

Development of Empirical Correlations Between Geotechnical Properties and Improvement of Black Cotton Soil in Kolhapur City

A THESIS SUBMITTED IN PARTIAL FULFILMENT FOR THE DEGREE

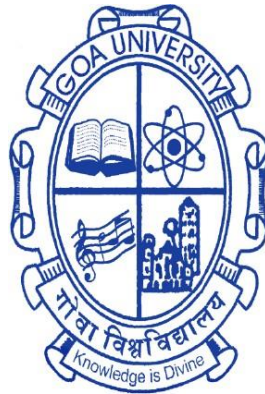
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In The Name of the Faculty of Engineering

Goa University



By

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JANUARY 2025

DECLARATION

I, Guruprasad Ajay Chavan hereby declare that this thesis represents work that has been carried out by me and that it has not been submitted, either in part or full, to any other University or Institution for the award of any research degree.

Place: Farmagudi Goa.

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CERTIFICATE

I hereby certify that the above Declaration of the candidate, Guruprasad Ajay Chavan is true and the work was carried out under my supervision.

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Date: 11/08/2025

Place: Goa College of Engineering, Farmagudi

Guruprasad Ajay Chavan

Dedicated to
my parents and my family

THESIS APPROVAL SHEET

Thesis entitled: **Development of Empirical Correlations Between Geotechnical Properties and Improvement of Black Cotton Soil in Kolhapur City** by **Shri. Guruprasad Ajay Chavan** is approved for the degree of **DOCTOR OF PHILOSOPHY**.

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Contents

Contents	i
List of tables	v
List of figures	vii
List of abbreviations	ix
List of symbols	xi
Abstract	xii
Chapter 1	1
Introduction	
1.1. Background and introduction	1
1.2. Indian soils	3
1.3. Black cotton soil (BCS)	6
1.3.1. Characteristics of BCS	6
1.3.2. Problem associated with BCS	9
1.4. Information of study area (Kolhapur city)	11
1.5. Black cotton soil in Kolhapur	13
1.6. Objectives of the research	16
1.7. Structure of thesis	17
Chapter 2	19
Literature survey	
2.1. Introduction	19
2.2. Stabilization of black cotton soil	19
2.3. Chemical stabilization of soil	23
2.4. Empirical correlation between black cotton soil properties	26
2.5. Bioenzyme and biopolymer stabilization	30
2.6. Critical appraisal of literature	31
2.7. Gap analysis	33
Chapter 3	35
Characterization of black cotton soil in Kolhapur region	
3.1. General	35
3.2. Methodology	35
3.2.1. Sample collection	36
3.2.2. Sampling locations around or at the boundaries of the city	37
3.2.3. Sampling locations in city	38

3.2.4. Test pit 1 (2.5m), Ramnagar, Kolhapur	39
3.2.5. Borehole- 1 (3.5m), Line Bazar, Kolhapur	39
3.2.6. Borehole- 2 (4.0m), near Rankala, Phulewadiroad,Kolhapur	40
3.3. Methods of sample collection	41
3.4. Test conducted as per standard codes	42
3.5. Hypothesis testing frameworks	42
3.6. Test result	43
3.7. Grain size distribution analysis of BCS	50
3.7.1. Hydrometer analysis	50
3.8. Consistency and classification of soil samples collected from study area	52
3.8.1. Plasticity chart for soil samples collected from 1.5 m depth	53
3.8.2. Plasticity chart for soil samples collected from 1.5 m depth	54
3.9. Field Emission Scanning Electron Microscopy (FESEM) analysis	55
3.10. X-ray diffraction (XRD) analysis	57
3.11. Energy-dispersive X-ray spectroscopy (EDX) analysis	60
3.12. Summary	62
Chapter 4	64
Engineering Behaviour and Empirical Co-relationship	64
4.1. Introduction	64
4.2. Variation of maximum dry unit weight and optimum moisture content	65
4.3. Variation of consistency limits, plasticity and free swell index	66
4.4. Variation of strength properties and CBR value	69
4.5. Empirical correlation of black cotton soil	72
4.6. Correlations between different soil properties with consideration of variation with depth	73
4.6.1. Liquid limit (LL) with California bearing ratio (CBR)	73
4.6.2. Maximum dry density (MDD) with California bearing ratio (CBR)	74
4.6.3. Plasticity index (PI) with unconfined compressive strength (UCS)	75
4.6.4. Free swellindex (FSI) with activity of black cotton soil (A)	76
4.6.5. Specific gravity (G) with plastic limit (PL)	77
4.7. Validation and Summary	78
Chapter 5	80
Stabilization of Black Cotton Soil	80
5.1. Introduction	80

5.2. Methods for soil improvement	81
5.3. Terrazyme as an admixture	82
5.3.1. Mechanism of soil stabilization by Terrazymbioenzyme	83
5.4. Experimental programme for Terrazyme	83
5.4.1. Specific gravity with Terrazyme	86
5.4.2. Consistency limits of black cotton soil with Terrazyme	87
5.4.3. Maximum dry unit weight and optimum moisture content of black cotton soil with Terrazyme	89
5.4.4. California bearing ratio value of black cotton soilwith Terrazyme	91
5.4.5. Unconfined compression strength of black cotton soil with Terrazyme	92
5.5. Xanthan gum as additive	93
5.5.1. Mechanism of soil stabilization for Xanthan gum	94
5.5.2. Maximum dry unit weight and optimum moisture content of black cotton soil with Xanthan gum	95
5.5.3. California bearing ratio value of black cotton soil with Xanthan gum	97
5.5.4. Unconfined compression strength of black cotton soil with Xanthan gum	98
5.6. Practical limitations of Bio-stabilization and cost analysis	99
5.6.1. Material Variability	99
5.6.2. Shelf-Life and storage conditions	100
5.6.3. Cost-benefit analysis	100
5.6.4. long-term effects and environmental implications	102
5.7. Summary	102
Chapter 6	104
Conclusion	
6.1. Conclusion	104
6.2. Contribution from the present research work	107
6.3. Scope of future work	107
References	109
Publications	121

List of Tables

Table 1.1 Characteristics of BCS	7
Table 1.2 Characteristics and chemical analysis of Indian black cotton soil	8
Table 3.1 Sampling locations in study area	37
Table 3.2 Sampling locations at boundary	37
Table 3.3 Sampling locations in city	39
Table 3.4 Test conducted and the relevant standard	42
Table 3.5 Test results of soil collected at boundary of the city	44
Table 3.6 Test results of soil collected in Kolhapur city	45
Table 3.7 Test results of soil collected from Test pit- 01	46
Table 3.8 Test results of soil collected from borehole- 01	47
Table 3.9 Test results of soil collected from borehole- 02	48
Table 3.10 Consolidation parameters	49
Table 3.11 Particle size distribution at sampling points	50
Table 3.12 XRD analysis- mineral compositions of BCS	59
Table 3.13 EDX results on soil samples collected in Ramnagar	62
Table 3.14 Characteristics of black cotton soil in study area	62
Table 4.1 Correlation of liquid limit (LL) with California bearing ratio (CBR)	74
Table 4.2 Correlation of maximum dry density (MDD) with California bearing ratio (CBR)	75
Table 4.3 Plasticity index (PI) with unconfined compressive strength (UCS)	76
Table 4.4 Free swell index (FSI) with activity (A) of black cotton soil	77
Table 4.5 Specific gravity (G) with plastic limit (PL)	78
Table 4.6 Validation of results obtained with published research	79
Table 5.1 Characteristics of Terrazyme	84
Table 5.2 Effect of Terrazyme on specific gravity	86
Table 5.3 Effect of Terrazyme on consistency of black cotton soil	87
Table 5.4 Effect of Terrazyme on maximum dry unit weight	89

Table 5.5 Effect of Terrazyme on CBR value	91
Table 5.6 Effect of Terrazyme on CBR value on curing	91
Table 5.7 Effect of Terrazyme on unconfined compression strength on curing	92
Table 5.8 Effect of Xanthan gum on maximum dry unit weight and optimum moisture content	96
Table 5.9 Effect of Xanthan gum on California bearing ratio value	97
Table 5.10 Effect of Xanthan gum on unconfined compression strength	98
Table 5.11 Cost-benefit analysis and detail comparison with conventional stabilizers	100

List of Figures

Figure 1.1 Proportion of expansive soils in some countries	2
Figure 1.2 Location map of study area on Indian boundary	12
Figure 1.3 Location map of study area on Maharashtra state boundary	12
Figure 1.4 Soil distributions in Kolhapur district	15
Figure 1.5 Distribution of black cotton soil in city	16
Figure 3.1 Sampling locations in study area	38
Figure 3.2 Test pit 1 (2.5m), Ramnagar, Kolhapur	40
Figure 3.3 Borehole 1 (3.5m), Line Bazar, Kolhapur	40
Figure 3.4 Borehole- 2 (4.0m), Phulewadi road, Kolhapur	41
Figure 3.5 Grain size distribution of soil collected from Line Bazar at 1.5m	51
Figure 3.6 Grain size distribution of soil collected from Line Bazar at 3.5m	51
Figure 3.7 Grain size distribution of soil collected from Rankala at 2.0 m	52
Figure 3.8 Grain size distribution of soil collected from Rankala at 4.0 m	52
Figure 3.9 Plasticity chart for samples from 1.5m depth	53
Figure 3.10 Plasticity chart for samples from different depths	54
Figure 3.11 FESEM image (Scale = 5 μ m) (Rankala-3.5m)	55
Figure 3.12 FESEM image (Scale = 2 μ m) (Rankala-3.5m)	56
Figure 3.13 FESEM image (Scale = 1 μ m) (Rankala-3.5m)	56
Figure 3.14 FESEM image (Scale = 500nm) (Rankala-3.5m)	57
Figure 3.15 XRD plot- intensity vs 2θ (Line Bazar-1.5m)	59
Figure 3.16 EDX plot (Rankala-1.5m)	61
Figure 3.17 EDX plot (Rankala-3.5m)	61
Figure 4.1 Variation of maximum dry unit weight	65
Figure 4.2 Variation of optimum moisture content with depth	66
Figure 4.3 Variation of liquid limit with depth	67
Figure 4.4 Variation of plastic limit with depth	67
Figure 4.5 Variation of shrinkage limit with depth	68
Figure 4.6 Variation of plasticity index with depth	68
Figure 4.7 Variation of free swell index with depth	69
Figure 4.8 Variation of cohesion with depth	70
Figure 4.9 Variation of friction angle with depth	70
Figure 4.10 Variation of California bearing ratio value with depth	71
Figure 4.11 Variation of unconfined compressive strength with depth	71

Figure 4.12 LL Vs CBR	74
Figure 4.13 MDD Vs CBR	75
Figure 4.14 PI Vs UCS	76
Figure 4.15 Activity Vs FSI	77
Figure 4.16 G Vs PL	78
Figure 5.1 Appearance of Terrazyme	84
Figure 5.2 Specific gravity with Terrazyme	87
Figure 5.3 Consistency of BC soil with Terrazyme	88
Figure 5.4 Plasticity index soil with Terrazyme	89
Figure 5.5 Maximum dry unit weight with Terrazyme	90
Figure 5.6 Optimum moisture content with Terrazyme	90
Figure 5.7 California bearing ratio value with Terrazyme	92
Figure 5.8 Unconfined compression strength with Terrazyme	93
Figure 5.9 Xanthan gum	95
Figure 5.10 Maximum dry unit weight with Xanthan gum	96
Figure 5.11 Optimum moisture content with Xanthan gum	97
Figure 5.12 California bearing ratio value with Xanthan gum	98
Figure 5.13 Unconfined compression strength with Xanthan gum	99

List of Abbreviations

AI	Artificial Intelligence
ANN	Artificial Neural Network
ANOVA	Analysis of Variance
ANFIS	Neuro-Fuzzy Inference System
BA	Bagasse Ash
BCS	Black Cotton Soil
CAH	Calcium Aluminate Hydrates
CSH	Calcium Silicate Hydrates
CBR	California Bearing Ratio
CS	Carbide Slag
CKD	Cement Kiln Dust
CH	Clay of High Plasticity
CI	Clay of Intermediate Plasticity
CNS	Cohesive Non-Swelling Soils
CPT	Cone Penetration Test
DT	Decision Trees
DCPT	Dynamic Cone Penetrometer Test
EDX	Energy-Dispersive X-Ray Spectroscopy
FC	Fibre Cast
FESEM	Field Emission Scanning Electron Microscopy
FSI	Free Swell Index
GGBS	Ground Granulated Blast Furnace Slag
GL	Ground Level
GPS	Global Positioning System
GSA	Groundnut Shell Ash
IOT	Iron Ore Tailings
KMC	Kolhapur Municipal Corporation
MDD	Maximum Dry Density
MIP	Mercury Intrusion Porosimetry
MP	Modified Proctor
MLRA	Multiple Linear Regression Analysis
MLP	Multi-Layer Perceptron
OMC	Optimum Moisture Content

OPC	Portland Cement
PC	Portland Cement
PMT	Pressure Meter Test
RCD	Recycled Concrete Dust
RF	Random Forests
RMP	Reduced Modified Proctor
RSP	Reduced Standard Proctor
RHA	Rice Husk Ash
SEM	Scanning Electron Microscopy
MH	Silt of High Plasticity
SHAP	Shapley Additive exPlanations
SLRA	Simple Linear Regression Analysis
SBC	Soil Bearing Capacity
SWCC	Soil-Water Characteristic Curves
SPT	Standard Penetration Test
SP	Standard Proctor
SS	Steel Slag
SVM	Support Vector Machines
XGBoost	eXtreme Gradient Boosting

List of Symbols

ϕ	Angle of Internal Friction
θ	Braggs Angle
c	Cohesion
C_c	Compression Index
R^2	Correlation Coefficient
D	Crystallite Size
ρ_d	Dry Density
ρ	Field Bulk Density
w	Field Moisture Content
LL	Liquid Limit
nm	Nano Meter
PI	Plasticity Index
Cr	Recompression Index
SL	Shrinkage Limit
λ	Wavelength of X-Ray

ABSTRACT

Soil is a crucial natural building material, containing soil solids, water, air, and organisms. It serves as a foundation for civil engineering structures, ensuring their strength and stability. Understanding soil properties is essential for confirming sustainability and safety in construction projects. Black cotton soil (BCS), a type of expansive clay with undesirable properties, are crucial in the construction industry. These soils, mainly located in India's Deccan Trap region, have low levels of nitrogen, phosphoric acid, and organic matter, while being high in calcium, potash, and magnesium. They contain various minerals and silicates, causing swelling and shrinkage. Engineers face challenges in these soils due to temperature and moisture variations, poor drainage capabilities, high plasticity and low load-bearing capacity, leading to settlements, swelling, and shrinkage. Urbanization raises land values, pushing every piece of land to be used for construction. This issue becomes more acute in emerging countries such as India, where urbanisation has led to economic growth. Construction activities are increasing rapidly, and soil conditions can be poor even at deeper depths. These soils can be commonly found in regions such as Andhra Pradesh, Western Madhya Pradesh, Gujarat, Maharashtra, Northern Karnataka, Tamil Nadu, and certain areas of Southern Uttar Pradesh. This study characterizes BCS collected from different depths in Kolhapur, Maharashtra, India. Samples of black cotton soil were collected from twenty-eight locations from Kolhapur city. Different properties of soil were determined, and results obtained from field as well as laboratory tests were analyzed. Variation of different soil properties with depth of investigation was explored. This research also seeks to establish empirical relationships between various properties of BCS to forecast its consistency, plasticity, swelling potential, California Bearing Ratio (CBR), and unconfined compression strength (UCS). Statistical models were developed and assessed by using CurveExpert Version 1.4. This will be helpful for civil engineers and contractors as quick guide especially when unmarked area is to be utilized for development in study area and for the soil with similar properties. Several attempts were made to enhance the performance characteristics of BCS by traditional stabilizers, various fibres, agricultural by-products, industrial by-products, chemical

stabilizers, natural adhesives etc. The current work proposes the use of biopolymer, Xanthan gum and bio-enzyme, Terrazyme to enhance the BCS collected in Kolhapur, Maharashtra, India. Both compounds were found to increase the properties of BCS such as plasticity, California bearing ratio, and unconfined compression strength. This impact is particularly apparent after curing.

Keywords: Black cotton soil, characterization, correlations, improvement, variation, stabilization.

Chapter 1

Introduction

1.1 Background and introduction

Soil is a fundamental component of ecosystems, providing key services such as manufacturing of food, fibre for paper and clothing. Furthermore, fuel for electricity generation, and foundations for roadways and structures. It also acts as a removal mechanism for pollutants, replenishes groundwater, circulates nutrients, and serves as a dwelling for living things and organisms. Soils are also used as components in confectionaries, pesticides, colours, pigments, cosmetics, and medications. Soil productivity shapes the ecosystem's appearance, influencing the distribution of species, timber productivity, ecosystem habitat diversity, and variety. Soil quality in farmed fields influences agricultural yield and lowers runoff in metropolitan areas. However, soil quality is frequently disregarded until it degrades, diminishing the important functions it formerly offered (Schoonover & Crim, 2015). Researchers also study soil composition to determine its suitability for different land uses, such as determining if it can support healthy ecosystems or if it is contaminated and requires remediation. Soil is a crucial component in numerous disciplines, and gaining insight into its characteristics is vital for promoting sustainable development and implementing effective land management strategies. India's soils lack organic matter, humus, mineral salts, and nitrogen somewhat noticeably. Alluvial and black soils which are found in many states are among the most productive, while laterite, alkaline and desert soils are among the least productive (Chandrakala et al., 2021). Alluvial and black soils support growth in plains and valleys, while less fertile laterite, desert, and alkaline soils require irrigation and fertilizer. Historically, Indian black soil, sometimes referred to as black cotton soil, had been utilized for cultivation. Land constraints and growing urbanization have recently led to the adaptation of this soil for development purposes. Classified as an expansive clayey soil, Black Cotton Soil (BCS) exhibits varying behavior depending on its mineral composition. Buildings constructed on black cotton soil may experience cracks and other damage due to the higher clay content in the soil. This causes such soils to shrink and swell in response to variations in the amount of moisture present. Soil stabilization and adequate drainage systems are two of the many

methods used for dealing with this during construction. Despite its challenges, the use of black cotton soil for construction has proven to be cost-effective and sustainable in many areas of India. Expansive soils are globally distributed, as seen in figure 1.1, which represents the percentage of total land area occupied by these soils in various nations.

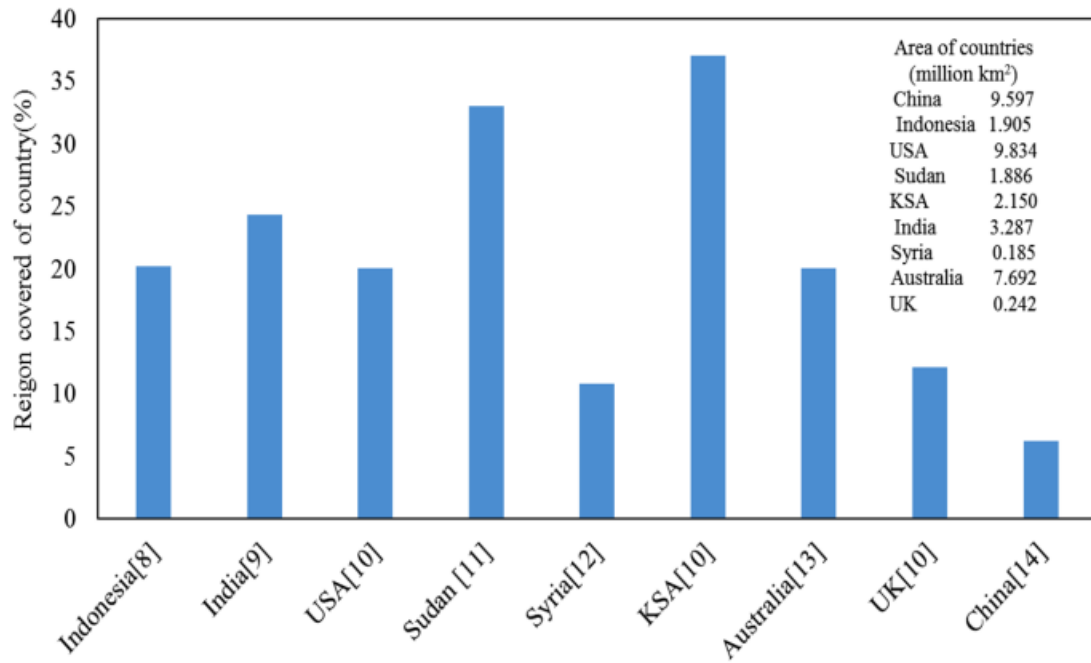


Figure 1.1: Proportion of expansive soils in some countries (Pashabavandpouri et al., 2023).

Expansive soil denotes soils that tend to swell as their moisture content increases. The presence of these features is frequently seen in soils that include the clay mineral montmorillonite. The expanding properties of Indian BCSs have earned them a well-deserved national reputation. This description is based on the fact that they are generally black in color and that they are used for growing an abundance of cotton. These soils are primarily found in Maharashtra and Gujarat, along with certain regions in Southern Uttar Pradesh, Eastern Rajasthan, Southern and Western Madhya Pradesh, a segment of Eastern Rajasthan, and a small part of Andhra Pradesh and Chennai, totaling over 0.8×10^6 sq. km, covering almost 25% area in the nation (Kumar et al., 2007). These black cotton soils are highly fertile and support the growth of various crops, making them agriculturally significant. However, their expanding nature poses challenges for construction activities in these regions. The high clay content in these soils causes them to swell during the monsoon season, leading to the cracking and shifting of structures built on them. Despite

these challenges, farmers have learnt to adapt to these soil characteristics and employ techniques such as contour ploughing and the use of natural materials to mitigate soil expansion effects.

The world is facing the environment degradation due to increase in urbanization. Every part of land which is not suitable for construction has to be used for construction. In India, urbanization is associated with economic development, which significantly enhances the national economy. Construction works are taking place at a very higher rate and every part of land is being brought under construction. Sometimes, soils are very weak even at greater depths. Every house has a foundation, and every foundation must be constructed efficiently, safely for longevity. Soils have different properties that influence foundation behaviour. The black cotton soil is a type of expansive soil with high plasticity and can retain moisture throughout the dry season hence, valuable for growing crops but it is one of the problematic soils for construction.

1.2 Indian soils

Indian soils are classified according to a number of criteria, including terrain, parent material, vegetation, and climate. According to system soils are classified as alluvial, black, red, laterite, and mountainous soils. Understanding the characteristics and applicability of various soil types for agriculture and other uses is made easier by these categories. Following are the details of each type:

1) Alluvial soils: formed from silt deposited by Indo-Gangetic-Brahmaputra rivers, are the largest soil group, covering 75 MHa and supporting over 40% of India's population. They exhibit high fertility, including humus, lime, and organic materials. They are located in the northern, northwestern, and northeastern regions of India, including Punjab, Haryana, Uttar Pradesh, Delhi, Madhya Pradesh, Assam, Bihar, West Bengal, and the coastal areas of Orissa, Gujarat, Tamil Nadu, and Kerala. The soil is permeable, facilitating effective drainage and suitable conditions for cultivation. They produce goods from agriculture like rice, wheat, sugarcane, tobacco, cotton, jute, maize, groundnut, potato, berseem, sunflower, oilseeds, vegetables, and fruits.

2) Black Soils: Black soil, referred to as Regur in central India, Karail in the lower Gangetic valley of Uttar Pradesh, Bhall in Gujarat, and Tal in Bihar, is a soil type characteristic of the arid and warm areas of the peninsula. It is abundant in calcium

carbonate, potash, lime, and magnesium carbonate, although deficient in phosphorus content. This soil is characterized by its clay composition, which enables it to retain significant moisture, becoming adhesive during the rainy season and forming cracks when desiccated. It is dispersed throughout 72 million hectares across the various states of India, such as Maharashtra, Madhya Pradesh, Gujarat, portions of Andhra Pradesh, Karnataka, and Tamil Nadu. A typical black soil is mostly argillaceous, including 30 to 80 percent clay. Soils formed on calcareous clay include CaCO_3 with a pH above 7.8 and reaching up to 9.4. The dark coloration results from clay-humus complexes, titaniferous magnetite minerals, and organic material. The limitations of these soils include their high reactivity to variations in moisture content, low infiltration rates, inadequate drainage and moisture stress, and deficient levels of organic carbon, nitrogen, sulphur, and phosphorus. Many states, including Maharashtra, mostly cultivate cotton, millet, sorghum, soybeans, and pigeon peas on black soils due to their intrinsic fertility (Chandrakala et al., 2021).

3) Red Soils: The formation of these soils results from the weathering processes acting on metamorphic and igneous rocks, covering an area of 70 million hectares. Their potassium content is abundant; however, they are deficient in phosphate, manganese, humus, and nitrogen levels. The color of red soils arises from the presence of ferric oxide and typically exhibits a pH range of 6.0 to 7.5. Their distribution spans across Tamil Nadu, Madhya Pradesh, Jharkhand, Odisha, Karnataka, South-East Maharashtra, Andhra Pradesh, Goa, and the Union territories of Pondicherry, Dadra Nagar Haveli, Daman, and Diu. Red soils, categorized as red loam and red earth, have limitations like surface crusting, low water content, soil erosion, excessive drainage, and compacted subsurface layers. They are deficient in nitrogen, phosphorus, calcium, zinc, and sulphur, and have low cation exchange capacity. They are used for plantation crops like millets, ragi, and mango.

