 15: 3: 1	1.42×10^{-8}

The coefficient of permeability is 9.85×10^{-8} cm/sec and 1.42×10^{-8}cm/sec for clay-municipal solid waste incineration ash-marble dust-cement mix and clay-municipal solid waste incineration ash-marble dust-cement-PPF mix respectively. Similar behavior of increase in coefficient of permeability of clay with addition of fiber has been reported by a few researchers (Abdi et al. 2008). Thus, based on the results, it can be concluded that the coefficient of permeability increases with addition of marble dust and cement and decreases with addition of municipal solid waste incineration ash. The coefficient of permeability is more in case of clay-municipal solid waste incineration ash marble dust-cement-PPF mix compared to other mixes followed by clay-municipal solid waste incineration ash-marble dust-cement mix and clay-marble dust mix respectively.

4.9 X-ray diffraction tests

X-ray diffraction (XRD) test is a fast, non-destructive technology for elemental analysis of heavy metals and other trace elements in soil. X-ray diffraction test is very important to analyse diverse behaviours of various types of soil during stabilization based on mineral soil properties, which are related to the compositional characteristics of soil (Whittig 1965). Various XRD tests were performed to determine the mineralogical composition of the soil and composite mix sampleskeeping 6 to 9 percent of cement for various mixes based on optimum content obtained from DFS, consistency and UCS values.Figure 4.40 showing the X-ray diffraction graph of clay reveals that the main constituent minerals are muscovite, quartz and montmorillonite. The swelling characteristics of clay are due to the presence of montmorillonite which shows high volume changes in the presence of water. The volume changes occur due to the presence of diffused double layer in montmorillonite which tend to push the clay particles away from each other.

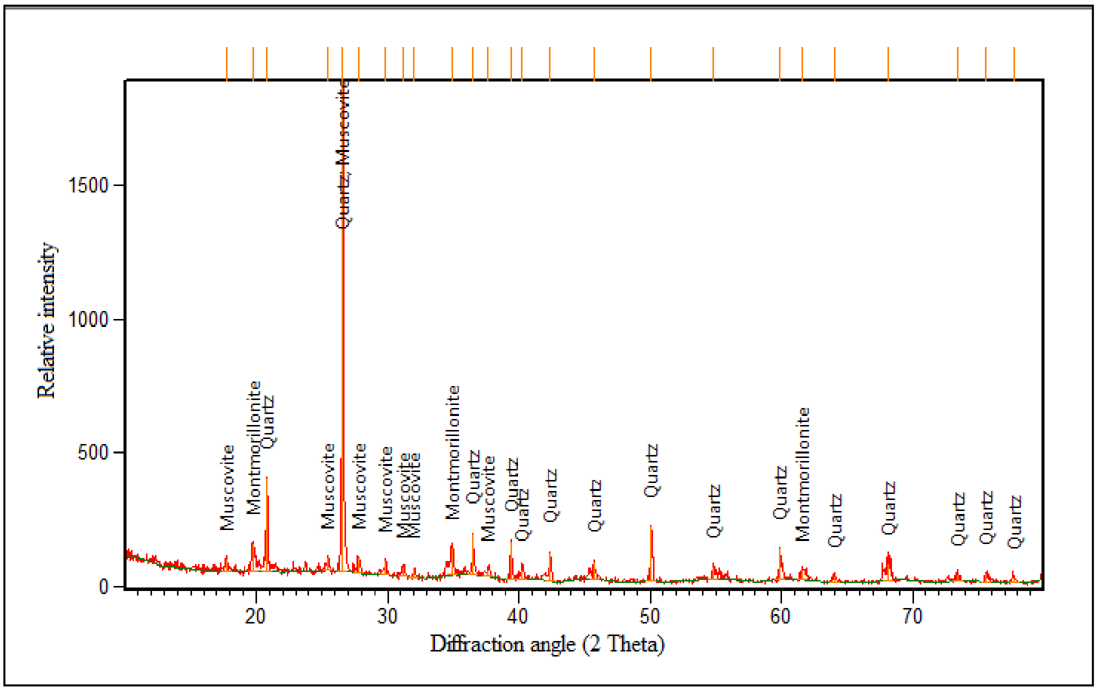


Figure 4.40: X-ray diffraction pattern of clay

Figure 4.41 shows the X-ray diffraction graph of municipal solid waste incineration ash which reveals the presence of minerals mullite and quartz as the main constituents. The presence of non-cohesive minerals in municipal solid waste incineration ash indicates its non-swelling nature in the presence of water.

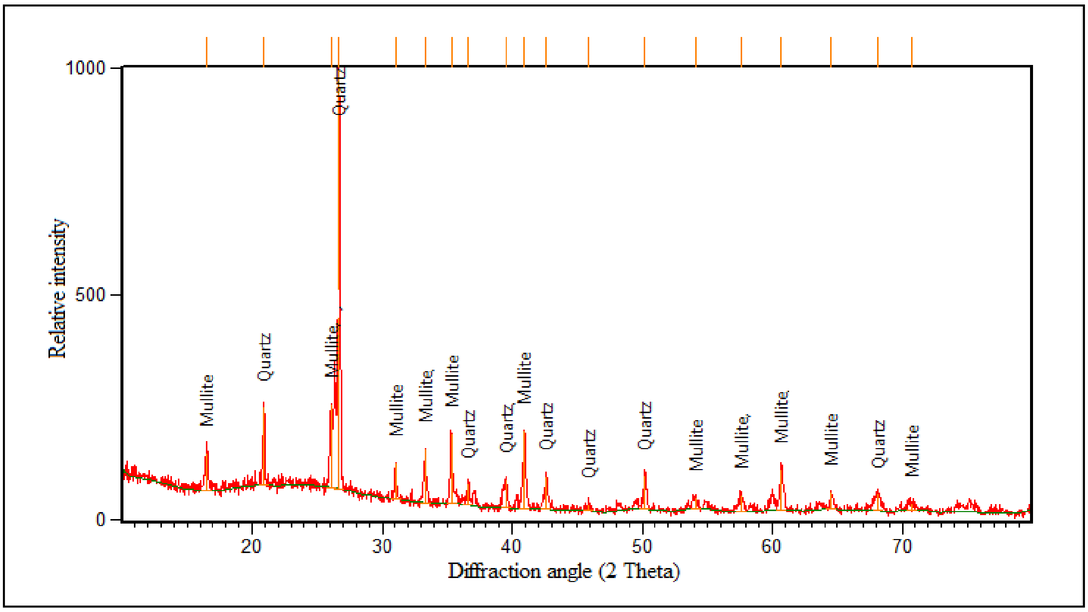


Figure 4.41: X-ray diffraction pattern of municipal solid waste incineration ash

The X-ray diffraction graph of marble dust is shown in Figure 4.42. The XRD pattern shows the presence of minerals quartz and calcite as main constituents. The non-cohesive nature of the minerals indicates the non-swelling nature of Marble dust.

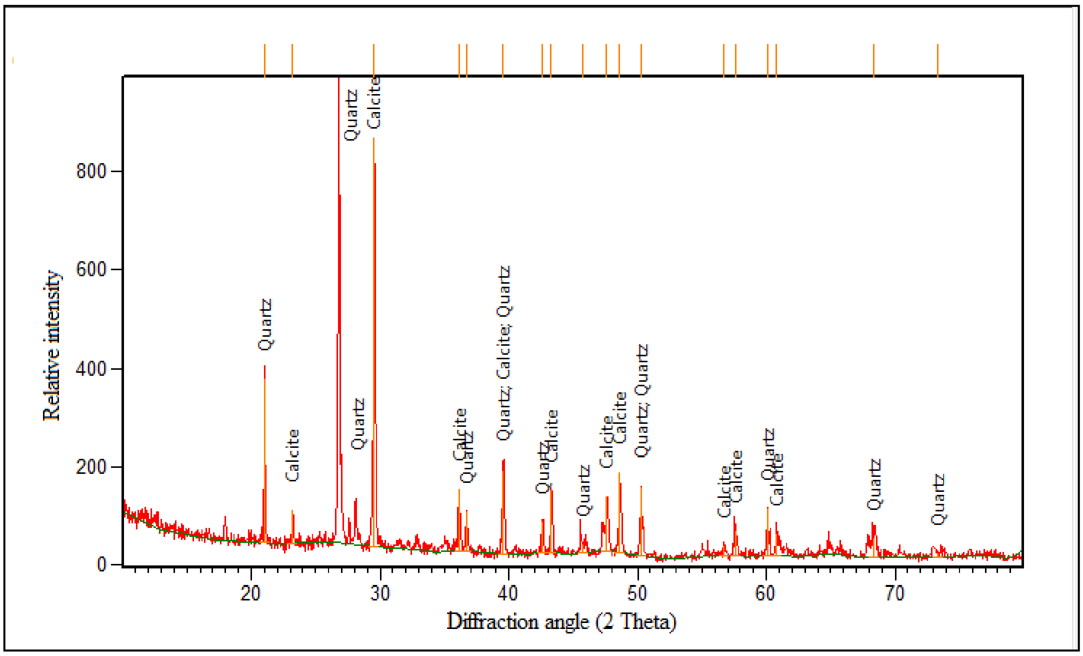


Figure 4.42: X-ray diffraction pattern of marble dust

Figure 4.43 shows the X-ray diffraction graph of clay-municipal solid waste incineration ash composite mix. The main constituent minerals of the composite are muscovite, quartz, montmorillonite and mullite. The swelling characteristics of clay are reduced on addition of municipal solid waste incineration ash due to the presence of mullite which is one of the main constituents of municipal solid waste incineration ash.

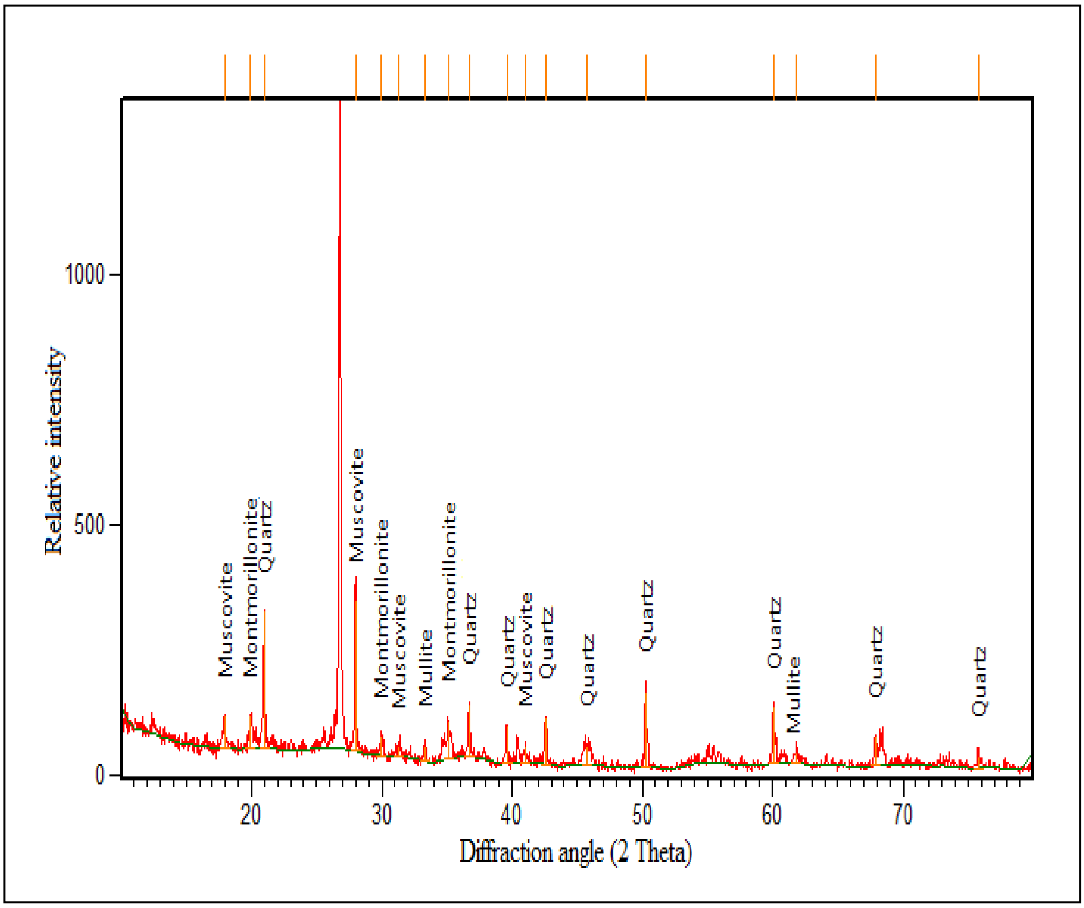


Figure 4.43: X-ray diffraction pattern of clay: MSWIA:80: 20

The X-ray diffraction graph of clay-marble dust composite mix is shown in Figure 4.44. The XRD pattern reveals that the main constituent minerals of the composite are quartz, montmorillonite and calciobetafite. The addition of marble dust to clay reduces the swelling characteristics due to the increase in quartz content and formation of new compound calciobetafite.

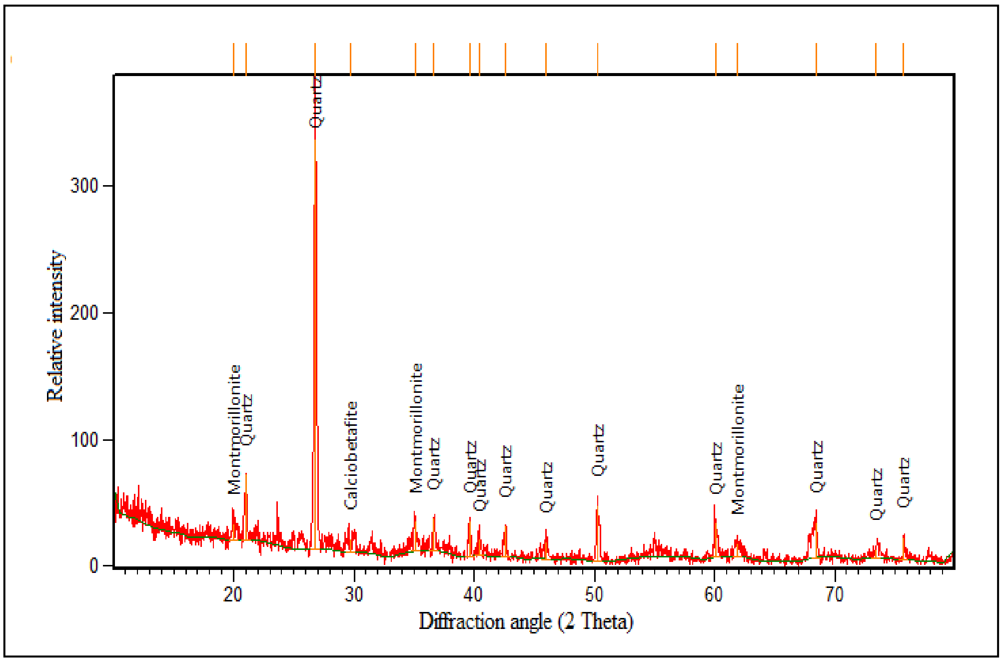


Figure 4.44: X-ray diffraction pattern of clay: marble dust:: 85: 15

Figure 4.45 shows the X-ray diffraction graph of clay-municipal solid waste incineration ash-cement composite mix. The main constituent minerals of the composite are quartz, montmorillonite and calcite. The increase in the strength of clay on addition of municipal solid waste incineration ash and cement is due to the presence of calcite which is one of the main constituents of cement.

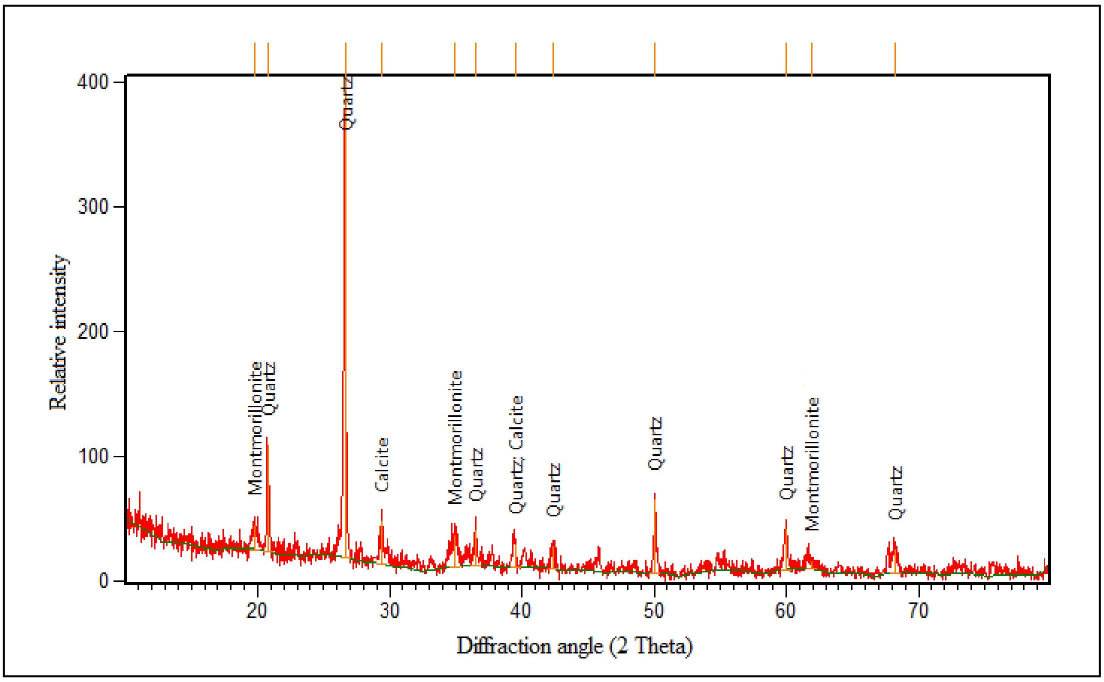


Figure 4.45: X-ray diffraction pattern of clay: municipal solid waste incineration ash: cement:: 71: 20:9

The X-ray diffraction graph of clay-marble dust-cement composite mix is shown in figure 4.46. The XRD pattern reveals that the main constituent minerals of the composite are quartz, muscovite, montmorillonite and calcite. The increase in strength and decrease in swelling on addition of marble dust and cement to clay is due to the presence of calcite and increase in quartz content respectively.

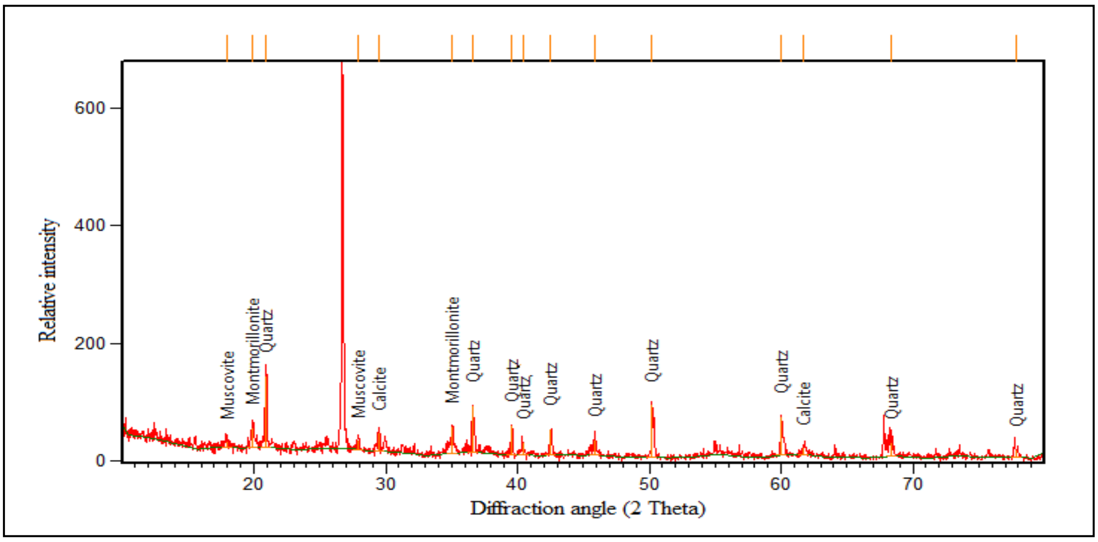


Figure 4.46: X-ray diffraction pattern of clay: marble dust: cement::76: 15: 9

The X-ray diffraction graph of clay-municipal solid waste incineration ash-marble dust composite mix is shown in Figure 4.47. The XRD pattern reveals that the main constituent minerals of the composite are quartz, montmorillonite and mullite. The reduction in swelling characteristics of clay with addition of municipal solid waste incineration ash and marble dust to clay is due to the quartz and mullite which are the main constituents of marble dust and municipal solid waste incineration ash respectively.

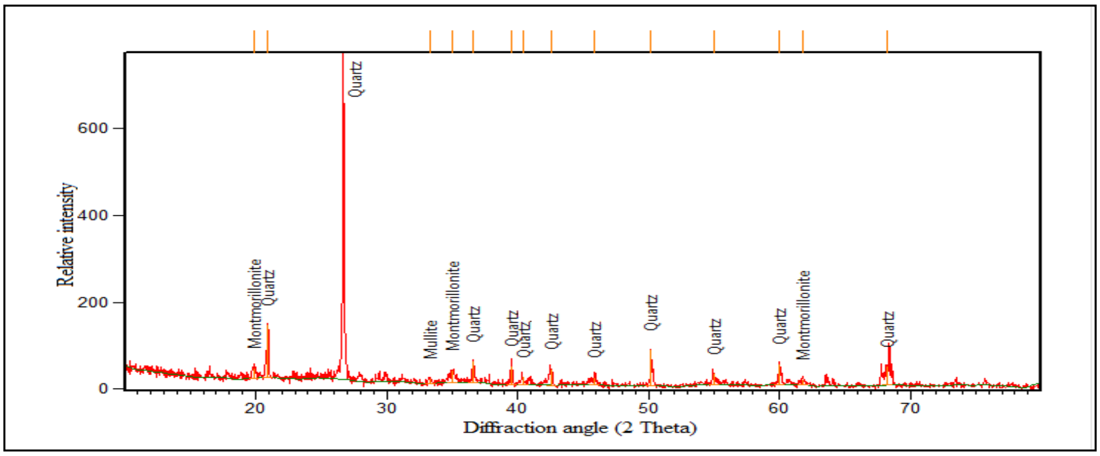


Figure 4.47: X-ray diffraction pattern of clay: municipal solid waste incineration ash: marble dust:: 65:20: 15

The X-ray diffraction graph of clay-municipal solid waste incineration ash-marble dust-cement composite mix is shown in Figure 4.48. The XRD pattern reveals that main constituent minerals of the composite are quartz, montmorillonite and calcite. The increase in strength and reduction in swelling characteristics of clay on addition of municipal solid waste incineration ash, marble dust and cement is due to the quartz and calcite which are the main constituents of marble dust & municipal solid waste incineration ash and cement respectively. Thus, the reason for improvement in engineering properties of clay on addition of different admixtures to clay can be analyzed using X-ray diffraction tests.

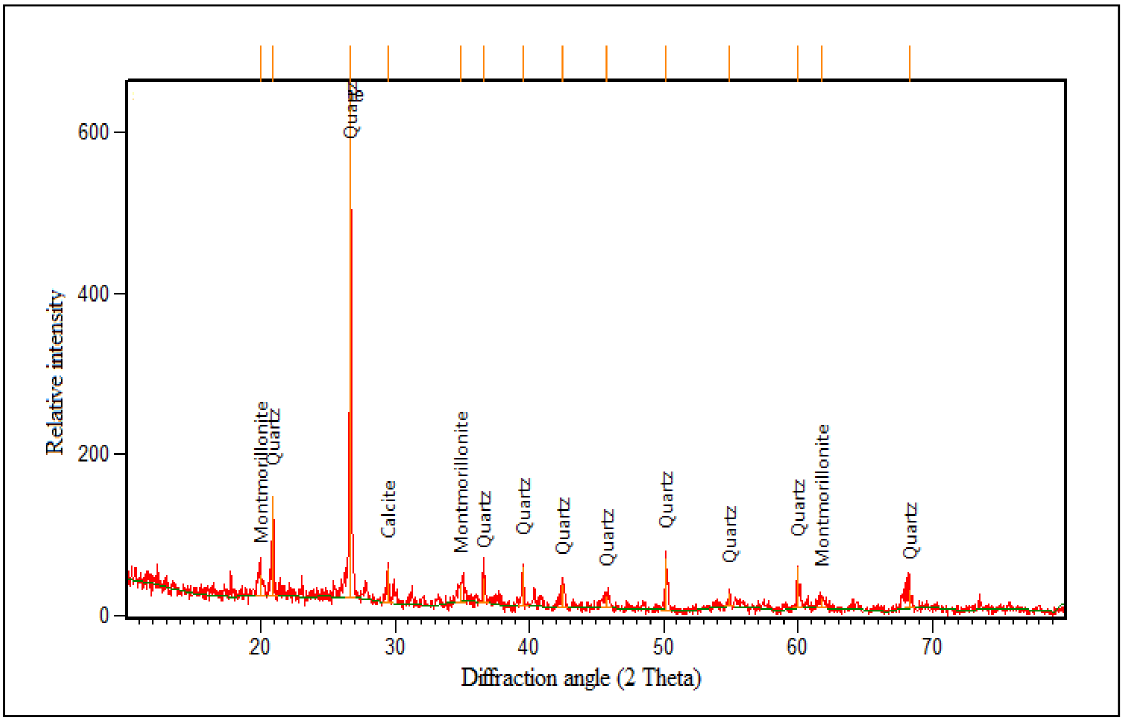


Figure 4.48: X-ray diffraction pattern of clay: municipal solid waste incineration ash: marble dust: cement:: 59: 20: 15: 6

4.10 Summary

The effect of addition of municipal solid waste incineration ash, marble dust, cement, and polypropylene fiber individually and in combination with each other on the differential free swell, pH, compaction characteristics, unconfined compressive strength, split tensile strength, California bearing ratio and permeability characteristics of the soil has been discussed in this chapter. The effect of these additives on the mineralogical characteristics has also been described. The results discussed in this chapter will be interpolated and analyzed to chosen the best mix for different application such as pavements, embankments, foundation, etc. in next chapter.

Chapter 5

Interpretation of Results

5.1 General

The effect of additives such as municipal solid waste incineration ash, marble dust, cement, and polypropylene fiber to clay on its swelling, compaction, strength and drainage characteristics has been discussed in chapter 4. The X-ray diffraction analysis of clay and optimum composite mixes is also described in the previous chapter. This chapter deals with the analysis of results to choose the best stabilizing material and the optimum composite mix to be used in various applications.

5.2 Differential free swell (DFS)

The differential free swell of clayey soil reduces with addition of additives. Figure 5.1 shows the comparison of effect of various additives on differential free swell of clayey soil. The addition of municipal solid waste incineration ash, marble dust and cement decrease the differential of clayey soil from 55% to 15% at 20% MSWIA; DFS decreases to 14% on adding 15% marble dust; DFS reduces to 20% at 9% cement content respectively and after that decreases. Thus, the additive content at which differential free swell reduces varies with the type of additive. The municipal solid waste incineration ash and marble dust additives used in this study are waste materials whereas cement is not a waste material and is costly as well. The municipal solid waste incineration ash is waste material and is available in huge quantity in municipal solid waste incineration ash plant and its disposal is a big challenge. The availability of marble dust is increasing now-a-days due to rapid construction of various infrastructure projects and its application in various fields is still under research. Thus, it can be inferred that the utilization of municipal solid waste and marble dust is an economical and eco-friendly option to reduce the swelling characteristics of clayey soil.