4) Laterite soils: Under alternating wet and dry seasons, lateritic soils occur in tropical and subtropical environments. They possess high concentrations of iron and aluminium, however are deficient in nitrogen, lime, potash, and humus; they exhibit a mushy consistency when saturated and a hardened state when dry. Farmers primarily cultivate them for rice, coconut, tea, coffee, cashew nuts, ragi, sugarcane, and rubber. Laterites have gibbsite and kaolinite clay minerals. They scatter across the hilltops and plateaus of Maharashtra, Goa, Orissa, Tamil Nadu, Andhra Pradesh, Assam, Kerala, and Karnataka.

5) Salt-Affected soils: These soils occur in arid and sub-humid regions of India, impacting an area of 10 million hectares. These soils release minerals such as magnesium

and calcium salts, sodium carbonate, sulphate and chloride as a result of weathering processes. Some of these minerals are carried by rivers and mixed with subsoils, making the soils saline and alkaline. These soils are found in Uttar Pradesh, Punjab, Gujarat, Rajasthan, Maharashtra, and Karnataka. India's soil is divided into two categories, such as saline and alkali. Saline-alkali soils are similar to saline soils but with a higher pH. Excess sodium can reduce productivity, alter soil structure, and affect water and nutrient availability. Proper drainage is required for these soils (Bhumbla and Abrol, 1979 and Abrol et al., 1980).

6) Desert / arid soil: Desert soil, located in hot dry areas of Western Rajasthan, South-West Punjab and Southern Haryana, is mostly formed by aeolian processes and has elevated salinity levels. It has a sandy texture with 90–95% sand and 5–10% clay content. The soil exhibits a yellowish-brown to light-brown hue, with a pH range between 7.2 and 9.2. It contains elevated salt levels that remain non-toxic. One can cultivate grassland, pasture, pomegranate, pearl millet, jujube and pulses on desert soil. Biomass accumulates in the rainy season, supplying dried sustenance to animals during the drought period.

7) Forest and hill soils: There are 75 million hectares of forest in India, covering regions including Uttar Pradesh, Arunachal Pradesh, Himachal Pradesh, Nagaland, Assam, Jammu and Kashmir, Meghalaya, Madhya Pradesh, Mizoram, Manipur, Odisha, Kerala, Maharashtra, and the Andaman and Nicobar Islands. Two types of soil formation exist in forest areas, i.e., acidic soils i.e. podzols and slightly acidic or neutral soils which is also referred as brown forest soil. Podzols located in Dalhousi, Shimla, and Manali do not qualify as true podzols. They exhibit a pH range of 4.5 to 6.0, possess high biotic matter content, and moderately high levels of clay.

8) Peaty or marshy soils: In Kerala and the Northeast, locations with high humidity and frequent rainfall gave rise to peaty soils. In Kerala, these soluble salt-containing soils are referred as Kari. It is Black-colored, fine textured, heavy soil with 20 to 40% organic content. Strongly acidic soils with a pH of 4.0 are produced when these soils are drained, oxidizing the pyrites (FeS_2) and forming sulphuric acid. In Southeast Asia, these soils are referred to as Cat-clay or Acid Sulphate soils. Moist soils may be found in a number of States, including Bihar, Sundarbans in West Bengal, Tamil Nadu, Uttaranchal, and other states that are located in coastal regions. Marshy soils mature in hypoxic saturated conditions, producing blue or greyish soils, in depressions caused by dried lakes in floodplains and coastal plain environments (Chandrakala et al., 2021).

1.3 Black cotton soil (BCS)

Black cotton soils are observed in Deccan Trap in Indian. They are of variable thickness, underlain by black sticky material known as “black soil”. These soils are predominant in States of Andhra Pradesh, Western Madhya Pradesh, Gujarat, Maharashtra, Northern Karnataka, Tamil Nadu and some parts of Southern Uttar Pradesh. These are clayey soils and form deep cracks during dry season. They are suitable for growing cotton. The colour of these soils is black due to the presence of iron and aluminium but is deficient in nitrogen, phosphoric acid, and organic matter but rich in calcium, potash, and magnesium. When BCS comes into contact with the water, it goes through a process of expansion or contraction, which results in the formation of internal stress or moments inside a structure. These moments remain disconnected from the normal forces generated by the loads on the structure. In general, this soil is not ideal for construction because of its propensity to experience significant volumetric changes. The soil exhibits substantial expansion and contraction due to the influence of fine clay particles within it. Recurrent swelling and shrinking in structures primarily cause differential settling. This necessitates treating black cotton soil with appropriate admixtures or stabilizing chemicals to enhance its stability for construction purposes. It has very low permeability, low bearing capacity, and significant volume fluctuations attributable to the presence of montmorillonite within its mineralogical composition. Due to its significant volumetric changes, it is unsuitable for embankments construction and other structures also. The design of flexible pavement over this kind of soil necessitates the creation of an unusually thick pavement layer, which leads to increased expenses and a diminished economic viability. They occur all over the world, and in India, large surface deposits are covered by BCS (Mishra, 2015).

1.3.1 Characteristics of BCS

This soil typically exhibits a colour ranging from reddish-brown to black. The depths of these formations vary, reaching anywhere from 0.50 m to 10 m beneath the surface, and they are characterized by significant compressibility. Table 1.1 describes the common properties of BCS.

Table 1.1: Characteristics of BCS (Nayak, 2015).

Sr. No.	Characteristic	Normal Range of Value
1	Grain size distribution	
	Gravel	0 to 10%
	Sand	15 to 25%
	Silt	15 to 30%
	Clay	25 to 70%
2	Consistency limits	
	Liquid limit	50 to 120%
	Plastic limit	30 to 60%
	Plasticity index	30 to 60%
	Shrinkage limit	8 to 18%
3	Soil classification	CI or CH or MH
4	Specific gravity	2.60 – 2.75
5	pH value	8 to 10
6	Organic content	0.4 – 2.4%
7	Differential free swell (DFS)	40 - 180%
8	Swelling pressure	50- 800 kN/m ²

The chemical composition of BCS is also important and needs to be studied. The behaviour of BCS or any soil depends upon its mineralogy, chemical composition, and structure. By analyzing the minerals present and studying its chemical makeup, researchers can gain insights into its stability, shrinkage, and swelling characteristics. Additionally, the chemical composition can provide valuable information about the soil's fertility and suitability for agricultural purposes. Therefore, a comprehensive study of its chemical composition is crucial for various engineering and agricultural applications. Generalized characteristics and chemical analysis of Indian black cotton soils as tabulated in Table 1.2(Raychaudhuri et al., 1963).

**Table 1.2: Characteristics and chemical analysis of Indian black cotton soil
(Raychaudhuri et al., 1963).**

Sr. No.	Properties	Range of values
1	Clay and silt fraction	70-80%
2	Coarse sand	4-8%
3	pH	7.2-8.5%
4	Total solids	0.05-1.5%
5	Salt concentration depth	5-7 ft.
6	Acid soluble	1-10%
7	Cation exchange capacity (CEC)	40 to 60 meq /100 g
8	Exchange calcium	15-42%
9	Exchange magnesium	6-20%
10	Exchange K ₂ O	0.1-0.6%
11	Exchange sodium	3-13%
12	Iron oxide (Fe ₂ O ₃)	9-13%
13	Aluminum oxide (Al ₂ O ₃)	16-23%
14	Calcium oxide (CaO)	2.5-7%
15	Magnesium oxide (MgO)	3-4%
16	Silicon dioxide (SiO ₂)	50-55%

Black clays, tropical black earth, or black cotton are expansive, heavy loam or clay soils with smectite-rich clay minerals, alkali earth elements, and occasionally calcium carbonate or magnesium oxide concretions (Gidigas and Gawu, 2013). The soil contains a variety of clay minerals, including montmorillonite, illite, and kaolinite. It is also composed of chemical substances like iron oxide and calcium carbonate, which frequently form kankar nodules, along with organic components such as humus. Among these, montmorillonite is the predominant mineral present in BCS. These minerals, which are water-containing silicates of magnesium and aluminum, mostly explain the behavior of this soil, marked by its propensity to expand and contract. The structure consists of alternating layers of silica in a tetrahedral configuration and alumina in an octahedral structure, stacked in a repeating

sequence. Montmorillonite contains three layers including expandable lattices. Because of the isomorphic substitution of certain aluminum ions with magnesium ions, the structure has a negative charge, and minerals become chemically active (Mishra, 2015). The minerals' chemical activity attracts and holds water molecules, causing the soil to swell. When the moisture content of the soil diminishes, the minerals lose their capacity to store water, causing the soil to shrink. If not correctly controlled, this behaviour of soil can have serious consequences for construction projects, resulting in uneven settling and structural damage.

1.3.2 Problem associated with BCS

This soil particularly in tropical countries like India, pose significant challenges to engineers due to its unique characteristics. These soils are highly compressible, causing significant consolidation settlements when saturated. Additionally, they can cause differential displacement during the wet season, causing structures supported by swollen soils to rise and collapse, leading to cracks (Mishra, 2015). Due to its considerable volumetric shift upon moisture absorption, black cotton soil presents major issues for geotechnical engineers during construction. Expansive soil deformations are more severe than elastic deformations, causing major damage to roads, canals, buildings, and lifelines. These soils also shrink and inflate, resulting in fissures up to 15 cm in width and 3 meters in depth. Electrical forces and ions in pore water alter the behaviour of clay minerals (Shukla, 2015). These challenges are most apparent in tropical nations such as India, where fluctuations in temperature and alternating parched and rainy seasons result in considerable differences in soil moisture levels (Patel & Solanki, 2019). As a result, while planning and constructing structures in these areas, engineers must carefully examine the behaviour of expansive soils. To counteract the impacts of soil expansion and contraction, special foundation procedures such as deep piling or soil stabilization measures may be necessary (Sharma et al., 2020). Regular monitoring and maintenance of structures built on expansive soils is also critical for recognizing and correcting possible problems before becoming major issues (Kumar & Reddy, 2018). Overall, engineers working in tropical nations must grasp the special properties of expansive soils to ensure the stability and lifespan of their projects.

Black cotton soil is considered critical for infrastructure and construction projects; hence, analysis and improvement of soil are necessary and also a requirement of the construction

field (Gupta & Verma, 2017). Many researchers have studied black cotton soil in the past and evaluated it with different stabilization techniques. Lime stabilization, cement stabilization, and chemical stabilization are examples of these techniques (Rao et al., 2016). Lime stabilization involves the incorporation of lime into soil to improve its properties, including increased strength and reduced plasticity (IS: 2720, Part 5, 1985). Cement stabilization, on the other hand, involves combining cement with soil to increase compressive strength while decreasing expansiveness (Pandey & Singh, 2019). Finally, chemical stabilization entails the application of different chemicals to change the qualities of the soil and make it appropriate for building (Das, 2015). These stabilizing procedures have been shown to be helpful in reducing the geotechnical issues caused by soil and assuring stable and durable structures erected on it (Mehta et al., 2021). Engineers globally have difficulties with black cotton soils stemming from fluctuations in temperature and moisture, especially in tropical nations such as India, which see significant seasonal changes (Rai & Joshi, 2020). The common problems in these soils are:

1. **Swelling and Shrinkage:** Black cotton soil exhibits considerable expansion upon moisture absorption and substantial contraction with desiccation. This seasonal displacement may result in cracks in structures, pavements, and foundations constructed on this soil (Sivapullaiah & Manju, 2012).
2. **Low Bearing Capacity:** The low bearing capacity of black cotton soil makes it unsuitable for supporting large buildings without further stabilization (Verma & Patel, 2018).
3. **High Compressibility:** Upon loading, black cotton soil undergoes substantial compression, resulting in uneven settling and consequently generating structural complications in buildings and roadways (Bera & Ghosh, 2017).
4. **Pavement Heaving:** The expansive characteristics of this soil may induce pavement heaving or uplift, leading to fissures and an irregular road surface, particularly during the wet season (Singh et al., 2015).
5. **Soil Erosion and Cracking:** In the arid season, black cotton soil loses its moisture, resulting in extensive, profound cracks. This cracking may weaken the soil structure, facilitating surface erosion during the wet season (Kumar & Yadav, 2016).

6. Foundation Instability: The displacement of black cotton soil can lead to instability in foundations built on it. This may result in uneven settlement, structural tilt, or potential foundation collapse (Rathod et al., 2014).
7. Difficult Excavation and Backfilling: Black cotton soil exhibits stickiness when saturated and considerable hardness when dry, which significantly affects excavation and backfilling operations in construction projects (Deshmukh & Patil, 2013).
8. Water Retention Issues: Poor drainage caused by low permeability can result in water accumulation and increased soil expansion, creating further difficulties for infrastructure (Jain & Bansal, 2020).

1.4 Information of study area (Kolhapur city)

Kolhapur is a city in the southwestern part of Maharashtra state in India. Its area is 7692 sq. km and total population is 35, 15,413. Kolhapur city is the headquarter of Kolhapur district, which is an ancient city, figure 1.2 shows location map of study area on Indian boundary. Location of city on Maharashtra State boundary is shown in figure 1.3. Kolhapur district has different types of soils at different locations. The physiography of the Kolhapur district divides it into three primary soil zones, such as the Western region, distinguished by heavy rainfall, mountainous terrain, and lateritic soils. The fertile central area is characterized by brownish, well-drained soils with a neutral pH. Unreliable rainfall and varying black soil depths characterize the arid Eastern zone, with deeper soils displaying a darker color and a higher percentage of clay.

"Dakshin Kashi" is a name attributed to the city of Kolhapur, situated along the Panchganga River. Kolhapur holds great significance in Indian mythology, being one of the revered Shaktipeeths, and is renowned as the abode of Goddess Mahalaxmi. Latitude and longitude of Kolhapur city are 16.7050°N and 74.2433°E. Its area is 66 sq. km and population are 7, 96,000. The temperature falls within a rather small range, which is between 10 °C to 35 °C; with average value of 28°C, wind at 13 km/h, 66% humidity. Kolhapur has an elevation of 569 meters (1867 ft).

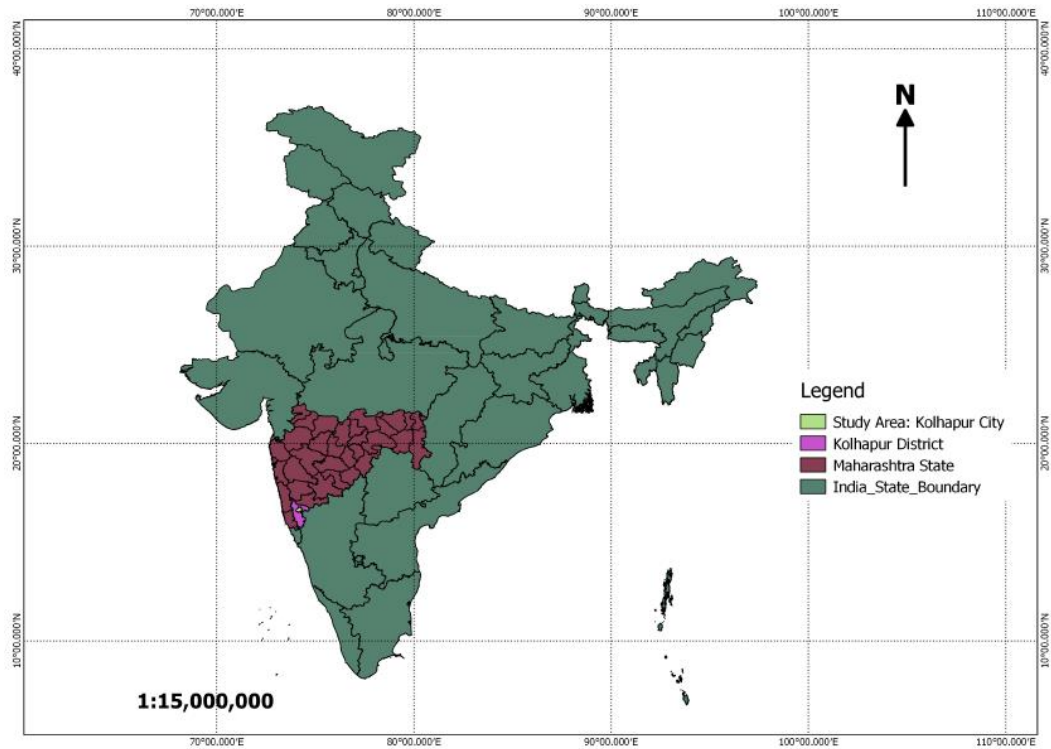


Figure 1.2: Location map of study area on Indian boundary (adapted from <https://www.diva-gis.org>).

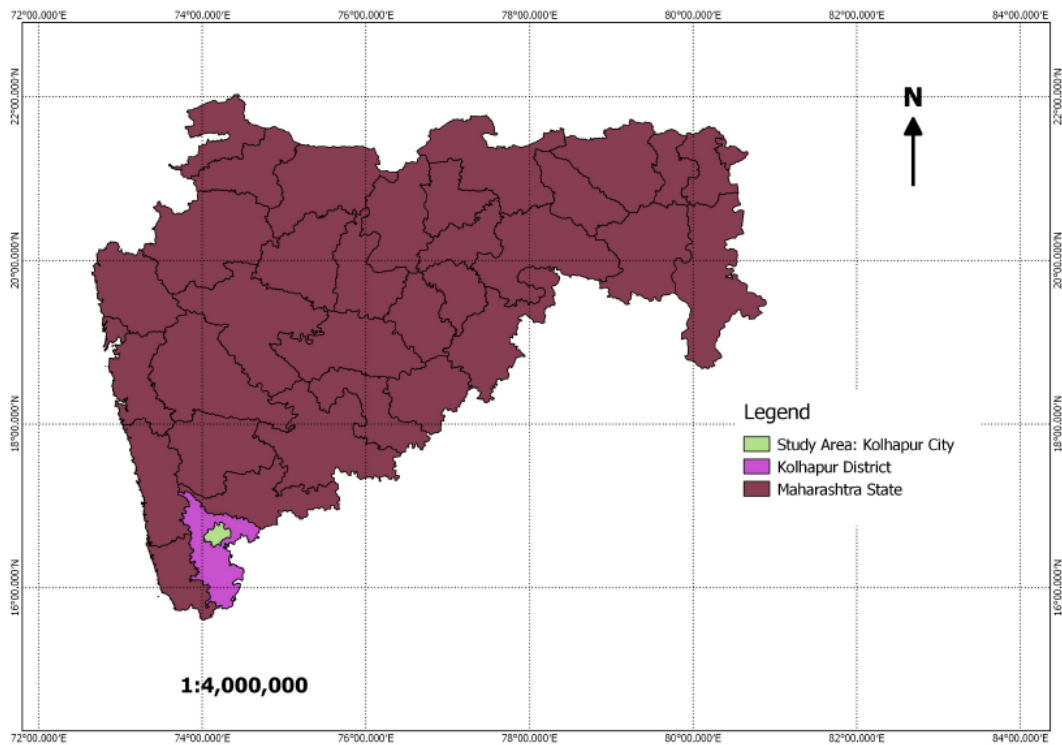


Figure 1.3: Location map of study area on Maharashtra state boundary (adapted from <https://www.diva-gis.org>).

The city experiences substantial precipitation from June to September because to its closeness to the Western Ghats. Intense precipitation often results in significant floods during this period. The years 2005, 2006, and 2019 had flooding events. Kolhapur is an important commercial and religious centre in western India. Known for its vibrant economy and rich cultural heritage, the city is home to numerous small businesses and hosts a variety of local events. The Kolhapur Municipal and Regional Development Authority aims to promote equitable development in Kolhapur city and its surrounding villages. KMC encounters challenges related to the expansion of Kolhapur city's civic limits, which have remained unchanged since 1972. Consequently, the city is unable to access the benefits of various government schemes.

1.5 Black cotton soil in Kolhapur

Kolhapur city is largely covered by BCS in several key areas, including those slated for future urban expansion. This type of soil presents significant challenges for construction and the development of infrastructure due to its specific properties. This type of soil is highly expansive and prone to shrinkage, making it difficult to build stable foundations. Additionally, the expansion plans for the city need to consider appropriate measures to address the issues associated with this soil type. Figure 1.4 shows distribution of soil in Kolhapur district.

Various regions of BCS were identified based on reconnaissance survey and extensive soil sampling. Initially, based on soil sampling, regions of BCS were identified in the city boundaries and soil distribution map was developed (Chavan and Savoikar, 2023) as shown in figure 1.5. When compared to interior regions, the region along to the Panchganga river has very deep black expansive soil that extends to a substantial depth below ground level.

This study aims to develop empirical correlation of black cotton soil properties by taking the number of samples from the different zones of Kolhapur; identification and classification of the soil in Kolhapur city is also important. Various empirical correlations were available to analyze the properties of soil. Past empirical correlation for different properties of soil with strength properties were developed by the researchers for different places cannot be applied directly for Kolhapur city without characterization of the soil. Various test required critical sample extraction and longer time durations. Civil engineer needs various test results to construct foundation, sub-grade on such soil. Hence, development of empirical correlations through statistical analysis, of all index properties

especially grain size, specific gravity, consistency limits, field density, maximum dry density (MDD) and optimum moisture content (OMC), swelling index, unconfined compressive strength (UCS), California bearing ratio value (CBR), cohesion (c) and angle of internal friction (ϕ), etc. is beneficial. This statistical study seeks to identify the most appropriate correlations for black cotton soil. Research institutes and working professionals will utilize the findings to promptly provide solutions for this field. The findings will also apply to soils with similar characteristics, provided there is no significant alteration in the geological composition of the strata. This study also aims, to identify, develop new material or method to enhance geotechnical properties, especially strength properties as well to reduce swelling behaviour of BCS. Various stabilizing agents were utilized for improving soil properties in past. This study aims to improve BCS properties especially maximum dry density (MDD), unconfined compression strength (UCS), California bearing ratio value (CBR) and swelling behaviour by using appropriate sustainable means.

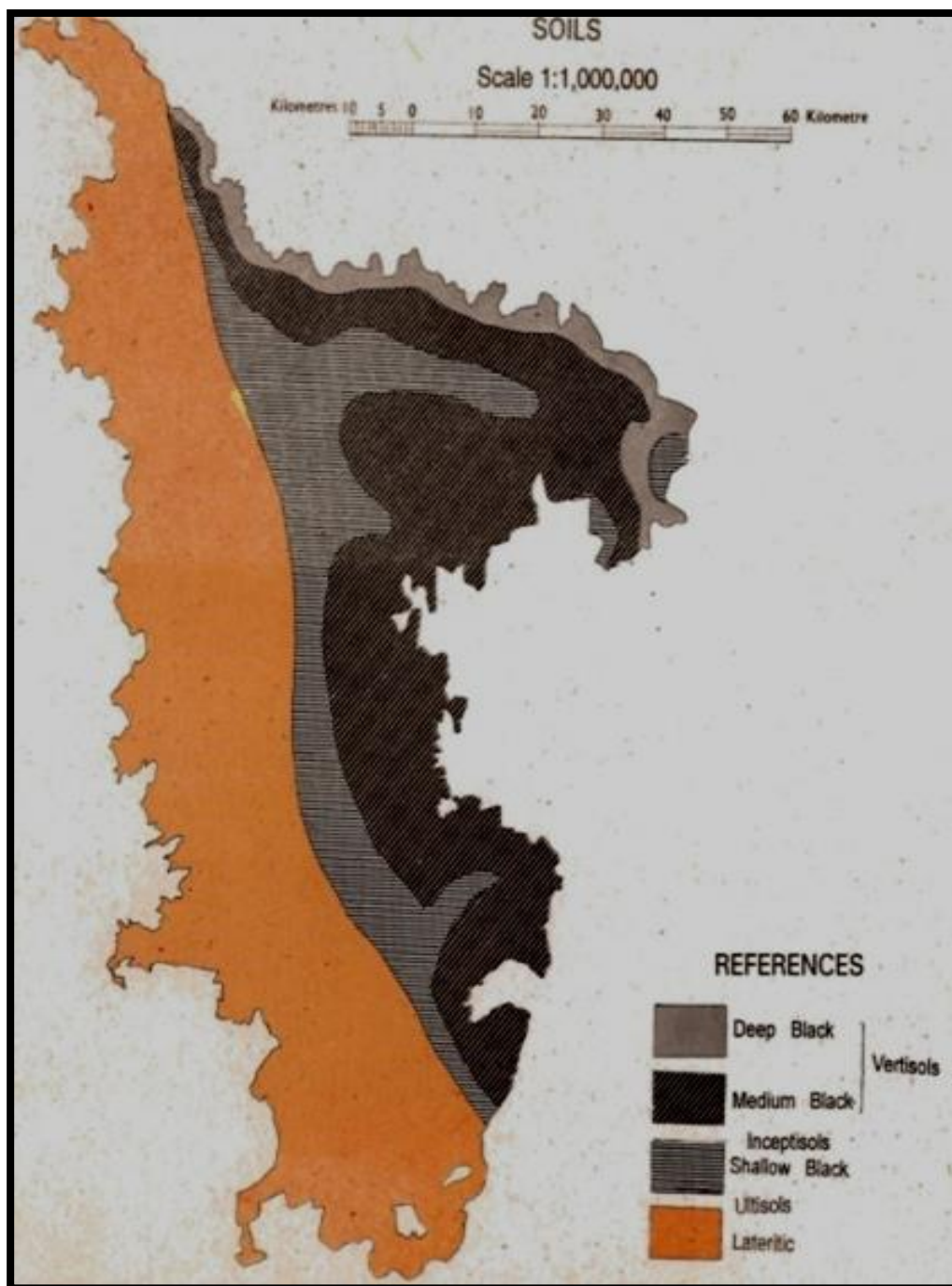


Figure 1.4: Soil distributions in Kolhapur district.

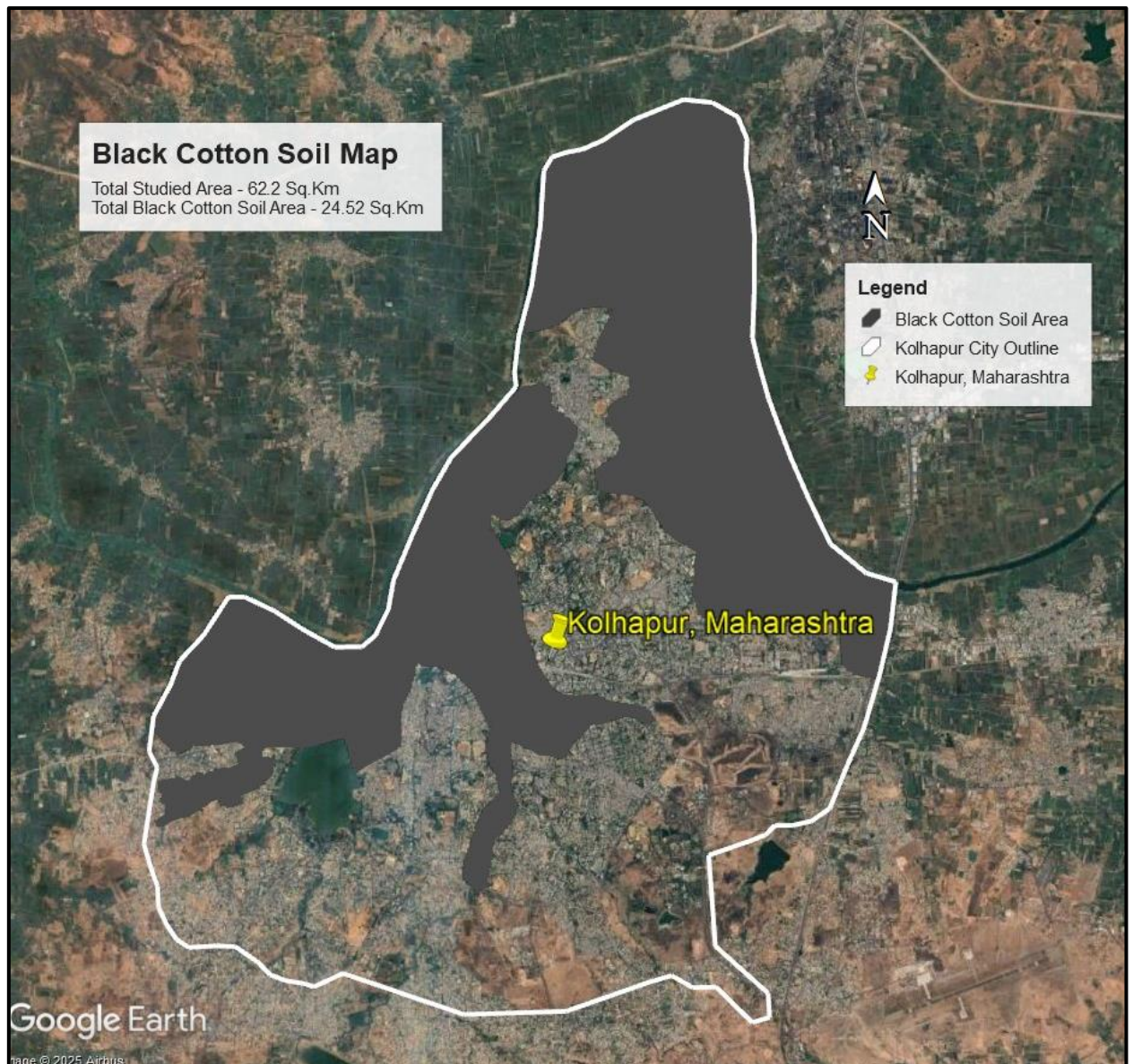


Figure 1.5: Distribution of black cotton soil in city (adapted from <https://earth.google.com>).

1.6 Objectives of the research

The motive of the present research work is to characterize black cotton soil and develop empirical correlations of its properties by sampling from various zones in Kolhapur while identifying and classifying the soil within Kolhapur city. Civil engineers require test results for foundations and sub-grades on black cotton soil. New correlations will be proposed for quick solutions, helping researchers to identify and develop new materials to enhance geotechnical properties. The objectives of the current research are:

- 1) To characterize the black cotton soil in Kolhapur city by finding out the index and strength properties of black cotton soil, like grain size distribution, specific gravity, consistency limits, field density, maximum dry density (MDD) and optimum moisture content (OMC), swelling index, unconfined compressive strength (UCS), California bearing ratio value (CBR), cohesion (c) and angle of internal friction (ϕ).
- 2) To develop correlation between different properties of black cotton soil by using regression analysis based on pattern of data available to predict swelling characteristics, maximum dry density (MDD), unconfined compressive strength (UCS) and California bearing ratio value (CBR).
- 3) To improve maximum dry density, unconfined compression strength and California bearing ratio value of black cotton soil by using bio-enzyme and biopolymer.
- 4) To find optimum percentages of additives to improve maximum dry density, unconfined compression strength, California bearing ratio value of black cotton soil by considering effect of curing period.

1.7 Structure of thesis

This research study presents an investigation of the development of empirical correlations between geotechnical properties and the enhancement of black cotton soil in Kolhapur city, structured as follows in the thesis:

Chapter 1 deals with an overview and introduction of the thesis, focusing on Indian soils, particularly black cotton soil, along with details on the research area. This chapter explores the key features of BCS and discusses the associated challenges. It focuses on outlining the purpose, goals, and scope of the topic.

Literature Survey is presented in chapter 2 with a comprehensive assessment of the various stabilization techniques and additives used in expansive soils, examining their impact on the soil's index and strength characteristics. It also covers the literature on initiatives to improve black cotton soil and the correlations between soil properties. Past researchers have reported actual associations with soil characteristics, leading to a comprehensive literature study that focuses on stabilizing the characteristics of black cotton soil. The discussion also includes a critical analysis of the literature survey and the identified research gaps.

Chapter 3 outlines the particulars of sample collection, including the methods employed, as well as the laboratory and field tests conducted, along with their respective results. This chapter provides a detailed characterization of the soil from the study area. Microscopic test details are also provided.

Chapter 4 presents a detailed assessment of the variation in geotechnical characteristics of BCS, structured by depth, based on samples collected from the study area. This chapter presents the details of empirical correlations between soil characteristics developed from the experimental program.

Stabilization of BCS by using bioenzyme and biopolymer is presented in chapter 5. This chapter outlines the improvements implemented to enhance the consistency, density, California bearing ratio value, and unconfined compression strength. This chapter also explores the impact of the curing period on the strength value.

Conclusion drawn from the present study are presented in chapter 6. It covers the most important findings that have been obtained through the current research as well as the extent of the proposed future work. The references are presented in the alphabetical order.

Chapter 2

Literature survey

2.1 Introduction

The literature is categorized into three parts, such as the application of stabilizing agents to enhance the black cotton soil (BCS), chemical stabilization, and empirical correlations developed for the BCS by researchers for different places in the past. Many researchers have previously utilized various stabilizing agents to improve BCS. In the literature survey, many of these agents were discussed, along with their possible benefits. Many researchers examine chemical stabilization; therefore, some research works were categorized as such. Empirical relationships between various soil parameters based on laboratory and field test results were also discussed. Various statistical tools and their input requirements were additionally addressed. Recent advancements in artificial intelligence (AI) and machine learning (ML) have markedly improved the predictive modelling capabilities associated with black cotton soil (BCS), as elaborated in the present study. These computational methodologies offer enhanced accuracy and reliability in forecasting the complex behaviour of BCS, particularly its pronounced swelling and shrinkage tendencies that frequently contribute to structural distress and foundation instability. Furthermore, the survey also highlighted the importance of considering environmental factors when choosing a stabilizing agent for black cotton soil. The researchers emphasized the need for sustainable solutions that not only improve soil stability but also minimize negative impacts on the surrounding ecosystem. Overall, the literature review provided valuable insights into the complexities of improving BCS and the diverse range of approaches that have been explored by researchers in the field.

2.2 Stabilization of black cotton soil

Kumar et al. (2007) studied the geotechnical properties of fly ash-soil mixtures with and without polyester fibre inclusions and with and without lime stabilisation. The geotechnical properties of fly ash-soil, lime-soil, and lime-fly ash-soil specimens that had varying amounts of randomly orientated fibres were investigated. It was concluded that soil-lime mixtures had a lower maximum dry density (MDD) and a higher optimal

moisture content (OMC) as lime concentration increased; also, this effect remains the same after the addition of fly ash to the soil-lime combination. Compaction studies on fly ash, soil, lime, and fibre mixes revealed that adding a small quantity of polyester fibres (0.5 to 2.0%) did not significantly change the maximum dry density or the ideal moisture content. When added to lime, fly ash is an effective soil amendment. Increasing the percentage of fly ash while maintaining the same quantity of lime causes the strength to rise until it reaches a maximum, after which it begins to fall. In fly ash-soil-lime mixes, an ideal proportion of lime is 8% and fly ash, 15%. An increase of 74% in unconfined compressive strength (UCS) and 100% in split tensile strength are produced by the addition of 1.5% plain or 1% crimped fibres, respectively. This finding highlights the effectiveness of polyester fibres, especially when applied to soil.

Babu et al. (2008) explored the enhanced strength, swelling, and compressibility properties of BCS randomly reinforced with coir fibres. Based on the results of extensive experimental studies using triaxial shear tests, swelling tests, and consolidation tests, it was concluded that both cohesiveness and the friction angle increased with increasing fibre content. Additionally, the addition of coir fibres reduced the swelling potential of BCS, thereby lowering the compression index and the major principal stress at failure.

Tang et al. (2008) studied synthetic polypropylene monofilament fiber-reinforced expansive soil from Xinxiang, China. Expansive soil reinforced with synthetic fibres was studied for its undrained strength behaviour, taking factors such as water content, degree of compaction, fibre percentage, and sample size into account. It was reported that the UCS increases as the degree of compaction and fibre content rise. On the other hand, as the z

Elayaraja and Arumairaj (2009) analysed the shear strength of BCS strengthened by geotextiles. Cylindrical samples prepared under saturated conditions and non-woven and woven geotextiles cut in circular discs. It was reported that, the geotextiles, whether woven or non-woven, increased strength as the number of reinforcing layers increased. The study reveals the shear strength of BCS increases with geosynthetics. It was concluded that the addition of non-woven geotextile increases the shear strength in all kinds of shear tests. Materials such as geogrid, geotextile, and geomembrane were examined. It was reported that the elevated tensile strength of the geogrid effectively improves drainage and provides substantial shear strength. Geotextile is effective for filtering. Geomembrane is effective for separation, particularly in fine soil.

Babu et al. (2010) introduced a modified cam clay model for the study of fibre-reinforced soil. The study demonstrated that the experimental findings, calculations from the suggested model, and outcomes from the numerical simulation of the triaxial compression test were consistent. Enhancing soil with fibres enriches the stress-strain behaviour of fine soil, especially clayey soil.

Oriola et al. (2010) presented the performance of BCS in Nigeria using groundnut shell ash (GSA). When the soil was treated with GSA, the maximal 7-day UCS values for the West African Standard Compactive effort (WA) were 455 kN/sq.m with 4% GSA as well as 526 kN/sq.m with 6% GSA. The criteria for base material stabilization using ordinary Portland cement (OPC) state values of 1710 kN/sq.m., which these values do not meet. At 6% (GSA), the max soaked CBR value was 4% at standard Proctor, and at 0% (GSA), it was 4% at WA, which did not meet the Nigerian General Specifications 1997, i.e., the specification for base and sub-base materials as well as material durability criteria.

Srivastava et al. (2014) utilized shredded tire waste as a partial replacement in order to enhance the geotechnical characteristics of BCS. The study concluded that expanding BCS with a shredded tire percentage between 30 and 50 significantly decreased the volume shift. The results indicated that a mixture with a slightly higher shear strength and a lower weight could be achieved by adding 5% shredded tire waste to BCS. Shredded tire waste is good for lightweight structures on weak soil.

Ashango et al. (2016) utilized steel slag (SS), rice husk ash (RHA), and quick lime to stabilize expansive soil and focused on strength and dynamic characteristics. The optimal mixture was determined to consist of 65% soil, 20% SS, 5% lime, and 10% RHA. Uncured soil samples showed a 45 percent increase, and cured soil samples showed a 90 percent increase in UCS in 30 days. Curing times ranging from seven to thirty days result in an improvement in strength, according to the soaking California bearing ratio test. It was found that the stabilized soil was 58 to 78 percent stiffer than the clay soil.

Gobinath et al. (2016) investigated the improvement of the geotechnical characteristics of BCS by using precipitated silica that comes from burning rice husks. It was found that precipitated silica with a percentage equal to 50 gives the maximum soaking strength, which is best for improving the subgrade properties of BCS that are meant to be used for pavement layers.

Dalal et al. (2016) demonstrated the use of industrial and agricultural waste, such as a blend of bagasse ash (BA), wood powder, and ground granulated blast furnace slag (GGBS), to stabilize the BCS. It was reported that wood powder, compared to the other two additives, enhanced consistency while reducing activity and plasticity. The hydrophilic properties of wood powder allowed it to limit the swelling of black cotton soil. While the addition of bagasse ash and GGBS enhanced compaction and strength, the control of swelling was mostly accomplished by wood powder.

Etim et al. (2017) utilized lime and iron ore tailings for improvement of soil properties, collected from Nigeria. Study concluded that the UCS and CBR peaks increased by 8 percent after curing of specimens by 7, 14 and 28 days. Addition of 8 percent lime and 8 percent IOT increased to 50 percent which satisfies the minimum criteria of 40 percent CBR for sub bases in light traffic roads. Also, it showed highest resistance to loss of strength of 37.56 percent, as regards the durability issue.

Miao et al. (2017) introduced a technique for geo-polymerizing BCS to enhance its potential application in subgrade construction. Stabilization of the soil was achieved using alkaline agents like calcium hydroxide ($\text{Ca}(\text{OH})_2$) or potassium hydroxide (KOH), resulting in the formation of cementitious geopolymer compounds. The study revealed that incorporating volcanic ash alongside these alkalis significantly reduced the soil's plasticity index from 34.8% to 14.2%, effectively minimizing expansion and improving overall strength. Among the stabilizers tested, potassium hydroxide demonstrated superior performance compared to calcium hydroxide in solidifying BCS. Furthermore, the mechanical strength of the stabilized soil reached 16.55 MPa after 90 days of curing at room temperature.

Aishwarya Lakshmi and Vishweshwaran (2017) evaluated shear strength using UCS tests on reinforced soil with different combinations of fibres. Natural fibres, such as coconut coir fibres and rice husk, and synthetic fibres, such as nylon and glass fibres, were used. It was discussed that glass fibres with rice husk yielded better results. The addition of 5% glass fibre and 10% rice husk resulted in a 45.85% increase in UCS and a 70.45% improvement in CBR.

Sai et al. (2020) investigated the reinforcement of BCS with geogrids to enhance its load-bearing capacity. The study concluded that geogrid reinforcement significantly improved the CBR values and reduced surface deformation, making it a viable method for subgrade improvement in road construction.

Darsi et al. (2021) examined enhancement of expansive soil properties using lime and ground GGBS. Different combinations were tested, including lime at 2%, 4%, and 6%, paired with 5% and 10% of GGBS. The findings revealed notable improvements in UCS and CBR. Specifically, the soaked and unsoaked CBR values increased by 9.02% and 8%, respectively. Additionally, the UCS of samples containing 6% lime and 10% GGBS showed an 84.16% enhancement, while the plasticity index was reduced by 9.48%.

Chouka and Venkat Ramana (2025) explored the use of recycled concrete dust (RCD) as a sustainable stabilizer for BCS. Their findings indicated that incorporating RCD improved the mechanical properties of BCS, including increased UCS and CBR values. This approach offers an eco-friendly alternative to traditional stabilizers like cement and lime.

2.3 Chemical stabilization of soil

Uppal and Chadda (1967) studied stabilization of BCS using lime. Addition of lime resulted in aggregation of clay particles from 0.02 mm to 0.05 mm and more than 0.075 mm with more amount of lime. CBR improvement reported was 13.2%, 59.2% and 80.5% when lime percentage was 2%, 3% and 5% respectively.

Wild et al. (1996) reported that can be added to clay – lime- gypsum mix to abstain better reduction in swelling behaviours but there was marginal improvement in strength. Presence of gypsum reduces swelling with not much appreciable improvement in strength but strength was observed to increase in absence of gypsum.

Punthutaecha et al. (2006) studied the effects of class F fly ash, bottom ash, polypropylene, and nylon fibres as stabilizers in sulphate-rich BCS. An improvement from 20 to 80 percent was observed in swelling, shrinkage, and plasticity properties. Fly ash with nylon fibres resulted in improved properties in expansive soil.

Puppala et al. (2006) explored the influence of fly ash, lime, and chemical additives on enhancing the geotechnical properties of BCS. The study utilized a pressure plate apparatus to analyse the soil water characteristic curve of BCS. Findings indicated that the soil treated with fly ash underwent significant changes in swell pressure behaviour. Among the various stabilisers tested, Class F fly ash proved particularly effective, yielding the most notable improvements. Specifically, fly ash applications reduced the swell pressures of untreated soils by approximately 65%, while bottom ash treatments achieved a

reduction of around 56%. The finer particle size of certain fly ash types contributed to a more substantial decrease in swell pressures due to particle size differences.

Amadi et al. (2013) investigated the chemical stabilization of black cotton soil using cement kiln dust (CKD) and coir fibre as reinforcing agents. BCS samples were treated with 8% CKD, considered the optimum content, and reinforced with coir fibres at varying proportions between 0 to 1% by weight of the soil. The coir fibres, cut to a length of 25 mm, were incorporated to assess the soil's performance as a pavement subgrade material. Results showed a slight reduction in MDD, while OMC and UCS increased with CKD addition. Although the CKD-enhanced soil exhibited improved compressive strength, it also became more brittle. Adding coir fibres addressed this issue by enhancing the toughness index, which increased with higher fibre content. The combination of 8% CKD and 1% coir fibre significantly improved the strength and toughness of the treated soil.

Baglari and Dash (2013) dealt with the strength improvement of BCS using lime and geosynthetic reinforcement. A series of UCS tests were conducted by varying lime content from 2% to 16% with a curing period of 3 to 28 days. It was reported that UCS improved 2.5 to 8.5 times. With the geosynthetic reinforcement in 3 layers, the soil-lime mixes showed improved strength of 2.6 to 11.3 times.

Oza and Gundaliya (2013) conducted a study on the effectiveness of three different stabilizing agents i.e. cement waste dust, cement dust, and lime powder, and lime alone in improving BCS with a high percentage of montmorillonite. The findings indicated that cement waste dust was the most effective stabilizer for enhancing consistency limits, reducing the plasticity index, and increasing the compressive strength of BC soil. A combination of 7% cement dust and 8% lime powder yielded the best results.

Estabragh et al. (2014) conducted a study on the reinforcement of soil using three types of fibres with varying lengths and proportions. Additionally, the soil was treated with different amounts of lime and cement and allowed for varying curing durations. The study focused on assessing the effects of fibres, lime, and cement on mitigating swelling potential and swelling pressure in expansive soils. The results showed that fibres greatly lowered the behaviour of swelling, with the amount of reduction depending on the shape, length, and number of fibres. Tape fibres proved more effective in minimizing swelling than bar fibres, with wider tape fibres providing enhanced control. Lime and cement treatments also mitigated swelling, with the effectiveness dependent on the concentration

and curing period. Among the two, cement showed superior performance in reducing swelling potential compared to lime.

Dasa and Sonib (2014) examined how the addition of lime and GGBS influences the hydraulic conductivity of expansive clay minerals, including kaolinite, montmorillonite, and illite. It was observed that incorporating lime and GGBS into kaolinite decreases its permeability. Additionally, lime was found to play a key role in enhancing properties such as strength, compressibility, and hydraulic conductivity.

Yaolin et al. (2015) conducted a study comparing the effectiveness of carbide slag, GGBS, and Portland cement for stabilizing soft clay using methods such as UCS tests, mercury intrusion porosimetry (MIP), X-ray diffraction (XRD), and scanning electron microscopy (SEM). It was observed that the ideal CS content for achieving maximum UCS in CS–GGBS-stabilized clay ranged between 4% and 6%. Additionally, the UCS value of clays stabilized with the optimal CS–GGBS combination was found to be more than double that of clays stabilized with cement alone.

Srinivas et al. (2016) explored methods to enhance the properties of BCS by incorporating cohesive non-swelling (CNS) soils. This approach aimed to mitigate issues related to swelling, plasticity, compaction, strength, and penetration, which are common challenges in problematic soils. The study highlighted the potential of CNS soils to not only improve these characteristics but also provide an environmentally sustainable solution. Results demonstrated that using CNS layers in expansive soil beds significantly enhanced their compressive load-bearing capacity.

Saride and Dutta (2016) investigated methods to enhance the properties of BCS by stabilizing it with class C fly ash. The study focused on improving the soil's swelling potential, stiffness, and damping characteristics. Fly ash was incorporated into the soil in varying amounts ranging from 5% to 20% of the soil's weight. Through resonant column tests, key parameters such as the shear modulus, damping ratio, and Poisson's ratio of both untreated and stabilized soil samples were measured. The results demonstrated that adding fly ash significantly increased the shear modulus of the soil, while the damping ratio exhibited a decreasing trend with higher fly ash content.

Ashis et al. (2016) investigated the influence of incorporating GGBS on the CBR of three types of clayey soils. Soaked CBR tests were conducted across varying GGBS proportions ranging from 0% to 50%. The findings revealed an initial increase in soaked CBR values

with the addition of GGBS, followed by a decline beyond a certain point. The optimal GGBS content for improving the CBR was identified as 30%.

Dang et al. (2016) evaluated the effect of bagasse fibres and hydrated lime on the shrink-swell behaviour of stabilised expansive soils. Bagasse fibres were added in a proportion of 0.5 to 2% with hydrated lime. It was reported that bagasse fibres along with lime enhanced the UCS of expansive soil and decreased liner shrinkage of soil. It was suggested that the hydrated lime and bagasse fibres can effectively stabilise expansive soils, reducing environmental impacts and construction costs by decreasing lime dosage and promoting sustainable development.

Batariet al. (2017) presented the effect of BA as an admixture to cement stabilized BCS. Cement was used in proportion of 0 to 8% while BA was used 0 to 6 % by weight of BCS. It was reported that addition of BA with cement improves soaked CBR and UCS. The optimum mix suggested was 5% BA and 8% cement which yielded CBR of 73% and UCS of 851 kN/ m² after 7 days curing.

Moghalet al. (2017) used synthetic fibres along with lime in stabilization to address shrink-swell issue of BCS. Fibrecast (FC) and Fibre Mesh, were added by 0.2% to 0.6% by weight of soil in 6- and 12-mm length and odometer tests were performed. It was reported that cast fibres performed well without lime in swelling context. In presence of lime both fibres produced similar results.

James et al. (2018) investigated the effect of the use of BA on the strength development of lime-stabilized expansive soil. It was observed that the lime content of 5.5 to 7% yields the best stabilization. It was also reported that the addition of BA produces a maximum strength gain of 58.3%.

2.4 Empirical correlation between black cotton soil properties

Erzin(2004) used multiple regression analyses to find a correlation between swell pressure and easily measurable soil properties. This made it possible to make quick predictions. The presented data trends and statistical analysis showed that the swell pressure is strongly related to the initial dry density and plasticity index, but it is not as strongly related to the initial water content.

Sahoo and Reddy (2009) explored the relationship between dynamic cone penetrometer (DCP) readings and CBR values for fine-grained soils. DCP tests were conducted to establish a connection between the DCP measurements taken in the field and the corresponding CBR values. The results indicated a strong correlation between the penetration depth recorded by the DCP and the CBR for the tested materials.

Berawala and Solanki (2010) conducted a study on the geotechnical characteristics of expansive soil found in the Surat region at depths ranging from 1.5 to 2 meters below ground level. The results showed that there were strong correlations between the swelling pressure and a number of soil parameters. These included the liquid limit, the plasticity index, the shrinkage index, the field moisture content, and the free swell index. These correlations significantly influence the accuracy of swelling pressure predictions.

Bera and Ghosh (2011) proposed log-linear regression models aimed at predicting the MDD and OMC of fine-grained soils. The study identified factors such as compaction energy, specific gravity, liquid limit, and grain size as key contributors to the accuracy of these models in estimating both MDD and OMC.

Elisha (2012) presented a prediction of the swell pressure of BCS by employing multiple regression analysis. The prediction was based on soil parameters such as the plasticity index, liquidity index, water content, and dry density. The findings revealed significant relationships between swell pressure and soil properties. Among them, the plasticity index and initial dry density were found to have a greater impact on swell pressure, while the initial water content played a comparatively minor role.

Zumrawi (2012) conducted a study on the swelling behaviour of four expansive soils compacted at varying water contents and dry densities. The research revealed a strong linear correlation between the surcharge pressure, swelling characteristics, and the initial soil state, which encompasses water content, dry density, and void ratio. The findings emphasized that these initial state parameters collectively influence swelling percentage and swelling pressure, as each parameter contributes to the soil's response to external pressures.