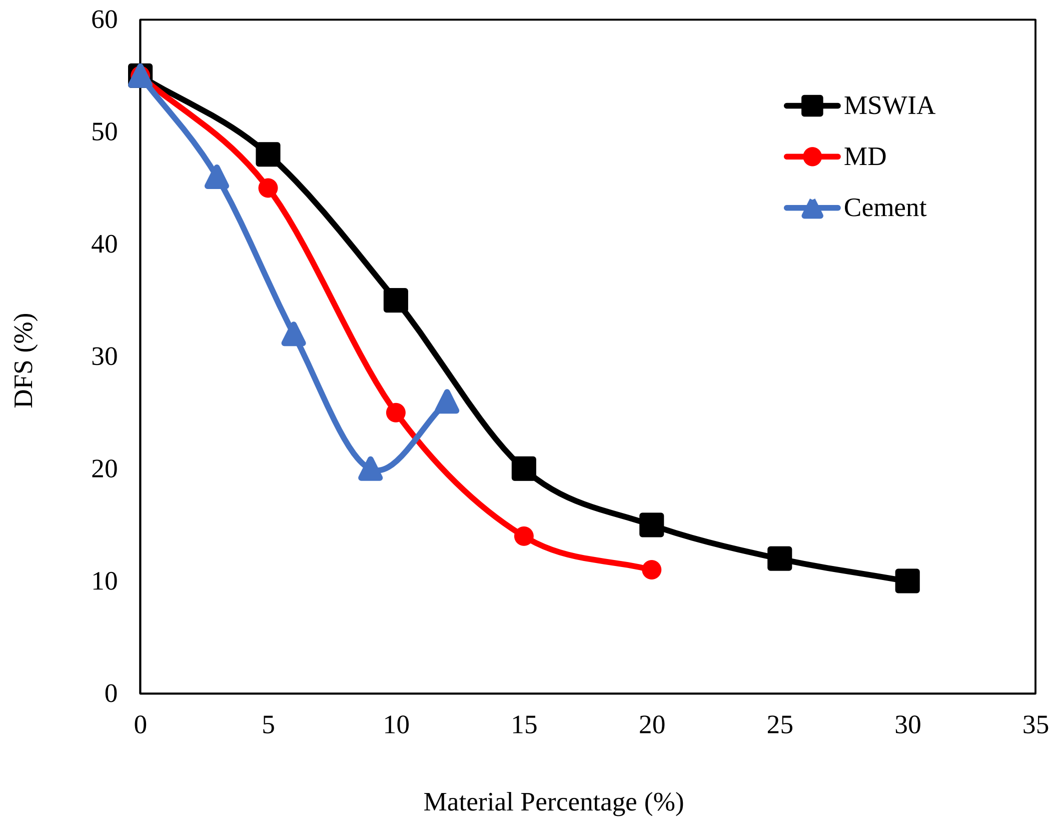


Figure 5.1: Effect of addition of various additives on differential free swell of clay

The further testing was carried out by adding two materials together by fixing percentage of one material and varying the percentage of other material. The DFS value reaches to zero on adding 15% marble dust to a mixture of clay: MSWIA:: 80: 20; the DFS value reduced to zero on adding 9% cement content along with clay: MSWIA:: 80: 20 and clay: MSWIA:: 85: 15 indicating that only 9% cement is required for the chemical reaction between cement and clay-MSWIA and clay-marble dust mix and higher percentages of cement, if added, increases DFS value. The reduction in DFS value on adding 9% cement to both the combinations may be due to the flocculation of clay particles causing increase in particle size and the resulting decrease in specific surface. Hence, it can be considered as the optimum cement content for fixation of cement in stabilization of clay-marble dust mix. Further on adding various percentages of cement to clay: MSWIA: MD, reduced the CBR value to zero at 6% cement content stating that the required cement content to reduce DFS value decreased by 3% leading to more economy. Hence S: MSWIA: MD: C:: 59: 20: 15: 6 mix may be considered as better material for stabilization of clayey soil.

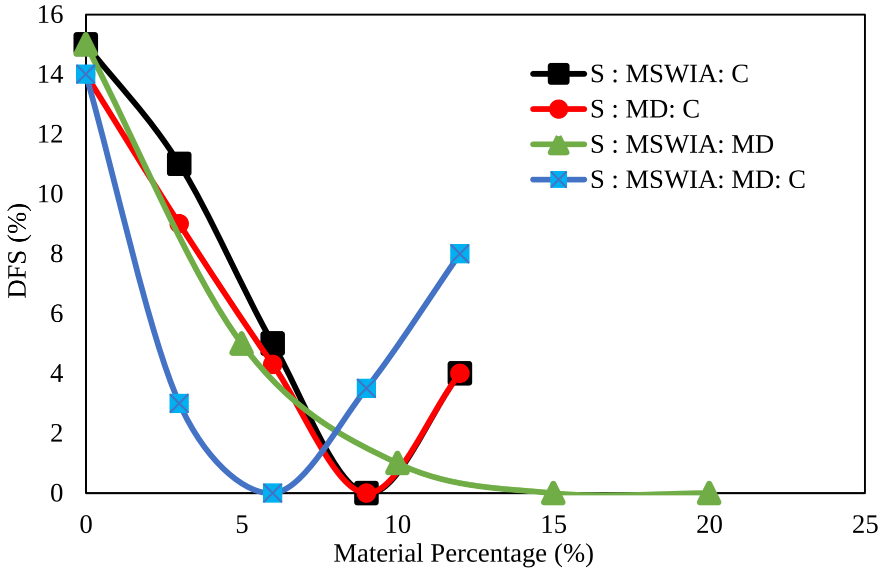


Figure 5.2: Effect of cement on differential free swell of various mixes

The reduction in DFS suggests that MSWIA and MD are effective in controlling the soil's swelling behavior by diluting the expansive clay minerals and altering the soil's physical structure. MSWIA, with its pozzolanic properties, and MD, acting as a filler, help in mitigating the soil's expansive tendencies, thereby improving its dimensional stability. The combination of these materials can reduce the risk of volumetric changes that typically cause structural damage. However, the inclusion of cement (C) in the mix further enhances the soil's strength and durability by chemically stabilizing the soil, improving cohesion, and solidifying the matrix. While the addition of MSWIA and MD alone is beneficial in reducing swelling, cement helps provide the necessary strength for long-term stability, making this combination a comprehensive solution for stabilizing clayey soils with high swelling potential. Therefore, the justification for the mix being "better" lies in its ability to balance swelling reduction with improved mechanical strength when all components, including cement, are used together.

5.3 Compaction characteristics

The effect of addition of different additives such as municipal solid waste incineration ash, marble dust, cement and polypropylene fiberindividually and in combination with each other on OMC and MDD of clay is discussed in subsequent sections. The effect of addition of polypropylene fiber on OMC and MDD of clay-municipal solid waste incineration ash-marble dust-cement mix is also discussed.

5.3.1 Clay-municipal solid waste incineration ash mix

The effect of addition of municipal solid waste incineration ash on maximum dry density and optimum moisture content of clay-municipal solid waste incineration ash mixes is shown in Figure 5.3.

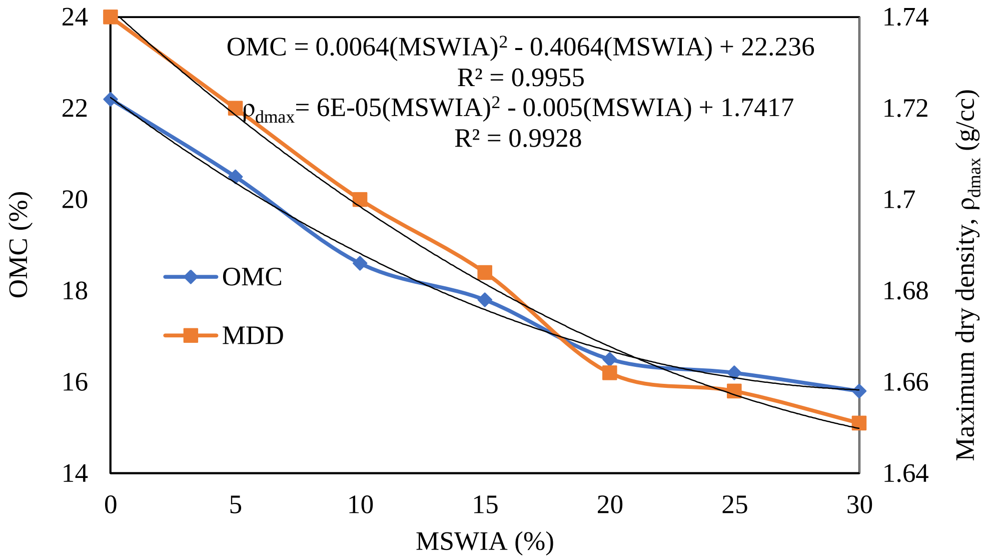


Figure 5.3: Effect of addition of municipal solid waste incineration ash on OMC and MDD of clay

MSWIA was procured from incineration plant Chandigarh and was mixed with the soil in varying proportion i.e., 0 to 30% by weight of the total soil mass in order to check its effect on compaction characteristics of the soil. For the same, testing was carried out in the laboratory of the Department of civil Engineering, Rayat University). On the basis of the results, it was observed that both the maximum dry density and the optimum moisture content decreases for clay-municipal solid waste incineration ash composite with increase in municipal solid waste incineration ash content. This may be due to the surface area of the particles or the water absorption capacity. The variation of maximum dry density with percentage of municipal solid waste incineration ash is represented by third order polynomial equation given below in equation 5.1 having R^2 value of 0.9928 in which maximum dry density is represented by 'ρ_{dmax}' and percentage of municipal solid waste incineration ash by 'MSWIA'.

$$\rho_{dmax} = 6E\text{-}05(MSWIA)^2 - 0.005(MSWIA) + 1.7417 \; [R^2 = 0.9928] \qquad [5.1]$$

The third order polynomial equations used to represent the variation of optimum moisture content with percentage of municipal solid waste incineration ash as given below in equation 5.2 having R^2 value of 0.9955 in which percentage of municipal solid waste incineration ash is represented by 'MSWIA'.

$$OMC = 0.0064(MSWIA)^2 - 0.4064(MSWIA) + 22.236 \; [R^2 = 0.9955] \qquad [5.2]$$

5.3.2 Clay-marble dust mix

The effect of addition of marble dust on optimum moisture content and maximum dry density of clay-marble dust mixes is shown in Figure 5.4. The results indicate that MDD increases and OMC decreased for clay-marble dust composite with increase in marble dust content. The increase in MDD value on increasing marble dust content may be due to the higher specific gravity of marble dust than that of clay; whereas, the reduction in OMC with increased marble dust content may be due the lesser OMC value of marble dust thus requiring less water.

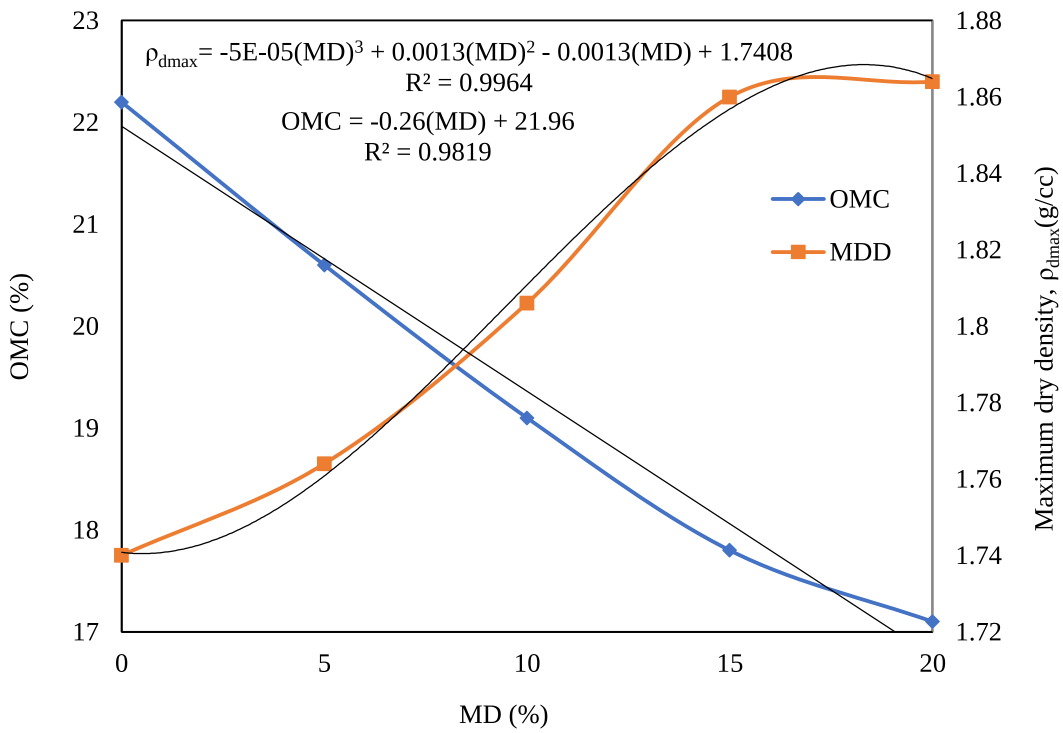


Figure 5.4: Effect of addition of marble dust on OMC and MDD of clay

The polynomial equation as shown in equation 5.3 having R^2 value of 0.9964 given below is used to represent the variation of maximum dry density 'ρ_{dmax}' with percentage of marble dust 'MD' as:

$$\rho_{dmax} = -5E\text{-}05(MD)^3 + 0.0013(MD)^2 - 0.0013(MD) + 1.7408 \; [R^2 = 0.9964] \qquad [5.3]$$

The change is optimum moisture content 'OMC' with addition of marble dust content 'MD' is represented by a linear equation as shown in equation 5.4 having R^2 value of 0.9819 given below in equation:

$$OMC = -0.26(MD) + 21.96 \; [R^2 = 0.9819] \qquad [5.4]$$

5.3.3 Clay-cement mix

The trend of change in optimum moisture content and maximum dry density with percentage of cement is shown in Figure 5.5. The results indicate that both maximum dry density and the optimum moisture content increases on addition of cement to clay. But the addition of cement beyond 9% decreases the OMC value.

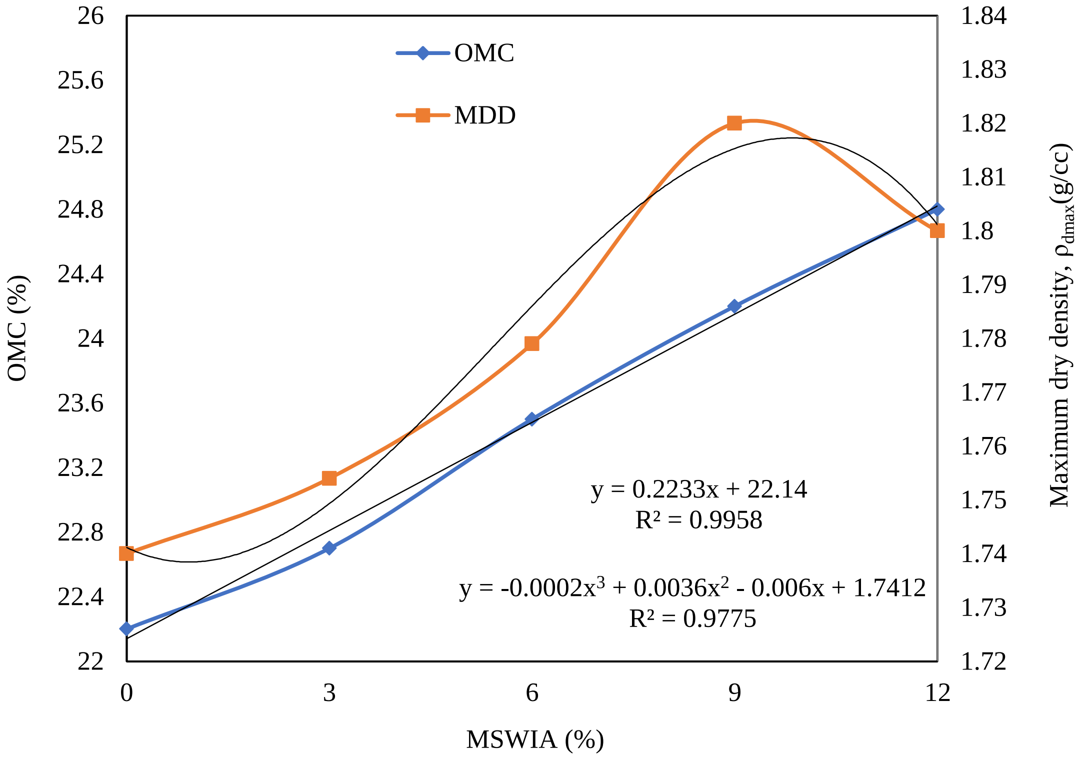


Figure 5.5: Effect of addition of cement on OMC and MDD of clay

The maximum dry density decreases in polynomial form with increase in cement content. The increase in optimum moisture content may also be due to water affinity upon addition of cement and also due to the pozzolanic reaction between clay particles and the cement. The improvement in MDD value may be due to the higher specific gravity of cement compared to that of clay. The results are in good agreement with the past few research works (Kavak and Akyarli 2007; Harichane et al. 2012; Bhardwaj and Sharma 2020). The linear equation expressed in equation 5.5 having R^2 value of 0.9775 is used to find the relationship between variation of OMC and percentage of cement which is as follows and in which maximum dry density is represented by 'ρ_{dmax}'and percentage of cement as 'C'.

$$\rho_{dmax} = -0.0002(C)^3 + 0.0036(C)^2 - 0.006(C) + 1.7412 \; [R^2 = 0.9775] \qquad [5.5]$$

The variation of optimum moisture content with percentage of cement is represented by the linear equation expressed in equation 5.6 having R^2 value of 0.9958 in which optimum moisture content is represented as ‘OMC’ and percentage of cement as ‘C’.

$$OMC = 0.2233(C) + 22.14 \; [R^2 = 0.9958] \qquad [5.6]$$

The linear trend in the OMC with increasing proportions of MSWIA can be attributed to several factors. As MSWIA is blended with clay, its fine particles fill the voids in the clay matrix, leading to more efficient water retention and a steady increase in OMC. The pozzolanic properties of MSWIA also facilitate gradual water absorption without drastically altering the soil structure. Additionally, MSWIA’s non-cohesive minerals can absorb moisture without swelling, reinforcing this linearity. Consistent experimental methods may further contribute to this smooth transition in moisture requirements, while the OMC primarily reflects water content for optimal compaction, explaining its steady behavior compared to possible fluctuations in MDD.

5.3.4 Clay-PPF mix

The trend of change in optimum moisture content and maximum dry density with percentage of PPF is shown in Figure 5.6. The results indicate that both maximum dry density and the optimum moisture content decreased on addition of PPF to clay. But the reduction in OMC is not significant and almost remains same. The slight reduction in MDD with some variation in OMC could be attributed to the low specific gravity of PP fiber, coupled with PP fiber and soil particles' physical interaction which might lead to different micro-structural arrangements.

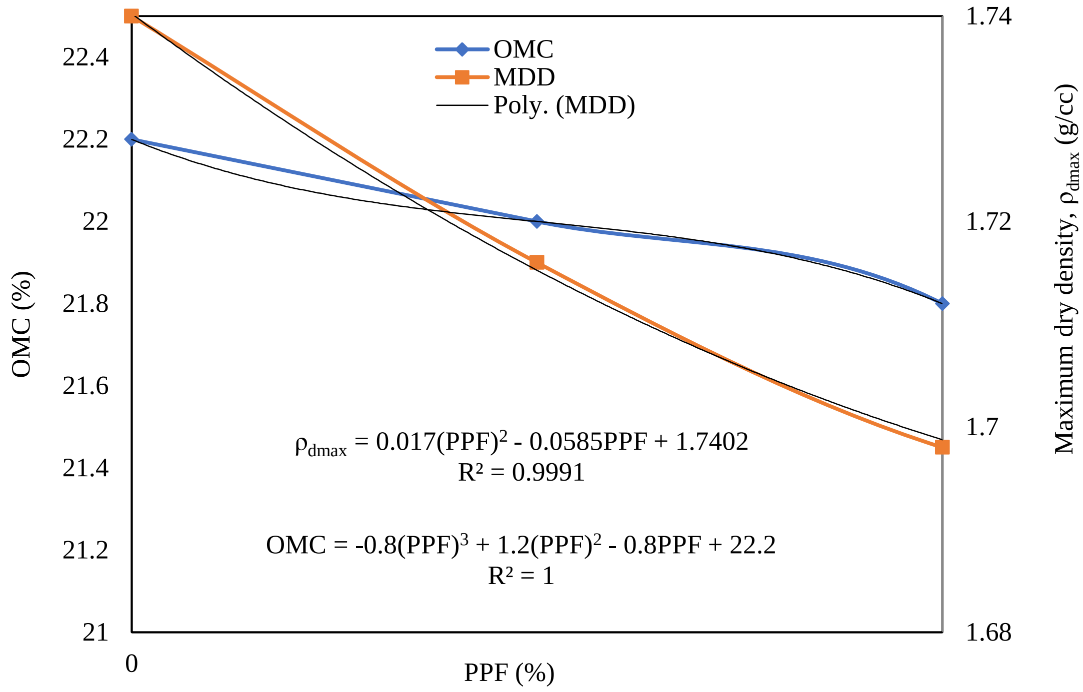


Figure 5.6: Effect of addition of cement on OMC and MDD of clay

The maximum dry density decreases in polynomial form with increase in polypropylene fiber content. The polynomial equation in equation 5.7 having R^2 value of 0.9991 is used to find the relationship between variation of OMC and percentage of polypropylene fiber which is as follows and in which maximum dry density is represented by 'ρ_{dmax}'and percentage of polypropylene fiber as 'PPF'.

$$\rho_{dmax} = 0.017(PPF)^2 - 0.0585PPF + 1.7402 \ [R^2 = 0.9991] \quad [5.7]$$

The variation of optimum moisture content with percentage of polypropylene fiber is represented by the polynomial equation in equation 5.8 having R^2 value of 1.000 in which optimum moisture content is represented as 'OMC' and percentage of polypropylene fiber as 'PPF'.

$$OMC = -0.8(PPF)^3 + 1.2(PPF)^2 - 0.8PPF + 22.2 \ [R^2 = 1] \quad [5.8]$$

5.3.5 Clay-municipal solid waste incineration ash-cement mix

The effect of addition of cement on optimum moisture content and maximum dry density of clay-municipal solid waste incineration ash mix is shown in Figure 5.7.

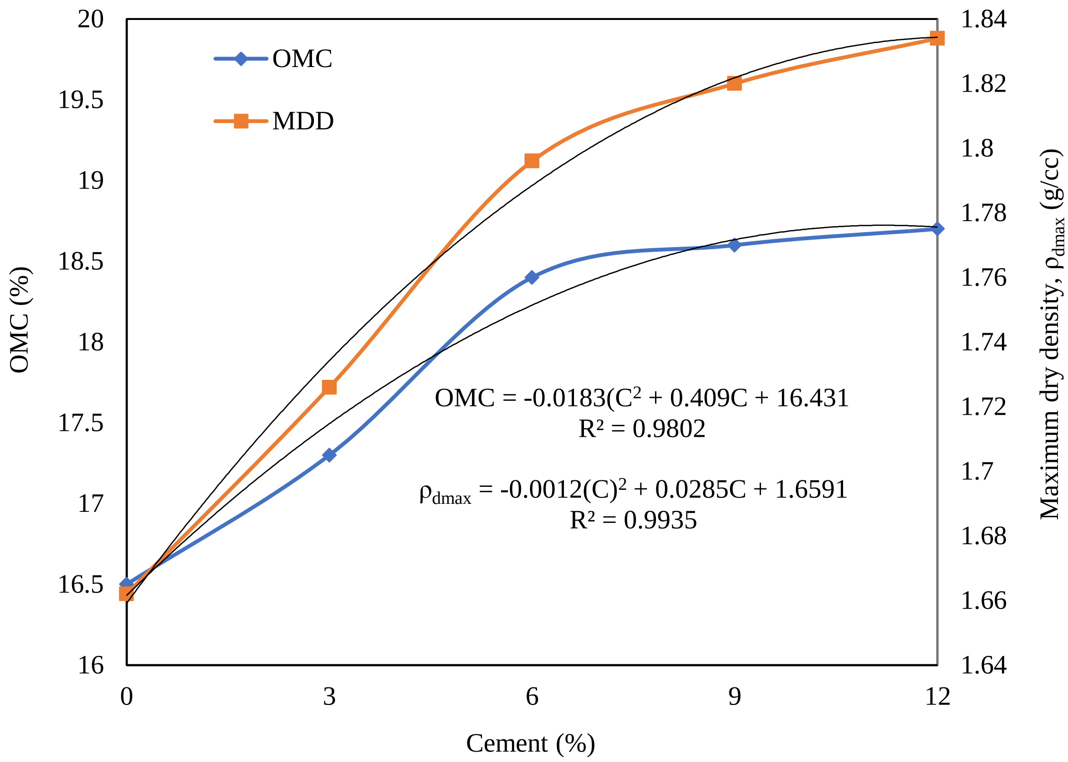


Figure 5.7: Effect of addition of cement on OMC and MDD of clay-municipal solid waste incineration ashmix

Addition of cement increases both the optimum moisture content the maximum dry density of clay-municipal solid waste incineration ash mix. The increase in MDD value on adding cement may be due to the higher specific gravity of cement compared to clay and MSWIA particles both. The little increase in OMC value may be due to the pozzolanic reaction occurring between cement and clay particles and also due to the very higher OMC of cement compared to that of MSWIA. Variation of maximum dry density 'ρ_{dmax}' with addition of cement content 'C' is represented by a polynomial equation in equation 5.9 having R^2 value of 0.9935:

$$\rho_{dmax} = -0.0012(C)^2 + 0.0285C + 1.6591 \; [R^2 = 0.9935] \qquad [5.9]$$

The polynomial equation 5.10 having R^2 value of 0.9802 is used to represent the variation of optimum moisture content 'OMC' with percentage of cement 'C' as:

$$OMC = -0.0183(C^2 + 0.409C + 16.431 \; [R^2 = 0.9802] \qquad [5.10]$$

5.3.6 Clay-marble dust-cement mix

The variation of maximum dry density and optimum moisture content of clay-marble dust mix with addition of cement is shown in Figure 5.8.