Bello (2012) presented a regression analysis to explore the relationship between the index properties of lateritic soils and their CBR within Osogbo town, Nigeria. Predictive models were developed to estimate the CBR based on experimentally determined index properties.

The results demonstrated a strong correlation between the index properties and the CBR values.

Chitra and Gupta (2014) analyzed soil properties, such as grain size distribution, consistency limits, and density, as input parameters. In the analysis, refined data points were utilized to train a model capable of predicting key soil characteristics, including true cohesion (c), angle of shearing resistance, effective cohesion, and effective angle of shearing resistance. The developed model was subsequently validated using the collected data.

Arulkumaran and Sukumar (2015) presented an analysis of soil properties, including grain size distribution, consistency limits, free swell index, and N value from the standard penetration test (SPT). Results reported correlations between SPT N values and other soil characteristics.

Agarwal et al. (2016) presented an experimental study to enhance the CBR of BCS by incorporating varying amounts of lime. The analysis of the test results revealed a reliable correlation for predicting the soaked CBR of the lime-soil mixtures.

Srinivasa et al. (2016) developed regression equations to estimate the CBR of BCS using their field strength characteristics from SPT and DCP tests with index properties.

Qazi et al. (2016) explored the correlation between electrical resistivity measurements and soil shear strength properties. Soil specimens were obtained from 40 distinct locations at depths ranging from 0.3 to 0.5 meters. The shear strength characteristics, including cohesion and friction angle, were assessed using direct shear testing.

Mozumder et al. (2017) utilized the support vector regression (SVR) method to predict the strength characteristics of clayey soil stabilized with a GGBS-based geopolymer. From the SVR model, an empirical chart and corresponding equations for estimating the strength of geopolymer-stabilized soil were developed. The study concluded that the SVR model effectively captured and generalized the physical processes involved in stabilization.

Kushwaha et al. (2017) conducted geotechnical investigations on soil samples and derived empirical relationships among various parameters. The result indicated a strong correlation between the CBR and the liquid limit. Multiple linear regressions with parameters like consistency limits and free swell index were used to try to predict UCS and swelling pressure, but the results were not statistically significant. Notably, the swelling pressure showed a better correlation with the free swell index, UCS and soaked CBR.

Prasanna et al. (2017) conducted a study on six soil samples from Mysore District, Karnataka, based on their index properties. They performed compaction tests under different energy levels. Results revealed equations to figure out the OMC and the MDD for different energy levels in coarse-grained soils. These equations can be used for the initial design process.

Anwar (2018) carried out standard penetration tests (SPT) in 17 boreholes at intervals of 1.5 meters, along with pressure meter tests, and proposed empirical correlations between the obtained parameters.

Obaji and Komolafe (2018) compiled a database of undrained cohesion values derived from triaxial tests performed on undisturbed soil samples. The results showed a strong relationship between the two soil properties at several sites. This led to the creation of an empirical equation that can be used to predict undrained cohesion based on the natural moisture content of the soil.

Cheshomi (2018) investigated the relationship between pore pressure and cone penetration test (CPT) results after conducting 22 CPTs and 50 unconfined compressive strength (UCS) tests to derive the undrained shear strength of clay based on pore pressure.

Chala and Ray (2023) conducted a comprehensive study focusing on the enhancement of geotechnical properties of black cotton soil (BCS) through the incorporation of waste materials, utilizing artificial intelligence (AI) methodologies for predictive modelling. Research aimed to determine the optimal percentage of waste additives to improve soil characteristics such as strength, stability, and durability. By employing AI techniques, the study provided a data-driven approach to soil stabilization, offering insights into the effective use of waste materials in geotechnical engineering applications.

Krishna et al. (2023) developed an ANN model to predict the UCS and CBR of BCS stabilized with additives like fly ash, lime, and cement. The model demonstrated high accuracy, with a strong correlation between predicted and experimental values. This approach aids in optimizing the stabilization process by reducing the need for extensive laboratory testing.

Zhang et al. (2023) highlighted the effectiveness of various ML algorithms, such as Random Forests (RF), Support Vector Machines (SVM), Decision Trees (DT), and eXtreme Gradient Boosting (XGBoost), in geotechnical applications. The study

emphasized the potential of these techniques in predicting soil behaviour, including that of BCS, thereby enhancing the accuracy of geotechnical assessments.

Murthy et al. (2024) employed various soft computing models, including Adaptive Neuro-Fuzzy Inference System (ANFIS), Multi-Layer Perceptron (MLP), Radial Basis Function (RBF), and Artificial Neural Networks (ANN), to predict the CBR values of BCS. Using 211 experimental datasets with inputs like particle size, Optimum Moisture Content (OMC), Maximum Dry Density (MDD), Plasticity Index (PI), Shrinkage Limit (SL), and swell pressure, the study found that the Levenberg-Marquardt algorithm within ANN provided the most accurate predictions. The optimal neural architecture identified was 7-5-1, indicating seven input neurons, five hidden neurons, and one output neuron.

Hsiao et al. (2024) utilized Shapley Additive exPlanations (SHAP) to interpret an eXtreme Gradient Boosting (XGB) model predicting lateral spreading due to liquefaction. The model, trained on data from the 2011 Christchurch Earthquake, identified key soil characteristics influencing predictions, aligning with established engineering knowledge.

Khatti and Grover (2024) applied soft computing techniques to classify soils in the Erenler region, which includes BCS. Research demonstrated that Artificial intelligence (AI) models could effectively predict soil classifications, aiding in better decision-making for construction projects.

2.5 Bioenzyme and biopolymer stabilization

Arivazhagan et al. (2016) explored methods for stabilizing BCS to enhance its suitability for road and building construction. Terrazyme was used as a stabilizing agent, applying it to expansive soil in dosages of 200 milliliters per 2, 2.5, and 3 cubic meters of soil, with curing periods ranging from 0 to 28 days. The results indicated that the UCS increased from 3.57% to 8.72% after 28 days of curing, and swelling pressure decreased by 85.2%. Additionally, the OMC was reduced from 22.80% to 21.80%, while both the liquid limit and plastic limit decreased, with values changing from 60.2% to 56.53% and from 32% to 30%, respectively.

Ganapathy et al. (2016) conducted a study to evaluate the effectiveness of a bio-enzyme for use in road pavement layers. The research involved analyzing the soil's microstructure using XRD and SEM. The results indicated that increasing the bioenzyme dosage led to a reduction in soil plasticity, permeability, and MDD. Conversely, the 28-day CBR, UCS,

and shear strength of the soil showed significant improvement. The study concluded that the bioenzyme effectively enhanced soil strength and plasticity while decreasing its permeability.

Suresh et al. (2017) investigated the effectiveness of using the Terrazyme as an additive for improving BCS. The study assessed the index and compaction properties, along with the CBR, using varying Terrazyme concentrations ranging from 0.25 to 1 milliliter/100 milliliters of water. The findings indicated that the optimal concentration was 0.5 milliliter of Terrazyme per 100 milliliters of water. This improvement in CBR values led to a 30% reduction in both pavement thickness and associated costs.

Dehghan et al. (2018) explored the use of biopolymers, specifically Xanthan gum and Guar gum, for enhancing the stability of collapsible soils. To evaluate the geotechnical characteristics of soil treated with varying biopolymer concentrations and curing durations, the study conducted compaction, consolidation, permeability, and triaxial tests. Additionally, scanning electron microscopy (SEM) was utilized to observe changes in the microstructure. The findings indicated that incorporating biopolymers reduced MDD and permeability of the soil. Furthermore, the research demonstrated that both biopolymer content and curing time significantly affected the stress-strain behaviour of the treated soil. SEM analysis highlighted the interaction between biopolymer strings and fine soil particles, contributing to the stabilization process.

Begum et al. (2021) explored the use of bioenzymes, such as Terrazyme, to enhance the geotechnical characteristics of soil. The results indicated that incorporating Terrazyme led to a decrease in clay content and an increase in the proportion of coarser particles. Additionally, the consistency limit values were lowered. The MDD increased, while OMC decreased as the Terrazyme content increased. Furthermore, the consolidation parameters showed a reduction.

2.6 Critical appraisal of literature

For improving the properties of BCS, past researchers used different admixtures, industrial waste, and agricultural waste products. After utilisation, they estimated the optimum percentage of additives based upon the properties of BCS in which they were interested. Experimental results are also well explained by past researchers related to their scope and extent of study.

For the stabilisation of BCS lime and iron ore tailings admixture, alkalis of calcium hydroxide or potassium hydroxide (KOH) and cementitious geo-polymers, fly ash, lime, and polyester fibres, polypropylene fibre, nylon fibres, fly ash–GGBS-based binder, a combination of bagasse ash and GGBS and wood powder, groundnut shell ash, bagasse fibres with hydrated lime, bagasse ash (BA) with cement, BA with lime, GGBS with lime, carbide slag with GGBS, cement dust with lime, bar fibre or tape fibre with lime and cement, geosynthetic reinforcement with lime, and cohesive non-swelling soil (CNS) as well as industrial and agricultural waste were evaluated as potential stabilizers. Every material was utilised for enhancing certain engineering properties of expansive BCS, such as plasticity, strength, permeability, compressibility, swelling behaviour, etc. BCS was tested for all index properties, UCS, split tensile strength, triaxial tests, CBR, consistency limits, compaction, and consolidation tests initially as well as after treatment for different proportions for estimating the potential of particular additives.

Many researchers revealed the potential of empirical correlation to predict important properties of BCS for different regions. Various empirical relationships or phenomenological relationships between BCS properties that were supported by experiment and observation were developed by many researchers in the past; some of them are listed in the literature survey. Statistical tools were utilised by many of the researchers supported by software analysis. Especially regression analysis, both simple and multiple regression analysis, was used for prediction of strength properties of BCS. Each researcher considered independent and dependent variables as per his interest and availability of experimental data. Many researchers used laboratory as well as field test results to develop equations. Past empirical correlations for different properties of soil with strength properties were developed by the researchers for different places and cannot be applied directly to certain areas. Various tests required critical sample extraction and longer time durations. Civil engineers need various test results to construct foundations and subgrades on soil.

Various materials were used to improve the geotechnical characteristics of expansive BCS, and particular additives were added in percentages and evaluated for certain capabilities; hence, there is scope for further research on producing new additives with an optimal proportion. Many previous researches did not attempt to take into account the cost of using stabilizers. Empirical relationships between additive dose and strength attributes are also not highlighted. Further exploration is required to assess the potential of bioenzymes in

enhancing the strength properties of BCS, as a detailed analysis of its strength characteristics remains necessary. Additionally, the use of biopolymers to improve black cotton soil has not been extensively researched, presenting opportunities for future studies.

2.7 Gap analysis

The identified gaps indicate a necessity for additional investigation to enhance the evidence base and elevate the quality of research within this domain. While it is important to address gaps in research, it is also crucial to acknowledge that all studies have limitations, and it may not always be feasible to address every potential gap. A thorough review and evaluation of the literature revealed the following gaps identified in the research studies:

- Past empirical correlations for different properties of soil with strength properties were developed by the researchers for different places and cannot be applied directly to all the regions.
- Most of the soil was collected from a certain depth, below GL, within a selected region, but depth-wise analysis or sample collection was not considered by past researchers.
- Details of black cotton soil properties or any relevant database related to the distribution of black cotton soil in a city are not available.
- Particular additives were utilized in percentage to improve black cotton soil and tested for certain properties only; hence, there is scope for further research to develop new additives with an optimum proportion.
- The cost factor for the utilization of stabilizing agents was also not considered in many of the past studies.
- While numerous studies have investigated the stabilization of black cotton soil using various additives, a critical gap exists in understanding the influence of curing period on the long-term performance of these stabilized soils, particularly under field conditions. Most existing research offers limited insight into how strength and durability evolve over time, which is essential for predicting the behavior of treated soil in real-world applications. Furthermore, there is a lack of comprehensive data on the spatial variability of black cotton soil properties in regions like Kolhapur, where soil behavior can vary

significantly with depth and location. Another significant shortcoming in past work is the limited exploration of cost-effective, sustainable stabilizing agents, such as industrial by-products or locally available materials, and their performance over different curing durations. These gaps have hindered the development of region-specific, durable, and economically viable stabilization techniques. Therefore, future research must focus on generating detailed datasets, evaluating the curing-dependent behavior of various additives, and exploring low-cost, environmentally friendly alternatives, to establish more efficient and practical stabilization methods for black cotton soils, particularly in semi-urban and rural construction contexts.

Chapter 3

Characterization of black cotton soil in Kolhapur region

3.1 General

On top of being a natural and complex construction material, soil is also a crucial component of the foundation stratum for every structure. Every soil has different characteristics and its behaviour is depending upon different properties such as, soil structure, mineral content, grain size, consistency, swell potential etc. Hence, analysis of soil characterization is important for evaluation of the soil's behaviour under different conditions and load combinations. Also to analyse the relationships between different soil properties, accurate characterization of the soil is necessary. Soil sampling is crucial stage before characterization of the soil for any study area. Soil samples should be representative, so that accurate investigation will be possible. Soil pattern identification via reconnaissance survey was the standard procedure for collecting samples from the research area.

3.2 Methodology

The study was conducted in Kolhapur city, Maharashtra, focusing on regions identified with significant deposits of black cotton soil (BCS). Sampling locations were selected to ensure spatial coverage across urban and peri-urban zones. To capture the spatial variability of soil properties, sampling locations were carefully selected across diverse geographical and functional zones of the city. These included Urban built-up areas, peri-urban fringes which are undergoing rapid development, Agricultural zones where traditional land use influences soil conditioning and Roadside embankments and low-lying flood-prone regions. This approach ensured a comprehensive representation of different subsoil conditions, moisture regimes, and anthropogenic influences within Kolhapur. The selection was further guided by historical soil maps, satellite imagery, and consultations with local geotechnical engineers and municipal authorities. Each location was geo-referenced using GPS coordinates, enabling precise BCS mapping and future site revisits

for long-term monitoring. This diverse spatial coverage was essential to develop robust and generalizable empirical correlations between native geotechnical properties and the behaviour of stabilized soil when treated with eco-friendly additives such as Terrazyme and Xanthan gum.

3.2.1 Sample collection

Various regions of BCS were identified based on reconnaissance surveys, and samples were collected in three phases at different depths from different regions of Kolhapur city. The initial sampling operations involved collecting samples at equal depths of 1.5m below ground level (GL). These samples were collected from the boundary of the study area and also at different locations within the study area. After analyzing soil patterns, three different locations covered with BCS were identified, and sampling was done at different depths to analyze the variation of BCS properties according to depth, below GL. The total number of 28 BCS samples collected from 28 different locations as shown in Table 3.1. These 28 locations were identified in 7 zones where BCS is found as per black cotton soil distribution map of the city. Also, the Study area with all sample locations is shown in figure 3.1.

Table 3.1: Sampling locations in study area.

Sr. No.	Zone No.	Area description	No. of locations	No. of Samples
1.	I	Phulewadi area	1.Rankala- 04 2.Chambukhadi- 02	04* 02
2.	II	Dasara chowk area	1.Ramnagar - 01 2. Sita colony - 02	01** 02
3.	III	Tarabai Park area	1. Karande mala - 02 1.Biranje Panand - 02	02 02
4.	IV	Bawada area	2.Sugar mill - 02 3. Line bazar - 01 4. Shirol- 03	02 01* 03
5.	V	Shiye Bawada road area	1. Shiye Bawada road - 02 2. MIDC area - 01	02

				01
				01
			1. Hockey stadium road-01.	01
6.	VI	Kandalgoan area	2. Mali colony, Rajarampuri-01.	01
			3. Kandalgoan area - 01	01
			1. Bapat Camp-01.	01
7.	VII	Kaneriwadi area	2. Uchgaon area – 01	01
			3. Kaneriwadi lake-01.	01
Total	07	07	28	28

*One borehole- samples collected from different depth below GL.

**One test pit- samples collected from different depth below GL.

3.2.2 Sampling locations around or at the boundaries of the city

The first sampling phase included the collection of samples from five distinct locations around the Kolhapur city boundaries. As shown in Table 3.2, a set of three BCS samples was taken from every location, collected from 1.5 m below GL, through test pits. Currently, Kolhapur city has BCS coverage at a number of key locations, as well as considering future city expansion. This study will provide valuable insights into the factors contributing to the development of the city, helping planners make informed decisions for future growth and infrastructure development. It will also help policymakers implement sustainable growth strategies and improve residents' quality of life.

Table 3.2: Sampling locations at boundary.

Sr. No.	Site Location	Sample ID
1	Kandalgaon	KG-I, KG-II & KG-III
2	Rankala (Balinga)	RK-I, RK-II & RK-III
3	Kaneriwadi	KW-I, KW-II & KW-III
4	Shiroli	SH-I, SH-II & SH-III
5	Shiye	VT-I, VT-II & VT-III

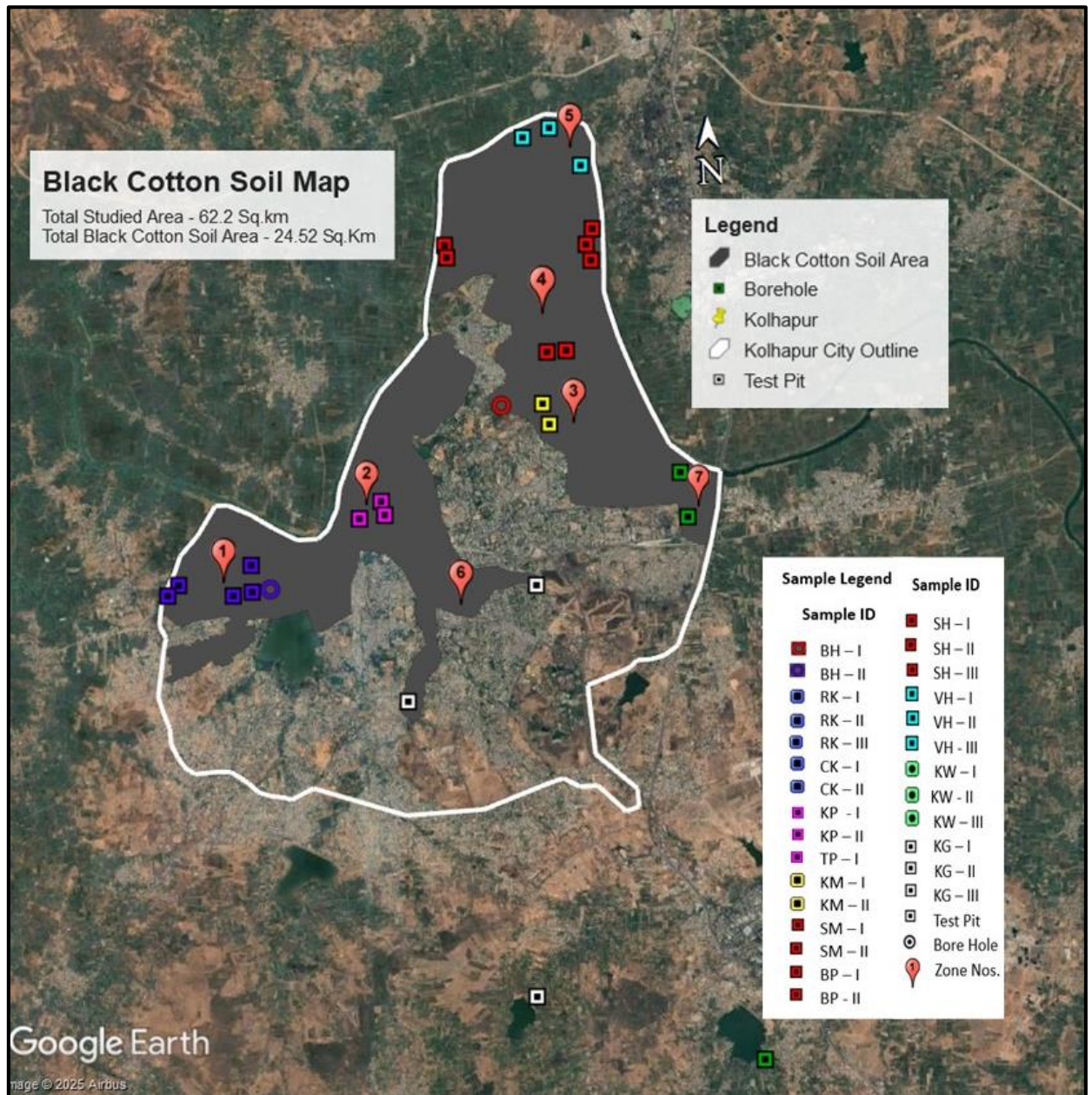


Figure 3.1: Sampling locations in study area (adapted from <https://earth.google.com>).

3.2.3 Sampling locations in city

Black cotton soil samples were collected from some regions from different wards of Kolhapur city. Various locations identified are listed in Table 3.3. A set of two samples of soil was taken from each site from 1.5 meters deep through test pits.

Table 3.3: Sampling locations in city.

Sr. No.	Site Location	Sample ID
1	Karande Mala, Tarabai Park	KM1 & KM2
2	Sugar Mill, Bawada	SM1 & SM2
3	BiranjePanand, Bawada	BP1 & BP2
4	Chambukhadi, Phulewadi	CK1 & CK2
5	Sita colony near Dasara Chowk	KP1 & KP2

3.2.4 Test pit 1 (2.5m), Ramnagar, Kolhapur

This study further evaluates the changes in soil properties in relation to the depth of investigation. To analyze the soil from different depth and to evaluate the change in characteristics if any, it is required to collect the samples from different depths at same location. Hence, one test pit was excavated at Ramnagar, Kolhapur (16°42'29.6"N 74°13'38.2"E), up to a depth of 2.5m as shown in figure 3.2. Samples were taken at depths of 0.5, 1.0, 1.5, 2.0, and 2.5 meters below GL. Several tests were carried out on samples in accordance with IS 2720.

3.2.5 Borehole- 1 (3.5m), Line Bazar, Kolhapur

One bore hole was excavated at Line Bazar, near Divisional Agriculture Co. Director Office, Kolhapur (16°43'26.1"N 74°14'47.3"E), as shown in figure 3.3, up to a depth of 3.5m by tractor mounted motorized auger. BCS samples were collected from 0.5, 1.5, 2.5 and 3.5 meters below GL. A comprehensive experimental program was undertaken for these samples in accordance with IS standards.

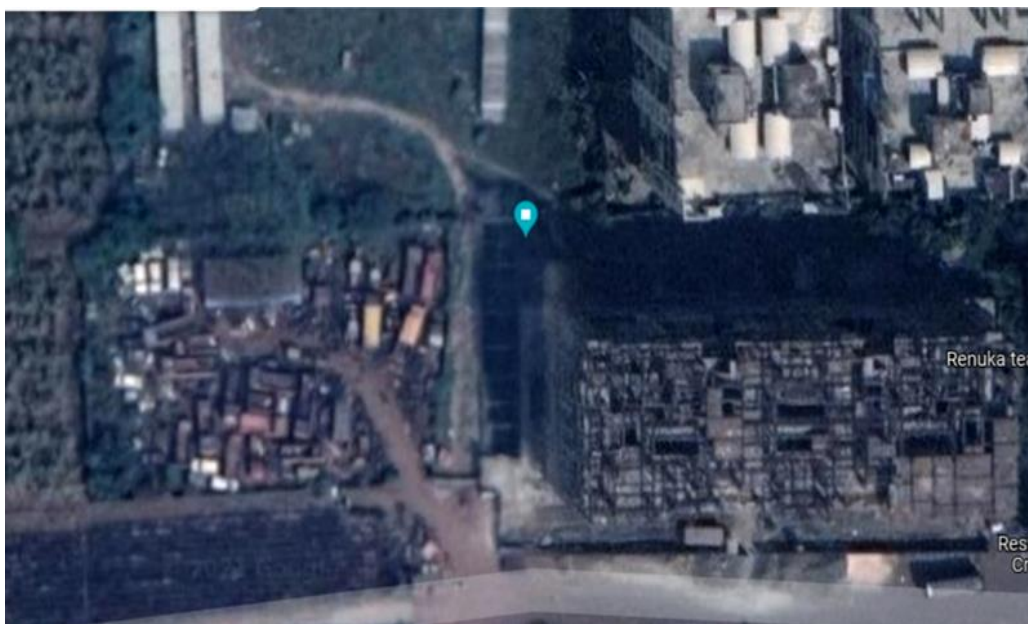


Figure 3.2: Test pit 1 (2.5m), Ramnagar, Kolhapur
(adapted from <https://earth.google.com>).

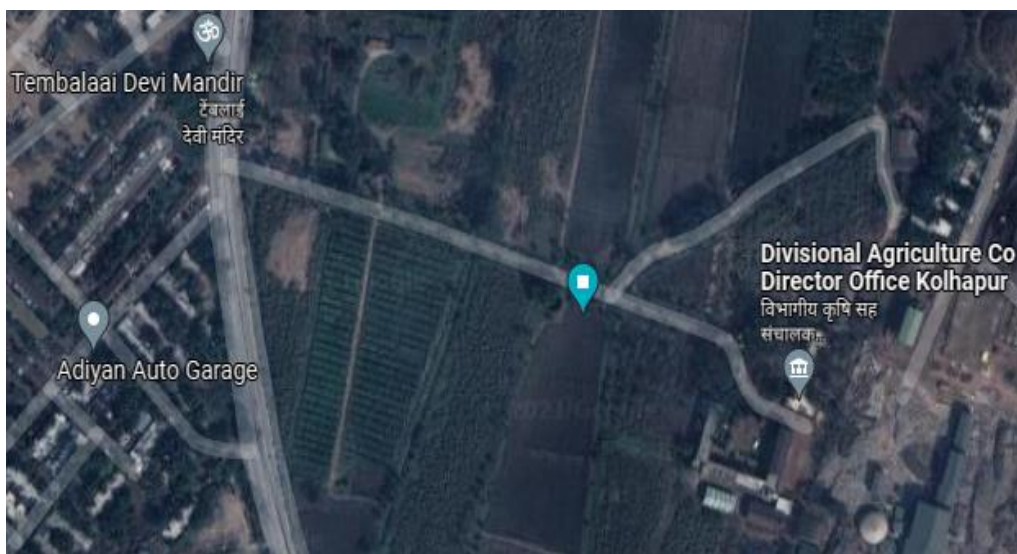


Figure 3.3: Borehole 1 (3.5m), Line Bazar, Kolhapur (adapted from <https://earth.google.com>).

3.2.6 Borehole- 2 (4.0m), near Rankala, Phulewadi road, Kolhapur

The black cotton soil samples were collected from the second borehole by manual auger boring. This borehole is located behind D-Mart, near Rankala, Phulewadi Road, Kolhapur ($16^{\circ}41'50.9''\text{N}$ $74^{\circ}12'29.9''\text{E}$), as shown in figure 3.4. Sampling is done up to a depth of

4.75 m in four different layers. Samples were taken at depths of 1.0, 2.0, 3.0, and 4.0 meters below the surface of the ground. Various tests were conducted on samples as per IS 2720. At the depth of 4.75 m, water table was found, and subsequently limestone was found at 5 m depth.



Figure3.4: Borehole- 2 (4.0m), Phulewadi road, Kolhapur (adapted from <https://earth.google.com>).

3.3 Methods of sample collection

Samples should be always representative, hence appropriate method for sample collection is needed to identify. As discussed, sampling was done at ten different locations from 1.5 below GL. Furthermore, samples were collected from three different locations at varying depths below ground level, ranging from 0.5 to 4.0 meters. Basically, soil is black cotton soil. All locations are situated in Kolhapur and nearby Kolhapur city and are developing areas of the city. Samples were collected by following methods,

- **core cutter:** - samples were collected from test pits of 1.5 m depth, by using core cutter at a required depth below ground level. Field water content was also calculated with field density and further utilized for lab testing.
- **test pits:** -different depths below ground level up to 2.5 meters were sampled at the Ramnagar site, near Dasara Chowk, Kolhapur.

- **boreholes:** -some samples were collected through boreholes at Line Bazar and Phulewadi Road, Kolhapur as the regions selected are now utilized for construction. Characterization of the BCS was undertaken after sample collection to further use it for correlations. The study also includes improvement of soil hence results of laboratory test were used as basis for enhancing black cotton soil properties.

3.4 Test conducted as per standard codes

Samples were collected from different regions of Kolhapur city as discussed previously. After sample collection various laboratory test were conducted on samples as per IS 2720, Table 3.4 shows the details of reference codes.

Table 3.4: Test conducted and the relevant standard.

Sr. No.	Name of the test	IS code/specification
1	Water content	IS:2720(Part 2)-1973
2	Specific gravity	IS:2720(Part 3/Sec. 1)-1980 and IS:2720(Part 3/Sec. 2)-1980
3	Grain size analysis	IS:2720(Part 4)-1985
4	Liquid and plastic limit	IS:2720(Part 5)-1985
5	Shrinkage limit	IS:2720-(Part6)-1972
6	Water content- dry density relation by compaction	IS:2720(Part 7)-1980 and IS:2720(Part 8)-1983
7	Direct shear test	IS:2720(Part 13)-1986
8	California bearing ratio value	IS:2720(Part 16)-1987
9	Dry density by the core-cutter method	IS:2720(Part 29)-1975
10	Differential free swell index	IS:2720(Part 40)-1977
11	Unconfined compression strength	IS:2720(Part10)-1991

3.5Hypothesis testing frameworks

A comprehensive sampling and experimental program were conducted to establish empirical relationships among BCS characteristics. In regression analysis, testing frameworks are crucial for assessing the statistical significance of correlations between

independent and dependent variables. The regression coefficient represents the estimated change in the dependent variable for a one-unit change in an independent variable, holding other variables constant. Hypothesis testing is typically conducted by formulating a null hypothesis (H_0) that the coefficient is equal to zero (no effect) and an alternative hypothesis (H_1) that the coefficient is not equal to zero. The P-value associated with each coefficient quantifies the probability of observing a test statistic as extreme as, or more extreme than, the observed value under H_0 . A low P-value ($P < 0.05$) indicates strong evidence against the null hypothesis, suggesting the corresponding predictor has a statistically significant effect on the response variable (Montgomery et al., 2012). The F-value from the analysis of variance (ANOVA) table tests the overall significance of the regression model by comparing the model with no predictors (intercept-only model) to the specified model. A high F-value and correspondingly low p-value for the F-test imply that the regression model explains a significant proportion of the variability in the dependent variable (Kutner et al., 2005). Together, these metrics form a robust framework for evaluating model validity and guiding variable selection in regression analysis.

3.6 Test result

A detailed experimental program was undertaken for the characterization of representative BCS samples collected from the study area. Some samples were collected from the boundary of Kolhapur; Table 3.5 shows details of laboratory test results on samples. Also, details of results of laboratory tests on samples from interior wards of the city are shown in Table 3.6. Some samples were collected from various depths below the ground surface at different locations in Kolhapur city to analyze the variation of all properties with depth. Table 3.7 presents the results of laboratory testing on samples collected from Ramnagar, Kolhapur, up to a depth of 2.5 m through test pits. Also, one borehole was excavated at Line Bazar, up to a depth of 3.5 m; results are listed in Table 3.8. The second borehole was taken near Rankala, Phulewadi Road, Kolhapur. Sampling is done up to the depth of 4.75 m in 4 different layers; Table 3.9 represents all test results. Consolidation parameters were calculated with reference to IS: 8009; Table 3.10 shows values for all parameters.

Table 3.5: Test results of soil collected at boundary of the city.

Sr. No.	Location	Sample ID	Specific Gravity	Liquid Limit (%) (Casagrande's Apparatus)	Liquid Limit(%) (Cone Penetration)	Plastic Limit (%)	Plasticity Index (%)	Dry Unit Weight (kN/m ³)	Free Swell Index (%)
1	Kandalgaon	KG-I	2.86	53.25	54.13	27.92	25.33	10.45	40.00
2		KG-II	2.70	52.77	52.4	29.72	23.05	13.00	40.00
3		KG-III	2.73	52.37	53.26	29.62	23.75	12.30	40.00
4	Rankala	RK-I	2.53	56.42	51.18	22.05	34.37	10.90	30.00
5		RK-II	2.54	53.20	54.06	27.58	25.62	13.70	30.00
6		RK-III	2.58	55.33	52.27	26.85	29.48	12.80	30.00
7	Kaneriwadi	KW-I	2.85	56.42	51.48	26.31	30.11	11.90	40.00
8		KW-I	2.41	53.68	53.04	22.50	31.18	12.00	40.00
9		KW-III	2.68	55.23	51.36	24.36	30.87	11.70	40.00
10	Shiroli	SH-I	2.51	53.25	54.39	24.30	28.95	11.90	30.00
11		SH-II	2.62	56.00	51.18	26.98	29.02	14.10	30.00
12		SH-III	2.58	55.78	51.12	25.2	30.58	12.30	30.00
13	Shiye	VH-I	2.50	55.18	58.23	24.78	30.40	12.10	30.00
14		VH-II	2.70	50.55	55.50	26.82	23.73	13.20	30.00
15		VH-III	2.65	54.24	55.17	24.39	29.85	13.20	30.00

Table 3.6: Test results of soil collected in Kolhapur city.

Sr. No.	Sample ID	Bulk Unit Weight (kN/m ³)	Field Moisture Content (%)	Dry Density (kN/m ³)	Specific Gravity	Liquid Limit (%)	Plastic Limit (%)	Shrinkage Limit (%)	Plasticity Index (%)	Maximum Dry Unit Weight (kN/m ³)	Optimum Moisture Content (%)	California Bearing Ratio Value-unsaturated (%)	Cohesion (kN/m ²)	Angle of Internal Friction (degree)	Free Swell Index (%)	Unconfined Compressive Strength (kN/m ²)
1	KM-I	18.60	25.33	14.80	2.43	52.30	35.27	11.50	17.03	16.30	20.40	4.54	23.54	21.00	18.00	66.20
2	KM-II				2.38	55.60	31.20	11.43	24.40	15.90	20.20	4.21	20.59	18.00	20.00	65.82
3	SM-I	15.20	38.00	11.00	2.14	55.20	38.40	10.58	16.80	14.10	20.30	2.92	24.52	17.00	40.00	62.30
4	SM-II				2.16	53.90	35.60	11.20	18.30	14.40	20.20	3.03	26.48	18.00	20.00	62.22
5	BP-I	17.20	41.13	12.20	2.26	40.30	23.33	11.03	16.97	14.60	17.10	3.41	21.57	20.00	30.00	63.31
6	BP-II				2.15	38.46	24.60	10.32	13.86	13.50	16.80	2.71	25.50	17.00	50.00	62.80
7	CK-I	15.50	42.02	10.90	2.26	53.30	32.50	12.30	20.80	14.00	20.10	2.60	22.56	21.00	50.00	63.22
8	CK-II				2.40	52.40	33.80	11.23	18.60	14.70	20.30	3.42	21.57	19.00	50.00	65.24
9	KP-I	13.80	10.20	12.50	2.36	52.80	36.30	11.32	16.50	14.30	20.90	3.21	19.61	18.00	50.00	64.30
10	KP-II				2.34	50.20	35.40	10.89	14.80	13.90	20.40	2.90	20.59	18.00	50.00	64.02

Table 3.7: Test results of soil collected from Test pit- 01.

Sr. No.	Depth below GL (m)	Bulk Unit Weight (kN/m ³)	Field Moisture Content (%)	Dry Density (kN/m ³)	Specific Gravity	Liquid Limit (%)	Plastic Limit (%)	Shrinkage Limit (%)	Plasticity Index (%)	Maximum Dry Unit Weight (kN/m ³)	Optimum Moisture Content (%)	California Bearing Ratio Value- unsoaked (%)	Cohesion (kN/m ²)	Angle of Internal Friction (degree)	Free Swell Index (%)	Unconfined Compressive Strength (kN/m ²)
1	0.5	16.81	34.50	12.50	2.2	65.50	51.55	11.00	13.95	13.70	16.80	3.20	37.27	8.75	60.00	66.95
2	1.0	17.95	35.30	13.27	2.3	65.30	50.34	13.00	14.96	14.10	16.80	3.23	34.32	9.82	50.00	65.88
3	1.5	18.60	35.83	13.69	2.3	64.50	50.45	15.30	14.05	14.50	16.60	3.33	30.4	15.64	50.00	65.86
4	2.0	19.18	35.89	14.11	2.38	64.39	47.30	15.80	17.09	14.70	16.50	3.40	28.44	14.52	50.00	64.24
5	2.5	19.27	36.71	14.10	2.39	64.25	47.20	16.30	17.05	15.20	16.20	3.38	27.89	15.64	40.00	64.10

Table 3.8: Test results of soil collected from borehole- 01.

Sr. No.	Depth below GL (m)	Bulk Unit Weight (kN/m ³)	Field Moisture Content (%)	Dry Density (kN/m ³)	Specific Gravity	Liquid Limit (%)	Plastic Limit (%)	Shrinkage Limit (%)	Plasticity Index (%)	Maximum Dry Unit Weight (kN/m ³)	Optimum Moisture Content (%)	California		Angle of Internal Friction (degree)	Free Swell Index (%)	Unconfined Compressive Strength (kN/m ²)
												Bearing Ratio Value- unsoaked (%)	Cohesion (kN/m ²)			
1	0.5	16.98	34.65	12.61	2.3	64.75	48.50	11.20	16.25	14.70	13.80	3.3	26.48	19.00	60.00	64.77
2	1.5	17.17	35.50	12.67	2.4	64.25	45.96	11.60	18.29	15.90	13.50	3.4	21.57	19.75	60.00	62.33
3	2.5	17.27	35.80	12.72	2.5	63.70	45.66	11.23	18.04	16.30	13.50	3.46	20.59	17.74	50.00	62.88
4	3.5	17.49	37.20	12.75	2.52	63.22	45.39	11.83	17.83	16.90	13.00	3.52	20.20	20.23	40.00	63.02

Table 3.9: Test results of soil collected from borehole- 02.

Sr. No.	Depth below GL (m)	Bulk Unit Weight (kN/m ³)	Field Moisture Content (%)	Dry Density (kN/m ³)	Specific Gravity	Liquid Limit (%)	Plastic Limit (%)	Shrinkage Limit (%)	Plasticity Index (%)	Maximum Dry Unit Weight (kN/m ³)	Optimum Moisture Content (%)	California		Angle of Internal Friction (degree)	Free Swell Index (%)	Unconfined Compressive Strength (kN/m ²)
												Bearing Ratio Value- unsoaked (%)	Cohesion (kN/m ²)			
1	1.0	17.30	34.59	12.85	2.34	64.30	48.12	11.80	16.18	14.40	14.50	3.33	27.46	20.15	60.00	65.42
2	2.0	17.37	34.88	12.88	2.38	63.78	45.80	12.40	17.98	16.00	14.00	3.43	26.56	21.28	60.00	63.10
3	3.0	17.52	35.20	12.96	2.40	62.62	45.41	13.33	17.21	16.50	13.80	3.48	25.50	21.32	30.00	63.23
4	4.0	17.89	35.36	13.22	2.41	62.20	45.20	13.38	17.00	16.90	13.00	3.55	19.61	21.31	30.00	64.45

Table 3.10: Consolidation parameters (Ref.- IS: 8009).

Sr. No.	Sampling Location	Depth (m)	Compression index (Cc)	Recompression index (Cr)
1	Ramnagar test pit 01	0.5	0.499	0.033
		1.0	0.498	0.033
		1.5	0.482	0.032
		2.0	0.470	0.031
		2.5	0.454	0.030
2	Line Bazar borehole 01	0.5	0.491	0.033
		1.5	0.484	0.032
		2.5	0.483	0.032
		3.5	0.470	0.031
3	Rankala borehole 02	1.0	0.491	0.033
		2.0	0.484	0.032
		3.0	0.474	0.032
		4.0	0.461	0.031

3.7 Grain size distribution analysis of BCS

Black cotton soil is basically fine-grained, expansive soil due to its mineralogical content. The grain size distribution was studied by performing both mechanical sieve analysis and hydrometer analysis. The details are discussed below.

3.7.1 Hydrometer analysis

Grain size distribution analysis by the hydrometer method is carried out for samples collected through the sampling program. It was observed that more than 90% of soil is finer than a 75-micron IS sieve. Test results indicated that soil contains almost zero fractions of gravel; a very low percentage of the sand fraction increased from coarse to fine. It was observed that there is a major percentage of silt and clay fractions present in soil. Also, it was observed that silt percentage increases with the depth, and there was a reduction in clay fractions at all locations in the study area. figure 3.5 and 3.6 show the reduction of clay fractions from 48.54% to 30.71% from 1.5m to 3.5m depth, below ground level. Also, figure 3.7 and 3.8 present a reduction of clay fractions from 52.0% to 22.0% from 2.0m to 4.0m depth below ground level. There was an increment in the medium sand fraction at the Rankala borehole, which was equal to about 8% of the total weight. Table 3.11 summarizes the results of the grain size distribution analysis.

Table 3.11: Particle size distribution at sampling points.

Type	Particle Size	Line Bazar (1.5m depth)	Line Bazar (3.5m depth)	Rankala (2.0 m depth)	Rankala (4.0 m depth)
Gravel (%)	Coarse	-	-	-	-
	Fine	-	-	-	1.88
Sand (%)	Coarse	0.10	0.10	0.20	2.20
	Medium	1.46	1.46	1.84	7.76
	Fine	1.84	1.84	1.92	3.14
Silt (%)	-	48.06	65.89	44.03	64.16
Clay (%)	-	48.54	30.71	52.00	22.74

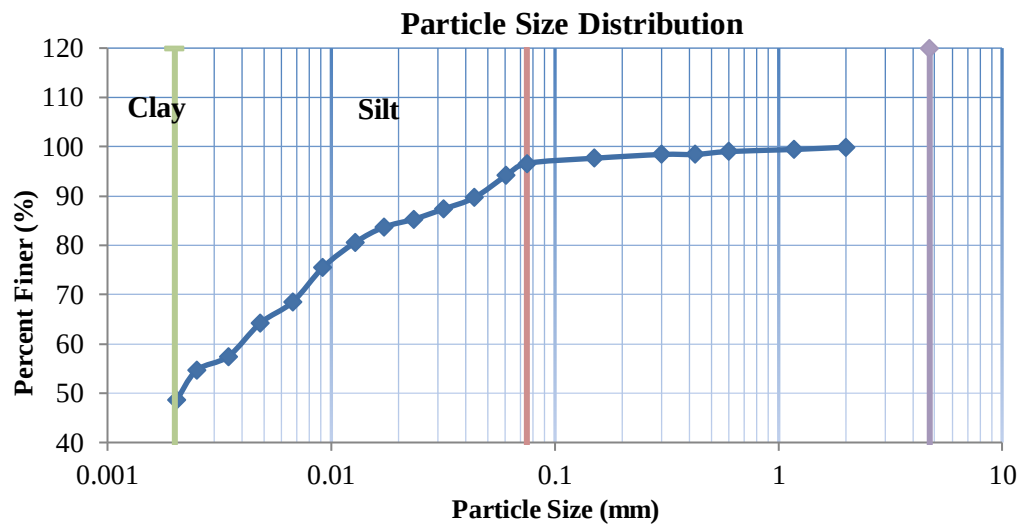


Figure3.5: Grain size distribution of soil collected from Line Bazar at 1.5m.

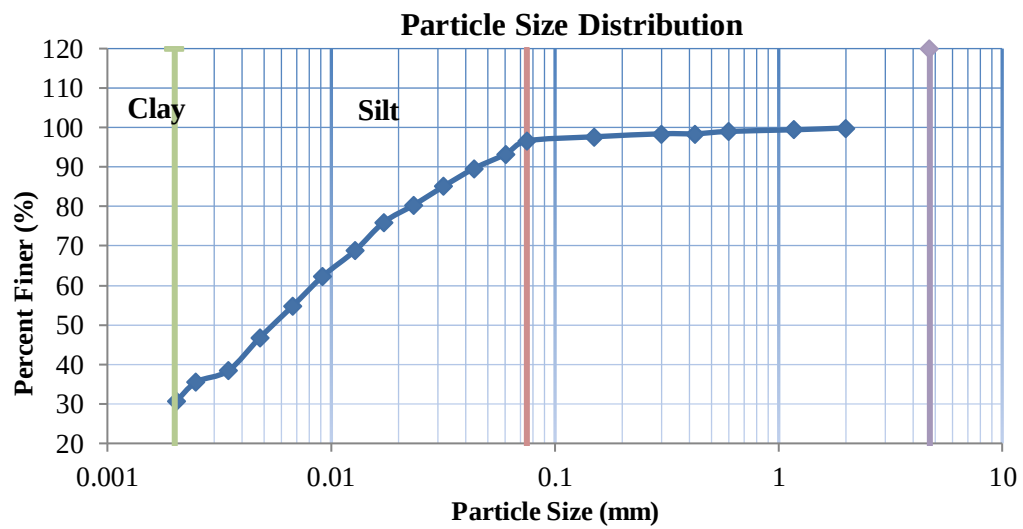


Figure 3.6: Grain size distribution of soil collected from Line Bazar at 3.5m.

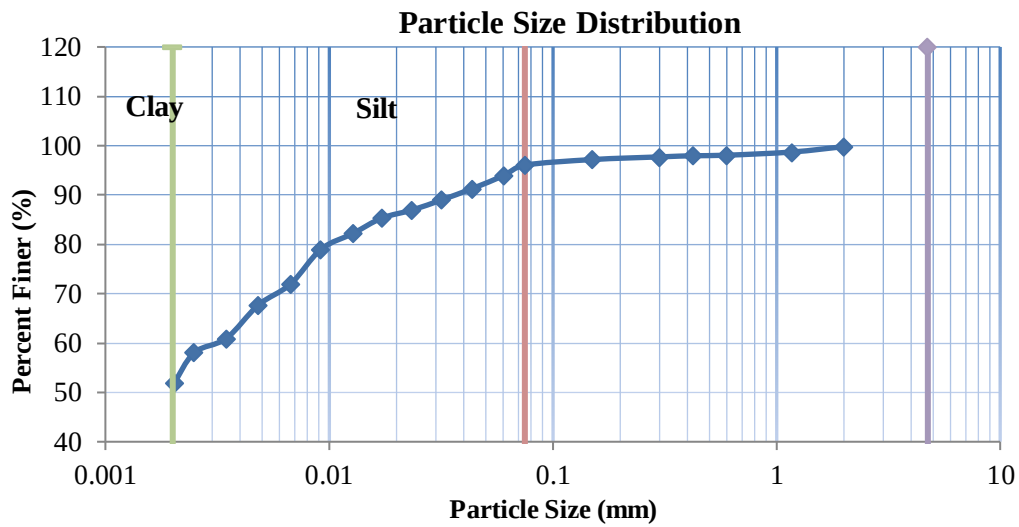


Figure3.7: Grain size distribution of soil collected from Rankala at 2.0 m.

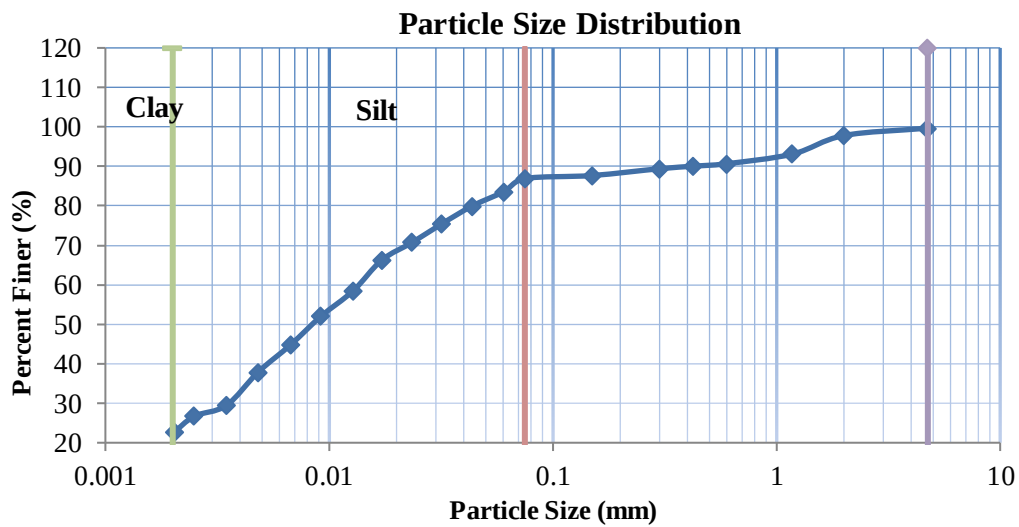


Figure3.8: Grain size distribution of soil collected from Rankala at 4.0 m.

3.8 Consistency and classification of soil samples collected from study area

The consistency of fine-grained soil pertains to its stiffness, which fluctuates with the water content. An incremental rise in water content induces a transformation of the soil's condition from solid to semi-solid, then to plastic, and ultimately to liquid. Fine-grained soils are defined as those in which over 50% of the material consists of particles

smaller than 0.075 mm. Clay particles possess a laminar morphology that facilitates water adhesion, hence conferring plasticity. An Indian standards plasticity chart, derived from the liquid limit (LL) and plasticity index (PI) values, is available for categorisation purposes. The 'A' line in this figure is represented as $PI = 0.73(LL - 20)$.

3.8.1 Plasticity chart for soil samples collected from 1.5 m depth

Soil was collected from the boundaries and various areas within different wards in Kolhapur city at a depth of 1.5 meters below ground level by open excavation as part of the sampling program. Samples were tested for consistency limits and classified according to the plasticity chart as shown in figure 3.9. It was observed that some soil samples appeared below the A line with a liquid limit greater than 50%; hence, they are classified as silts of high plasticity (MH). Also, it was observed that approximately equal numbers of samples appeared above the A line with a liquid limit greater than 50%; hence, they are classified as clays of high plasticity (CH). Only a small number of samples were found in the intermediate plasticity zone, with a liquid limit ranging from 35% to 50% and a PI exceeding the A line, which led to their classification as clay of intermediate plasticity (CI).