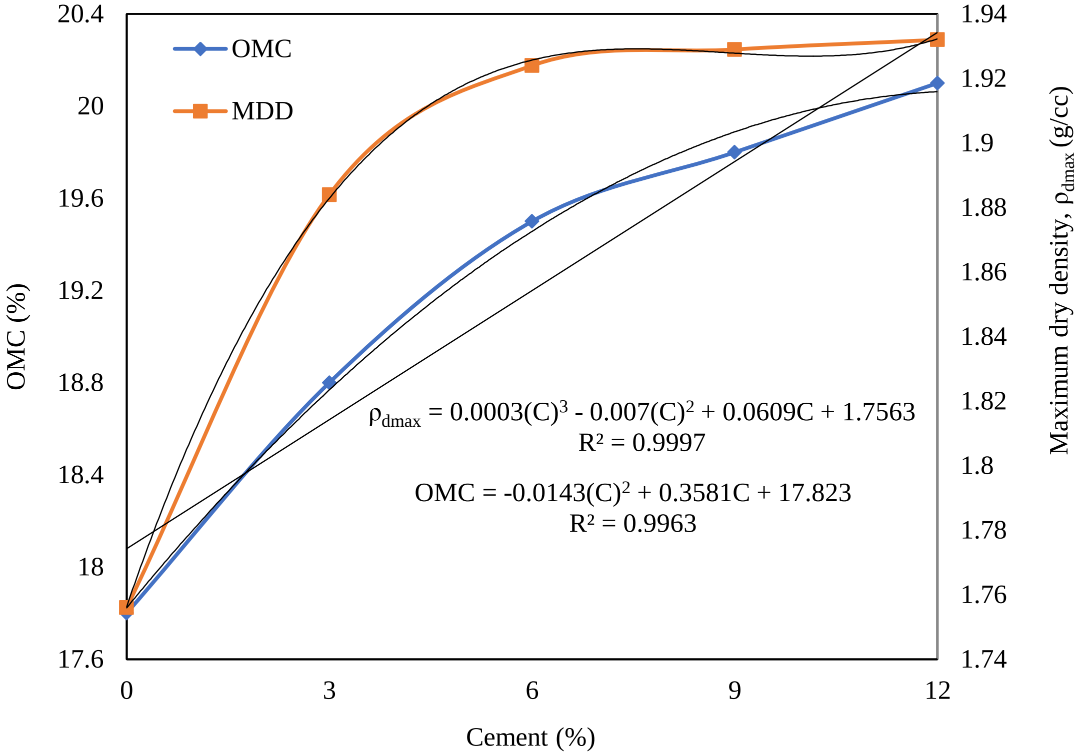


Figure 5.8: Effect of addition of cement on OMC and MDD of clay-marble dust mix

The results indicate that both maximum dry density and the optimum moisture content increases on addition of cement to clay-marble dust mix. The increase in MDD value on adding cement to soil and marble dust mixture may be due to the higher specific gravity of both cement and marble dust compared to clay. The little increase in OMC value may be due to the pozzolanic reaction occurring between cement and soil: marble dust mixtures and also due to the very higher OMC of cement compared to that of marble dust. The addition of cement content 'C' changes the maximum dry density 'ρ_{dmax}' represented by third degree polynomial equation 5.11 having R^2 value of 0.9997 given below:

$$\rho_{dmax} = 0.0003(C)^3 - 0.007(C)^2 + 0.0609C + 1.7563 \; [R^2 = 0.9997] \qquad [5.11]$$

The variation of optimum moisture content 'OMC' with percentage of cement 'C' is represented second degree polynomial 5.12 having R^2 value of 0.9963 equation as:

$$OMC = -0.0143(C)^2 + 0.3581C + 17.823 \; [R^2 = 0.9963] \qquad [5.12]$$

5.3.7 Clay-municipal solid waste incineration ash-polypropylene fiber mix

The effect of addition of polypropylene fiber on the maximum dry density and optimum moisture content of soil-municipal solid waste incineration ash mix is shown in Figure 5.9.

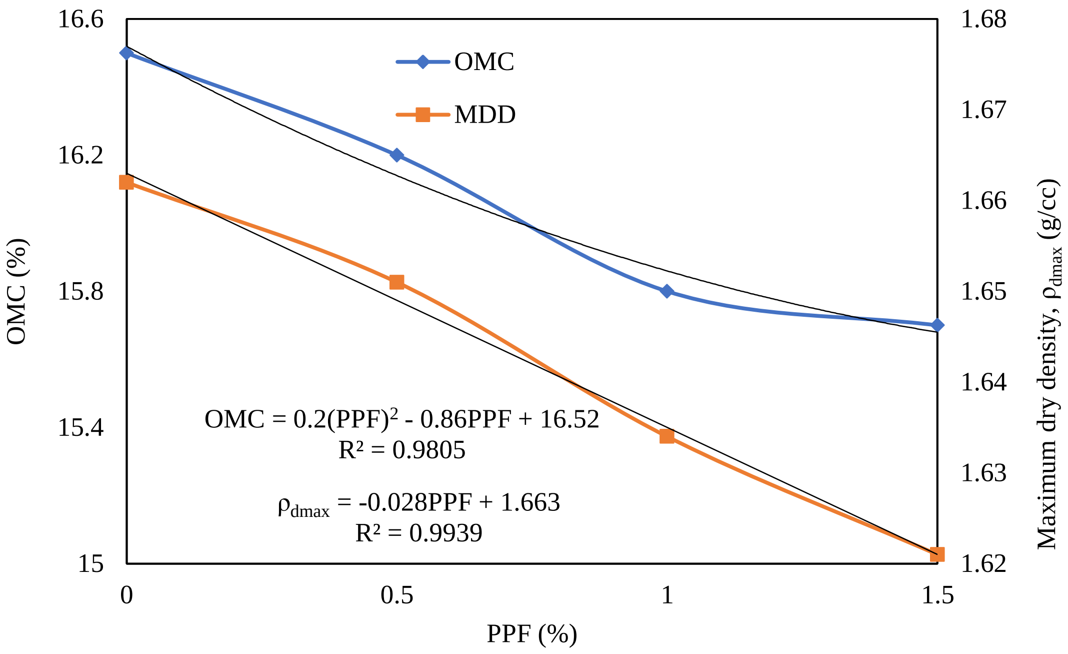


Figure 5.9: Effect of addition of cement on OMC and MDD of clay-municipal solid waste incineration ash- polypropylene fiber mix

The results indicate that both maximum dry density decreases and optimum moisture content decreases on addition of polypropylene fiber to clay-municipal solid waste incineration ash mix. The minor reduction in MDD including some fluctuation in OMC might be due to the low specific gravity of PP fiber, along with the physical interaction of PP fiber and soil particles, which could result in various micro-structural arrangements. The addition of PPF content decreases the maximum dry density 'ρ_{dmax}' linearly represented by a linear equation 5.13 having R^2 value of 0.9939 given below:

$$\rho_{dmax} = -0.028PPF + 1.663 \; [R^2 = 0.9939] \quad [5.13]$$

The variation of the optimum moisture content 'OMC' with percentage of polypropylene fiber content 'PPF' is represented by a polynomial equation 5.14 having R^2 value of 0.9805 given below:

$$OMC = 0.2(PPF)^2 - 0.86PPF + 16.52 \; [R^2 = 0.9805] \quad [5.14]$$

5.3.8 Clay-marble dust-polypropylene fiber mix

The effect of addition of polypropylene fiber on the maximum dry density and optimum moisture content of soil-marble dust mix is shown in Figure 5.10.

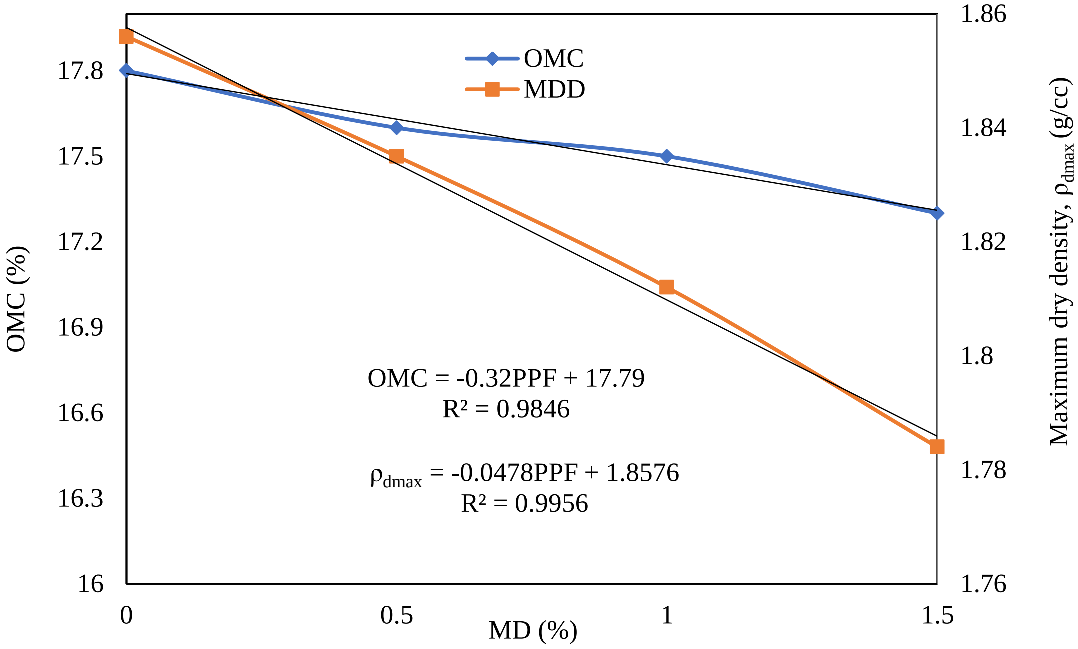


Figure 5.10: Effect of addition of polypropylene fiber on OMC and MDD of clay-marble dust mix

The results indicate that the maximum dry density decreases and the optimum moisture content also decreases on addition of polypropylene fiber to clay-marble dust mix. The decrease in MDD, as well as some variability in OMC, might be related to the low specific gravity of PP fibre, as well as the physical contact between PP fibre and soil particles, which could lead in a variety of micro-structural formations. The addition of polypropylene fiber content 'PPF' decreases the maximum dry density 'ρ_{dmax}' linearly represented by a linear equation 5.15 having R^2 value of 0.99956 given below:

$$\rho_{dmax} = -0.0478PPF + 1.8576 \ [R^2 = 0.9956] \qquad [5.15]$$

The variation of the optimum moisture content 'OMC' with percentage of polypropylene fiber content 'PPF' is represented by a linear equation 5.16 having R^2 value of 0.9846 given below:

$$OMC = -0.32PPF + 17.79 \ [R^2 = 0.9846] \qquad [5.16]$$

5.3.9 Clay-cement-polypropylene fiber mix

The effect of addition of polypropylene fiber (PPF) on the maximum dry density and optimum moisture content of soil-cement mix is shown in Figure 5.11.

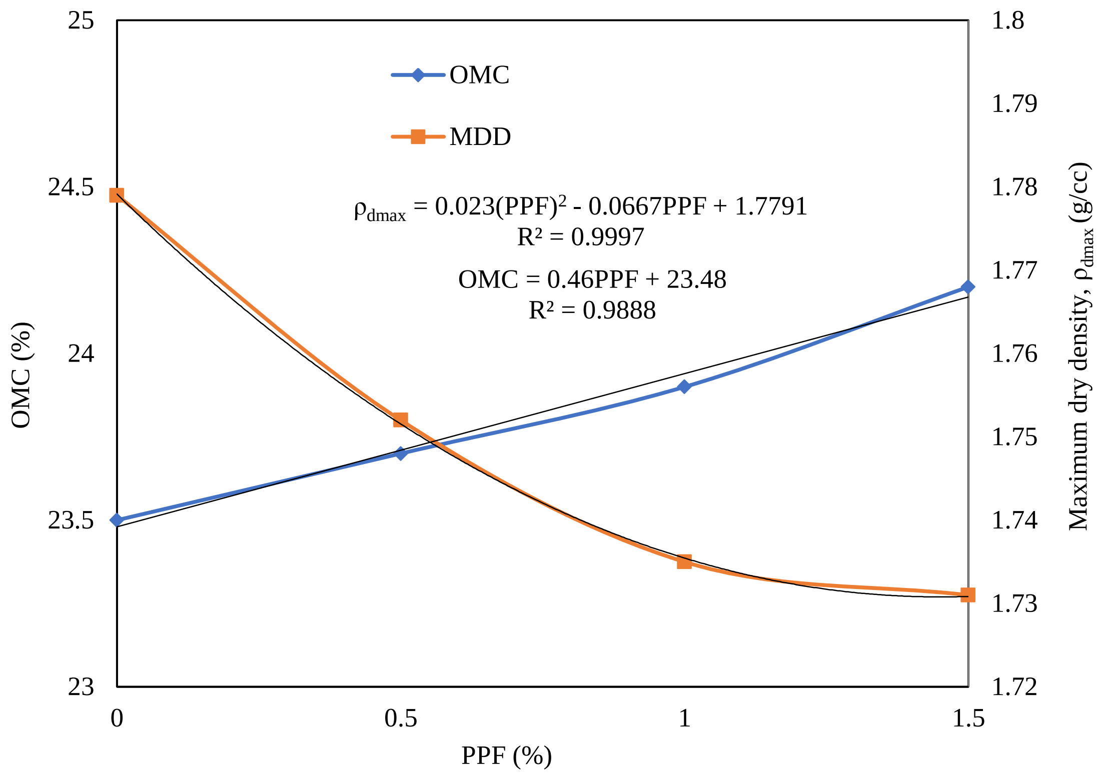


Figure 5.11: Effect of addition of polypropylene fiber on OMC and MDD of clay-cement mix

The results indicate that the maximum dry density decreases and the optimum moisture content remains almost constant on addition of polypropylene fiber to clay-cement mix. The decrease in MDD along with some variability in OMC might be attributed to PP fiber's low specific gravity, as well as physical interaction between PP fiber and soil particles, which could result in a range of micro-structural compositions. The addition of polypropylene fiber content 'PPF' decreases the maximum dry density 'ρ_{dmax}' polynomially represented by a equation 5.17 having R^2 value of 0.9997given below:

$$\rho_{dmax} = 0.023(PPF)^2 - 0.0667PPF + 1.7791 \; [R^2 = 0.9997] \qquad [5.17]$$

The variation of the optimum moisture content 'OMC' with percentage of polypropylene fiber content 'PPF' is represented by a linear equation 5.18 having R^2 value of 0.9888 given below:

$$OMC = 0.46PPF + 23.48 \; [R^2 = 0.9888] \qquad [5.18]$$

5.3.10 Clay-municipal solid waste incineration ash-marble dust mix

The effect of addition of marble dust on the maximum dry density and optimum moisture content of soil-municipal solid waste incineration ash mix is shown in Figure 5.12.

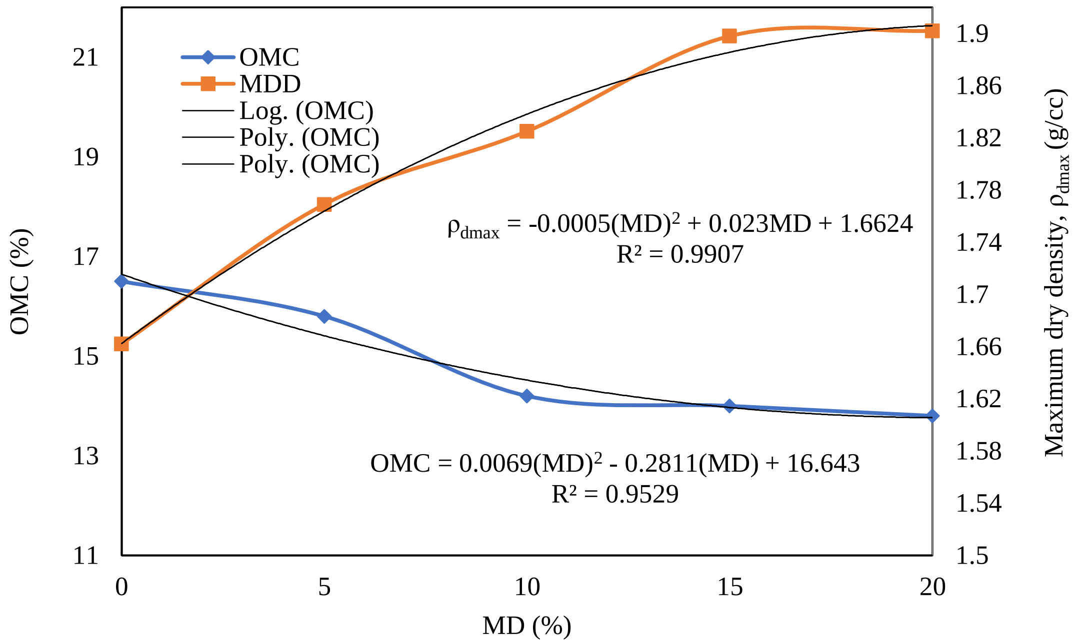


Figure 5.12: Effect of addition of marble dust on OMC and MDD of clay-municipal solid waste incineration ash mix

The results indicate that the maximum dry density increases and the optimum moisture content decreases on addition of marble dust to clay-municipal solid waste incineration ash mix. The rise in MDD value with rising marble dust percentage may be owing to marble dust's greater specific gravity than clay, whilst the decrease in OMC with increasing marble dust percentage may be related to marble dust's lower OMC value, needing less water. The addition of marble dust content 'MD' increases the maximum dry density 'ρ_{dmax}' polynomially represented by an equation 5.19 having R^2 value of 0.9907 given below:

$$\rho_{dmax} = -0.0005(MD)^2 + 0.023MD + 1.6624 \; [R^2 = 0.9907] \qquad [5.19]$$

The variation of the optimum moisture content 'OMC' with percentage of marble dust content 'MD' is represented by a polynomial equation 5.20 having R^2 value of 0.9529 given below:

$$OMC = 0.0069(MD)^2 - 0.2811(MD) + 16.643 \; [R^2 = 0.9529] \qquad [5.20]$$

5.3.11 Clay-municipal solid waste incineration ash-marble dust-cement mix

The effect of addition of cement on the maximum dry density and optimum moisture content of soil-municipal solid waste incineration ash-marble dust mix is shown in Figure 5.13.

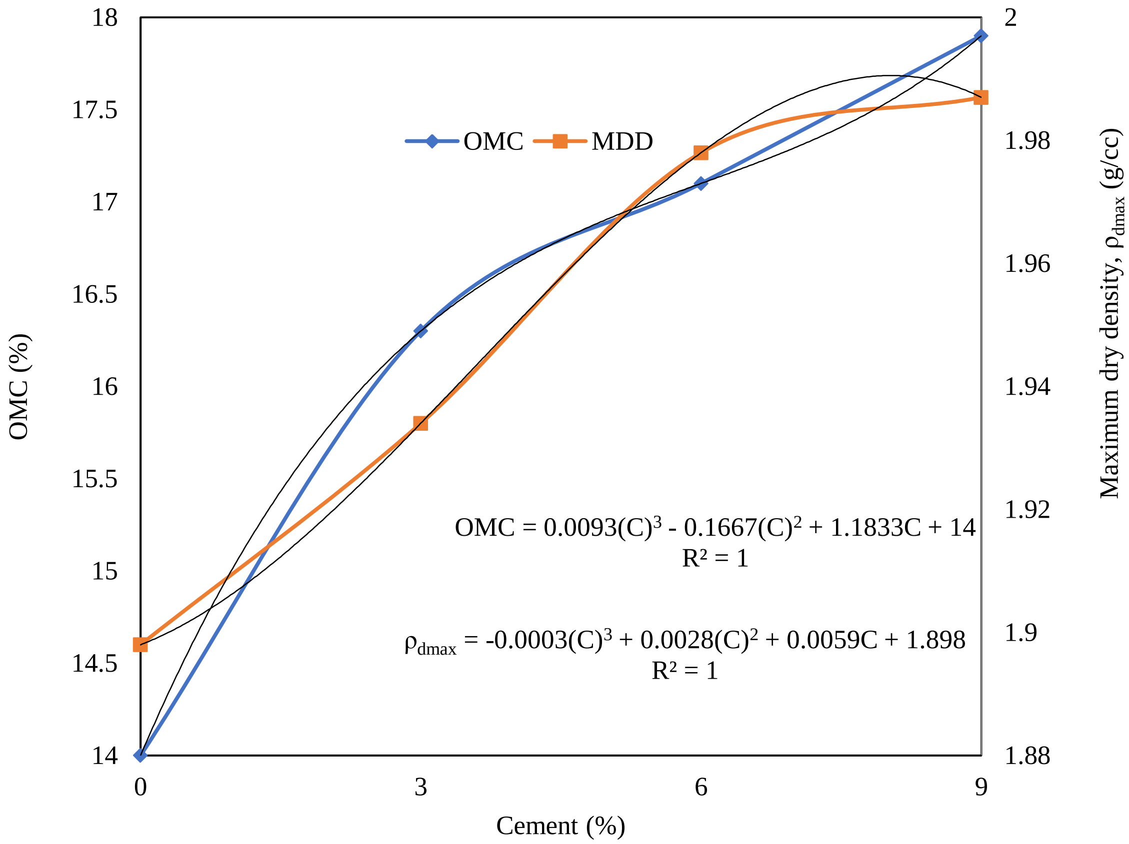


Figure 5.13: Effect of addition of cement on OMC and MDD of clay-municipal solid waste incineration ash-marble dust mix

The results indicate that the maximum dry density increases and the optimum moisture content decreases on addition of cement to clay-municipal solid waste incineration ash-marble dust mix. The increase in OMC value may be due to the pozzolanic reaction occurring between cement and soil: municipal solid waste incineration ash: marble dust mixtures and also due to the very higher OMC of cement compared to that of municipal solid waste incineration ash and marble dust. The addition of cement content 'C' increases the maximum dry density 'ρ_{dmax}' represented by a third-degree polynomial equation 5.21 having R^2 value of 1.0 given below:

$$\rho_{dmax} = -0.0003(C)^3 + 0.0028(C)^2 + 0.0059C + 1.898 \; [R^2 = 1] \qquad [5.21]$$

The variation of the optimum moisture content 'OMC' with percentage of cement content 'C' is represented by a third-degree polynomial equation 5.22 having R^2 value of 1.0 given below:

$$OMC = 0.0093(C)^3 - 0.1667(C)^2 + 1.1833C + 14 \quad [R^2 = 1] \qquad [5.22]$$

5.3.12 Clay-municipal solid waste incineration ash-marble dust-cement-polypropylene fiber mix

The effect of addition of polypropylene fiber on the maximum dry density and optimum moisture content of soil-municipal solid waste incineration ash-marble dust-cement mix is shown in Figure 5.14.

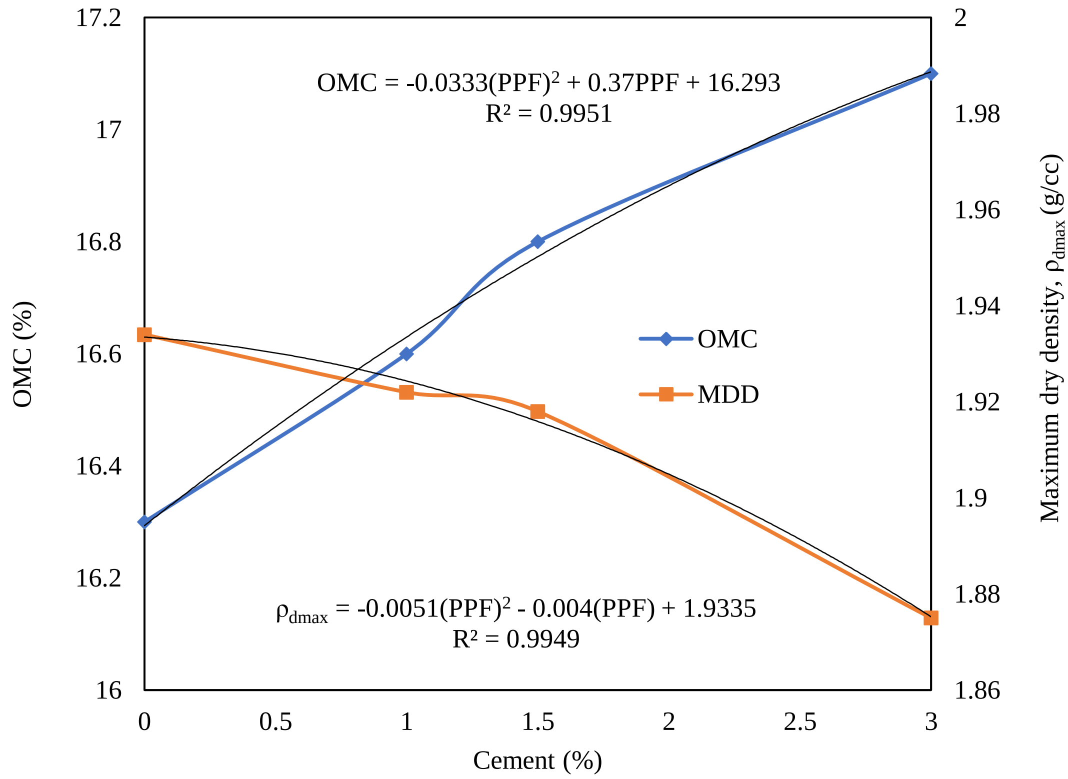


Figure 5.14: Effect of addition of polypropylene fiber on OMC and MDD of clay-municipal solid waste incineration ash-marble dust-cement mix

The results indicate that the maximum dry density decreases and the optimum moisture content increases on addition of polypropylene fiber to clay-municipal solid waste incineration ash-Marble dust mix. The decrease in MDD along with some variability in OMC might be attributed to PP fiber's low specific gravity, as well as physical interaction between PP fiber and soil particles, which could result in a range of micro-structural compositions. The addition of polypropylene fiber content 'PPF' decreases the maximum dry density 'ρ_{dmax}' linearly represented by a linear equation 5.23 having R^2 value of 0.9949 given below:

$$\rho_{dmax} = -0.0051(PPF)^2 - 0.004(PPF) + 1.9335 \; [R^2 = 0.9949] \quad [5.23]$$

The variation of the optimum moisture content 'OMC' with percentage of polypropylene fiber content 'PPF' is represented by a polynomial equation 5.24 having R^2 value of 0.9951 given below:

$$OMC = -0.0333(PPF)^2 + 0.37PPF + 16.293 \; [R^2 = 0.9951] \quad [5.24]$$

5.3.13 Validation of compaction results

The results obtained from experimental testing of compaction was validated using regression analysis and the percentage difference was calculated among the various values for different random combinations between minimum and maximum contents of each admixture.

Table 5.1 and Table 5.2 presents the various values of OMC and MDD for validation purpose.

Table 5.1: Validation of OMC results

Combinations	Clay	MSWIA	MD	Cement	PPF	Observed OMC	Predicted OMC	%age Error
17.5% MSWIA	82.5	17.5	0	0	0	17.15	16.85	1.75
22.5% MSWIA	77.5	22.5	0	0	0	16.35	15.36	6.08
12.5% MD	87.5	0	12.5	0	0	18.45	17.30	6.25
17.5% MD	82.5	0	17.5	0	0	17.45	17.07	2.19
7.5% Cement	92.5	0	0	7.5	0	14.06	14.03	0.24
10.5% Cement	89.5	0	0	10.5	0	13.12	12.53	4.50
0.75% PPF	99.25	0	0	0	0.75	21.90	19.49	11.01
1.25% PPF	98.75	0	0	0	1.25	21.40	20.57	3.90
20% MSWIA + 7.5% cement	72.5	20	0	7.5	0	18.50	16.16	12.64
15% MD + 7.5% cement	77.5	0	15	7.5	0	19.65	17.71	9.88
20% MSWIA + 0.75% PPF	79.25	20	0	0	0.75	16.00	17.25	-7.83
20% MSWIA + 1.25% PPF	78.75	20	0	0	1.25	15.75	18.33	-16.39
15% MD + 0.75% PPF	84.25	0	15	0	0.75	17.55	18.80	-7.12
15% MD + 1.25% PPF	83.75	0	15	0	1.25	17.40	19.88	-14.24
6% cement + 0.75% PPF	93.25	0	0	6	0.75	23.80	22.86	3.95
6% cement + 1.25% PPF	92.75	0	0	6	1.25	24.05	23.50	2.29
20% MSWIA + MD 12.5%	67.5	20	12.5	0	0	14.10	15.06	-6.83
20% MSWIA + MD 17.5%	62.5	20	17.5	0	0	13.90	14.83	-6.71
20% MSWIA + 15% MD + 4.5% Cement	60.5	20	15	4.5	0	16.70	15.26	8.60
20% MSWIA + 15% MD + 7.5% Cement	57.5	20	15	7.5	0	17.50	16.89	3.49
20% MSWIA + + 15% MD + 4.5% Cement + 0.75% PPF	59.75	20	15	4.5	0.75	16.70	16.88	-1.08
20% MSWIA + 15% MD + 7.5% Cement + 1.25% PPF	59.25	20	15	4.5	1.25	16.95	17.96	-5.95

Table 5.2: Validation of MDD results

Combinations	Clay	MSWIA	MD	Cement	PPF	Predicted MDD	Observed MDD	%age Error
17.5% MSWIA	82.5	17.5	0	0	0	1.67	1.67	0.48
22.5% MSWIA	77.5	22.5	0	0	0	1.66	1.69	-2.05
12.5% MD	87.5	0	12.5	0	0	1.83	1.83	0.31
17.5% MD	82.5	0	17.5	0	0	1.86	1.88	-1.21
7.5% Cement	92.5	0	0	7.5	0	1.80	1.79	0.61
10.5% Cement	89.5	0	0	10.5	0	1.81	1.83	-1.10
0.75% PPF	99.25	0	0	0	0.75	1.71	1.66	2.61
1.25% PPF	98.75	0	0	0	1.25	1.69	1.65	2.66
20% MSWIA + 7.5% cement	72.5	20	0	7.5	0	1.81	1.80	0.60
15% MD + 7.5% cement	77.5	0	15	7.5	0	1.93	1.96	-1.65
20% MSWIA + 0.75% PPF	79.25	20	0	0	0.75	1.64	1.67	-1.86
20% MSWIA + 1.25% PPF	78.75	20	0	0	1.25	1.63	1.66	-1.99
15% MD + 0.75% PPF	84.25	0	15	0	0.75	1.82	1.83	-0.59
15% MD + 1.25% PPF	83.75	0	15	0	1.25	1.80	1.82	-1.28
6% cement + 0.75% PPF	93.25	0	0	6	0.75	1.74	1.75	-0.15
6% cement + 1.25% PPF	92.75	0	0	6	1.25	1.73	1.73	0.00
20% MSWIA + MD 12.5%	67.5	20	12.5	0	0	1.86	1.84	1.38
20% MSWIA + MD 17.5%	62.5	20	17.5	0	0	1.90	1.89	0.37
20% MSWIA + 15% MD + 4.5% Cement	60.5	20	15	4.5	0	1.96	1.93	1.48
20% MSWIA + 15% MD + 7.5% Cement	57.5	20	15	7.5	0	1.98	1.97	0.69
20% MSWIA + + 15% MD + 4.5% Cement + 0.75% PPF	59.75	20	15	4.5	0.75	1.92	1.91	0.66
20% MSWIA + 15% MD + 7.5% Cement + 1.25% PPF	59.25	20	15	4.5	1.25	1.90	1.89	0.12

5.4 Unconfined compressive strength

The variation of unconfined compressive strength of clay and different composites with curing period is discussed in subsequent sections.