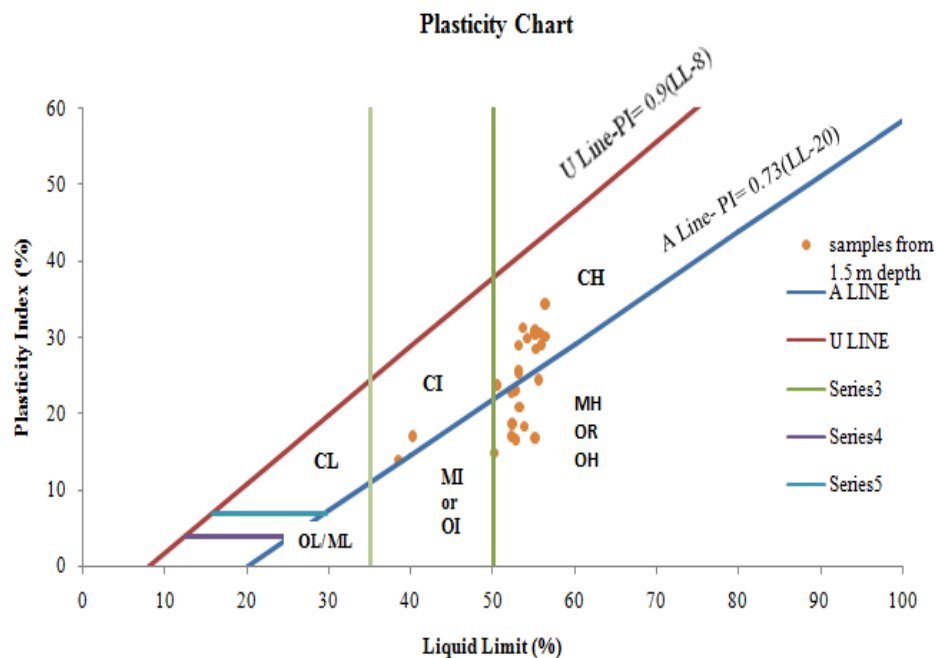


Figure3.9: Plasticity chart for samples from 1.5m depth.

3.8.2 Plasticity chart for soil samples collected from different depths

In this study, to analyze variation of all properties with depth, some samples were collected from different depths below ground surface at different locations in Kolhapur city. One pit was excavated at Ramnagar, Kolhapur up to a depth of 2.5m. Also, one bore hole was excavated at Line Bazar, near Divisional Agriculture Co. Director Office, Kolhapur, up to a depth of 3.5m by tractor mounted motorized auger. Second bore hole was taken by manual augur boring at identified location behind D-Mart, near Rankala, Phulewadi Road, Kolhapur. Sampling is done up to the depth of 4.75 m in 4 different layers. In this way samples were collected from different depths below ground level as 0.5m, 1m, 1.5m, 2m, 2.5m 3.0m, 3.5m and at 4.0m. Various tests were conducted on samples collected and results were analyzed. Samples were tested for consistency limits and classified according to plasticity chart as shown in figure 3.10. It was observed that all soil samples were appeared below A line with liquid limit greeter than 50%, hence they are classified as silt of high plasticity (MH).

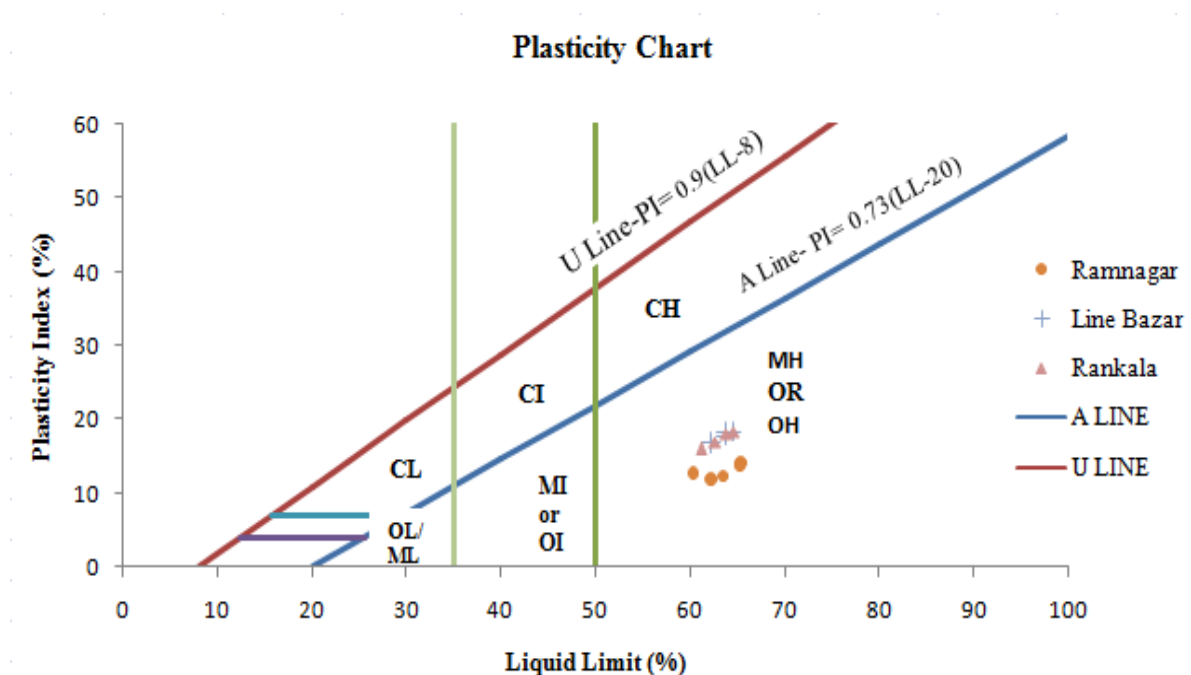


Figure 3.10: Plasticity chart for samples from different depths.

3.9Field Emission Scanning Electron Microscopy (FESEM) analysis

With a depth of focus that is almost infinite and magnifications ranging from 10x to 300,000x, emission scanning electron microscopy (FESEM) offers topographical and elemental data. Another area of its use is in determining grain size. FESEM has a spatial resolution as low as 11/2 nanometers, three to six times better than traditional scanning electron microscopy (SEM), and it also creates pictures with less electrostatic distortion. This study uses FESEM to determine the grain size of soil particles. figure 3.11 to 3.14 present FESEM analysis with scales of 5 μm to 500 nm, respectively, for the samples collected from the Rankala borehole up to a depth of 4.0 m. The grain size was found to be equal to 0.503 μm based on FESEM analysis.

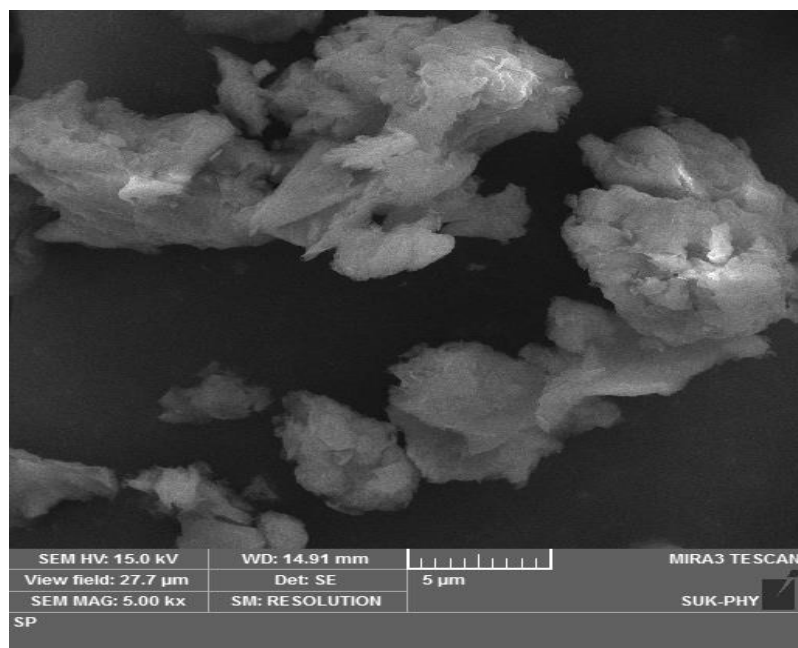


Figure 3.11: FESEM image (Scale = 5 μm)(Rankala-3.5m).

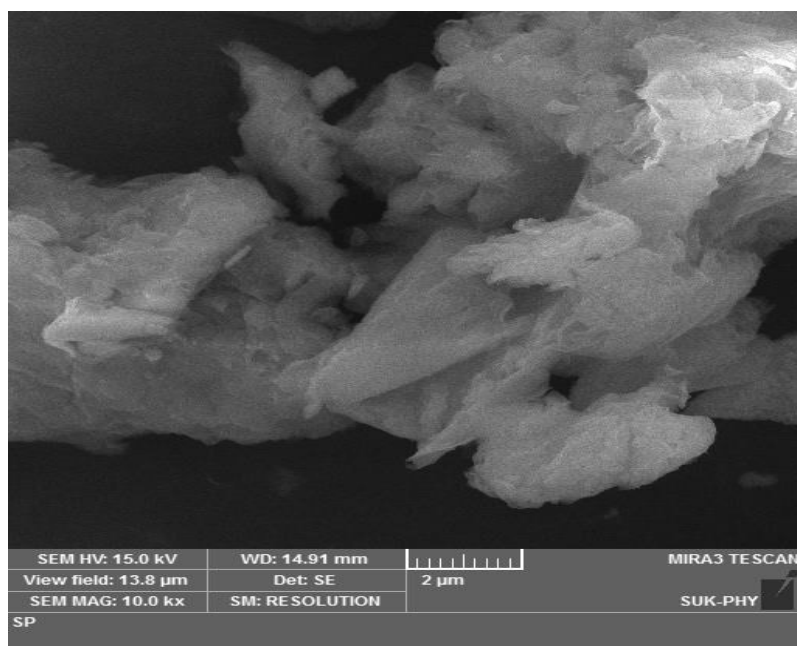


Figure 3.12: FESEM image (Scale = 2 μ m) (Rankala-3.5m).

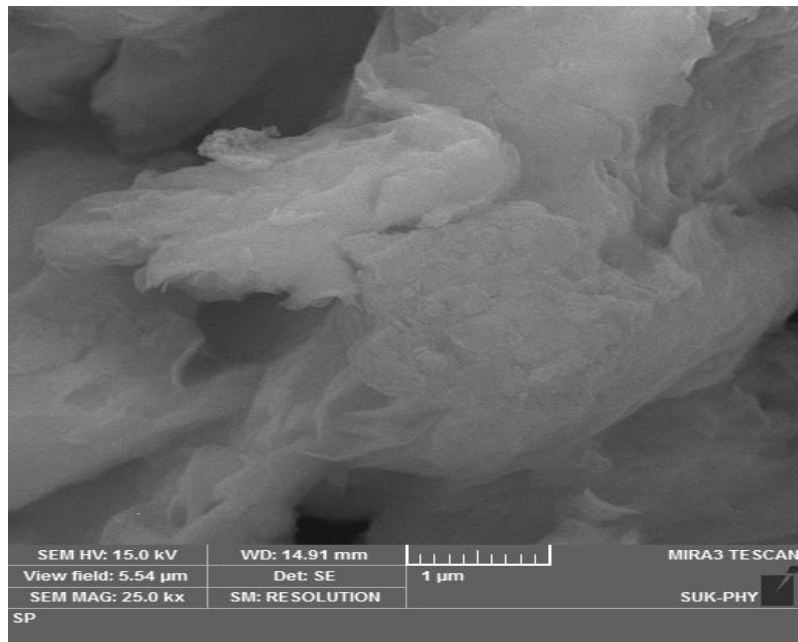


Figure 3.13: FESEM image (Scale = 1 μ m) (Rankala-3.5m).

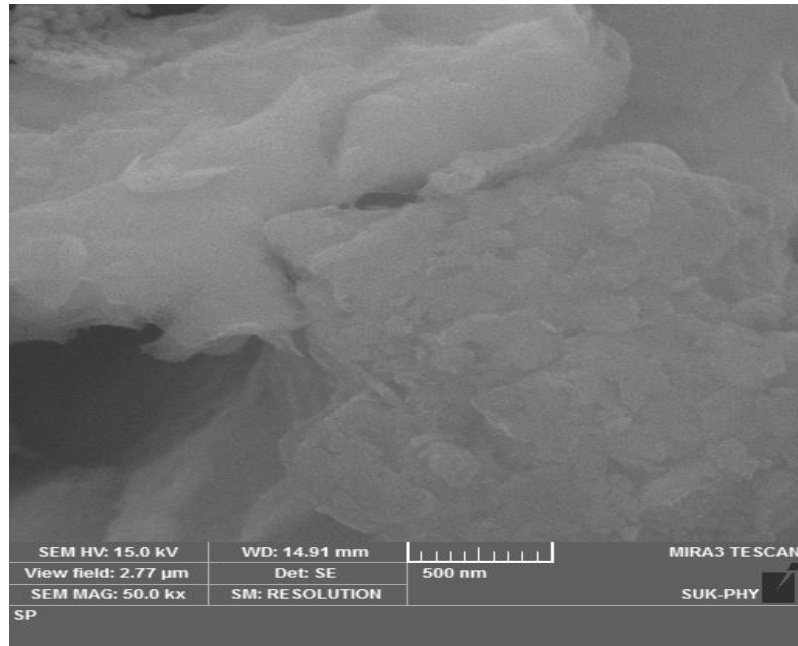


Figure 3.14: FESEM image(Scale = 500nm) (Rankala-3.5m).

The Field Emission Scanning Electron Microscopy (FESEM) image of untreated Black Cotton Soil at 50,000× magnification reveals a highly flocculated microstructure, characteristic of montmorillonitic clay. The image shows irregularly shaped and loosely packed clay particles with a significant presence of interparticle voids. The flake-like morphology and disordered particle arrangement indicate weak interparticle bonding and high potential for water adsorption and swelling. The rough surface texture and dispersed structure suggest a lack of cementation or binding agents in the native soil, which is consistent with its known poor engineering properties such as low shear strength, high plasticity, and volumetric instability under moisture variations. These microstructural characteristics underline the need for stabilization interventions to enhance the soil's performance in geotechnical applications.

3.10 X-Ray Diffraction (XRD) analysis

X-ray diffraction (XRD) is a prevalent method for determining the phases present in diverse sample types. This approach entails examining the atomic and molecular configuration of crystals. When X-rays engage with a crystalline substance, the ordered configuration of atoms results in the scattering of X-rays in designated directions. Through the examination of the angles and intensities of the scattered beams, researchers may produce a three-dimensional representation of the electron density inside the crystal, elucidating its structural characteristics. XRD is performed on the samples collected from

borehole at Line Bazar and it is matched with the Montmorillonite-15A. The chemical formula for sample is $\text{Na}_{0.3}(\text{Al}, \text{Mg})_2\text{Si}_4\text{O}_{10}(\text{OH})_2 \cdot 4\text{H}_2\text{O}$ and its name is Montmorillonite-15A. It is matched with JCPDS Card No.:00-029-1498. The crystallite size (D) for sample for intense plane was calculated using Debye-Scherrer formula given by,

$$D = \frac{0.9\lambda}{\beta \cos \theta}$$

Where, D represents crystallite size (nm), λ denotes wavelength of X-ray ($\lambda=1.5406 \text{ \AA}$) for Cu K_{α} line, β is full width at half maximum (FWHM) and θ is the Braggs angle. The wavelength (λ) of X-ray for Cu $K_{\alpha \text{ line}}$ is $\lambda=1.5406 \text{ \AA}$, β full width at half maximum (FWHM) value is 0.0984 and θ is the Braggs angle having value 13.32° . So, the estimated value of crystallite size (D) for sample is 86.69nm. The figure 3.15 shows XRD plot of the samples collected through bore hole at Line Bazar.

The X-ray Diffraction (XRD) analysis of Black Cotton Soil reveals the presence of both crystalline and clay minerals. A dominant sharp peak near $2\theta \approx 27^\circ$ indicates a high content of quartz, while broader peaks around 20° – 25° suggest the presence of expansive clay minerals such as montmorillonite and possibly kaolinite. Additional moderate peaks in the range of 35° – 50° indicate the presence of secondary minerals like feldspars or illite. The mixture of sharp and broad peaks reflects a combination of well-crystalline and poorly crystalline (amorphous) phases. This mineralogical composition confirms that black cotton soil exhibits high plasticity and swelling potential, which aligns with its known problematic behavior in geotechnical applications. This analysis is crucial for assessing the effectiveness of stabilization techniques using additives like Terrazyme and Xanthan Gum. Also, the Table 3.12 shows the percentage of montmorillonite, kaolinite and illite. These minerals are majorly responsible for behavior of BCS.

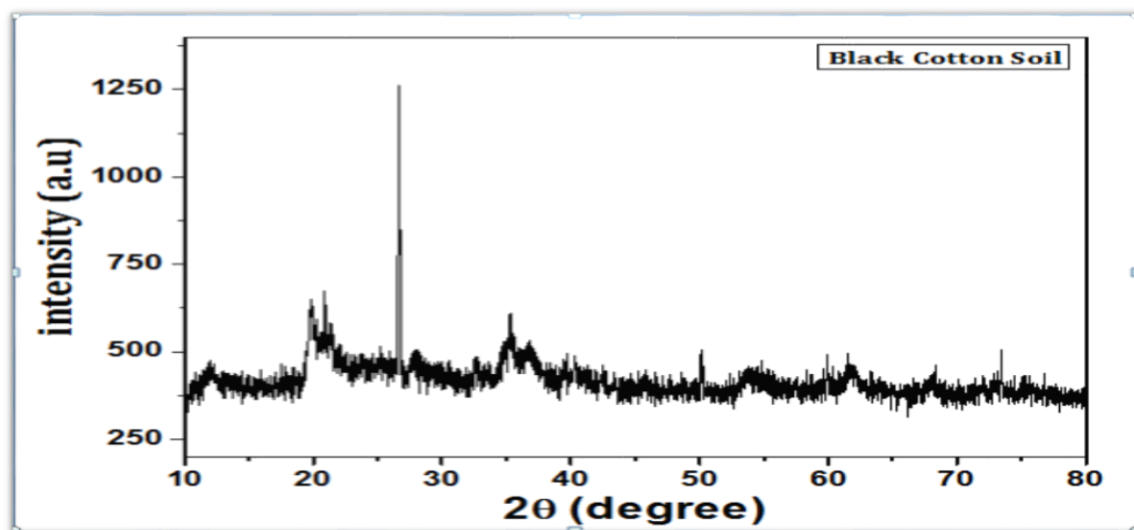


Figure 3.15: XRD plot-intensity vs. 2θ (Line Bazar-1.5m).

Table 3.12: XRD analysis- mineral composition of BCS.

Mineral	Quantity (wt.-%)	H (wt.-%)	Li (wt.-%)	O (wt.-%)	Mg (wt.-%)	Al (wt.-%)	Si (wt.-%)	K (wt.-%)	Fe (wt.-%)
Illite	10.3	0.0	0.0	48.58	0.0	27.31	14.21	9.89	0.0
Kaolinite	44.3	1.56	0.0	55.78	0.0	20.9	21.76	0.0	0.0
Montmorillonite	45.4	0.0	0.18	52.93	1.13	7.68	36.24	0.0	1.85
Weighted total	100.0	0.69	0.08	53.74	0.51	15.56	27.56	1.02	0.84

The XRD analysis, as per the Table 3.12 shows that, Black Cotton Soil is predominantly composed of montmorillonite (45.4%), followed closely by kaolinite (44.3%), and a smaller portion of illite (10.3%). These minerals are all types of clay minerals, each with different properties that significantly affect the behaviour of the soil.

Montmorillonite is a highly expansive clay mineral, known for its high shrink-swell capacity, making soils containing it highly reactive to moisture changes. High Si (36.24%) and O (52.93%) content supports its layered silicate structure. The presence of Mg (1.13%) and Fe (1.85%) suggests substitution within the clay layers, which can affect cation exchange capacity and reactivity. Whereas kaolinite, a non-expanding clay with a

relatively stable structure, is also present in soil. Higher Al (20.9%) and moderate Si (21.76%) content reflects the 1:1 layer structure typical of kaolinite. This mineral contributes to low plasticity and moderate cohesion, improving workability compared to montmorillonite. The third important clay mineral is illite, a moderately reactive clay intermediates between kaolinite and montmorillonite. Notable for its high K content (9.89%), which helps stabilize its structure by holding layers together. High Al (27.31%) and moderate Si (14.21%) content confirms its layered phyllosilicate nature. Overall, the dominance of montmorillonite makes the soil highly plastic, moisture-sensitive, and prone to swelling and shrinkage. The presence of kaolinite balances this behaviour slightly by adding stability and reducing excessive plasticity. Illite, although minor, contributes some strength and structural consistency due to its potassium content.

The combined mineralogical composition indicates that BCS is highly moisture-sensitive and structurally unstable, making it unsuitable for direct use in construction without stabilization. Therefore, chemical or biological treatments such as Terrazyme or Xanthan Gum are recommended to improve its engineering performance by reducing plasticity and enhancing load-bearing capacity.

3.11 Energy-dispersive X-ray spectroscopy (EDX) analysis

The elemental analysis or chemical characterization of a sample is accomplished using energy-dispersive X-ray spectroscopy (EDX). To promote the emission of distinctive X-rays from the soil sample, a high-energy beam of charged particles, such as electrons or protons, or an X-ray beam, is focused on the soil sample. An energy-dispersive spectrometer is used to detect the amount and energy of X-rays emitted by the soil sample. FESEM microstructure pictures aid in forecasting shear strength, and EDS analysis reveals changes in chemical composition such as Si, Ca, Al, Fe, and Mg, which are responsible for increased soil stabilization. The EDX plot for the samples taken from the Rankala borehole at 1.5 m is shown in Figure 3.16. The plot for the soil taken from 3.5 m below ground level is shown in figure 3.17.

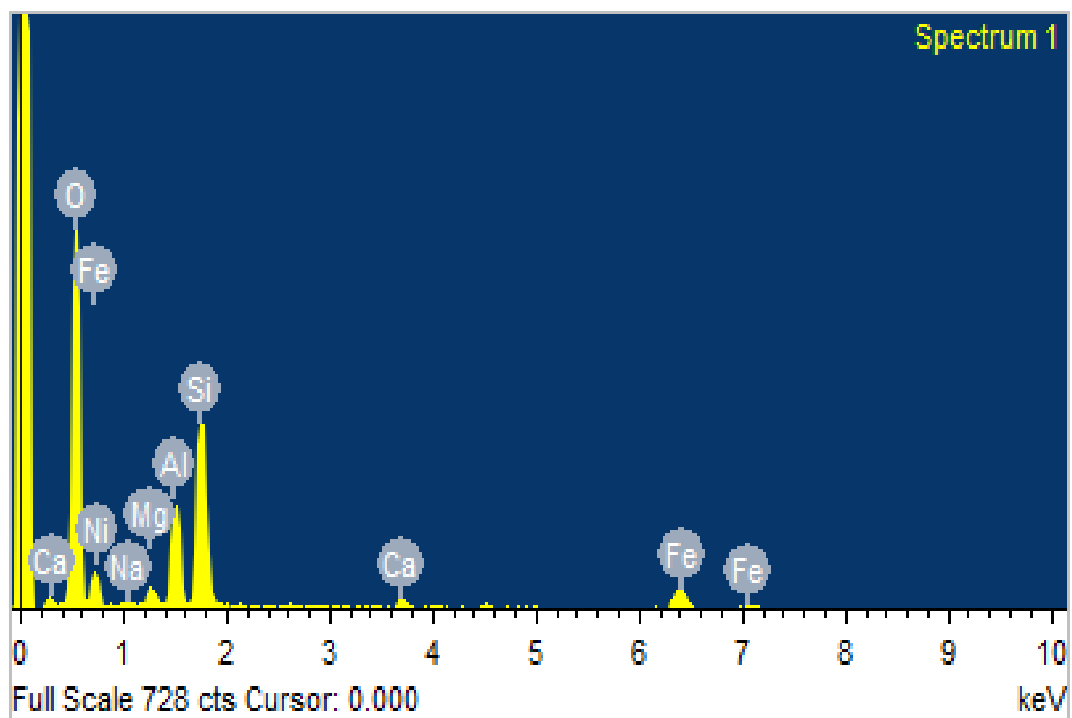


Figure 3.16: EDX plot (Rankala-1.5m).

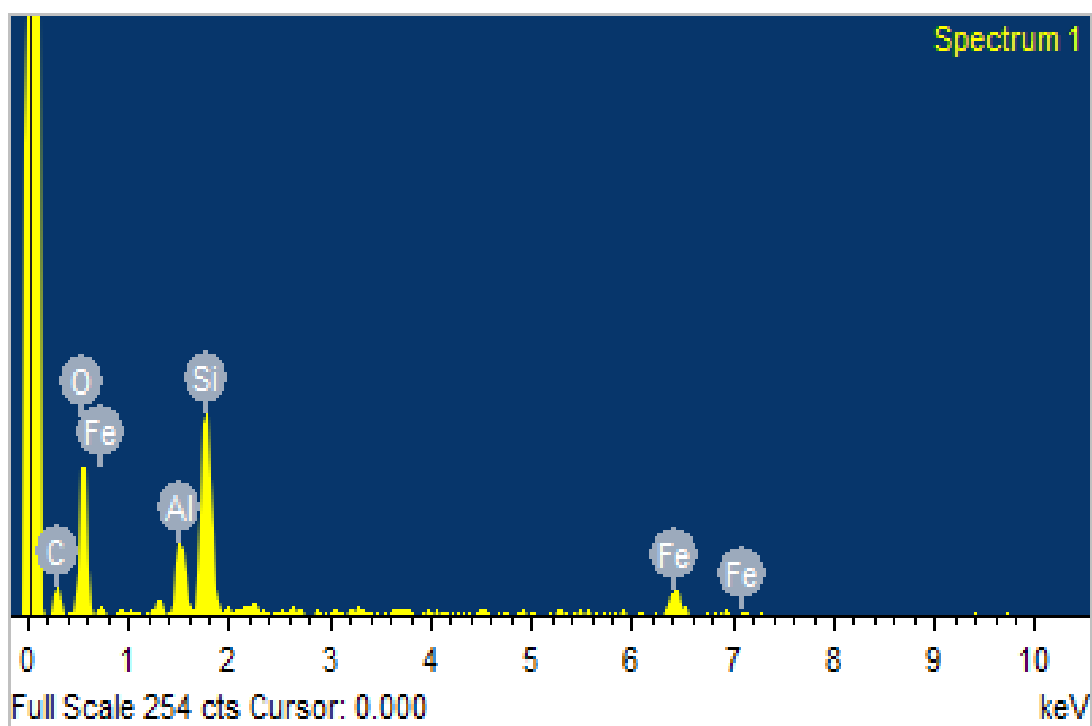


Figure 3.17: EDX plot (Rankala-3.5m).