5.4.1 Effect of curing period on UCS of clay-municipal solid waste incineration ash mix

The unconfined compressive strength increases with addition of municipal solid waste incineration ash and with curing period as shown in Figure 5.15. The UCS of clay-municipal solid waste incineration ash mix increases with curing period and increase in strength from 3 to 7 days is abrupt; however, from 7 days to 28 days the increase in UCS slows down with a very little increment on increasing curing period from 28 days to 56 days.

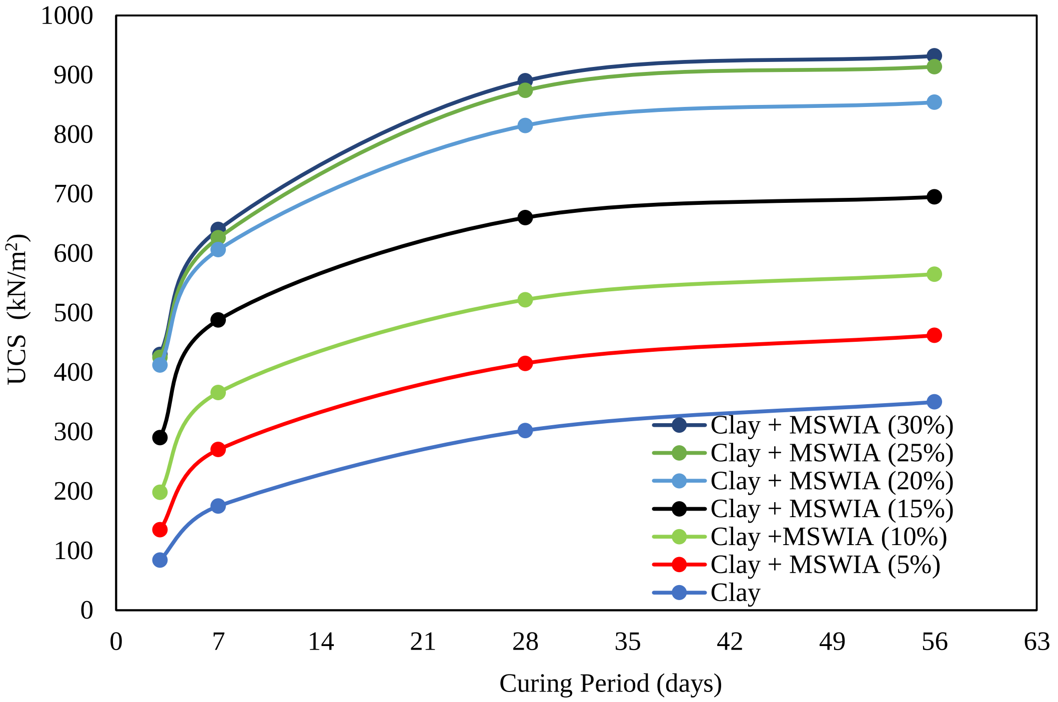


Figure 5.15: Variation in UCS of clay and clay-municipal solid waste incineration ash mixes with curing period

The figure reveals that variation of unconfined compressive strength with curing period for 20%, 25% and 30% municipal solid waste incineration ash contents is almost linear. The difference between UCS values corresponding to 25% and 30% municipal solid waste incineration ash contents is less compared to that between 20% and 25% municipal solid waste incineration ash contents. This indicates that the rate of increase in UCS decreases as the municipal solid waste incineration ash content varies from 20% to 25% and therefore 20% municipal solid waste incineration ash content may be considered as the optimum dosage for stabilization of clayey soil. The increase in UCS value on adding MSWIA may be due to the pozzolanic reaction between MSWIA and clay particles and also may be due to the frictional resistance offered by MSWIA particles. A similar increase in UCS value on adding MSWIA has been reported earlier (Ashango and Patra 2016; Liu et al. 2019; Kolias et al 2005; Sezer et al 2006).

5.4.2 Effect of curing period on UCS of clay-marble dust mix

The variation of UCS of clay and clay-Marble dust mixes with curing periods is shown in Figure 5.16. The increase in UCS from 3 days to 7 days curing period is very fast and after that the increase in UCS value from 7 to 28 days lowers down with an almost linear trend on increasing curing period from 28 to 56 days for all the marble dust contents. This shows that with addition of marble dust the strength gain will be more between 7 days and 28 days. The increase in UCS is more for 15% marble dust content compared to that for other combinations and, hence, 85% clay: 15% Marble dust may be considered as optimum content for soil stabilization.

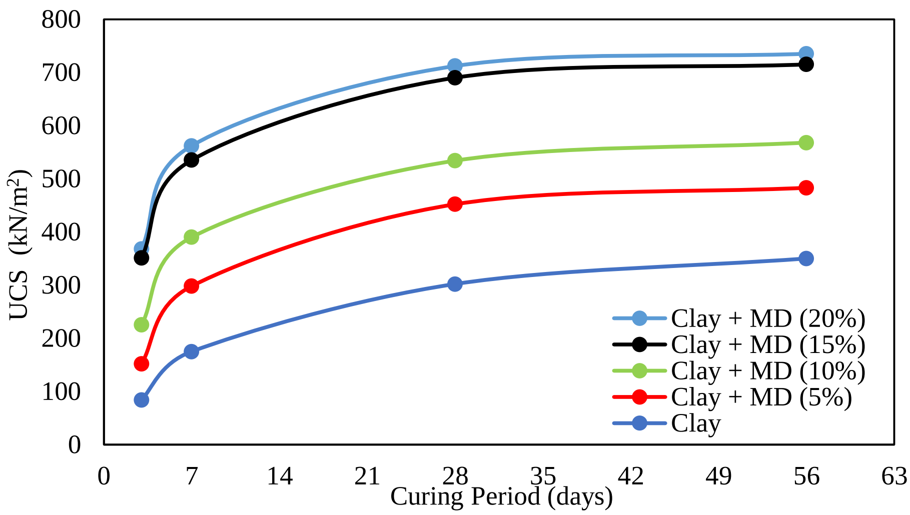


Figure 5.16: Variation in UCS of clay and clay-marble dust mixes with curing period

From the above paragraphs, it can be concluded that the unconfined compressive strength increases with curing period for all the material combinations. The increase in strength with addition of marble dust for 3 days and 7 days curing periods is higher by about 5% in comparison with addition of 20% MSWIA content to clay. The 28 days unconfined compressive strength of clay- municipal solid waste incineration ash mixes and clay- marble dust mix is almost same only for the case where addition 20% municipal solid waste incineration ash and marble dust shows significant change in UCS values. The 56 days unconfined compressive strength of clay- municipal solid waste incineration ash mixes and clay- marble dust mix is almost same. The increase in UCS value by addition of marble dust may be due to the pozzolanic reaction between soil particles and marble dust. Similar results indicating the increase in UCS have been reported in the past (Ola 1977; Attoh-Okine 1995; Bell 1996; Manasseh and Olufemi 2008; Sakr et al. 2009; Dash and Hussain 2012).

The municipal solid waste incineration ash and marble dust being the waste materials and, hence, can be used but municipal solid waste incineration ash is available near incinerationplants whereas marble dust is available almost in every small town even. Hence, addition of marble dust for stabilization of clayey soil is a viable option compared to that of municipal solid waste incineration ash even though MSWIA is possessing higher UCS values for all curing periods.

5.4.3 Effect of curing period on UCS of clay-cement mix

The effect of curing period on unconfined compressive strength of clay and clay-cement mixes is shown in Figure 5.17. The unconfined compressive strength of clay and clay-cement mixes increases with curing period. The figure reveals that the increase in strength is more for clay up to 28 days curing period after which the rate of increase in UCS is less. For 97% clay: 3% cement mix, the rate of increase in UCS is less between 7 days and 28 days curing period compared to the rate of increase in UCS between 3 days and 7 days.

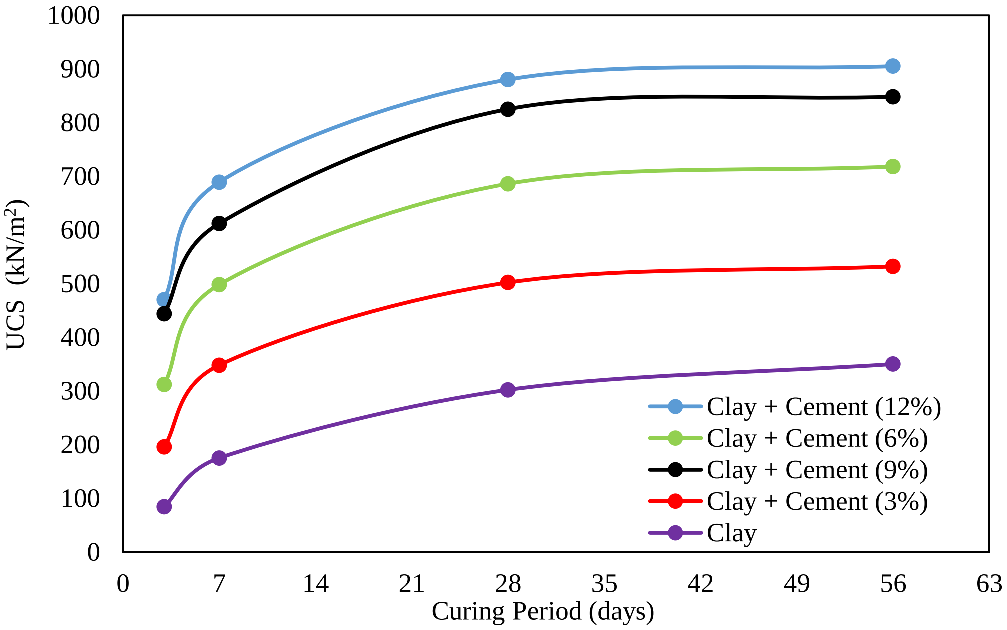


Figure 5.17: Variation in UCS of clay and clay-cement mixes with curing period

There is marginal increase in strength between 28 days and 56 days whereas for 9% and 12% cement contents, the rate of increase in UCS is almost linear. Thus, based on the results it can concluded that UCS increases with curing period and the increase is more for 9% cement content. Hence, it can conclude that unconfined compressive strength increases with increase in curing period and 9% cement is the optimum cement dosage for stabilization of clayey soil.

It may be due to fact that during curing, soil particles naturally rearrange and densify due to consolidation, reducing void spaces and enhancing cohesion, which leads to higher UCS. Additionally, the gradual reduction in moisture content during curing increases effective stress in the soil matrix, strengthening inter-particle bonds and facilitating tighter locking of soil particles. This time-dependent strength gain, often referred to as thixotropy, allows clay soils to recover strength as electrochemical bonds reform over time. Moreover, the initial compaction of the soil sample plays a crucial role; well-compacted soils may exhibit higher initial densities that, when combined with decreased moisture, result in enhanced UCS. The intrinsic properties of clay, particularly those with high plasticity, further contribute to strength improvements through particle realignment as water migrates or evaporates. Finally, the absence of detrimental factors, such as excessive moisture or over-stabilization with cement—which can lead to brittle behavior—allows for a more natural strength gain in uncemented soils, demonstrating their inherent capacity to improve over time.

5.4.4 Effect of curing period on UCS of clay-polypropylene fiber mix

The effect of curing period on unconfined compressive strength of clay and clay-cement mixes is shown in Figure 5.18. The unconfined compressive strength of clay and clay- polypropylene fiber mixes increase with curing period. The figure reveals that the increase in strength is more for clay up to 28 days curing period after which the rate of increase in UCS is less. For all UCS value of clay- polypropylene fiber mix, the rate of increase in UCS is lesser between 7 days and 28 days curing period followed by and UCS between 28 and 56 days which is further followed by UCS between 3 days and 7 days.

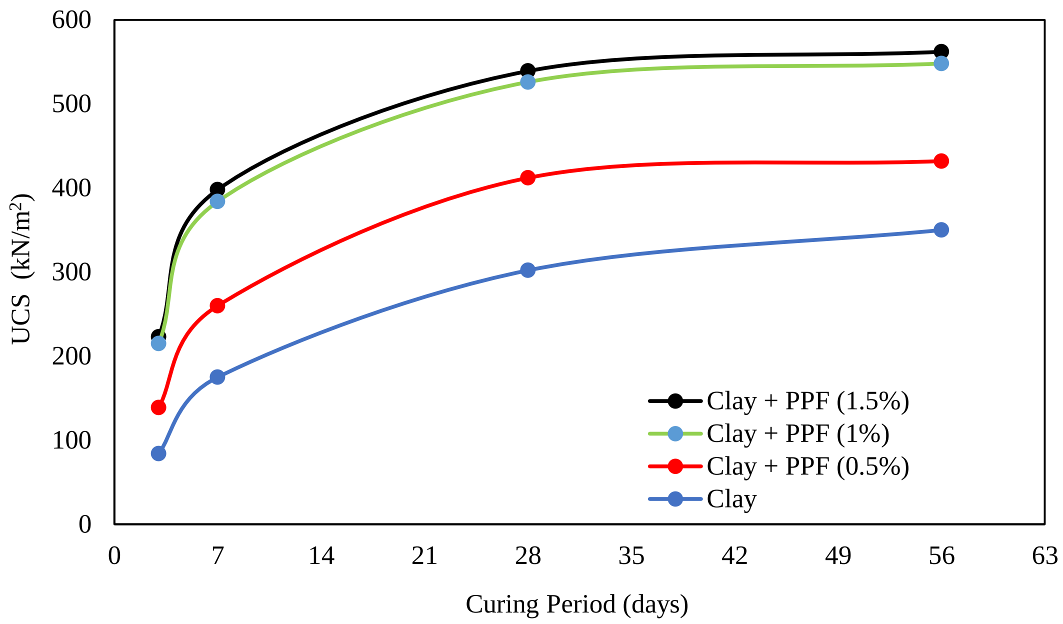


Figure 5.18: Variation in UCS of clay and clay-polypropylene fiber mixes with curing period

There is marginal increase in strength between 28 days and 56 days whereas for 1% and 1.5% polypropylene fiber contents, the rate of increase in UCS is almost linear. The increase in UCS value on adding fiber may be due proper bond between all materials due to fiber content. A similar increase in UCS value on adding polypropylene fiber to clay has been reported earlier (Kumar et al. 2006; Puppala and 2000). Thus, based on the results it can concluded that UCS increases with curing period and the increase is more for 1% polypropylene Fiber content. Hence, it can be concluded that unconfined compressive strength increases with increase in curing period and 1% polypropylene fiber is the optimum content for stabilization of clayey soil.

5.4.5 Effect of curing period on UCS of clay-municipal solid waste incineration ash-cement mix

The effect of curing period on unconfined compressive strength of clay, clay-municipal solid waste incineration ash mixes and clay-municipal solid waste incineration ash-cement mixes is shown in Figure 5.19.

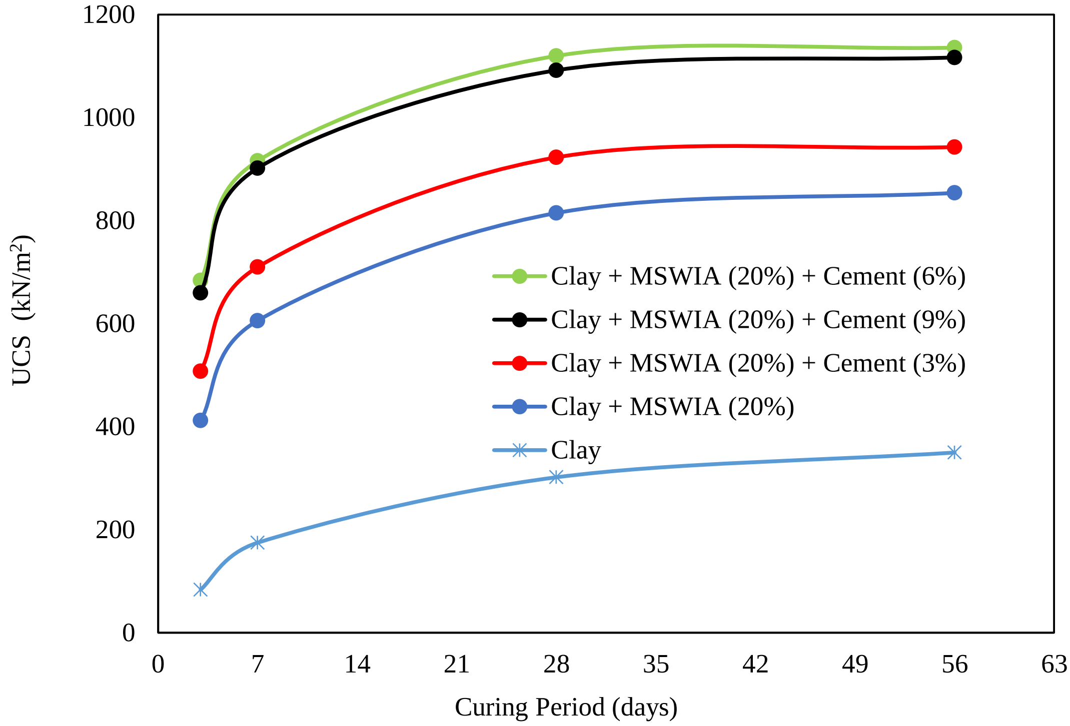


Figure 5.19:UCS of clay, clay-municipal solid waste incineration ash mixes and clay-municipal solid waste incineration ash-cement mixes with curing period

The unconfined compressive strength increases with increase in curing period for all the combinations. The increase in strength is more between 3 days to 7 days compared with that from 7 days to 28 days and 28 days to 56 days curing periods for clay-municipal solid waste incineration ash-cement mixes. There is an increase in UCS values with addition of 6%cementand the further addition of cement reduces UCS value for all curing periods. Hence, 6% cement may be chosen as optimum cement dosage for clay-municipal solid waste incineration ash mix. The increase in strength up to 6% cement may be due chemical reaction between cement and soil- municipal solid waste incineration ash mix.

5.4.6 Effect of curing period on UCS of clay-marble dust-cement mix

The effect of curing period on UCS of clay-marble dust-cement mixes is shown in Figure 5.20. The unconfined compressive strength of the composite mix remains almost constant with addition of more than 6% cement content.

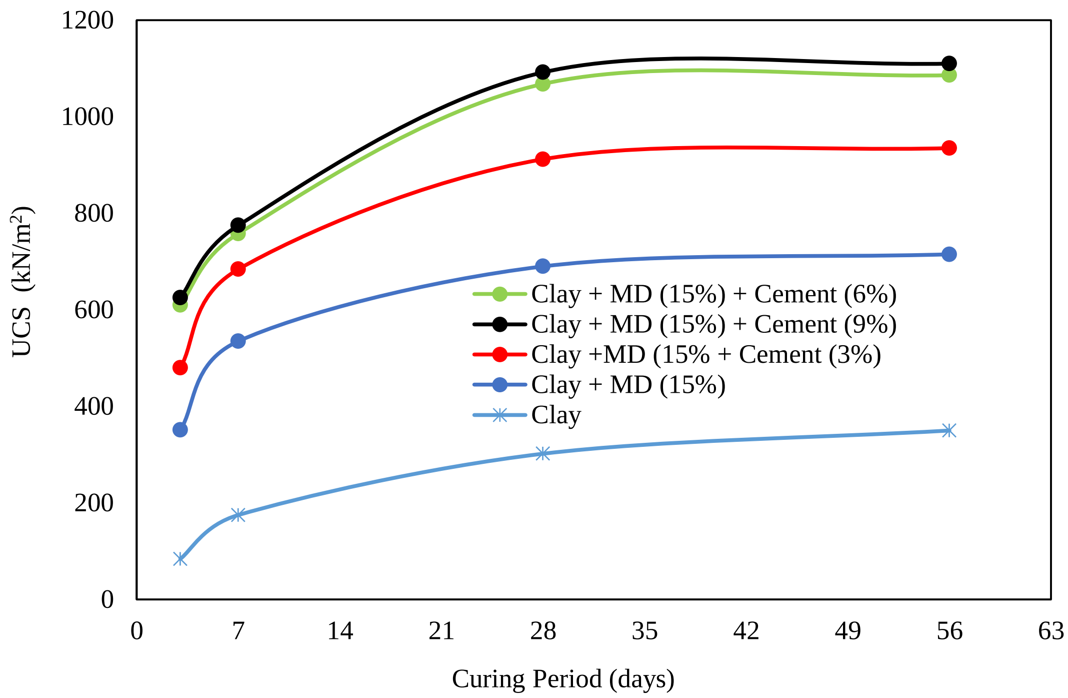


Figure 5.20: UCS of clay, clay-marble dust mix and clay-marble dust-cement mixes with curing period

The increase in strength is almost same between 3 days to 7 days and between 7 days to 28 days compared to 28 days to 56 days curing periods for clay-marble dust-cement mixes. This indicates that longer curing period is required for marble dust to gain strength compared with that in case of municipal solid waste incineration ash and cement. The UCS increases by about 54% on addition of 6% cement content in clay-marble dust (15%) mix for 28 days curing period. The difference in UCS of the composite mix between 3 days and 56 days curing period is nearly 78%. The increase in strength on adding cement is due chemical reaction between cement and soil-marble dust mix.

5.4.7 Effect of curing period on UCS of clay-municipal solid waste incineration ash-polypropylene fiber mix

The effect of curing period on UCS of clay-municipal solid waste incineration ash-polypropylene fiber mixes is shown in Figure 5.21. The unconfined compressive strength of the composite mix decreases with addition of more than 1% polypropylene fiber content.

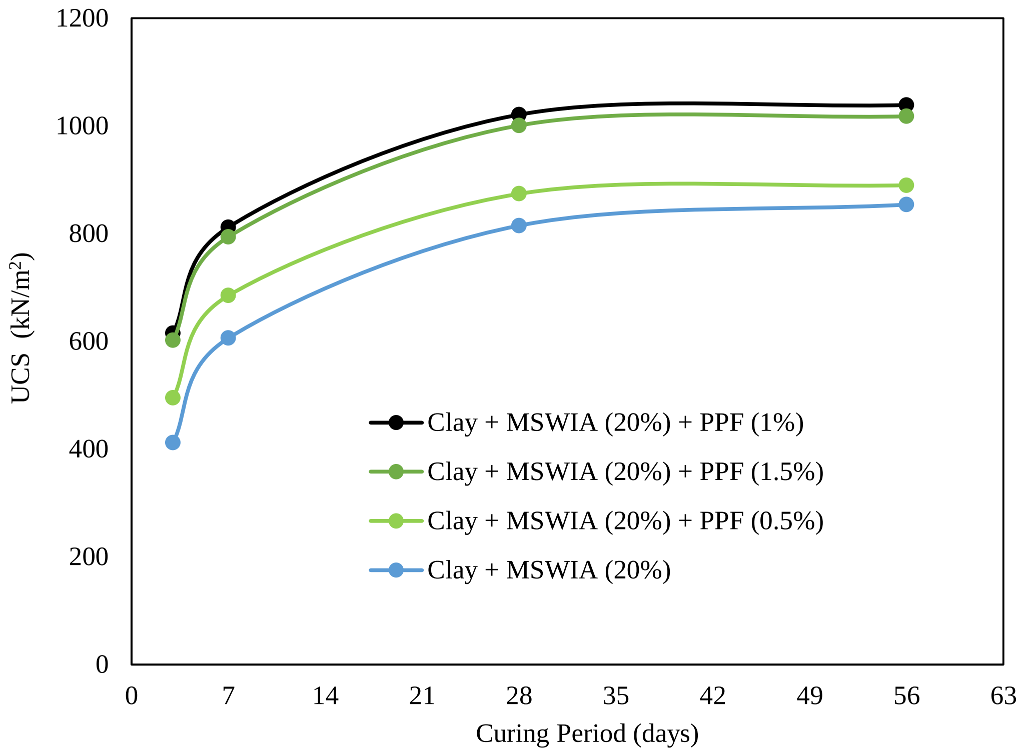


Figure 5.21: UCS of clay- clay-municipal solid waste incineration ash mixes and clay-municipal solid waste incineration ash-polypropylene fiber mixes with curing period

The percentage increase in strength is highest between 3 days to 7 days followed by 7 days to 28 days and is further followed by 28 days to 56 days curing periods for clay-municipal solid waste incineration ash-polypropylene fiber mixes. This indicates that shorter curing period is required for PPF to gain strength compared with that in case of municipal solid waste incineration ash and marble dust when added. The UCS increases by about 25% on addition of 1% polypropylene fiber content in clay- municipal solid waste incineration ash (20%) mix for 28 days curing period. The difference in UCS of the composite mix (for 1% PPF content) between 3 days and 56 days curing period is nearly 69%. The further addition of PPF beyond 1% decreases the UCS value and hence 1% PPF may be selected as the optimum content to be added to clay-municipal solid waste incineration ash mix for gaining strength. The increase in UCS value on adding fiber may be due proper bond between all materials due to fiber content. A similar increase in UCS value on adding polypropylene fiber to clay has been reported earlier (Kumar et al. 2006; Puppala and 2000).

5.4.8 Effect of curing period on UCS of clay-marble dust- polypropylene fiber mix

The effect of curing period on UCS of clay-marble dust-polypropylene fiber mixes is shown in Figure 5.22. The unconfined compressive strength of the composite mix decreases with addition of more than 1% polypropylene fiber content.

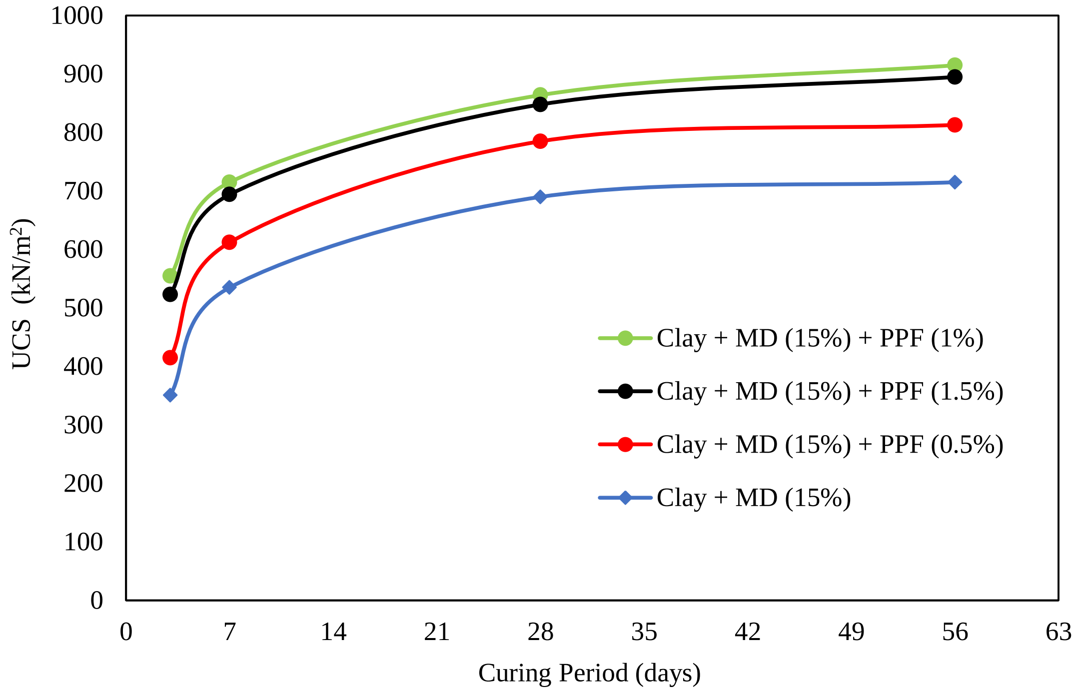


Figure5.22:UCS of clay-marble dust mix and clay-marble dust- polypropylene fiber mixes with curing period

The percentage increase in strength is highest between 3 days to 7 days followed by 7 days to 28 days and is further followed by 28 days to 56 days curing periods for clay-marble dust-polypropylene fiber mixes. This indicates that shorter curing period is required for PPF to gain strength compared with that in case of municipal solid waste incineration ash and marble dust when added. The UCS increases by about 25% on addition of 1% polypropylene fiber content in clay- marble dust (15%) mix for 28 days curing period. The difference in UCS of the composite mix (for 1% PPF content) between 3 days and 56 days curing period is nearly 65%. The further addition of PPF beyond 1% decreases the UCS value and hence this much PPF content may be selected as the optimum content to be added to clay-marble dust mix for gaining strength. The increase in UCS value on adding fiber in clay-marble dust mix may be attributed to good bond among all materials due to presence of optimum fiber content. A similar increase in UCS value on adding polypropylene fiber to clay has been reported earlier (Kumar et al. 2006; Puppala and 2000).

5.4.9 Effect of curing period on UCS of clay-cement-polypropylene fiber mix

The effect of curing period on UCS of clay-cement-polypropylene fiber mixes is shown in Figure 5.23. The unconfined compressive strength of the composite mix is almost constant with addition of more than 1% polypropylene fiber content.

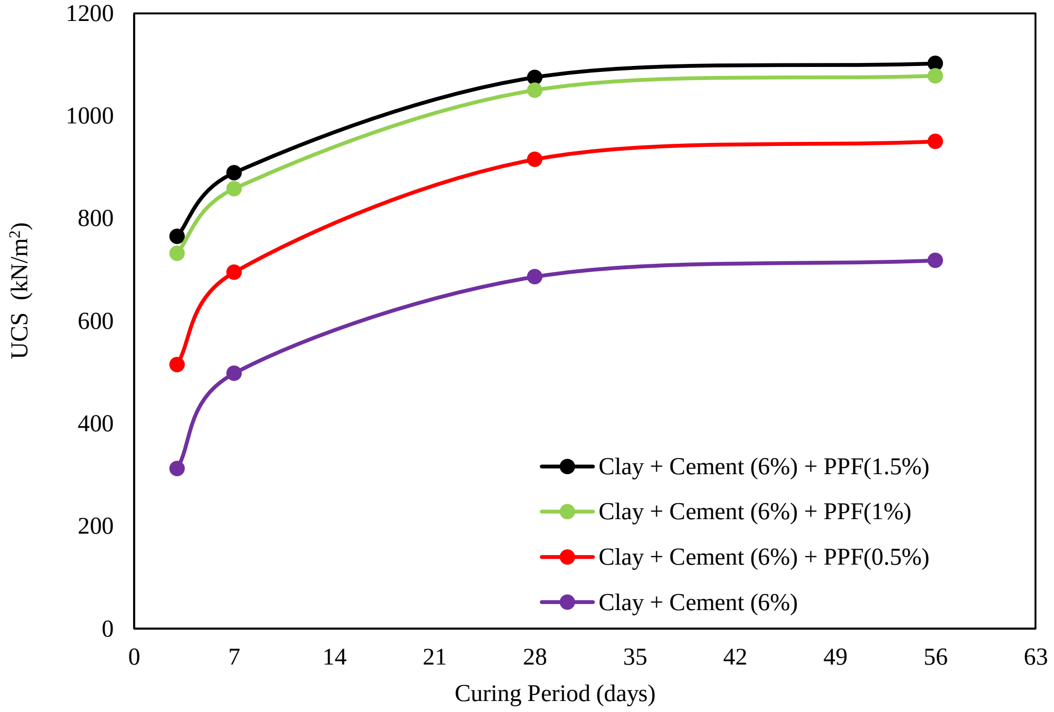


Figure 5.23: UCS of clay-cement mix and clay-cement- polypropylene fiber mixes with curing period

The percentage increase in strength is highest between 3 days to 7 days followed by 7 days to 28 days and is further followed by 28 days to 56 days curing periods for clay-cement-polypropylene fiber mixes. This indicates that shorter curing period is required for PPF to gain strength compared with that in case of cement when added alone. The UCS increases by about 54% on addition of 1% polypropylene fiber content in clay-cement (6%) mix for 28 days curing period. The difference in UCS of the composite mix (for 1% PPF content) between 3 days and 56 days curing period is nearly 47%. The further addition of PPF beyond 1% decreases the UCS value and hence this much PPF content may be selected as the optimum content to be added to clay- cement mixture for gaining strength. The increase in UCS value on adding fiber may be due proper bond between all materials due to fiber content.

5.4.10 Effect of curing period on UCS of clay-municipal solid waste incineration ash-marble dust mix

The effect of curing period on UCS of clay-municipal solid waste incineration ash-marble dust mix is shown in Figure 5.24 which indicates that unconfined compressive strength increases with curing period up to 15% marble dust content and after that it starts decreasing for higher marble dust values.

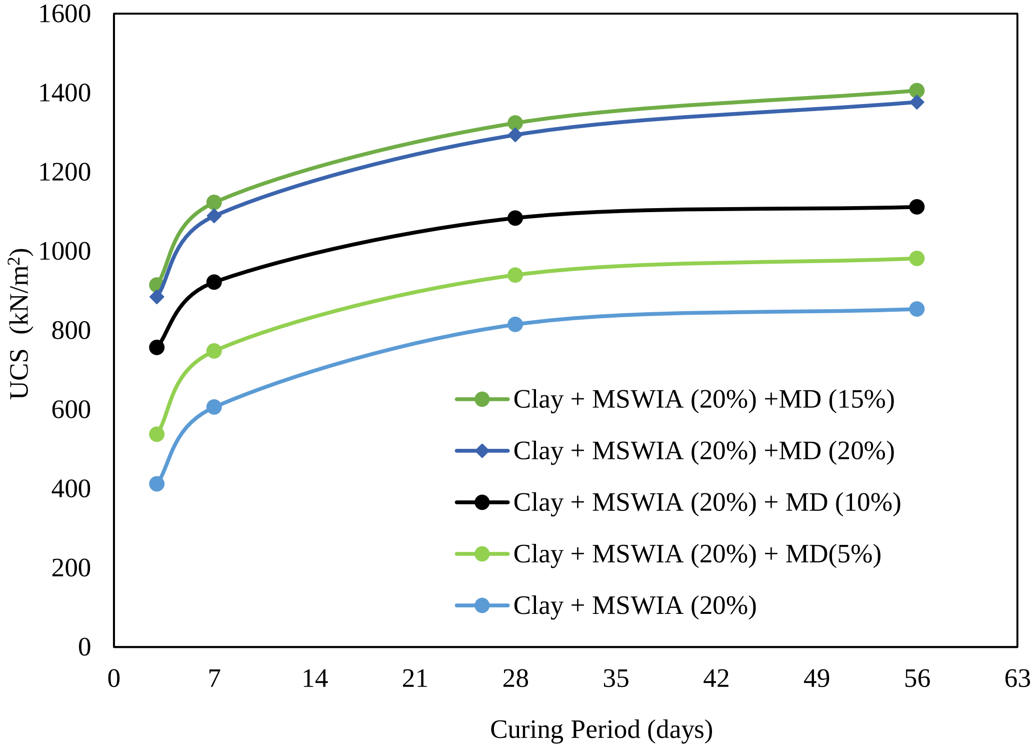


Figure 5.24: UCS of clay-MSWIA mix and clay-MSWIA-MD mixes with curing period

The addition of marble dust in various amount to clay-MSWIA (20%) mix increases the UCS value for all percentages of marble dust content up to 15% and the further addition of marble dust beyond 15% decreases the UCS value of the composite slightly for all curing period. The highest value for UCS for all curing periods is obtained at clay-MSWIA (20%)-MD (15%) content. The curves also show that the percentage increase in UCS values is higher for lesser curing period for all MD percentages. For a curing period of 28 days, the percentage increase in UCS value for clay-MSWIA (20%)-MD (15%) mix is around 62% when compared with clay-MSWIA (20%) mix. The increase in UCS value by addition of marble dust is due to the pozzolanic reaction between soil particles and marble dust.

5.4.11 Effect of curing period on UCS of clay-municipal solid waste incineration ash-marble dust-cement mix

The effect of curing period on UCS of clay-municipal solid waste incineration ash-marble dust-cement mix is shown in Figure 5.25 which indicates that unconfined compressive strength increases considerably with curing period up to 6% cement content and after that it increases at a very low rate on adding 9% cement content.

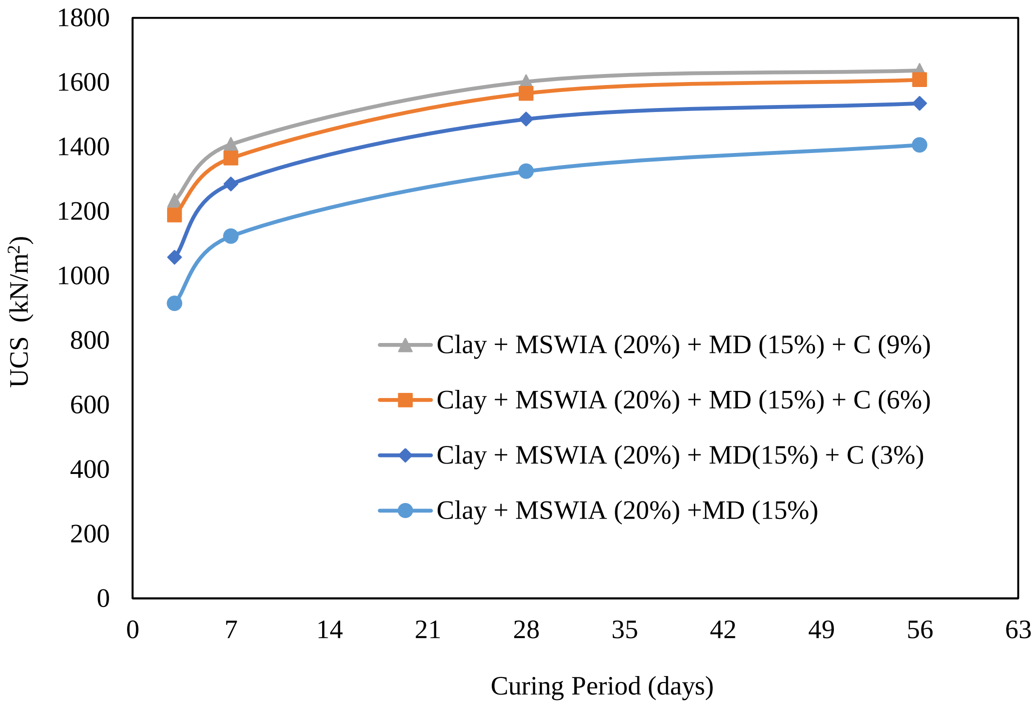


Figure 5.25: UCS of clay-MSWIA-MD mix and clay-MSWIA-MD-cement mixes with curing period

The addition of cement in various amount to clay-MSWIA (20%)- MD (15%) mix increases the UCS value for all percentages of cement content all curing period. The highest value for UCS for all curing periods is obtained at clay-MSWIA (20%)-MD (15%)-cement (9%) content but it is almost same as clay-MSWIA (20%)-MD (15%)-cement (6%). Although the strength gain of composite on adding 9% cement is highest but cement being a costly material should be used in lesser amount and hence 6% cement content may be chosen as optimum content for clay-MSWIA (20%)- MD (15%) mix. The curves also show that the percentage increase in UCS values is higher for lesser curing period for all cement percentages. The increase in strength on adding cement is due chemical reaction between cement and soil-municipal solid waste incineration ash-marble dust mix.

5.4.12 Effect of curing period on UCS of clay-municipal solid waste incineration ash-marble dust-cement-polypropylene fiber mix

The effect of curing period on UCS of clay-municipal solid waste incineration ash-marble dust-cement-polypropylene fiber mix is shown in Figure 5.26 which indicates that unconfined compressive strength increases with curing period up to 1% fiber content and after that it starts decreasing.

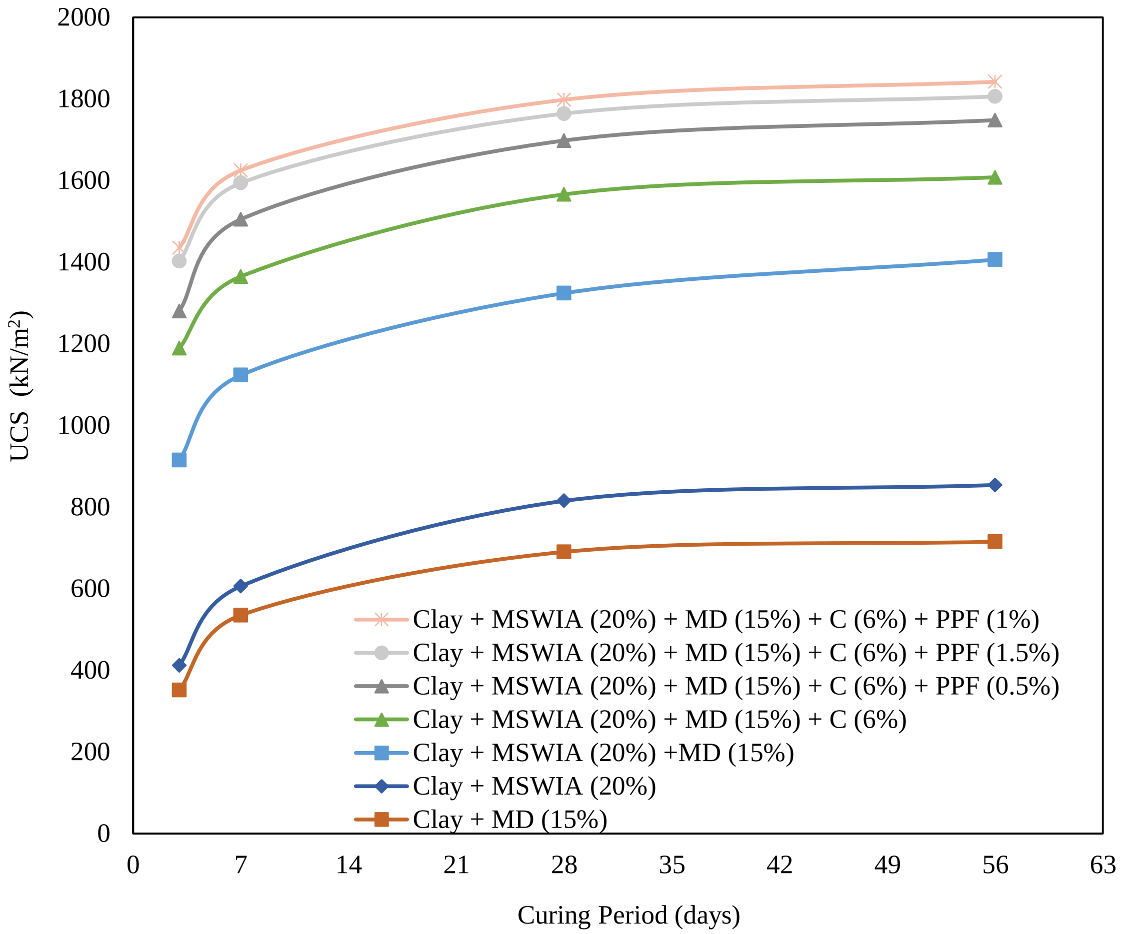


Figure 5.26: Variation in UCS of, clay- MSWIA, clay-MD, clay-MSWIA-MD, clay-MSWIA-MD -C mix and clay-MSWIA-MD-C-PPF mixes with curing period

The addition of PPF in various amount to clay-MSWIA (20%)- MD (15%)- C (6%) mix increases the UCS value for all percentages of PPF content all curing period upto 1% PFF and after that it starts decreasing. The highest value for UCS for all curing periods is obtained at clay-MSWIA (20%)-MD (15%)-cement (9%)- PPF (1%) content followed by other admixtures. Based on the UCs results it can be concluded that this combination provides highest UCs values for all curing periods among other combinations and is bested suited for increasing early strength of the composite. The increase in UCS value on adding fiber may be due proper bond between all materials due to fiber content.

5.4.13 Validation of UCS Results

The results obtained from experimental testing of UCS were validated using regression analysis and the percentage difference was calculated among the various values for different random combinations between minimum and maximum contents of each admixture. Table 5.3 presents the results of various combinations chosen between the optimum results of various admixtures.

Table 5.3: Percentage difference of various UCS admixtures

Combinations	**UCS values from experimental data (kPa)**	**UCS values from numerical data (kPa)**	**Percentage difference (%)**
17.5% MSWIA	508.48	451.93	11.12
	535.16	478.61	10.57
	675.23	618.67	8.38
	861.98	805.43	6.56
22.5% MSWIA	621.59	565.03	9.10
	648.27	591.71	8.72
	788.33	731.78	7.17
	975.09	918.54	5.80
12.5% MD	442.48	378.08	14.56
	469.16	404.76	13.73
	609.23	544.82	10.57
	795.98	731.58	8.09
17.5% MD	571.30	506.89	11.27
	597.98	533.57	10.77
	738.04	673.64	8.73
	924.80	860.39	6.96
7.5% Cement	541.54	460.62	14.94
	568.22	487.30	14.24
	708.28	627.37	11.42
	895.04	814.12	9.04
10.5% Cement	703.37	622.45	11.50
	730.05	649.13	11.08
	870.11	789.20	9.30
	1056.87	975.95	7.66
0.75% PPF	269.76	216.33	19.81
	296.43	243.01	18.02
	436.50	383.07	12.24
	623.26	569.83	8.57
1.25% PPF	376.61	323.18	14.19

	403.29	349.86	13.25
	543.35	489.93	9.83
	730.11	676.68	7.32
20% MSWIA + 7.5% cement	993.97	913.06	8.14
	1020.65	939.74	7.93
	1160.72	1079.80	6.97
	1347.47	1266.56	6.00
15% MD + 7.5% cement	927.97	847.06	8.72
	954.65	873.74	8.48
	1094.72	1013.80	7.39
	1281.48	1200.56	6.31
20% MSWIA + 0.75% PPF	722.19	668.76	7.40
	748.87	695.44	7.13
	888.93	835.51	6.01
	1075.69	1022.26	4.97
20% MSWIA + 1.25% PPF	829.04	775.62	6.44
	855.72	802.29	6.24
	995.79	942.36	5.37
	1182.54	1129.12	4.52
15% MD + 0.75% PPF	656.19	602.76	8.14
	682.87	629.44	7.82
	822.94	769.51	6.49
	1009.69	956.27	5.29
15% MD + 1.25% PPF	763.05	709.62	7.00
	789.72	736.30	6.77
	929.79	876.36	5.75
	1116.55	1063.12	4.79
6% cement + 0.75% PPF	593.42	539.99	9.00
	620.09	566.67	8.62
	760.16	706.73	7.03
	946.92	893.49	5.64
6% cement + 1.25% PPF	700.27	646.84	7.63
	726.95	673.52	7.35
	867.02	813.59	6.16
	1053.77	1000.34	5.07

20% MSWIA + MD 12.5%	894.92	830.51	7.20
	921.60	857.19	6.99
	1061.66	997.26	6.07
	1248.42	1184.01	5.16
20% MSWIA + MD 17.5%	1023.73	959.32	6.29
	1050.41	986.00	6.13
	1190.47	1126.07	5.41
	1377.23	1312.82	4.68
20% MSWIA + 15% MD + 4.5% Cement	1218.58	1137.66	6.64
	1245.26	1164.34	6.50
	1385.32	1304.41	5.84
	1572.08	1491.16	5.15
20% MSWIA + 15% MD + 7.5% Cement	1380.41	1299.49	5.86
	1407.09	1326.17	5.75
	1547.15	1466.24	5.23
	1733.91	1652.99	4.67
20% MSWIA + + 15% MD + 4.5% Cement + 0.75% PPF	1432.29	1378.86	3.73
	1458.96	1405.54	3.66
	1599.03	1545.60	3.34
	1785.79	1732.36	2.99
20% MSWIA + 15% MD + 7.5% Cement + 1.25% PPF	1539.14	1485.71	3.47
	1565.82	1512.39	3.41
	1705.88	1652.46	3.13
	1892.64	1839.21	2.82

5.5 California bearing ratio

Soaked CBR testing was conducted on clayey soil (S) and on all optimal blends of various material combinations. Figure 5.27 illustrates the impact of adding municipal solid waste incineration ash (MSWIA), cement (C), and marble dust (MD) individually, as well as in combination with each other, on the soaked CBR value of clay. Additionally, the effect of adding polypropylene fiber (PPF) to the clay-municipal solid waste incineration ash-marble dust-cement mix on soaked CBR value is depicted, with the CBR values for optimal material proportions provided in Table 5.4. The initial soaked CBR value of clay measured at 1.90% indicates its unsuitability for use as a pavement sub-grade material due to its low strength. The introduction of

20% municipal solid waste incineration ash doubled the soaked CBR value; however, it remained inadequate for pavement sub-grade use. Conversely, the addition of 9% cement alone increased the soaked CBR value by fivefold, providing a viable sub-grade material for pavements. Similarly, the inclusion of 15% marble dust boosted the soaked CBR value by 2.5 times, although it remained insufficient. Combining 20% municipal solid waste incineration ash with 15% marble dust increased the soaked CBR value by 3.42 times, rendering it suitable for sub-grade use. Furthermore, adding 6% cement alongside 20% municipal solid waste incineration ash increased the soaked CBR value by 5.5 times, making it suitable as a sub-grade material for pavements. Additionally, the addition of 6% cement and 15% marble dust to clayey soil increased the soaked CBR value approximately sixfold, indicating its suitability for sub-grade use in pavements. The combination of 20% municipal solid waste incineration ash, 15% marble dust, and 3% cement increased the soaked CBR value by about sixfold, yielding an effective sub-grade material.

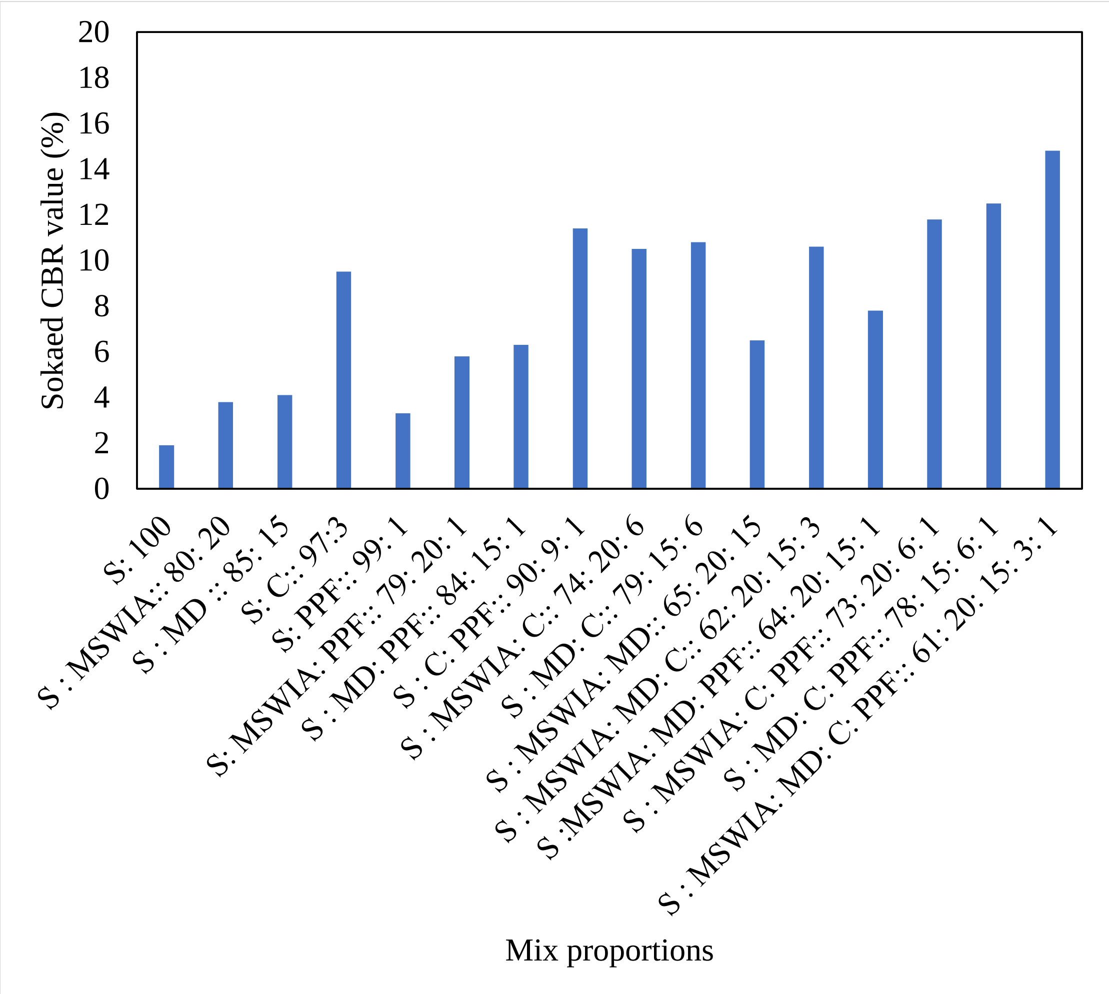


Figure 5.27: Variation of soaked CBR values on addition of different admixtures

The difference in soaked CBR values between the clay-municipal solid waste incineration ash-marble dust-cement mix and the clay-municipal solid waste incineration ash-marble dust-cement-polypropylene fiber mix is approximately 1.4% (Table 5.4). The observed increase in CBR values across various combinations, both individually and in combination, can be attributed to the coarser nature of municipal solid waste incineration ash (MSWIA), marble dust (MD), and cement particles compared to clay. This coarser texture facilitates friction mobilization, leading to increased strength. Therefore, based on the aforementioned findings, it can be inferred that although the CBR value is higher with the addition of cement alone, it necessitates a higher cement content, which incurs greater costs. On the other hand, combining municipal solid waste incineration ash, marble dust, and cement proves to be both cost-effective and environmentally friendly, as the required amount of cement is reduced in the clay-municipal solid waste incineration ash-marble dust-cement mix. This reduces the overall cost of cement usage, and the safe disposal of municipal solid waste incineration ash and marble dust contributes to environmentally friendly clay stabilization. Among the options of clay-municipal solid waste incineration ash-cement and clay-marble dust-cement, the latter is preferred due to its lower cement requirement, making it more economical. Additionally, marble dust is widely available at construction sites, whereas municipal solid waste incineration ash is limited to areas near waste plants, which may involve transportation costs. As the disposal of polypropylene fiber poses challenges, its incorporation into the clay-municipal solid waste incineration ash-marble dust-cement mixes as a sub-grade material presents a viable solution.