EDX analysis was performed on samples taken at two distinct depths in Rankala, 1.5m and 3.5m. Table 3.13, shows each component and its proportion using this method. It can be seen that at Ramnagar site, SiO_2 content is predominant in the soil. Iron oxide is also found in appreciable quantities.

Table 3.13: EDX results on soil samples collected in Ramnagar.

Sr. No.	Element	Percentage by Weight of soil (at 1.5m depth)	Atomic weight % (at 1.5m depth)	Percentage by Weight of soil (at 3.5m depth)	Atomic weight % (at 3.5m depth)
1	Oxygen	37.66	46.13	60.44	75.77
2	Sodium	-	-	0.11	0.09
3	Magnesium	-	-	1.34	1.11
4	Aluminium	6.73	4.89	8.05	5.98
5	Silicon	20.32	14.18	17.01	12.15
6	Calcium	-	-	1.46	0.73
7	Iron	17.80	6.25	11.33	4.07
8	Nickel	-	-	0.27	0.09
9	Carbon	17.49	28.55	-	-
10	Total	100.00		100.00	

3.12 Summary

Sampling locations were identified from various wards of Kolhapur city through reconnaissance surveys where black cotton soil is present. Sampling was done at twenty-eight different locations. Samples were collected from different depths below GL, such as 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, and at 4.0 meters. Various tests were conducted on samples collected, and results were analyzed; soil characteristics are listed in Table 3.14. Classification of soil was done on the basis of a plasticity chart with the help of soil test results. After experimental analysis, various locations were marked on a plasticity chart; this will be used as a database for many civil engineering works.

Table 3.14: Characteristics of black cotton soil in study area.

Sr. No.	Soil property	Range of values
1	Mechanical analysis	
	Sand	15 to 30%
	Silt and clay	60 to 95%

2	Consistency limits	
	Liquid limit (LL)	38.46 – 65.40%
	Plastic limit (PL)	22. – 51.71%
	Plasticity index (PI)	11.89-30 %
	Shrinkage limit (SL)	9.15 - 16%
3	Soil classification	CH – MH-CI
4	Specific gravity(G)	2.08 - 2.73
5	Bulk unit weight (γ)	13.8-19.8kN/m ³
6	Dry unit weight	10.45 - 14.80 kN/m ³
7	Maximum dry unit weight (light compaction)	13.5 - 17.2 kN/m ³
8	Optimum moisture content (OMC)	13.50 - 20.90 %
9	Differential free swell index	20 - 60 %
10	California bearing ratio (CBR un-soaked)	2.4 - 4.60 %
11	Cohesion (c)	19.61 - 37.27 kN/m ²
12	Angle of internal friction (ϕ)	8.75 - 24.32°
13	Unconfined compression strength (UCS)	62.22 - 68.95 kN/m ²
14	Compression index (Cc)	0.454-0.499
15	Recompression index (Cr)	0.030-0.033

Chapter 4

Engineering behaviour and empirical co-relationship

4.1 Introduction

The development of empirical correlations between different black cotton soil (BCS) properties is very important due to its engineering behavior. For this, extensive sampling is necessary to analyze the variation in different characteristics and the resulting change in the behaviour of soil. In the course of this research work, BCS samples were obtained from various areas in Kolhapur for the sake of identification and classification. A civil engineer needs soil characteristics to construct a foundation or subgrade on the soil. Hence, correlations of all index properties, especially particle size, specific gravity, field density, consistency, maximum dry density (MDD), optimum moisture content (OMC), swell index, unconfined compressive strength (UCS), California bearing ratio value (CBR), cohesion (c), angle of internal friction (ϕ), etc., are beneficial. To develop empirical correlations, an accurate data set is required as input to achieve better accuracy. Correlations should always be supported by experimental analysis as well as extensive sampling of soil. For this study, sampling locations are identified in various wards of Kolhapur city where BCS is present through reconnaissance surveys. Sampling was done at twenty-eight different locations. Samples were collected from different depths below ground level, and characterization was done. The strength parameters that are important to evaluate safe bearing capacity (SBC) were also obtained. The main aim of this study is to develop an empirical correlation between BCS properties and their improvement. For this purpose, soil was tested for index and strength properties. After analyzing BCS, it was found that the properties of soil varied significantly across the different depths below ground level. Consistency limits showed distinct trends as the depth increased. Similarly, the strength properties, including shear strength and compressibility, exhibited notable variations with depth. The study underscores the significance of understanding the properties of BCS at various depths for efficient engineering and construction practices and thereby enhancing soil stability.

4.2 Variation of maximum dry unit weight and optimum moisture content

Variation of maximum dry unit weight and optimum moisture content through the standard Proctor test were analyzed and presented in figure 4.1 and figure 4.2. Various tests were conducted on samples as per IS: 2720; variations of properties with depth of excavation were analyzed. The analysis revealed that an increase in maximum dry unit weight across all three sites corresponds with a decrease in OMC as depth increases.

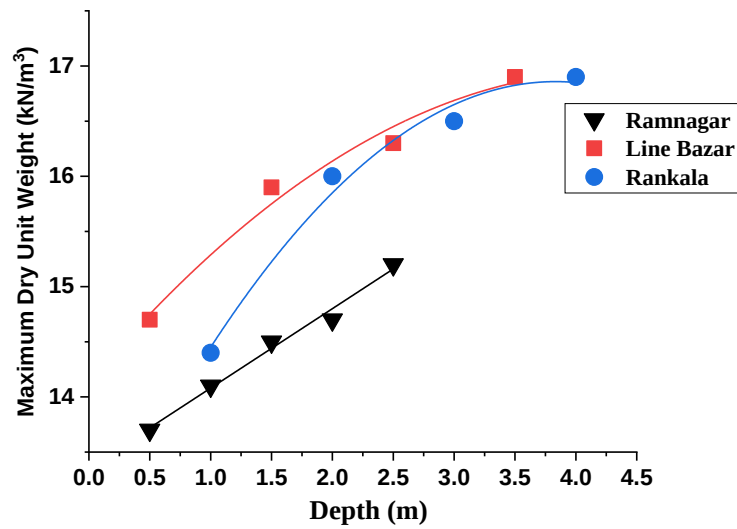


Figure 4.1: Variation of maximum dry unit weight.

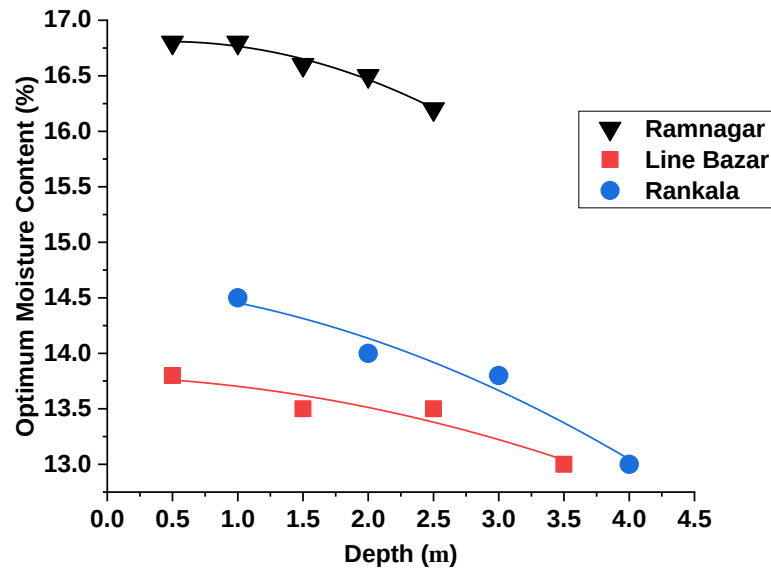


Figure 4.2: Variation of optimum moisture content with depth.

4.3 Variation of consistency limits, plasticity and free swell index

Variation of liquid limit, plastic limit, shrinkage limit, plasticity and differential free swell index were analyzed. Variation in each property is presented in figures 4.3 to 4.7. For all three sites, it was found that both liquid limit and plastic limit decreased with depth since clay content was found to reduce with depth while silt content increased. The plasticity index showed an initial increase to a depth of 1.5 m, followed by a subsequent decrease. For the Rankala site, a similar variation was observed in lesser proportion. However, the shrinkage limit increased with depth by about 10 to 15 percent. The differential free swell index decreased from about 60 percent to 30–40 percent with depth.

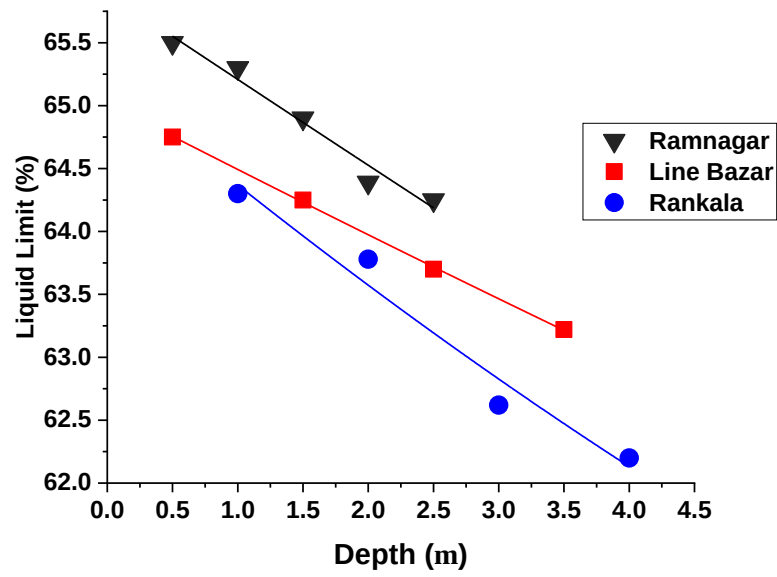


Figure 4.3: Variation of liquid limit with depth.

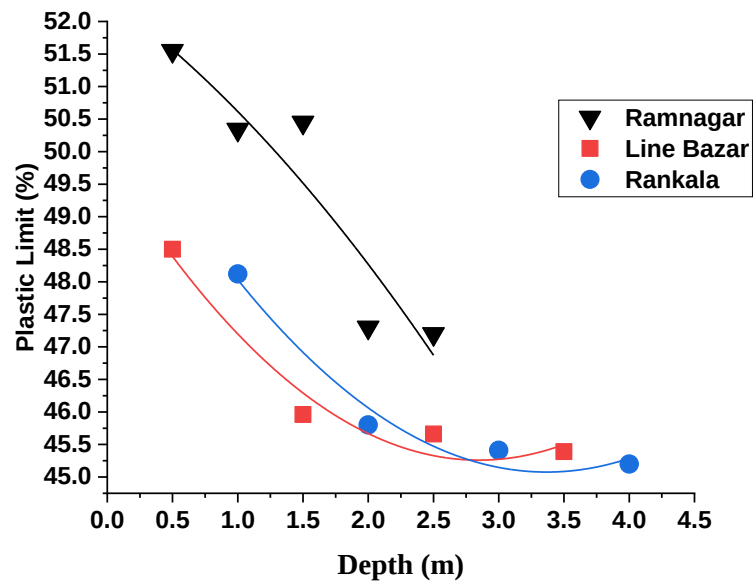


Figure 4.4: Variation of plastic limit with depth.

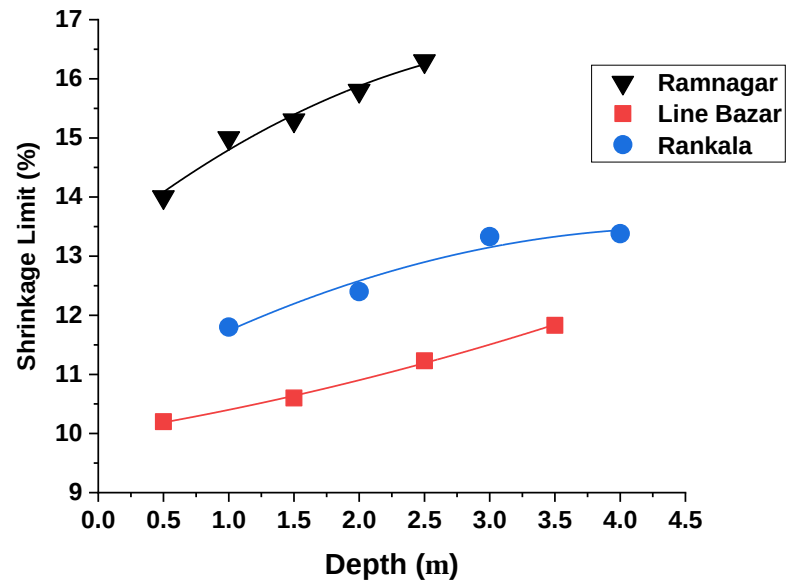


Figure 4.5: Variation of shrinkage limit with depth.

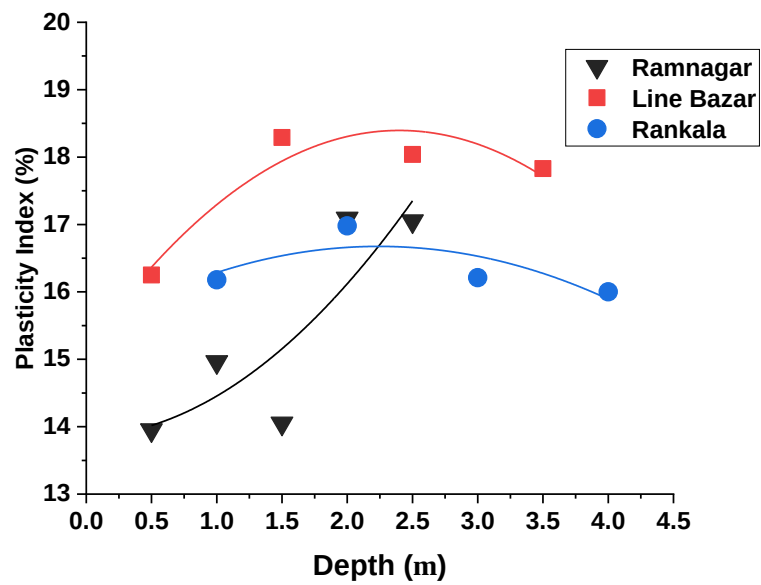


Figure 4.6: Variation of plasticity index with depth.

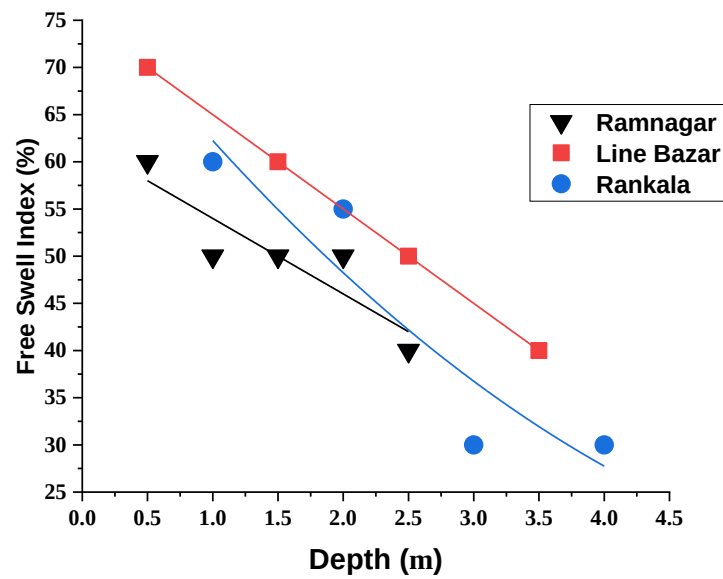


Figure 4.7: Variation of free swell index with depth.

4.4 Variation of strength properties and CBR value

Variations of cohesion, friction angle, unconfined compressive strength, and California bearing ratio value were obtained. Variations of each property are presented in figures 4.8 to 4.11. At all site locations, an increase in silt content and a decrease in clay content were observed with depth. At the Ramnagar site, the friction angle doubled and cohesion decreased by 20 percent with depth. This was due to the fact that for this site, silt content was higher as compared to the other two sites. CBR values increased by 10 percent with depth, whereas UCS values initially decreased by about 10 percent up to 2 meters and then remained constant.

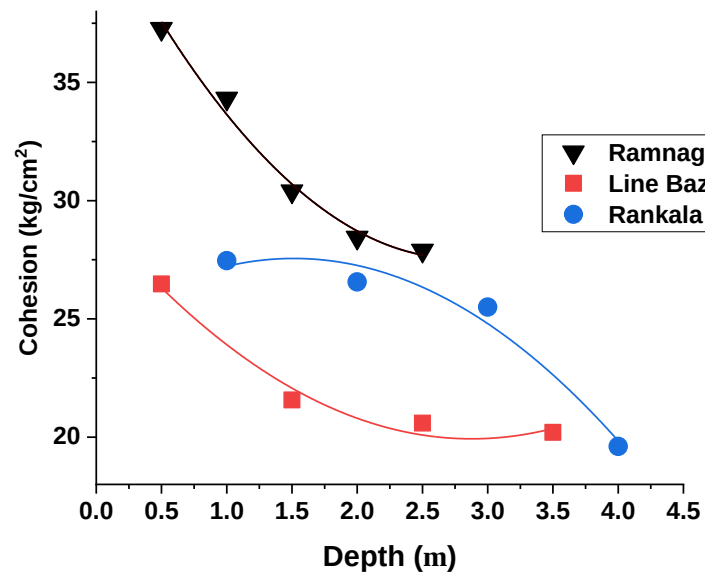


Figure 4.8: Variation of cohesion with depth.

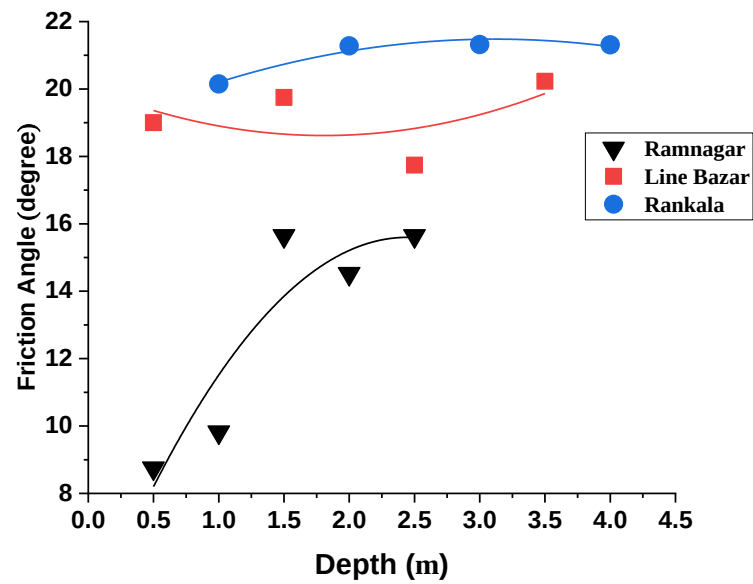


Figure 4.9: Variation of friction angle with depth.

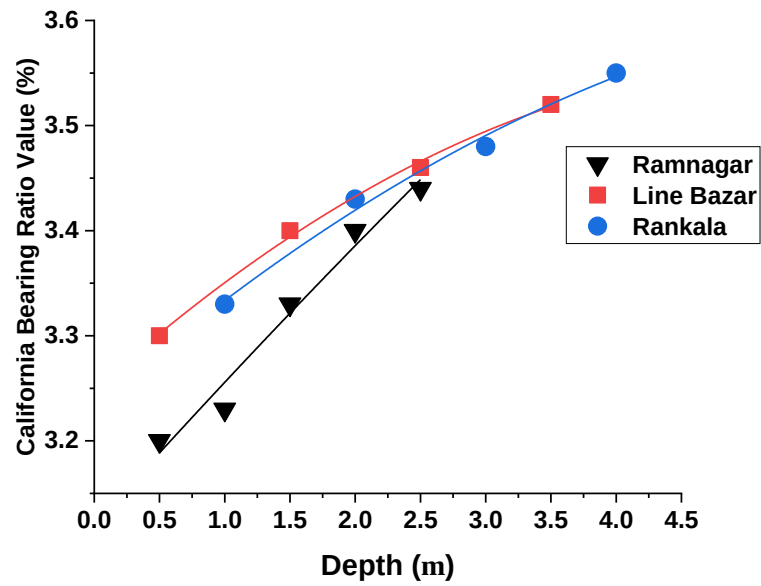


Figure 4.10: Variation of California bearing ratio value with depth.

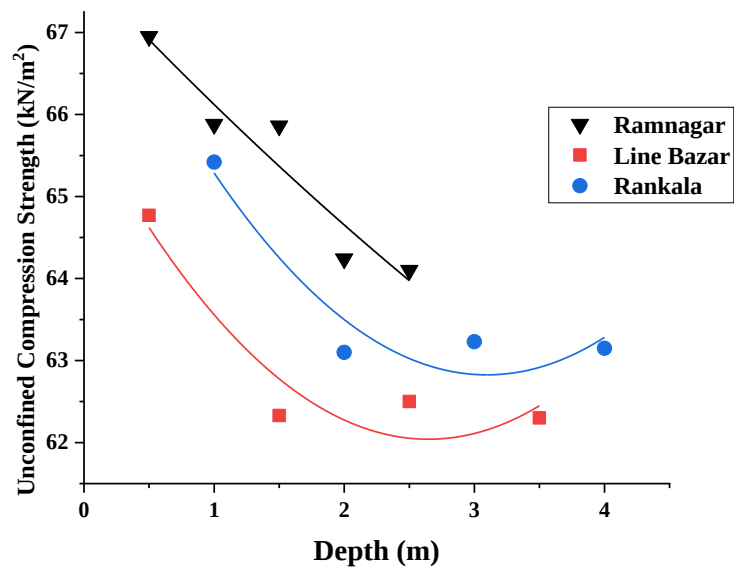


Figure 4.11: Variation of unconfined compression strength with depth.

The current investigation of the variation of characteristics with depth will be useful in making judgements about soil improvement and designing foundations in sampling

areas. These details may be utilised in a wide range of software programs, including those that are designed for stability analysis and design.

4.5 Empirical correlation of black cotton soil

This study aims to develop empirical correlation of black cotton soil properties by taking the number of samples from the different zones of Kolhapur; identification and classification of the soil for Kolhapur city is also important. Past empirical correlations for different properties of soil with strength properties developed by the researchers for different places cannot be applied directly to Kolhapur city. Analyzing the correlations of various index properties, including grain size, specific gravity, field density, consistency, optimum moisture content (OMC) and maximum dry density (MDD), swelling index, unconfined compressive strength (UCS), California bearing ratio (CBR), cohesion (c), and angle of internal friction, is advantageous for Kolhapur city. This study involved conducting a statistical analysis to identify the most suitable relationships. Correlations were developed and presented for BCS located in Kolhapur city. This database will be useful for engineers and consultants in the planning and designing of structures on these BCS in the entire Kolhapur region. In this study, regression analysis is identified as a statistical tool for the development of co-relationships between BCS properties. Focusing on the correlation between a dependent variable and one or more independent variables necessitates the use of several methodologies for modelling and analyzing multiple variables. Regression analysis is useful in understanding how the changes in independent variables affect the dependent variables, keeping other independent variables constant. One can discover whether independent variables are associated with the dependent variable and how these relationships resemble each other by using regression analysis. Regression analysis can infer the correlation between independent and dependent variables under certain conditions. There is a plethora of methods for performing regression analysis. Parametric regression is used by well-known methods like ordinary least squares and linear regression to create the regression function. These approaches estimate a finite number of unknown parameters from the data. In this study, based on pattern of data available swelling characteristics, maximum dry unit weight, unconfined compressive strength (UCS) and California bearing ratio value (CBR) were correlated. These properties were treated as dependent parameters and other index properties as independent parameters.

4.6 Correlations between different soil properties with consideration of variation with depth

Soil samples were collected from different locations and from different depths were utilized for various laboratory tests. To collect samples from different depths below ground level one test pit and two bore holes were excavated and samples were collected at different depth below GL. Test results were used to develop correlations by using regression analysis in CurveExpert 1.4 software. Correlations are analyzed on the basis of correlation coefficient (R^2) value, P- value and F- value.

In regression model analysis, the P-value and F-value are essential statistical tools used to evaluate the significance of predictors and the overall model fit. The P-value tests the null hypothesis that a particular coefficient in the regression model is equal to zero, which implies that the predictor has no effect on the dependent variable. A low P-value (typically ≤ 0.05) indicates that the null hypothesis can be rejected, suggesting that the predictor is statistically significant. A small P-value ($P\text{-value} \leq 0.05$) indicates strong evidence against the null hypothesis, so the null hypothesis can be rejected. (Montgomery et al., 2012). If the P- value is less than 0.05 then it indicates that predictor is statistically significant. This value is crucial for identifying which independent variables contribute meaningfully to the model.