The optimal design for achieving a CBR in the 5-8% range focuses on an appropriate balance of MSWIA, MD, and cement. The addition of MSWIA (20%), MD (15%), and cement (5-9%) provides enough pozzolanic reaction and filler effect to strengthen the subgrade without over-stabilizing it.From the analysis in Table 5.4, a combination of 5-9% cement is optimal, as this range achieves the required CBR of 5-8% without excessively increasing the cost. Adding too much cement (e.g., 12%) might result in higher CBR values but would lead to unnecessary costs, exceeding the target CBR range needed for economical pavement design.

The mix of S: MSWIA: MD: Cement (5-9%) ensures the CBR is within 5-8%, meeting the strength requirements for a flexible pavement subgrade. This combination makes effective use of low-cost waste materials (MSWIA and MD), while minimizing the amount of cement required to achieve sufficient strength. By carefully controlling the cement content, the mix provides an economically viable solution, avoiding overuse of expensive stabilizers like cement or unnecessary additives like PPF, which have limited impact on CBR.

Table 5.4: Soaked CBR values of clay and different optimum mix

Sr. No.	Combination	CBR value (%)
1	S: 100	1.90
2	S : MSWIA:: 80: 20	3.80
3	S : MD :: 85: 15	4.10
4	S: C:: 91: 9	9.42
5	S: PPF:: 99: 1	2.80
6	S: MSWIA: PPF:: 79: 20: 1	5.81
7	S : MD: PPF:: 84: 15: 1	6.30
8	S : C: PPF:: 90: 9: 1	11.41
9	S : MSWIA: C:: 74: 20: 6	10.50
10	S : MD: C:: 79: 15: 6	10.83
11	S : MSWIA: MD:: 65: 20: 15	6.50
12	S : MSWIA: MD: C:: 62: 20: 15: 3	10.62
13	S :MSWIA: MD: PPF:: 64: 20: 15: 1	7.80
14	S : MSWIA: C: PPF:: 73: 20: 6: 1	11.83
15	S : MD: C: PPF:: 68: 15: 6: 1	12.50
16	S : MSWIA: MD: C: PPF:: 61: 20: 15: 3: 1	14.84

5.6 Determination of resilient modulus of subgrade

Resilient modulus (M_R) is the amount of its elastic performance and is determined from CBR values. It is an important parameter to design the pavements and is calculated according toIRC 37: 2012as follows:

M_R (MPa) = 10.0 * (CBR) for CBR $\leq$ 5

M_R (MPa) = 17.6 * (CBR)$^{0.64}$ for CBR > 5

The values of resilience modulus for various mixtures shown in Table 5.5disclose an increase in resilience modulus on adding various admixtures to clayey soil.

Table 5.5: Resilient modulus for various admixtures

Sr. No.	**Composition**	**Resilient modulus, Mpa**
1	S: 100	19.00
2	S : MSWIA:: 80: 20	38.00
3	S : MD :: 85: 15	41.00
4	S: C:: 91: 9	73.10
5	S: PPF:: 99: 1	28.00
6	S: MSWIA: PPF:: 79: 20: 1	53.66
7	S : MD: PPF:: 84: 15: 1	56.51
8	S : C: PPF:: 90: 9: 1	82.64
9	S : MSWIA: C:: 74: 20: 6	78.36
10	S : MD: C:: 79: 15: 6	79.93
11	S : MSWIA: MD:: 65: 20: 15	57.65
12	S : MSWIA: MD: C:: 62: 20: 15: 3	78.93
13	S: MSWIA: MD: PPF:: 64: 20: 15: 1	64.79
14	S : MSWIA: C: PPF:: 73: 20: 6: 1	84.58
15	S : MD: C: PPF:: 68: 15: 6: 1	87.61
16	S : MSWIA: MD: C: PPF:: 61: 20: 15: 3: 1	97.78

5.7 Thickness of flexible pavement

The design of flexible pavements, comprising granular base and granular sub-base layers, relies on Plate 1-8 of IRC 37: 2018. Utilizing this standard, design calculations were conducted for different admixtures mixed with soil, based on CBR test results, for traffic loads ranging from 2 to 150 million standard axles (msa). As per IRC 37: 2018 specifications, a minimum CBR value of 5% is required for designing the thickness of flexible pavements. The diverse pavement thickness values obtained for various mixes, as presented in Table 5.6, indicate a reduction in pavement thickness when soil was stabilized using different admixtures alone or in combination with each other.

Table 5.6: Pavement thickness for various mixes

Composition	Pavement thickness (mm) for cumulative traffic (msa)							
	2	5	10	20	30	50	100	150
S: 100	-	-	-	-	-	-	-	-
S: MSWIA:: 80: 20	265	285	330	330	330	330	330	330
S: MD :: 85: 15	265	285	330	330	330	330	330	330
S: C:: 91: 9	150	150	200	200	200	200	200	200
S: PPF:: 99: 1	335	335	380	380	380	380	380	380
S: MSWIA: PPF:: 79: 20: 1	175	210	260	260	260	260	260	260
S: MD: PPF:: 84: 15: 1	175	210	260	260	260	260	260	260
S: C: PPF:: 90: 9: 1	150	200	200	200	200	200	200	200
S: MSWIA: C:: 74: 20: 6	150	200	200	200	200	200	200	200
S: MD: C:: 79: 15: 6	150	200	200	200	200	200	200	200
S: MSWIA: MD:: 65: 20: 15	150	180	230	230	230	230	230	230
S: MSWIA: MD: C:: 62: 20: 15: 3	150	200	200	200	200	200	200	200
S: MSWIA: MD: PPF:: 64: 20: 15: 1	150	150	200	200	200	200	200	200
S : MSWIA: C: PPF:: 73: 20: 6: 1	150	200	200	200	200	200	200	200
S: MD: C: PPF:: 68: 15: 6: 1	150	200	200	200	200	200	200	200
S: MSWIA: MD: C: PPF:: 61: 20: 15: 3: 1	100	150	200	200	200	200	200	200

5.8 Permeability

Permeability tests were carried out on clay and various material combinations, and their coefficient of permeability is compared in Figure 5.28. Initially, the coefficient of permeability of the clayey soil was measured at 3.26×10^{-8} cm/sec. Upon introducing cement and marble dust, there was an increase in permeability, whereas the addition of MSWIA resulted in a decrease. Notably, the increase in permeability was more pronounced with the addition of marble dust compared to cement and municipal solid waste incineration ash. Therefore, marble dust emerges as the preferable stabilizer for clayey soil. The addition of cement to clay-MSWIA mixes and clay-marble dust mixes led to an increase in permeability. This can be attributed to the binding nature of cement, which, upon mixing with water, forms a solid matrix. This matrix fills the voids between clay particles, solidifying the mixture and reducing porosity, thus decreasing water flow resistance and increasing permeability. However, the addition of cement to a clay-marble dust mix typically reduced permeability due to the formation of a more compact and less permeable structure. The coefficient of permeability of a clay-municipal solid waste incineration ash-marble dust mix was found to be higher than that of a clay-municipal solid waste incineration ash mix but lower than that of a clay-marble dust mix. This suggests that addition of marble dust alone is superior to the addition of municipal solid waste incineration ash or cement, either individually or in combination with others. Furthermore, the coefficient of permeability increased notably with the addition of polypropylene fiber, especially in mixes like clay-municipal solid waste incineration ash-marble dust-cement-polypropylene fiber and clay-municipal solid waste incineration ash-marble dust-cement. This increase is attributed to the provision of passage paths for water by the polypropylene fiber, making it useful for drainage requirements. Despite a slight increase in cost due to the addition of cement to clay-municipal solid waste incineration ash-marble dust mixes, this combination emerges as the most suitable for sub-grade use due to appreciable CBR values and coefficient of permeability.

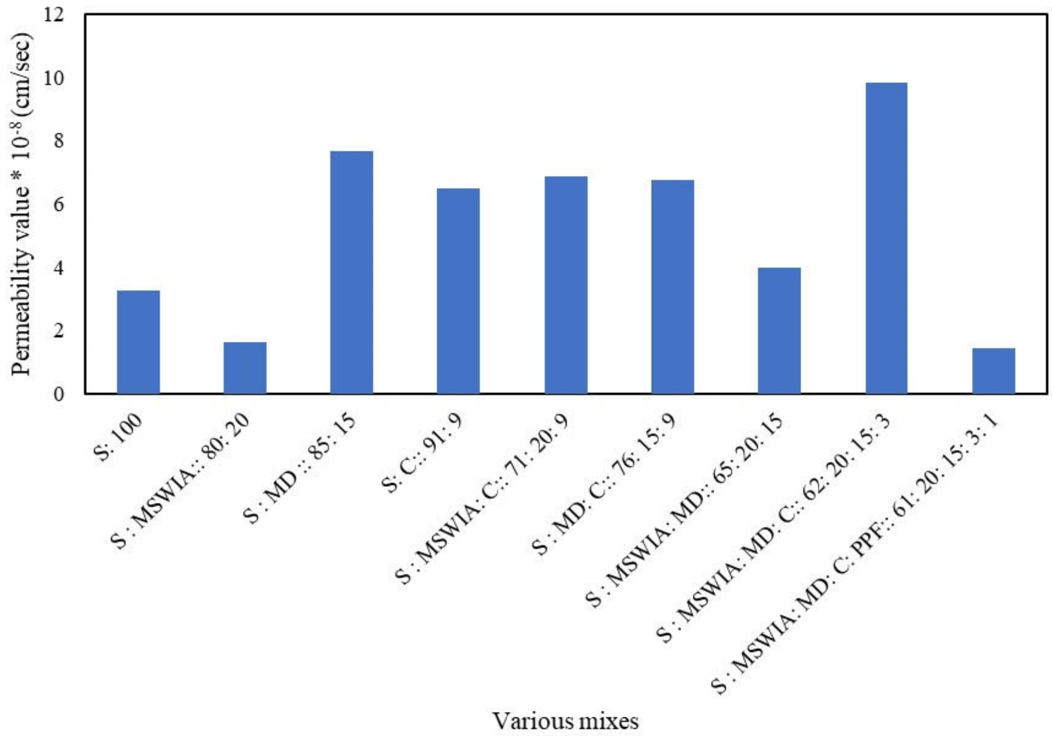


Figure 5.28: Comparison of coefficient of permeability of clay and optimum mixes

5.9 X-ray diffraction

The X-ray diffraction analysis of clay indicates the presence of minerals like muscovite, quartz, and montmorillonite, while municipal solid waste incineration ash exhibits minerals such as mullite and quartz. Marble dust's XRD pattern indicates quartz and calcite as its main constituents. The reduction in swelling upon adding municipal solid waste incineration ash and marble dust, both individually and combined, is attributed to the increased presence of quartz, a principal constituent in both materials. The enhanced strength observed upon adding marble dust is linked to the formation of a new compound, calciobetafite, as evidenced by XRD patterns. The increased strength in composite mixes like clay-municipal solid waste incineration ash-cement, clay-marble dust-cement, and clay-municipal solid waste incineration ash-marble dust-cement can be attributed to the presence of mineral calcite, as revealed by X-ray diffraction graphs.

5.10 Cost analysis

Punjab Public Works Department (Border & Roads)- PWD (B&R) rates of handbook 2020 were used to analyse the cost of single lane highway for the design of flexible pavement layer. In the present study, the length of road assumed was 1000m and various layers are considered as follow:

Bituminous Course;

DBM Course;

WBM Course;

Sub-base Course;

Subgrade.

The cost analysis was carried out for soil alone and along with optimum combinations of various materials as shown in Table 5.7. The cost analysis was carried out for soil alone and along with optimum combinations of various materials as shown in Table 5.7. The cost of 1000m single road (Top width 3.75 meter) was analysed to be around 3.15 crore which further kept of decreasing as the soil was replaced with waste materials and other admixtures stating an economic gain in the cost. The per metric cubic rates (m^3) of cement, bituminous course, DBM course, granular base, granular sub base, WBM Course, subgrade and PPF are 3150, 31400, 20000, 6800, 5500, 6800, 3100 and 200 INR respectively. The combination of S: MSWIA: MD: PF:: 64: 20: 15: 1 provided the highest economy of by saving around 81 Lacs for designing one 1km flexible pavement

S. No.	Material combinations		Top Width (m)	Bottom width (m)	Height (m)	Volume (m3)	Volume (m3)	Rate per m3 (INR)	Cost (INR)	Overall Cost (INR)	Saving in Cost (INR LACS)
1	S:: 100	**Bitumnious Course**	3.75	3.87	0.03	0.1143	114.3	31400	3589020	31571270	NA
		DBM Course	3.87	4.13	0.065	0.26	260	20000	5200000		
		Granular Base	4.13	5.13	0.25	1.1575	1157.5	6800	7871000		
		Granular Sub Base	5.13	5.73	0.15	0.8145	814.5	5500	4479750		
		Subgrade (S: 100)	5.73	7.73	0.5	3.365	3365	3100	10431500		
S. No.	**Material combinations**		**Top Width (m)**	**Bottom width (m)**	**Height (m)**	**Volume (m3)**	**Volume (m3)**	**Rate per m3 (INR)**	**Cost (INR)**	**Overall Cost (INR)**	
2	S : MSWIA :: 80: 20	**Bitumnious Course**	3.75	3.87	0.03	0.1143	114.3	31400	3589020	29395370	2175900
		DBM Course	3.87	4.13	0.065	0.26	260	20000	5200000		
		WBM Course	4.13	5.13	0.25	1.1575	1157.5	6800	7871000		
		Sub-base Course	5.13	5.73	0.15	0.8145	814.5	5500	4479750		
		Subgrade (S: 80, MSWIA: 20)	5.73	7.73	0.5	3.365	3365	3100	10431500		
		S: 80	-	-	-	-	2624	3100	8134400		
		MSWIA: 20	-	-	-	-	606	200	121200		
S. No.	**Material combinations**		**Top Width (m)**	**Bottom width (m)**	**Height (m)**	**Volume (m3)**	**Volume (m3)**	**Rate per m3 (INR)**	**Cost (INR)**	**Overall Cost (INR)**	
3	S : MD :: 85: 15	**Bitumnious Course**	3.75	3.87	0.03	0.1143	114.3	31400	3589020	30432975	1138295
		DBM Course	3.87	4.13	0.065	0.26	260	20000	5200000		

		WBM Course	4.13	5.13	0.25	1.1575	1157.5	6800	7871000		
		Sub-base Course	5.13	5.73	0.15	0.8145	814.5	5500	4479750		
		Subgrade (S: 80, MD: 20)	5.73	7.73	0.5	3.365	3365	3100	10431500		
		S: 85	-	-	-	-	2970.75	3100	9209325		
		MD: 15	-	-	-	-	524.25	160	83880		
S. No.	**Material combinations**		**Top Width (m)**	**Bottom width (m)**	**Height (m)**	**Volume (m3)**	**Volume (m3)**	**Rate per m3 (INR)**	**Cost (INR)**	**Overall Cost (INR)**	
4	S : C :: 91: 9	**Bitumnious Course**	3.75	3.87	0.03	0.1143	114.3	31400	3589020	31600482.5	-29212.5
		DBM Course	3.87	4.13	0.06	0.24	240	20000	4800000		
		WBM Course	4.13	5.13	0.25	1.1575	1157.5	6800	7871000		
		Sub-base Course	5.13	5.73	0.15	0.8145	814.5	5500	4479750		
		Subgrade (S: 91, C: 9)	5.73	7.73	0.5	3.365	3365	3100	10431500		
		S: 91	-	-	-	-	2970.75	3100	9209325		
		C: 9	-	-	-	-	524.25	3150	1651387.5		

S. No.	combinations		Top Width (m)	Bottom width (m)	Height (m)	Volume (m3)	Volume (m3)	Rate per m3 (INR)	Cost (INR)	Overall Cost (INR)	
5	S: PF:: 99: 1	**Bitumnious Course**	3.75	3.87	0.03	0.1143	114.3	31400	3589020	31473685	97585
		DBM Course	3.87	4.13	0.065	0.26	260	20000	5200000		
		WBM Course	4.13	5.13	0.25	1.1575	1157.5	6800	7871000		
		Sub-base Course	5.13	5.73	0.15	0.8145	814.5	5500	4479750		
		Subgrade (S: PF:: 99: 1)	5.73	7.73	0.5	3.365	3365	3100	10431500		
		S: 99	-	-	-	-	3331.35	3100	10327185		
		PF: 1	-	-	-	-	33.65	200	6730		
S. No.	**Material combinations**		**Top Width (m)**	**Bottom width (m)**	**Height (m)**	**Volume (m3)**	**Volume (m3)**	**Rate per m3 (INR)**	**Cost (INR)**	**Overall Cost (INR)**	
6	S : MSWIA: PF :: 79: 20: 1	**Bitumnious Course**	3.75	3.87	0.03	0.1143	114.3	31400	3589020	29118095	2453175
		DBM Course	3.87	4.13	0.06	0.24	240	20000	4800000		
		WBM Course	4.13	5.13	0.25	1.1575	1157.5	6800	7871000		
		Sub-base Course	5.13	5.73	0.15	0.8145	814.5	5500	4479750		
		Subgrade (S : MSWIA: PF :: 79: 20: 1)	5.73	7.73	0.5	3.365	3365	3100	10431500		
		S: 79	-	-	-	-	2658.35	3100	8240885		
		MSWIA: 20	-	-	-	-	673	200	134600		
		PF: 1					33.65	200	1682.5		

S. No.	Material combinations		Top Width (m)	Bottom width (m)	Height (m)	Volume (m3)	Volume (m3)	Rate per m3 (INR)	Cost (INR)	Overall Cost (INR)	
7	S : MD: PF :: 84: 15: 1	**Bitumnious Course**	3.75	3.87	0.03	0.1143	114.3	31400	3589020	25392772.5	6178497.5
		DBM Course	3.87	4.13	0.03	0.12	120	20000	2400000		
		WBM Course	4.13	5.13	0.25	1.1575	1157.5	6800	7871000		
		Sub-base Course	5.13	5.73	0.09	0.4887	488.7	5500	2687850		
		Subgrade (S : MD: PF :: 84: 15: 1)	5.73	7.73	0.5	3.365	3365	3100	10431500		
		S: 84	-	-	-	-	2826.6	3100	8762460		
		MD: 15	-	-	-	-	504.75	160	80760		
		PF: 1					33.65	200	1682.5		

S. No.	Material combinations		Top Width (m)	Bottom width (m)	Height (m)	Volume (m3)	Volume (m3)	Rate per m3 (INR)	Cost (INR)	Overall Cost (INR)	
8	S :MSWIA: MD: PF :: 64: 20: 15: 1	**Bitumnious Course**	3.75	3.87	0.03	0.1143	114.3	31400	3589020	23441072.5	8130197.5
		DBM Course	3.87	4.13	0.03	0.12	120	20000	2400000		
		WBM Course	4.13	5.13	0.25	1.1575	1157.5	6800	7871000		
		Sub-base Course	5.13	5.73	0.09	0.4887	488.7	5500	2687850		
		Subgrade (S :MSWIA: MD: PF :: 64: 20: 15: 1)	5.73	7.73	0.5	3.365	3365	3100	10431500		
		S: 64	-	-	-	-	2153.6	3100	6676160		
		MSWIA: 20	-	-	-	-	673	500	134600		
		MD: 15	-	-	-	-	504.75	160	80760		

		PF: 1	-	-	-	-	33.65	50	1682.5		
S. No.	**Material combinations**		**Top Width (m)**	**Bottom width (m)**	**Height (m)**	**Volume (m3)**	**Volume (m3)**	**Rate per m3 (INR)**	**Cost (INR)**	**Overall Cost (INR)**	
8	S : MSWIA: C: PF::73: 20: 6: 1	**Bitumnious Course**	3.75	3.87	0.03	0.1143	114.3	31400	3589020	24940180	6631090
		DBM Course	3.87	4.13	0.03	0.12	120	20000	2400000		
		WBM Course	4.13	5.13	0.25	1.1575	1157.5	6800	7871000		
		Sub-base Course	5.13	5.73	0.09	0.4887	488.7	5500	2687850		
		Subgrade (S : MSWIA: C: PF::73: 20: 6: 1)	5.73	7.73	0.5	3.365	3365	3100	10431500		
		S: 73	-	-	-	-	2456.45	3100	7614995		
		MSWIA: 20	-	-	-	-	673	200	134600		
		C: 6	-	-	-	-	201.9	3150	635985		
		PF: 1	-	-	-	-	33.65	200	6730		
S. No.	**Material combinations**		**Top Width (m)**	**Bottom width (m)**	**Height (m)**	**Volume (m3)**	**Volume (m3)**	**Rate per m3 (INR)**	**Cost (INR)**	**Overall Cost (INR)**	
9	S : MD: C: PF:: 68: 15: 6: 1	**Bitumnious Course**	3.75	3.87	0.03	0.1143	114.3	31400	3589020	24364765	7206505
		DBM Course	3.87	4.13	0.03	0.12	120	20000	2400000		
		WBM Course	4.13	5.13	0.25	1.1575	1157.5	6800	7871000		
		Sub-base Course	5.13	5.73	0.09	0.4887	488.7	5500	2687850		
		Subgrade (S : PF:: 68: 15: 6: 1)	5.73	7.73	0.5	3.365	3365	3100	10431500		
		S: 68	-	-	-	-	2288.2	3100	7093420		

		MD: 15	-	-	-	-	504.75	160	80760		
		C: 6	-	-	-	-	201.9	3150	635985		
		PF: 1	-	-	-	-	33.65	200	6730		
S. No.	**Material combinations**		**Top Width (m)**	**Bottom width (m)**	**Height (m)**	**Volume (m3)**	**Volume (m3)**	**Rate per m3 (INR)**	**Cost (INR)**	**Overall Cost (INR)**	
10	S : MSWIA: MD: C: PF :: 61: 20: 15: 3: 1	**Bitumnious Course**	3.75	3.87	0.03	0.1143	114.3	31400	3589020	23762630	7808640
		DBM Course	3.87	4.13	0.03	0.12	120	20000	2400000		
		WBM Course	4.13	5.13	0.25	1.1575	1157.5	6800	7871000		
		Sub-base Course	5.13	5.73	0.09	0.4887	488.7	5500	2687850		
		Subgrade (S : MSWIA: MD: C: PF :: 61: 20: 15: 3: 1)	5.73	7.73	0.5	3.365	3365	3100	10431500		
		S: 61	-	-	-	-	2052.65	3100	6363215		
		MSWIA: 20	-	-	-	-	673	500	134600		
		MD: 15	-	-	-	-	504.75	160	80760		
		C: 6	-	-	-	-	201.9	3150	635985		
		PF: 1	-	-	-	-	33.65	200	6730		

The cost analysis indicating a savings of approximately ₹81 lakhs for designing a 1 km flexible pavement with a blend ratio of S: MSWIA: MD: PPF :: 64: 20: 15: 1 emphasizes the effectiveness of using Municipal Solid Waste Incineration Ash (MSWIA) and Marble Dust (MD) as primary stabilizers. However, considering the elimination of Polypropylene Fiber (PPF) to further enhance cost savings necessitates a careful assessment of its technical role in soil stabilization. PPF primarily improves the tensile strength and crack resistance of the stabilized soil, providing reinforcement that controls shrinkage cracks and enhances resistance to deformation under tensile stresses. This is particularly crucial for flexible pavements, where tensile stresses from traffic loads and temperature variations can induce surface cracking. While removing PPF would yield immediate cost savings, it could compromise crack resistance, potentially leading to premature pavement failures and increased maintenance costs over time. Although MSWIA and MD significantly improve strength and compaction characteristics, they lack the flexural or tensile strength improvements provided by PPF. The incremental savings from PPF's removal might not justify the potential loss in performance and durability; thus, the ₹81 lakhs in savings already achieved through optimizing the use of cost-effective waste materials like MSWIA and MD could be negated by future repair and rehabilitation expenses resulting from decreased pavement longevity.

5.11 Conclusion

Considering the increasing volumes of waste generated globally, Municipal Solid Waste Incineration Ash (MSWIA) has emerged as a highly effective and sustainable additive for the stabilization of clayey soils. Experimental results from various soil stabilization tests, including Unconfined Compressive Strength (UCS) and Split Tensile Strength (STS) tests, have shown that soil treated with MSWIA exhibits superior performance compared to traditional stabilizers like marble dust and cement. MSWIA, being a by-product of waste management, not only provides a cost-effective solution but also promotes an eco-friendly approach to soil stabilization by reducing the burden on landfills.

When comparing different combinations of stabilizing materials, the mixture of soil-MSIA-marble dust-cement-polypropylene fibers outperformed other formulations. This combination maximized both compressive and tensile strengths, indicating enhanced load-bearing capacity and resistance to deformation. In contrast, the absence of polypropylene fibers or the use of only two additives (such as soil-MSIA-cement or soil-marble dust-cement) showed comparatively lower strength gains, highlighting the synergistic effect of combining all four additives.

From a pavement design perspective, the addition of MSWIA, marble dust, cement, and polypropylene fibers as a composite stabilizer resulted in significant improvements in California Bearing Ratio (CBR) values. This enhancement in CBR reflects the material’s increased resistance to penetration, making it ideal for sub-grade applications in flexible pavements. Moreover, the mix exhibited favorable permeability characteristics, ensuring that the stabilized soil maintains adequate drainage without compromising its structural integrity.

In summary, the soil-MSIA-marble dust-cement-polypropylene fiber mix presents an optimal solution for improving clayey soil properties in both strength and durability. Its use not only meets the technical requirements for sub-grade materials in pavements but also supports sustainability goals by utilizing waste materials. The major conclusions derived from this study, which will be discussed in detail in Chapter 6, emphasize the superior performance of MSWIA as an additive and its potential to replace or complement traditional soil stabilizers in various geotechnical applications.

Chapter 6

Conclusions and Future Scope

6.1 Introduction

There is a need for utilization of municipal solid waste incineration ash and marble dust which is produced in huge quantity in India. This research is one among those utilization techniques. Thus, based on the analysis of the experimental results and interpretation in previous chapters, the major conclusions of this research work regarding the usage of municipal solid waste incineration ash, marble dust, cement and polypropylene fiber in soil stabilization and the optimum mix to be used as a sub-grade material are presented below:

6.2 Major conclusions drawn from experimental results

1. Adding optimum amount of MSWIA, MD and cement to clayey soil alone and in combination to each other is helpful in reducing the swelling potential of clayey soil by decreasing its differential free swell value. The DFS value of all the combinations lies below 20% (stating degree of expansion of clayey soil as low as per IS) and making it useful for construction purpose.
2. The overall plasticity index of clayey soil decreases on introducing MSWIA, MD and cement to clayey soil alone and in combination to each other. The obtained PI lies in the range of (6-8) for optimum combinations which is suitable for sub-grade construction as per IRC.
3. The curves obtained from compaction test (MDD and OMC values) doesn't depict any clear idea about the optimum content to be used for soil stabilization but is an important factor for designing subgrade for pavements and needs to be considered always.
4. The UCS values of all the mixtures improves irrespective of the curing period for all the mixes alone and in combination to each other revealing that obtained optimum mixes are useful for increasing strength values.
5. The CBR values are highest for the combinations containing cement for all the admixtures. But the higher content of cement may prove to be costly for low budget projects and hence may not be used in every project. However, addition of MSWIA and MD along with PPF in optimum percentage are enough for designing thickness for subgrade (CBR> 5% is necessary as per IRC).
6. The variable head permeability test results show an improvement in the drainage characteristics on adding various mixes alone and in combination to each other in clayey

soil. The increase in coefficient of permeability is more in case of addition of marble dust compared to that of cement and municipal solid waste incineration ash.

7. The increase in coefficient of permeability is more in case of S:MSWIA:MD:C:PPF:: 61:20:15:3:1 followed by S:MSWIA:MD:C:: 59:20:15:6 further followed by S:MSWIA:: 65:20:15 mixtures.
8. The results of X-ray diffraction technique notices that the clayey soil improves its behavior by changing mineralogical composition (from montmorillonite to quartz) on adding various kinds of additives thereby making converting the clayey soil from highly swelling to low or no swelling so that it may be employed as a construction material.
9. The multiple linear regression analysis performed on various combinations based on unconfined compressive strength values gives coefficient of determination, R^2= 0.984 and the percentage error for all the selected combinations is also <10%, stating the accuracy of results.
10. On the basis of cost analysis, it may be inferred that, the use of cement in low volume flexible pavements and for small construction projects may not be a vital decision. Instead, municipal solid waste incineration ash or marble dust or both (depending upon availability) along with polypropylene fiber (to reduce temperature stresses) may be added to clayey soil for achieving more economy.

The current study is not helpful in reducing the cost of low volume flexible pavement but also provides a cost-effective and environmentally friendly technique for solving the disposal issues of various kinds of wastes from households and industries thereby leading to sustainable goals.

6.3 Future Scope

1. The fluctuations in shear strength characteristics of clayey soils under different drainage conditions, combined with the incorporation of additives can be studied.
2. The impact of incorporating additives on the load-deformation behavior of clayey soil can be examined.
3. The changes in consolidation behavior of clayey soil resulting from the addition of additives can be investigated.
4. The research may involve conducting model tests to validate findings under real field conditions.
5. Analysis of pavement thickness and cost for rigid pavement can be conducted.

REFERENCES

1. Singh, G., Babu, R., Narain, P., Bhushan, L. S., & Abrol, I. P. (1992). Soil erosion rates in India. *Journal of Soil and water Conservation*, *47*(1), 97-99.
2. Singh, D., & Kumar, A. (2017). Performance evaluation and geo-characterization of municipal solid waste incineration ash material amended with cement and fibre. *International Journal of Geosynthetics and Ground Engineering*, *3*, 1-9.
3. Sharma, A., & Sharma, R. K. (2020). Strength and drainage characteristics of poor soils stabilized with construction demolition waste. *Geotechnical and Geological engineering*, *38*(5), 4753-4760.
4. Singh, M., Singh, K., & Sharma, A. (2022). Strength Characteristics of Clayey Soil Stabilized with Brick Kiln Dust and Sisal Fiber. In *Advances in Construction Materials and Sustainable Environment: Select Proceedings of ICCME 2020* (pp. 927-936). Springer Singapore.
5. Miller, A. B., Nelson, R. W., Scott-Moncrieff, J. C., Neal, L., & Bottoms, G. D. (1992). Serial thyroid hormone concentrations in healthy euthyroid dogs, dogs with hypothyroidism, and euthyroid dogs with atopic dermatitis. *British Veterinary Journal*, *148*(5), 451-458.
6. Jha, A. K., Sharma, C., Singh, N., Ramesh, R., Purvaja, R., & Gupta, P. K. (2008). Greenhouse gas emissions from municipal solid waste management in Indian mega-cities: A case study of Chennai landfill sites. *Chemosphere*, *71*(4), 750-758.
7. Phanikumar, B. R. (2009). Effect of lime and fly ash on swell, consolidation and shear strength characteristics of expansive clays: a comparative study. *Geomechanics and Geoengineering: An international journal*, *4*(2), 175-181.
8. Katti, R. K. (1978). *Search for solutions to problems in black cotton soils*. Bombay: Indian Institute of Technology.
9. Shanker, N. B., & Maruthi, G. (1989). Use of lime-soil piles for in-situ stabilization of black cotton soils. In *Proceedings of Indian Geotechnical Conference. Meerut* (Vol. 1, pp. 149-53).
10. Patel, N. A., Mishra, C. B., Parmar, D. K., & Gautam, S. B. (2015). Subgrade soil stabilization using chemical additives. *International Research Journal of Engineering and Technology (IRJET)*, *2*(04), 1089-1095.
11. Afrin, H. (2017). A review on different types soil stabilization techniques. *International Journal of Transportation Engineering and Technology*, *3*(2), 19-24.
12. Maaitah, O. N. (2012). Soil stabilization by chemical agent. *Geotechnical and Geological Engineering*, *30*, 1345-1356.
13. Archibong, G. A., Sunday, E. U., Akudike, J. C., Okeke, O. C., & Amadi, C. (2020). A review of the principles and methods of soil stabilization. *International Journal of Advanced Academic Research| Sciences*, *6*(3), 2488-9849.
14. Firoozi, A. A., Guney Olgun, C., Firoozi, A. A., &Baghini, M. S. (2017). Fundamentals of soil stabilization. *International Journal of Geo-Engineering*, *8*, 1-16.
15. Takhelmayum, G., Savitha, A. L., & Krishna, G. (2013). Laboratory study on soil stabilization using fly ash mixtures. *International Journal of Engineering Science and Innovative Technology (IJESIT)*, *2*(1), 477-482.

16. Zha, F., Liu, S., Du, Y., & Cui, K. (2008). Behavior of expansive soils stabilized with fly ash. *Natural hazards*, *47*, 509-523.
17. Ahmed, A. G. A. (2014, May). Fly ash utilization in soil stabilization. In *Proceedings of the International Conference on Civil, Biological and Environmental Engineering* (pp. 76-78).
18. Bose, B. (2012). Geo engineering properties of expansive soil stabilized with fly ash. *Electronic Journal of Geotechnical Engineering*, *17*(1), 1339-1353.
19. Nath, B. D., Molla, M. K. A., & Sarkar, G. (2017). Study on strength behavior of organic soil stabilized with fly ash. *International scholarly research notices*, *2017*.
20. Negi, A. S., Faizan, M., Siddharth, D. P., & Singh, R. (2013). Soil stabilization using lime. *International journal of innovative research in science, engineering and technology*, *2*(2), 448-453.
21. Jawad, I. T., Taha, M. R., Majeed, Z. H., & Khan, T. A. (2014). Soil stabilization using lime: Advantages, disadvantages and proposing a potential alternative. *Research Journal of Applied Sciences, Engineering and Technology*, *8*(4), 510-520.
22. Zambri, N. M., &Ghazaly, Z. M. (2018). Peat soil stabilization using lime and cement. In *E3S Web of Conferences* (Vol. 34, p. 01034). EDP Sciences.
23. Higgins, D. D., Kinuthia, J. M., & Wild, S. (1998). Soil stabilization using lime-activated ground granulated blast furnace slag. *Special Publication*, *178*, 1057-1074.
24. Joe, M. A., & Rajesh, A. M. (2015). Soil stabilization using industrial waste and lime. *International Journal of Scientific Research Engineering & Technology (IJSRET)*, *4*(7).
25. Sani, J. E., Etim, R. K., & Joseph, A. (2019). Compaction behaviour of lateritic soil–calcium chloride mixtures. *Geotechnical and Geological Engineering*, *37*, 2343-2362.
26. Prasad, A. S. S. V., Prasad, D. S. V., & Babu, R. D. (2015). Efficiency of Calcium Chloride and Vitrified Tiles Sludge on the Strength Characteristics of Expansive Soil. *Int. J. Adv. Res. Educ. Technol*, *2*, 202-205.
27. Shon, C. S., Saylak, D., & Mishra, S. K. (2010). Combined use of calcium chloride and fly ash in road base stabilization. *Transportation research record*, *2186*(1), 120-129.
28. Chen, H., & Wang, Q. (2006). The behaviour of organic matter in the process of soft soil stabilization using cement. *Bulletin of Engineering Geology and the Environment*, *65*, 445-448.
29. Adeyanju, E. A., & Okeke, C. A. (2019, November). Clay soil stabilization using cement kiln dust. In *IOP conference series: materials science and engineering* (Vol. 640, No. 1, p. 012080). IOP Publishing.
30. Ghadir, P., & Ranjbar, N. (2018). Clayey soil stabilization using geopolymer and Portland cement. *Construction and Building Materials*, *188*, 361-371.
31. Ramaji, A. E. (2012). A review on the soil stabilization using low-cost methods. *Journal of Applied Sciences Research*, *8*(4), 2193-2196.
32. Chen, F. H. (1975). Foundations on Expansive Soils, Elsevier Scientific Publication Company.
33. Ola, S. A. (1978). The geology and geotechnical properties of the black cotton soils of northeastern Nigeria. *Engineering Geology, 12,* 375-391.
34. Plait, R. M. (1953, August). Determination of swelling pressure of black cotton soil-A method. In *proceedings of 3rd international conference on soil mechanics and foundation engineering* (Vol. 1, pp. 170-172).

35. Osinubi, K. J. (2000). Stabilisation of tropical black clay with cement and pulverised coal bottom ash admixture. In *Advances in unsaturated geotechnics* (pp. 289-302).
36. Gidigasu, S. S. R., &Gawu, S. K. Y. (2013). The mode of formation, nature and geotechnical characteristics of black cotton soils-a review. *Sci Res Essays*, *1*, 377-90.
37. Lam, C. H. K., Barford, J. P., & McKay, G. (2011). Utilization of municipal solid waste incineration ash in Portland cement clinker. *Clean technologies and environmental policy*, *13*, 607-615.
38. Show, K. Y., Tay, J. H., & Goh, A. T. (2003). Reuse of incinerator fly ash in soft soil stabilization. *Journal of materials in civil engineering*, *15*(4), 335-343.
39. Mohamedzein, Y. E. A., Al-Aghbari, M. Y., & Taha, R. A. (2006). Stabilization of desert sands using municipal solid waste incinerator ash. *Geotechnical & Geological Engineering*, *24*, 1767-1780.
40. Jadhav, U., Khan, A. H., Belim, N., Khan, M. I., & Siddiqui, A. M. R. (2018). Soil stabilization by using municipal solid waste ash.
41. Mohamedzein, Y. E. A., & Al-Aghbari, M. Y. (2012). The use of municipal solid waste incinerator ash to stabilize dune sands. *Geotechnical and Geological Engineering*, *30*, 1335-1344.
42. Vizcarra, G. O. C., Casagrande, M. D. T., & da Motta, L. M. G. (2014). Applicability of municipal solid waste incineration ash on base layers of pavements. *Journal of materials in civil engineering*, *26*(6), 06014005.
43. Greenwood, W., Zekkos, D., &Sahadewa, A. (2015). Spatial variation of shear wave velocity of waste materials from surface wave measurements. *Journal of Environmental and Engineering Geophysics*, *20*(4), 287-301.
44. Abdulfatah, A. Y., Kiru, S. G., & Adedokun, T. A. (2013). Compaction Characteristics of Lateritic Soil-Stabilized Municipal Solid Waste Bottom Sediment. *International Journal of Environmental Science and Development*, *4*(3), 304.
45. Vizcarra, G. O. C., Casagrande, M. D. T., & da Motta, L. M. G. (2014). Applicability of municipal solid waste incineration ash on base layers of pavements. *Journal of materials in civil engineering*, *26*(6), 06014005.
46. Leong, E. C., &Eriktius, D. T. (2014). Improvement of peaty soils with municipal solid waste fly ash. *Environmental Geotechnics*, *1*(4), 200-209.
47. Kim, J., An, J., Nam, B. H., & Tasneem, K. M. (2016). Investigation on the side effects of municipal solid waste incineration ashes when used as mineral addition in cement-based material. *Road Materials and Pavement Design*, *17*(2), 345-364.
48. Bresson, L. M., Koch, C., Le Bissonnais, Y., Barriuso, E., & Lecomte, V. (2001). Soil surface structure stabilization by municipal waste compost application. *Soil Science Society of America Journal*, *65*(6), 1804-1811.
49. Wasim, J., Hasan, A. K. M., & Nine, J. (2017). Present outlook of sustainable solid waste management: a case study of Dhaka. *Proceedings of the WasteSafe*.
50. Singh, D., & Kumar, A. (2017). Geo-environmental application of municipal solid waste incinerator ash stabilized with cement. *Journal of rock mechanics and geotechnical engineering*, *9*(2), 370-375.
51. Tang, Q., Zhang, Y., Gao, Y., & Gu, F. (2017). Use of cement-chelated, solidified, municipal solid waste incinerator (MSWI) fly ash for pavement material: mechanical and environmental evaluations. *Canadian Geotechnical Journal*, *54*(11), 1553-1566.

52. Kumar, A., & Mittal, A. (2019). Utilization of municipal solid waste ash for stabilization of cohesive soil. In *Environmental Geotechnology: Proceedings of EGRWSE 2018* (pp. 133-139). Springer Singapore.
53. Baruah, D., Goel, S., Gupta, C., & Sahu, A. K. (2020). Ground improvement using municipal solid waste ash. In *Advances in Sustainable Construction Materials and Geotechnical Engineering: Select Proceedings of TRACE 2018* (pp. 271-280). Springer Singapore.
54. Li, L., Zang, T., Xiao, H., Feng, W., & Liu, Y. (2023). Experimental study of polypropylene fibre-reinforced clay soil mixed with municipal solid waste incineration bottom ash. *European Journal of Environmental and Civil Engineering*, *27*(8), 2700-2716.
55. Liang, S., Chen, J., Guo, M., Feng, D., Liu, L., & Qi, T. (2020). Utilization of pretreated municipal solid waste incineration fly ash for cement-stabilized soil. *Waste management*, *105*, 425-432.
56. Sharma, V., & Singh, S. (2020). Modeling for the use of waste materials (Bottom ash and fly ash) in soil stabilization. *Materials Today: Proceedings*, *33*, 1610-1614.
57. Gautam, K. K., Sharma, R. K., & Sharma, A. (2021). Effect of municipal solid waste incinerator ash and lime on strength characteristics of black cotton soil. In *Sustainable Development Through Engineering Innovations: Select Proceedings of SDEI 2020* (pp. 115-123). Springer Singapore.
58. Kumar, S., & Singh, D. (2021). Municipal solid waste incineration bottom ash: a competent raw material with new possibilities. *Innovative Infrastructure Solutions*, *6*, 1-15.
59. Singh, P., Boora, A., & Gupta, A. K. (2022). Sub-grade characteristics of clayey soil incorporating municipal solid waste incineration ash and marble dust. *Journal of Engineering, Design and Technology*, *20*(3), 712-726.
60. Tabyang, W., Suksiripattanapong, C., Phetchuay, C., Laksanakit, C., &Chusilp, N. (2022). Evaluation of municipal solid waste incineration fly ash based geopolymer for stabilised recycled concrete aggregate as road material. *Road Materials and Pavement Design*, *23*(9), 2178-2189.
61. Zimar, Z., Robert, D., Sidiq, A., Zhou, A., Giustozzi, F., Setunge, S., & Kodikara, J. (2022). Waste-to-energy ash for treating highly expansive clays in road pavements. *Journal of Cleaner Production*, *374*, 133854.
62. Chauhan, R., & Deka, S. (2022). Improvement of Geotechnical Properties of Fine-Grained Soil by Using Lime and Guwahati Municipal Solid Waste Ash. In *Advances in Geo-Science and Geo-Structures: Select Proceedings of GSGS 2020* (pp. 81-96). Springer Singapore.
63. Randhawa, K. S., Chauhan, R., & Kumar, R. (2022). An investigation on the effect of lime addition on UCS of Indian black cotton soil. *Materials Today: Proceedings*, *50*, 797-803.
64. Okagbue, C. O., &Onyeobi, T. U. S. (1999). Potential of marble dust to stabilise red tropical soils for road construction. *Engineering Geology*, *53*(3-4), 371-380.
65. Sabat, A. K., & Nanda, R. P. (2011). Effect of marble dust on strength and durability of Rice husk ash stabilised expansive soil. *International Journal of Civil & Structural Engineering*, *1*(4), 939-948.
66. Sheikh, A. Y., Gupta, R., & Kumar, E. N. (2018). Stabilization of soil with Marble Dust and Rice Husk in highway subgrade. *Volume*, *6*, 1245-1251.

67. Patel, M. A., & Patel, H. S. (2012). A review on effects of stabilizing agents for stabilization of weak soil. *Civil and Environmental Research*, *2*(6), 1-7.
68. Özen, S., Durgun, M. Y., Kobya, V., Karakuzu, K., & Mardani-Aghabaglou, A. (2022). Effect of colemanite ore wastes utilization on fresh properties and compressive strength of cementitious systems. *Arabian Journal for Science and Engineering*, *47*(10), 12873-12887.
69. Prasad, D. S. V., Anjan Kumar, M., & Prasada Raju, G. V. R. (2017). Influence of quarry dust and tile waste on geotechnical properties of expansive soil. In *Indian geotechnical conference GeoNEst, IIT Guwahati, Th* (Vol. 9, pp. 761-764).
70. Chandra, S., Kumar, P., &Feyissa, B. A. (2002). Use of marble dust in road construction. *Road Materials and Pavement Design*, *3*(3), 317-330.
71. Singh, P. S., & Yadav, R. K. (2014). Effect of marble dust on index properties of black cotton soil. *Int J Engg Res Sci Tech*, *3*, 158-63.
72. Gupta, C., & Sharma, R. K. (2014). Influence of marble dust, fly ash and beas sand on sub grade characteristics of expansive soil. *Journal of Mechanical and Civil Engineering*, *13*, 13-18.
73. Ali, R., Khan, H., & Shah, A. A. (2014). Expansive soil stabilization using marble dust and bagasse ash. *Int. J. Sci. Res*, *3*(6), 2812-2816.
74. Saygili, A. (2015). Use of waste marble dust for stabilization of clayey soil. *materials science*, *21*(4), 601-606.
75. Minhas, A., & Devi, V. U. (2016). Soil stabilization of alluvial soil by using marble powder. *Int. J. Civ. Eng. Technol*, *7*(5), 87-92.
76. Saygili, A. (2015). Use of waste marble dust for stabilization of clayey soil. *materials science*, *21*(4), 601-606.
77. Yilmaz, F., & Yurdakul, M. U. H. A. M. M. E. T. (2017). Evaluation of marble dust for soil stabilization. *Acta Physica Polonica A*, *132*(3), 710-711.
78. Karthika, T., Shalini, S., Kothai, P. S., & Arumugam, K. (2021, November). Impact of dyeing industry effluents on geotechnical properties of soil. In *Journal of Physics: Conference Series* (Vol. 2070, No. 1, p. 012233). IOP Publishing.
79. Abdelkader, H. A., Hussein, M. M., & Ye, H. (2021). Influence of waste marble dust on the improvement of expansive clay soils. *Advances in Civil Engineering*, *2021*, 1-13.
80. Firat, S., Khatib, J. M., Yilmaz, G., &Comert, A. T. (2017). Effect of curing time on selected properties of soil stabilized with fly ash, marble dust and waste sand for road sub-base materials. *Waste Management & Research*, *35*(7), 747-756.
81. Sheikh, A. Y., Gupta, R., & Kumar, E. N. (2018). Stabilization of soil with Marble Dust and Rice Husk in highway subgrade. *Volume*, *6*, 1245-1251.
82. Yadav, A. P., & Kumar, E. N. (2019). A Comparative Study of Waste Foundry Sand and Marble Dust for Stabilization of Subgrade Soil. *International Journal for Research in Applied Science and Technolgy*.
83. Rathore, P., & Tiwari, S. K. (2023). Soil Stabilization using Ceramic Waste: an Experimental Study. *Journal of Mining and Environment*, *14*(1), 47-65.
84. Jain, A. K., & Jha, A. K. (2020). Geotechnical behaviour and micro-analyses of expansive soil amended with marble dust. *Soils and Foundations*, *60*(4), 737-751.
85. Waheed, A., Arshid, M. U., Khalid, R. A., & Gardezi, S. S. S. (2021). Soil improvement using waste marble dust for sustainable development. *Civil Engineering Journal*, *7*(9), 1594-1607.

86. Gupta, C., & Sharma, R. K. (2014). Influence of marble dust, fly ash and beas sand on sub grade characteristics of expansive soil. *Journal of Mechanical and Civil Engineering*, *13*, 13-18.
87. Chen, H., & Wang, Q. (2006). The behaviour of organic matter in the process of soft soil stabilization using cement. *Bulletin of Engineering Geology and the Environment*, *65*, 445-448.
88. Otoko, G. R., Battistelle, R. A. G., & Neves, C. (2014). On the economic use of cement in soil stabilization. *International Journal of Engineering and Technology Research*, *Vol2*, (1), 01-07.
89. Tremblay, H., Duchesne, J., Locat, J., &Leroueil, S. (2002). Influence of the nature of organic compounds on fine soil stabilization with cement. *Canadian geotechnical journal*, *39*(3), 535-546.
90. Xiao, Y., Tong, L., Che, H., Guo, Q., & Pan, H. (2022). Experimental studies on compressive and tensile strength of cement-stabilized soil reinforced with rice husks and polypropylene fibers. *Construction and Building Materials*, *344*, 128242.
91. Wang, F., Li, K., & Liu, Y. (2022). Optimal water-cement ratio of cement-stabilized soil. *Construction and Building Materials*, *320*, 126211.
92. Yu, H., Yi, Y., Romagnoli, A., & Tan, W. L. (2022). Cement soil stabilization for underground liquid natural gas storage. *Cold Regions Science and Technology*, *194*, 103438.
93. Thanushan, K., &Sathiparan, N. (2022). Mechanical performance and durability of banana fibre and coconut coir reinforced cement stabilized soil blocks. *Materialia*, *21*, 101309.
94. Liu, L., Deng, T., Deng, Y., Zhan, L., Horpibulsuk, S., & Wang, Q. (2022). Stabilization nature and unified strength characterization for cement-based stabilized soils. *Construction and Building Materials*, *336*, 127544.
95. Kulkarni, P. P., & Mandal, J. N. (2022). Strength evaluation of soil stabilized with nano silica-cement mixes as road construction material. *Construction and Building Materials*, *314*, 125363.
96. Amiri, M., Kalantari, B., &Porhonar, F. (2023). The effect of thermal stabilization process on mineralogy, morphology and engineering properties of red soil in southern Iran. *Case Studies in Construction Materials*, *19*, e02454.
97. Chandra, G. S., Satyanarayana, P. V. V., & Naidu, P. G. (2021, March). CBR Characteristics of Cementitious Graded Gravel Soils by Curing Methods. In *IOP Conference Series: Materials Science and Engineering* (Vol. 1126, No. 1, p. 012078). IOP Publishing.
98. Etim, R. K., Ekpo, D. U., Ebong, U. B., &Usanga, I. N. (2021). Influence of periwinkle shell ash on the strength properties of cement-stabilized lateritic soil. *International Journal of Pavement Research and Technology*, 1-17.
99. Ghadir, P., Zamanian, M., Mahbubi-Motlagh, N., Saberian, M., Li, J., & Ranjbar, N. (2021). Shear strength and life cycle assessment of volcanic ash-based geopolymer and cement stabilized soil: A comparative study. *Transportation Geotechnics*, *31*, 100639.
100. Mohanty, S., Roy, N., Singh, S. P., & Sihag, P. (2021). Strength and durability of flyash, GGBS and cement clinker stabilized dispersive soil. *Cold Regions Science and Technology*, *191*, 103358.

101. Sagidullina, N., Abdialim, S., Kim, J., Satyanaga, A., & Moon, S. W. (2022). Influence of Freeze–Thaw Cycles on Physical and Mechanical Properties of Cement-Treated Silty Sand. *Sustainability*, *14*(12), 7000.
102. Bandara, N., Hettiarachchi, H., Jensen, E., & Binoy, T. H. (2020). Upcycling potential of industrial waste in soil stabilization: use of kiln dust and fly ash to improve weak pavement subgrades encountered in Michigan, USA. *Sustainability*, *12*(17), 7226.
103. Adeyanju, E. A., & Okeke, C. A. (2019, November). Clay soil stabilization using cement kiln dust. In *IOP conference series: materials science and engineering* (Vol. 640, No. 1, p. 012080). IOP Publishing.
104. Ifediniru, C., &Ekeocha, N. E. (2022). Performance of cement-stabilized weak subgrade for highway embankment construction in Southeast Nigeria. *International Journal of Geo-Engineering*, *13*(1), 1.
105. Beyene, A., Merka, H., & Tsige, D. (2023). Suitability analysis of vertically installed scoria gravel drains for enhancing consolidation performance of clayey ground. *Results in Engineering*, *17*, 100975.
106. Ezreig, A. M. A., Mohamad Ismail, M. A., &Ehwailat, K. I. A. (2022). Hydrophobic Effect of Soil Stabilization for a Sustainable Subgrade Soil Improvement. *Materials*, *15*(9), 3087.
107. Wibisono, G., Kamaldi, A., & Olivia, M. (2019). Peat soil mass stabilization using geopolymeric hybrid material in early age. In *MATEC Web of Conferences* (Vol. 276, p. 05003). EDP Sciences.
108. Iyaruk, A., Promputthangkoon, P., &Lukjan, A. (2022). Evaluating the Performance of Lateritic Soil Stabilized with Cement and Biomass Bottom Ash for Use as Pavement Materials. *Infrastructures*, *7*(5), 66.
109. Arifin, Y. F., Agustina, E., Andhi, F., & Agus, S. S. (2021). The role of additives in soil-cement subjected to wetting-drying cycles. *Infrastructures*, *6*(3), 48.
110. Yang, Y., Li, S., Li, C., Wu, L., Yang, L., Zhang, P., & Huang, T. (2020). Comprehensive laboratory evaluations and a proposed mix design procedure for cement-stabilized cohesive and granular soils. *Frontiers in Materials*, *7*, 239.
111. Sadek, Y., Rikioui, T., Abdoun, T., & Dadi, A. (2022). Influence of Compaction Energy on Cement Stabilized Soil for Road Construction. *Civil Engineering Journal*, *8*(3), 580-594.
112. Rivera, J. F., Orobio, A., de Gutiérrez, R. M., &Cristelo, N. (2020). Clayey soil stabilization using alkali-activated cementitious materials. *Materiales de Construcción*, *70*(337), e211-e211.
113. James, J., Natesan, A., Manohar, A., & Subramanian, V. (2021). Potential of Portland pozzolana cement in the stabilization of an expansive soil subjected to alternate cycles of wetting and drying. *Građevinskimaterijaliikonstrukcije*, *64*(2), 81-91.
114. Minh, D. H., & Nien, N. T. (2022). Experimental Study on the Use of the Modifying Agent for Expansive Soil Stabilization: Mockup Test on a Case Study. *International Journal of Sustainable Construction Engineering and Technology*, *13*(1), 159-166.
115. MotahariTabari, S., &Shooshpasha, I. (2021). Evaluation of coarse-grained mechanical properties using small direct shear test. *International Journal of Geotechnical Engineering*, *15*(6), 667-679.

116. Marik, S., Ransinchung, G. D., Singh, A., & Khot, P. (2022). Investigation on use of silica-based additive for sustainable subgrade construction. *Case Studies in Construction Materials*, *17*, e01229.
117. Amiri, M., Kalantari, B., &Porhonar, F. (2023). The effect of thermal stabilization process on mineralogy, morphology and engineering properties of red soil in southern Iran. *Case Studies in Construction Materials, 19,* e02454.
118. Zaika, Y., Munawir, A. A., &Pujiraharjo, A. (2021). Remediation of Soft Soil by Hydrated Lime. In *ICCOEE2020: Proceedings of the 6th International Conference on Civil, Offshore and Environmental Engineering (ICCOEE2020)* (pp. 819-827). Springer Singapore.
119. Bakaiyang, L., Madjadoumbaye, J., Boussafir, Y., Szymkiewicz, F., & Duc, M. (2021). Re-use in road construction of a Karal-type clay-rich soil from North Cameroon after a lime/cement mixed treatment using two different limes. *Case Studies in Construction Materials*, *15*, e00626.
120. Jaffar, S. T. A., Oderji, S. Y., Zhang, S. A., & Chen, L. Z. (2018). Effect of cement solidification on strength and leaching properties of Heavy Metals Contaminated Soil.
121. Malekzadeh, M., &Bilsel, H. (2012). Effect of polypropylene fiber on mechanical behaviour of expansive soils. *EJGE*, *17*(A), 55-63.
122. Jiang, H., Cai, Y., & Liu, J. (2010). Engineering properties of soils reinforced by short discrete polypropylene fiber. *Journal of Materials in civil Engineering*, *22*(12), 1315-1322.
123. Tang, C., Shi, B., Gao, W., Chen, F., & Cai, Y. (2007). Strength and mechanical behavior of short polypropylene fiber reinforced and cement stabilized clayey soil. *Geotextiles and Geomembranes*, *25*(3), 194-202.
124. Xiao, Y., Tong, L., Che, H., Guo, Q., & Pan, H. (2022). Experimental studies on compressive and tensile strength of cement-stabilized soil reinforced with rice husks and polypropylene fibers. *Construction and Building Materials*, *344*, 128242.
125. Karboua, L., Bekhiti, M., &Zaitri, R. (2023). Optimizing the mechanical behavior of clay using cement and PVC aggregates with the application of a mixture design method. *Construction and Building Materials*, *405*, 133343.
126. Behera, R. (2022). An experimental study on evaluation of fiber Reinforced-Fly ash stabilized black cotton soil as a sustainable subgrade material. *Materials Today: Proceedings*, *62*, 6182-6188.
127. Uday, R. A., Kiran, D., GS, A. K., Prakash, K. G., &Maddodi, B. S. (2022). Effect of Polypropylene Macro Fiber on Geotechnical Characteristics of Black Cotton Soil: An Experimental Investigation and Correlation Analysis. *Engineered Science*, *21*, 775.
128. Surya, I., Chong, E. W. N., Khalil, H. A., Funmilayo, O. G., Abdullah, C. K., Aprilia, N. S. &Oyekanmi, A. A. (2021). Augmentation of physico-mechanical, thermal and biodegradability performances of bio-precipitated material reinforced in Eucheuma cottonii biopolymer films. *Journal of Materials Research and Technology*, *12*, 1673-1688.
129. Kalantari, B., & Huat, B. B. (2008). Peat soil stabilization, using ordinary portland cement, polypropylene fibers, and air curing technique. *Electron. J. Geotech. Eng*, *13*, 1-13.
130. Sujatha, E. R., Atchaya, P., Darshan, S., & Subhashini, S. (2021). Mechanical properties of glass fibre reinforced soil and its application as subgrade reinforcement. *Road Materials and Pavement Design*, *22*(10), 2384-2395.

131. Ashiq, S. Z., Akbar, A., Farooq, K., & Mujtaba, H. (2022). Sustainable improvement in engineering behavior of Siwalik Clay using industrial waste glass powder as additive. *Case Studies in Construction Materials*, *16*, e00883.
132. Syed, M., &GuhaRay, A. (2020). Effect of fiber reinforcement on mechanical behavior of alkali-activated binder-treated expansive soil: reliability-based approach. *International journal of Geomechanics*, *20*(12), 04020225.
133. Liu, J., Bai, Y., Song, Z., Kanungo, D. P., Wang, Y., Bu, F., ... & Shi, X. (2020). Stabilization of sand using different types of short fibers and organic polymer. *Construction and Building Materials*, *253*, 119164.
134. Meddah, A., Goufi, A. E., & Pantelidis, L. (2022). Improving very high plastic clays with the combined effect of sand, lime, and polypropylene fibers. *Applied Sciences*, *12*(19), 9924.
135. Chowdary, B., V, R. M., & Pillai, R. J. (2022). Efficacy of Slag-Based Geopolymer Binder Reinforced with Polypropylene Fibers in the Stabilization of Soft Clays. *Transportation Infrastructure Geotechnology*, 1-16.
136. Radwan, M. K., Lee, F. W., Woon, Y. B., Yew, M. K., Mo, K. H., & Wai, S. H. (2021). A study of the strength performance of peat soil: A modified cement-based stabilization agent using fly ash and polypropylene fiber. *Polymers*, *13*(23), 4059.
137. Soltani, A., Deng, A., & Taheri, A. (2018). Swell–compression characteristics of a fiber–reinforced expansive soil. *Geotextiles and Geomembranes*, *46*(2), 183-189.
138. Moghal, A. A. B., Chittoori, B. C., & Basha, B. M. (2018). Effect of fibre reinforcement on CBR behaviour of lime-blended expansive soils: reliability approach. *Road Materials and Pavement Design*, *19*(3), 690-709.
139. Tiwari, N., & Satyam, N. (2019). Experimental study on the influence of polypropylene fiber on the swelling pressure expansion attributes of silica fume stabilized clayey soil. *Geosciences*, *9*(9), 377.

LIST OF PUBLICATIONS

Journal Publications

1. Singh, P., Boora, A., & Gupta, A. K. (2022). Sub-grade characteristics of clayey soil incorporating municipal solid waste incineration ash and marble dust. *Journal of Engineering, Design and Technology, 20(3), 712-726.* *http://dx.doi.org/10.1108/JEDT-08-2020-0347* *(Scopus)*
2. Singh, P., Boora, A., & Gupta, A. K. (2021). Geotechnical characteristics of clayey soil admixed with municipal solid waste incineration ash, cement and polypropylene fiber. *Innovative Infrastructure Solutions, 6, 1-9.* *http://dx.doi.org/10.1007/s41062-021-00547-4* *(Scopus)*

Conference Publications

1. Singh, P., Boora, A., & Gupta, A. K. (2023, February). A Review on Utilizing Municipal Solid Waste Incineration (MSWIA) in Construction Activities. *In IOP Conference Series: Earth and Environmental Science (Vol. 1110, No. 1, p. 012042). IOP Publishing.* *http://dx.doi.org/10.1088/1755-1315/1110/1/012042* *(Scopus Indexed)*
2. Singh, P., Boora, A., & Gupta, A. K. (2023, February). Effect of Industrial Waste and Polyester Fiber on Geotechnical Characteristics of Local Clay. *In IOP Conference Series: Earth and Environmental Science (Vol. 1110, No. 1, p. 012042). IOP Publishing.* *http://dx.doi.org/10.1088/1755-1315/1110/1/012043* *(Scopus Indexed)*

Appendix 1

Design of Flexible pavement for different million standard axle

Table 1: Road Section for 5 msa

Sr. No.	Combination	Pavement Design Parameters	Pavement section				
		Design traffic	Total pavement thickness (mm)	GSB (mm)	GB (mm)	DBM (mm)	BC/SDBC (mm)
1	S: 100	5	495	150	250	65	30
2	S : MSWIA:: 80: 20	5	495	150	250	65	30
3	S : MD :: 85: 15	5	495	150	250	65	30
4	S: C:: 97:3	5	480	150	250	50	30
5	S: PPF:: 99: 1	5	495	150	250	65	30
6	S: MSWIA: PPF:: 79: 20: 1	5	490	150	250	60	30
7	S : MD: PPF:: 84: 15: 1	5	480	150	250	50	30
8	S : C: PPF:: 90: 9: 1	5	480	150	250	50	30
9	S : MSWIA: C:: 74: 20: 6	5	480	150	250	50	30
10	S : MD: C:: 79: 15: 6	5	480	150	250	50	30
11	S : MSWIA: MD:: 65: 20: 15	5	480	150	250	50	30
12	S : MSWIA: MD: C:: 62: 20: 15: 3	5	480	150	250	50	30
13	S :MSWIA: MD: PPF:: 64: 20: 15: 1	5	480	150	250	50	30
14	S : MSWIA: C: PPF:: 73: 20: 6: 1	5	480	150	250	50	30
15	S : MD: C: PPF:: 78: 15: 6: 1	5	480	150	250	50	30
16	S : MSWIA: MD: C: PPF:: 61: 20: 15: 3: 1	5	480	150	250	50	30

Table 2: Road Section for 10 msa

Sr. No.	Combination	Pavement Design Parameters	Pavement section				
		Design traffic	Total pavement thickness (mm)	GSB (mm)	GB (mm)	DBM (mm)	BC/SDBC (mm)
1	S: 100	5	570	200	250	80	40
2	S : MSWIA:: 80: 20	5	570	200	250	80	40
3	S : MD :: 85: 15	5	570	200	250	80	40
4	S: C:: 97:3	5	530	200	250	50	30
5	S: PPF:: 99: 1	5	570	200	250	80	40
6	S: MSWIA: PPF:: 79: 20: 1	5	560	200	250	70	40
7	S : MD: PPF:: 84: 15: 1	5	550	200	250	70	30
8	S : C: PPF:: 90: 9: 1	5	530	200	250	50	30
9	S : MSWIA: C:: 74: 20: 6	5	530	200	250	50	30
10	S : MD: C:: 79: 15: 6	5	530	200	250	50	30
11	S : MSWIA: MD:: 65: 20: 15	5	550	200	250	70	30
12	S : MSWIA: MD: C:: 62: 20: 15: 3	5	530	200	250	50	30
13	S :MSWIA: MD: PPF:: 64: 20: 15: 1	5	540	200	250	60	30
14	S : MSWIA: C: PPF:: 73: 20: 6: 1	5	530	200	250	50	30
15	S : MD: C: PPF:: 78: 15: 6: 1	5	530	200	250	50	30
16	S : MSWIA: MD: C: PPF:: 61: 20: 15: 3: 1	5	530	200	250	50	30

Table 3: Road Section for 20 msa

Sr. No.	Combination	Pavement Design Parameters	Pavement section				
		Design traffic	Total pavement thickness (mm)	GSB (mm)	GB (mm)	DBM (mm)	BC/SDBC (mm)
1	S: 100	5	595	200	250	105	40
2	S : MSWIA:: 80: 20	5	595	200	250	105	40
3	S : MD :: 85: 15	5	595	200	250	105	40
4	S: C:: 97:3	5	560	200	250	70	40
5	S: PPF:: 99: 1	5	595	200	250	105	40
6	S: MSWIA: PPF:: 79: 20: 1	5	585	200	250	95	40
7	S : MD: PPF:: 84: 15: 1	5	580	200	250	100	30
8	S : C: PPF:: 90: 9: 1	5	545	200	250	55	40
9	S : MSWIA: C:: 74: 20: 6	5	545	200	250	55	40
10	S : MD: C:: 79: 15: 6	5	545	200	250	55	40
11	S : MSWIA: MD:: 65: 20: 15	5	580	200	250	100	30
12	S : MSWIA: MD: C:: 62: 20: 15: 3	5	545	200	250	55	40
13	S :MSWIA: MD: PPF:: 64: 20: 15: 1	5	570	200	250	90	30
14	S : MSWIA: C: PPF:: 73: 20: 6: 1	5	545	200	250	55	40
15	S : MD: C: PPF:: 78: 15: 6: 1	5	530	200	250	50	30
16	S : MSWIA: MD: C: PPF:: 61: 20: 15: 3: 1	5	530	200	250	50	30

Table 4: Road Section for 50 msa

Sr. No.	Combination	Pavement Design Parameters	Pavement section				
		Design traffic	Total pavement thickness (mm)	GSB (mm)	GB (mm)	DBM (mm)	BC/SDBC (mm)
1	S: 100	5	630	200	250	140	40
2	S : MSWIA:: 80: 20	5	630	200	250	140	40
3	S : MD :: 85: 15	5	630	200	250	140	40
4	S: C:: 97:3	5	595	200	250	105	40
5	S: PPF:: 99: 1	5	630	200	250	140	40
6	S: MSWIA: PPF:: 79: 20: 1	5	620	200	250	130	40
7	S : MD: PPF:: 84: 15: 1	5	615	200	250	125	40
8	S : C: PPF:: 90: 9: 1	5	590	200	250	100	40
9	S : MSWIA: C:: 74: 20: 6	5	590	200	250	100	40
10	S : MD: C:: 79: 15: 6	5	590	200	250	100	40
11	S : MSWIA: MD:: 65: 20: 15	5	615	200	250	125	40
12	S : MSWIA: MD: C:: 62: 20: 15: 3	5	590	200	250	100	40
13	S :MSWIA: MD: PPF:: 64: 20: 15: 1	5	595	200	250	105	40
14	S : MSWIA: C: PPF:: 73: 20: 6: 1	5	590	200	250	100	40
15	S : MD: C: PPF:: 78: 15: 6: 1	5	575	200	250	85	40
16	S : MSWIA: MD: C: PPF:: 61: 20: 15: 3: 1	5	575	200	250	85	40

Appendix 2

Flexible pavement thickness for various mixtures at various million standard axle

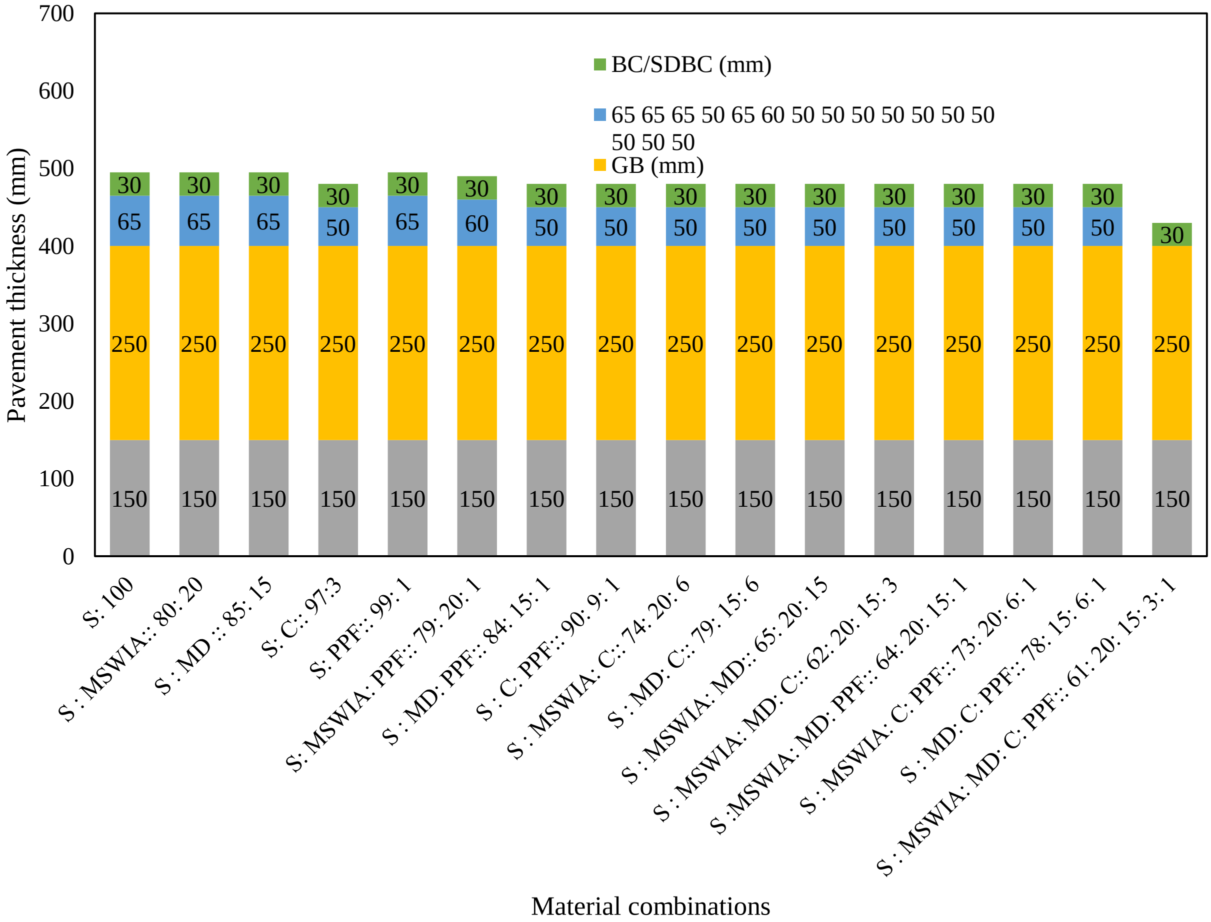


Figure 1: Thickness of flexible pavement for 5 msa

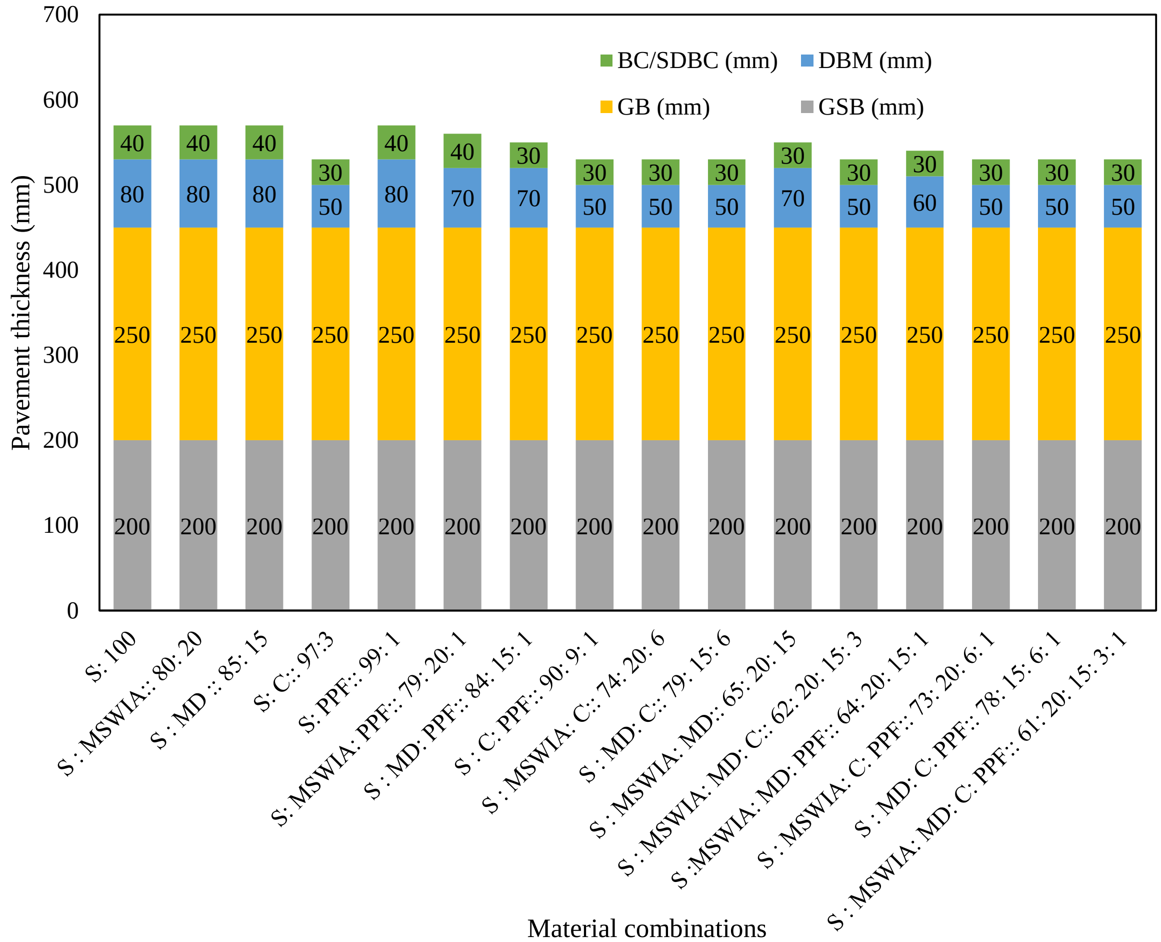


Figure 2: Thickness of flexible pavement for 10 msa

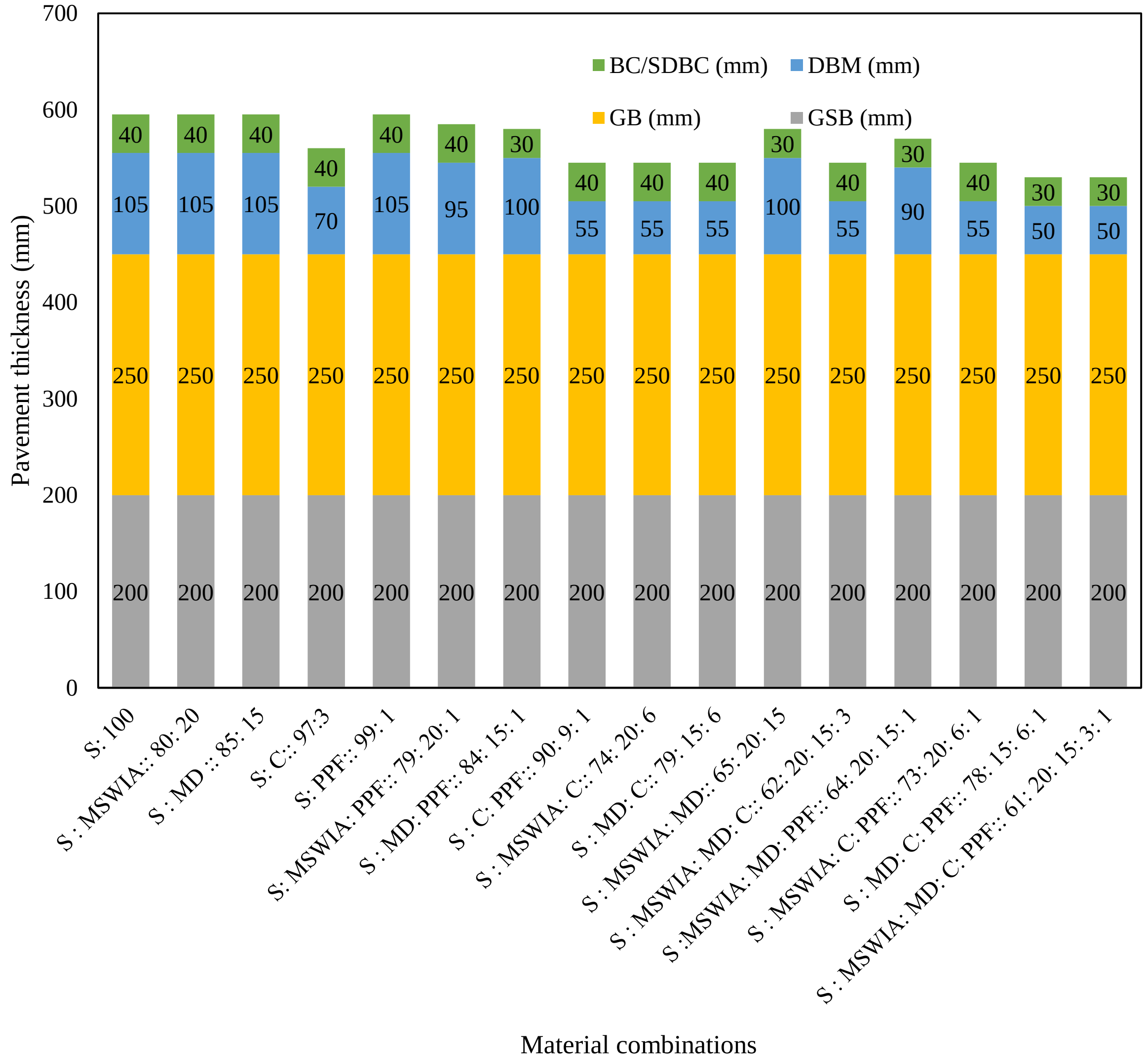


Figure 3: Thickness of flexible pavement for 20 msa

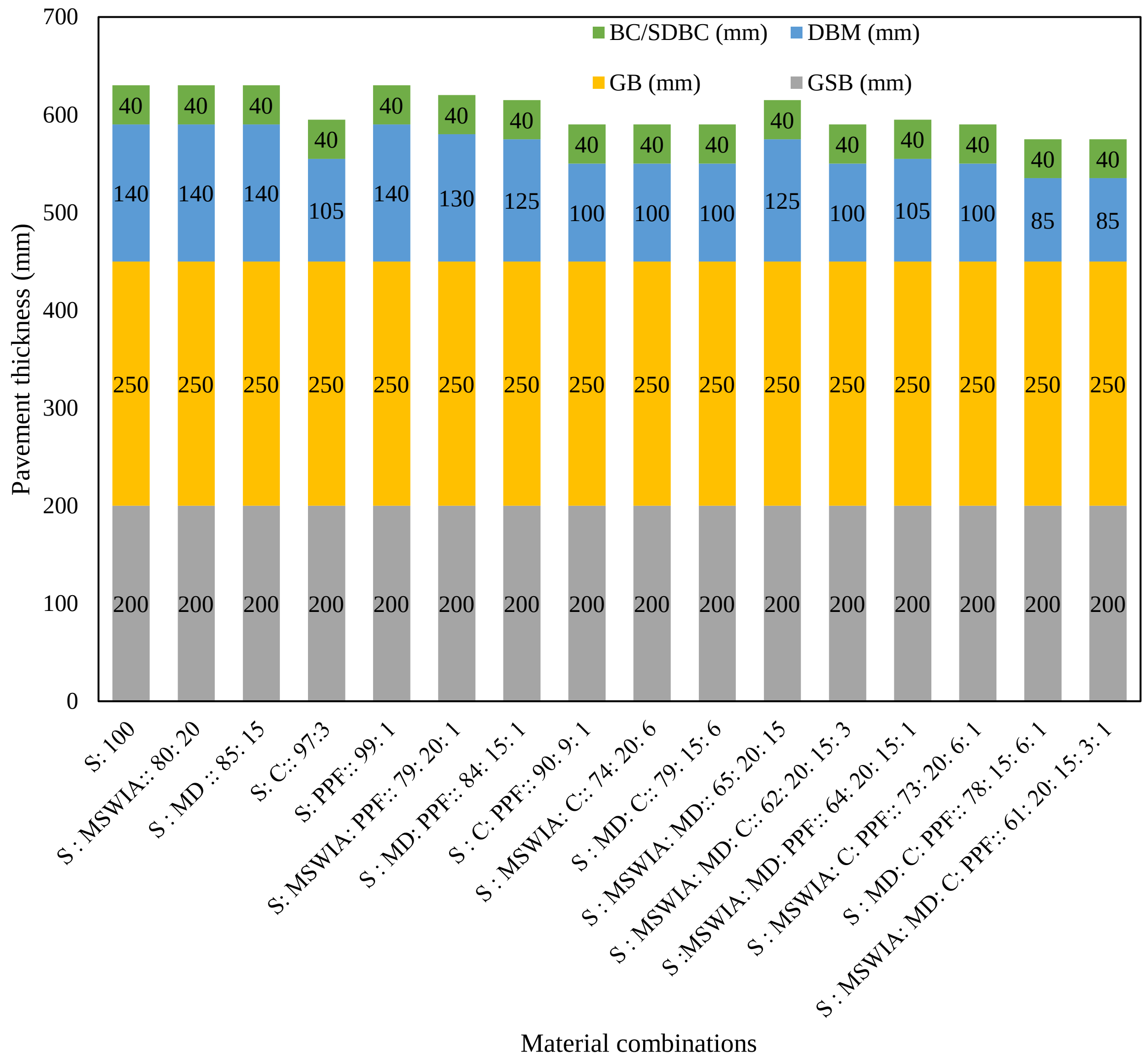


Figure 4: Thickness of flexible pavement for 50 msa