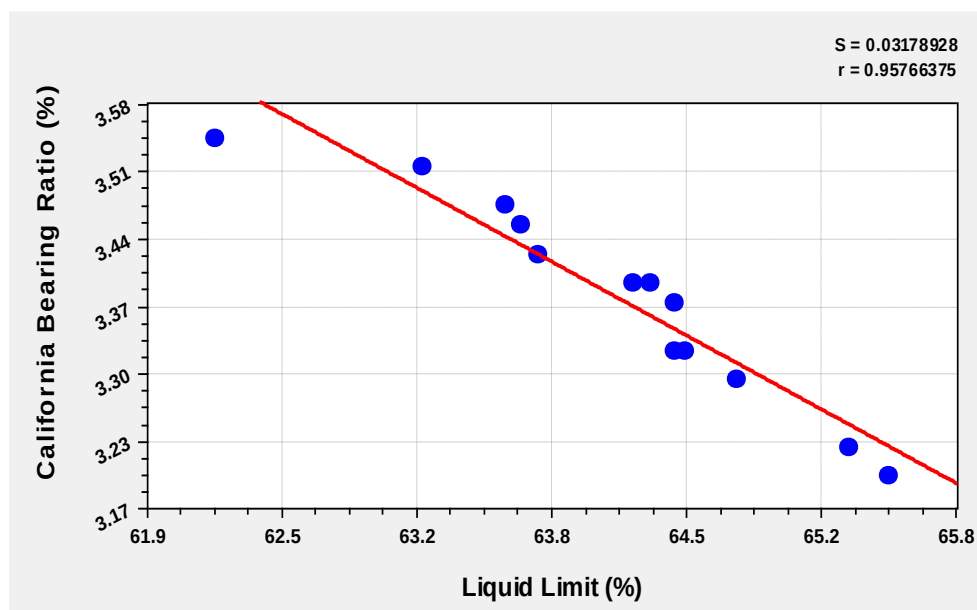
The F-value assesses the overall significance of the regression model. It tests the null hypothesis that all regression coefficients are equal to zero versus the alternative that at least one is not. A high F-value and a corresponding low P-value suggest that the model provides a better fit than a model with no independent variables. The F-test in regression compares a model with no predictors to the specified regression model and determines whether the latter explains a significant portion of the variability in the response (Kutner et al., 2005). A large F-value indicates that the regression model fits the data well. A small F-value (with $P > 0.05$) implies the model is not significantly better than a null model. Based on depth wise sampling of black cotton soil, some correlations were developed using regression analysis and listed below.

4.6.1 Liquid limit (LL) with California bearing ratio (CBR)

Correlation of CBR value with liquid limit was analyzed and shown in figure 4.12. Also, equation and correlation coefficient are reported in Table 4.1.

Table 4.1: Correlation of liquid limit (LL) with California bearing ratio(CBR).

Soil property	Equation	Correlation Coefficient	Standard Error	P- Value	F- Value Calculated	F- Value Tabulated
Liquid limit (LL) with California bearing ratio (CBR)	$CBR = 10.83 - 0.12 LL$	0.96	0.032	$2.87E^{-6}$	87.811	4.965

**Figure 4.12: LL Vs CBR.**

4.6.2 Maximum dry density (MDD) with California bearing ratio (CBR)

Correlation of maximum dry density with CBR value was analyzed and shown in figure 4.13. Also, equation and correlation coefficient are reported in Table 4.2.

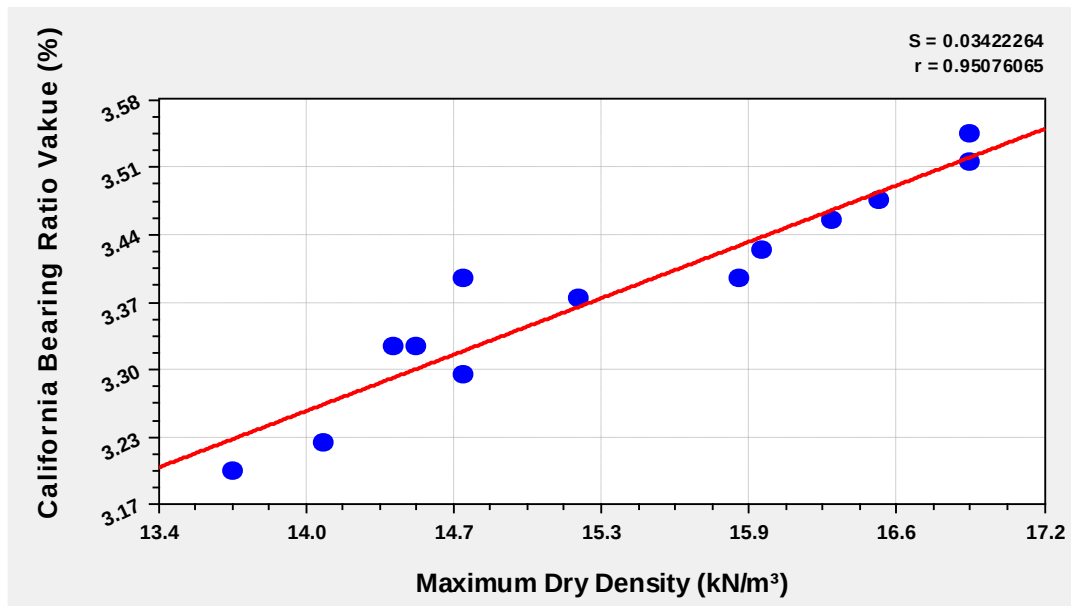


Figure 4.13:MDD Vs CBR.

Table 4.2: Correlation of maximum dry density with California bearing ratio (CBR).

Soil property	Equation	Correlation Coefficient	Standard Error	P- Value	F- Value Calculated	F- Value Tabulated
Maximum dry density (MDD) with California bearing ratio (CBR)	$CBR = 1.98 + 0.09 \text{ MDD}$	0.95	0.034	$5.85E^{-6}$	74.967	4.965

4.6.3 Plasticity index (PI) with unconfined compressive strength (UCS)

Correlation of PI with UCS was analyzed and shown in figure 4.14. Also, equation and correlation coefficient are given in Table 4.3.

Table 4.3:Plasticity index (PI) with unconfined compressive strength (UCS).

Soil property	Equation	Correlation Coefficient	Standard Error	P- Value	F- Value Calculated	F- Value Tabulated
Plasticity index (PI) with Unconfined compressive strength (UCS)	UCS = 79.46 - 0.91 PI	0.95	0.044	9.33E^-6	67.481	4.965

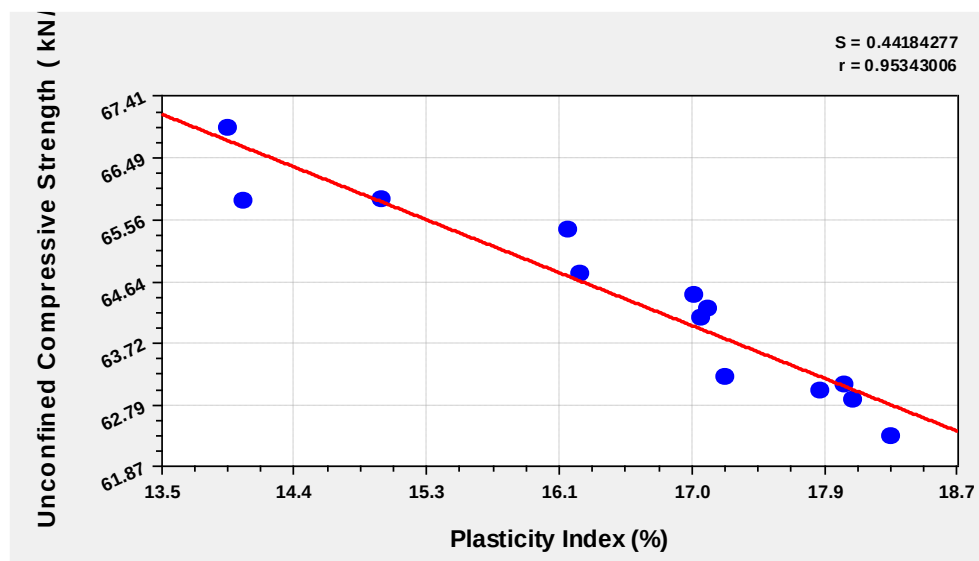


Figure4.14:PI Vs UCS.

4.6.4Free swell index (FSI) with activity(A) of black cotton soil

Correlation of free swell index with activity of black cotton soil was analyzed and shown in figure 4.15. Also, equation and correlation coefficient are given in Table 4.4.

Table 4.4: Free Swell Index (FSI) with activity of black cotton soil (A).

Soil property	Equation	Correlation Coefficient	Standard Error	P- Value	F- Value Calculated	F- Value Tabulated
Free Swell Index (FSI) with Activity of soil (A)	FSI = 91.62 – 85.04 A	0.95	3.65	3.25E ⁻⁷	140.802	4.965

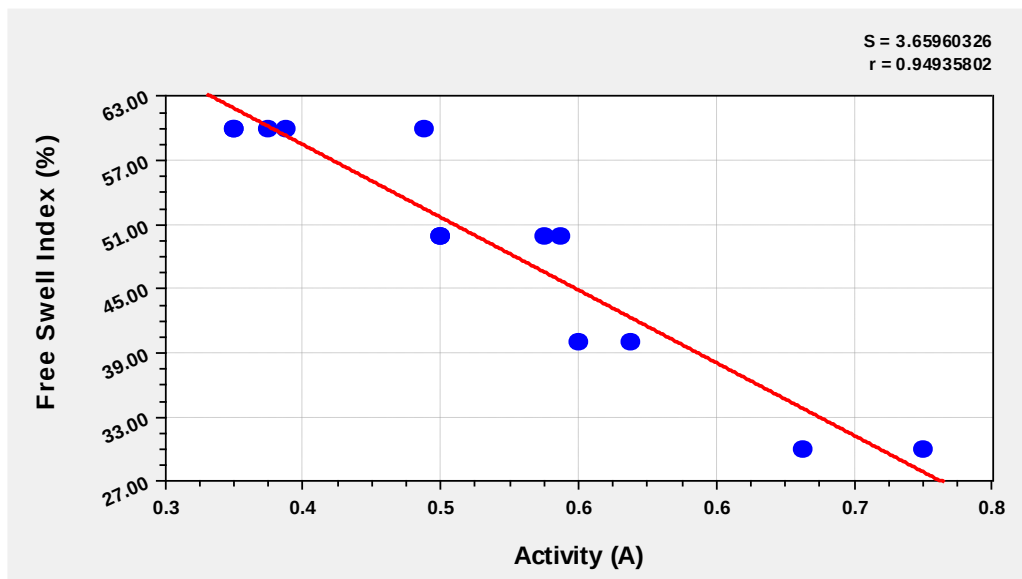


Figure 4.15: Activity Vs FSI.

4.6.5 Specific gravity (G) with plastic limit (PL)

Correlation of specific gravity with plastic limit of black cotton soil was analyzed and shown in figure 4.16. Also, equation and correlation coefficient are given in Table 4.5.

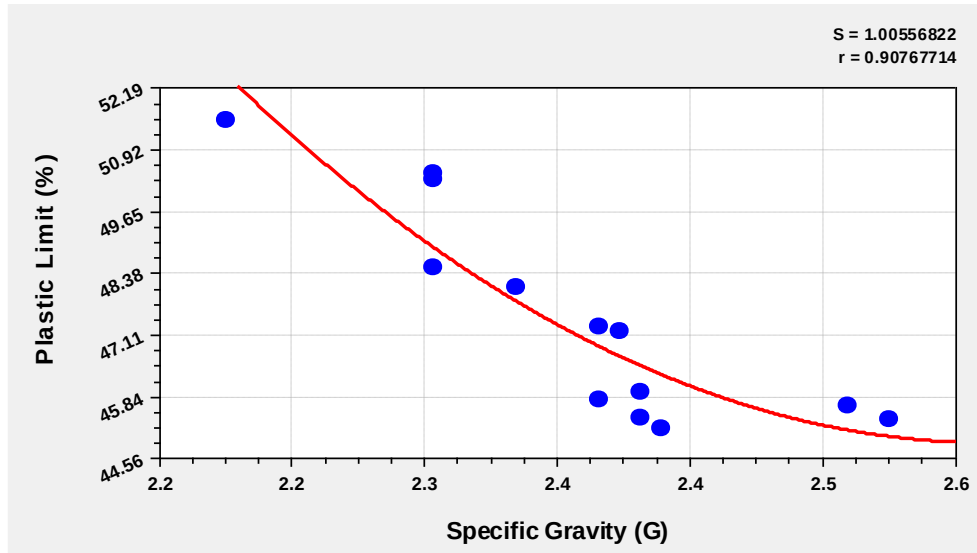


Figure 4.16: G Vs PL.

Table 4.5: Specific gravity (G) with plastic limit (PL)

Soil property	Equation	Correlation Coefficient	Standard Error	P- Value	F- Value Calculated	F- Value Tabulated
Specific gravity (G) with Plastic Limit (PL)	$PL = 412.23 - 286G + 55.67 G^2$	0.91	1.0	0.00136	19.244	4.965

4.7 Validation and Summary

This study will be beneficial at the time of soil improvement and hence can be utilized for designing of foundation in these regions, as an input data. This study can be utilized for many software packages also, to analyze the soil. Five different Empirical correlation models of black cotton soil properties were developed by taking the number of samples from the different zones of Kolhapur. The statistical evaluation of the five regression models developed for black cotton soil demonstrates a high degree of reliability and predictive strength. All models yielded correlation coefficients (R^2) approximately equal to 0.95, indicating a very strong positive linear relationship between the dependent and independent variables. Furthermore, the P values associated with the regression coefficients in all models were found to be less than 0.05, signifying that the predictor variables are statistically significant at the 95% confidence level. This implies a low probability that the observed relationships occurred by random chance. Additionally, for each model, the calculated F-value exceeded the corresponding tabulated F-value, confirming that the overall regression models are statistically significant. This indicates that the variation explained by the regression is significantly greater than the unexplained

variation, thereby validating the effectiveness and suitability of the developed models for analyzing the behavior of black cotton soil. The close agreement of these correlations with trends reported in previous research on similar soil types further validates their reliability and applicability for predicting key geotechnical parameters such as CBR, UCS, FSI, and plastic limits. Validation of results obtained with published research is shown in Table 4.6.

Table 4.6 Validation of results obtained with published research

Property vs Variable	Equation (Kolhapur – This Study)	Soil Type	R²	Research reporting similar trends
CBR vs LL	$CBR = 10.83 - 0.12 LL$	Black Cotton Soil	0.96	Sabat & Nanda (2011), Osinubi (1998), Dash & Hussain (2012), Pandian et al. (2009), Phanikumar & Sharma (2004), Vinod et al. (2010)
CBR vs MDD	$CBR = 1.98 + 0.09 MDD$	Black Cotton Soil	0.95	Phanikumar & Sharma (2004), Sabat & Nanda (2011), Osinubi (1998), Amadi (2010), Pandian et al. (2009), Shukla et al. (2016), Vinod et al. (2010)
UCS vs PI	$UCS = 79.46 - 0.91 PI$	Black Cotton Soil	0.95	Sabat & Nanda (2011), Sharma & Bora (2003), Osinubi (1998), Sridharan & Nagaraj (2005), Pandian et al. (2008), Phanikumar & Sharma (2004)
FSI vs A	$FSI = 91.62 - 85.04 A$	Black Cotton Soil	0.95	Pandian et al. (2008), Phanikumar & Sharma (2004), Rao & Reddy (1993), Sridharan & Prakash (2000)
PL vs G	$PL = 412.23 - 286G + 55.67 G^2$	Black Cotton Soil	0.91	Pandian et al. (2008), Sridharan & Nagaraj (2000), Rao & Reddy (1993), Phanikumar & Sharma (2004)

Chapter 5

Stabilization of black cotton soil

5.1 Introduction

Developing suitable sustainable solutions to enhance black cotton soil (BCS) is essential because of its engineering behaviour. Identification of novel materials for enhancing the geotechnical properties of BCS is also vital. Previously, various stabilising compounds have been utilised to enhance soil properties. This study aims to utilise appropriate additives to enhance the characteristics of BCS, specifically focusing on maximum dry density (MDD), unconfined compression strength (UCS), California bearing ratio value (CBR), and swelling behaviour. The effect of stabilisation compounds on consistency of BCS was also evaluated. For stabilization of BCS, past researchers have evaluated numerous additives and compounds in the form of chemical stabilization, both in the form of conventional methods or mixtures of conventional and some new additives. Lime treatment is one of the methods that was utilized by many of the researchers in combination with other supplements, such as cement, cement waste dust, iron ore tailings, bagasse fibres, geosynthetic reinforcement, alkalis of calcium hydroxide or potassium hydroxide (KOH), cementitious geo-polymers, fly ash, bagasse ash (BA), ground granulated blast furnace slag (GGBS), etc. Also, cement was utilized with other stabilizing agents such as BA, GGBS, etc. Many studies considered industrial and agricultural waste for the improvement of BCS, such as steel slag, precipitated silica, rice husk ash, shredded tire waste, bagasse ash with GGBS and wood powder, groundnut shell ash, carbide slag with GGBS etc. Also, various fibre as reinforcements were focused by many of the researchers in different proportions, shapes, and sizes. Geosynthetic fibres were used widely for enhancement. These fibres were used with conventional stabilizers like lime and cement also. Soil replacement by non-swelling types of soil (CNS) was also utilized for improvement.

Every material is utilized to enhance certain characteristics of expansive BCS such as, plasticity, strength, permeability, compressibility, swelling behaviour etc. Soil was tested for all index properties, unconfined compression test, split tensile strength, strain controlled cyclic triaxial test, CBR, consistency, compaction, consolidation, initially as

well as after treatment with different mix proportions for estimating potential of particular additives. Particular additives were added in percentage and tested for certain properties only, hence there is scope of further research to develop new additive with optimum proportion. Soil improvement is a broad term; various methods are available to improve soil properties.

5.2 Methods for soil improvement

Soil improvement is an essential part of the present situation since land is scarce in metropolitan areas and must be exploited for development. In this aspect, the soil bearing capacity is quite crucial. There are several techniques for improving soil capacity or compressibility, such as:

1) Mechanical stabilization: This method involves physically altering the soil structure to improve its loadbearing capacity. Techniques include:

- **Compaction:** Densifying soil using rollers, vibratory plates, or tamping rammers. Compaction increases soil strength and reduces voids.
- **Dynamic Compaction:** Dropping heavy weights on the soil surface to increase density (Das, 2013).
- **Soil replacement:** Removing weak soil and replacing it with compacted granular materials.

2) Chemical Stabilization: Chemical agents are used to modify soil properties. Key methods include:

- **Cement Stabilization:** Mixing Portland cement with soil creates a hardened matrix, enhancing loadbearing capacity (Mitchell & Soga, 2005).
- **Lime Stabilization:** Quicklime or hydrated lime reacts with soil particles to improve plasticity and strength. Ideal for clay soils.
- **Polymer Stabilization:** Polymers bind soil particles and reduce permeability (Ingles & Metcalf, 1992).

3) Soil Reinforcement: Reinforcing materials are introduced to enhance tensile strength:

- **Geosynthetics:** Materials like geotextiles as well as geogrids, or geocells are embedded in the soil (Koerner, 2012).
- **Fiber Reinforcement:** Natural or synthetic fibers are mixed with soil to improve shear strength and reduce cracking.

4) Drainage Improvement: Controlling water content significantly improves soil stability:

- Vertical Drains: Prefabricated vertical drains (PVDs) expedite consolidation by providing drainage paths (Holtz et al., 1991).
- Dewatering Systems: Techniques like well points and vacuum pumps remove excess water, reducing hydrostatic pressure.

4) Grouting Techniques: Injection of stabilizing materials into the soil:

- Cement Grouting: Injecting cementitious slurry to fill voids and stabilize soil.
- Chemical Grouting: Solutions like sodium silicate are used for fine-grained soils (Karol, 2003).

5) Soil Freezing: Temporary stabilization by freezing water within soil pores, forming a rigid structure. Common in excavation for tunnels (Harris, 1995).

6) Vibro-Compaction: A vibrating probe densifies granular soils, increasing shear strength and reducing settlements. Suitable for sandy soils (Broms, 1986).

7) Electrokinetic Stabilization: Using electric currents to transport ions, reducing soil permeability and increasing shear strength. Applicable for soft clay soils (Bjerrum et al., 1967).

8) Biotechnological Methods: Microbial-Induced Calcite Precipitation (MICP): Bacteria induce calcite precipitation, enhancing soil stiffness and reducing permeability (DeJong et al., 2006).

5.3 Terrazyme as an admixture

Terrazyme is an enzymatic soil stabilizer widely used for improving the characteristics of soil. It is a natural, bioenzyme based product designed to increase soil stability, strength, and durability. Its application is popular in road construction and soil stabilization projects. Terrazyme is derived from natural, non-toxic organic sources through fermentation processes. It is a liquid enzyme concentrate. Terrazyme interacts with the organic matter in the soil, specifically targeting and breaking down the hydrophilic (water-attracting) properties of the particles of soil. This reaction reduces the voids space and enhances densification effect. The enzymatic action creates a permanent bonding of soil particles, making the soil hydrophobic and resistant to water infiltration (Jha et al., 2015).

It is beneficial in stabilizing subgrades and base layers, reducing the need for expensive aggregates. It improves bearing capacity and reduces deformation under load. Also, it enhances soil structure for better water management.

5.3.1 Mechanism of soil stabilization by Terrazyme bio-enzyme

Terrazyme is an enzymatic soil stabilizer specifically engineered to improve soil properties for construction applications. The process leverages bioenzymatic reactions to modify soil structure, enhance loadbearing capacity, and reduce deformation. Terrazyme is widely used for road construction, embankments, and erosion control projects. Terrazyme works by altering the physical and chemical interactions between soil particles. It generally functions by catalyzing biochemical reactions that reduce the affinity of soil particles for water. Terrazyme reacts with the organic content of the soil, reducing its water absorption capacity. This results in lower plasticity and improved compaction (Amin & Ahuja, 2017). It makes the soil particles more likely to establish intermolecular bonds, which strengthens the matrix and makes it less susceptible to erosion and deformation. By reducing the soil's water retention ability, Terrazyme facilitates better drainage and prevents waterlogging. Treated soils become hydrophobic, improving their durability and resistance to weathering (Moghaddam et al., 2018). It was observed that it provides permanent modification of soil properties. It also reduces plastic limit and shrink-swell potential of expansive soils. It offers increased density and decreased permeability. Terrazyme is mixed in the soil after determining the properties such as plasticity, organic content, and grain size distribution. Dosage of Terrazyme is based on soil type and in percentage of the soil weight. Terrazyme is mixed with water and applied to the soil surface, thereafter blended thoroughly with a grader or disc Plow. Compaction is required for the treated soil using rollers to achieve maximum density. We observed that curing the soil ensures optimal stabilization effects. Terrazyme works efficiently in soil containing clay and silt as well as with high organic content. Its effectiveness in granular soils like sand is limited. Also, optimal enzymatic reactions occur within specific temperature ranges.

5.4 Experimental programme for Terrazyme

Terrazyme is a bio-enzyme soil stabilizer made from fermented vegetable extracts. It is mostly made up of carbohydrates and nonionic surfactants. This material is frequently utilised to improve the engineering characteristics of soils, especially expansive clays such

as BCS. Table 5.1 presents the standard characteristics of Terrazyme, as provided by the supplier. Figure 5.1 illustrates the appearance of the liquid.



Figure 5.1: Appearance of Terrazyme.

Table 5.1: Characteristics of Terrazyme.

Sr. No.	Description	Terrazyme
1	Hazardous Components	none
2	Boiling point	212F
3	Specific Gravity	1.05
4	Melting point	liquid
5	Evaporation rate	similar to water
6	Water solubility	complete
7	Appearance and Odor	brownish liquid, non-obnoxious
8	Conditions to avoid	pH <3.5 and pH >9.5
9	Incompatibility	caustics, strong bases
10	Storing	temperature below 45°C

Experimental programs have been conducted to analyze the efficiency of the Terrazyme in soil improvement based on various laboratory tests. Sample preparation is a crucial stage in laboratory tests when using any of the stabilizing agents or bioenzymes, like Terrazyme. BCS samples collected from the second borehole by manual auger boring at the identified location behind D-Mart, near Rankala, Phulewadi Road, Kolhapur, were treated with

Terrazyme as an admixture. Sampling was done up to a depth of 4.75 m in four different layers; hence, soil from 4.0 m below ground level was considered for all tests. Characterization of soil was done, which provides the soil's physical and engineering properties. Soil was treated with different Terrazyme dosages, i.e., 0.5 ml, 1.0 ml, 1.5 ml, 2.0 ml, and 2.5 ml per 100 ml of water, to determine the optimal amount for stabilization. The Terrazyme was mixed with water and evenly added to the soil to ensure uniform distribution. The impact of Terrazyme on consistency, plasticity, maximum dry unit weight, optimum moisture content, unconfined compressive strength, and unsoaked California bearing ratio was assessed and documented. The treated soil was then allowed to cure for specified periods to facilitate the enzymatic reactions. Samples were cured under controlled temperature and humidity to simulate field conditions.

Curing is helpful in UCS and CBR testing as regards the strength development, simulating the field conditions and for obtaining consistent and reliable data. Proper curing allows for the full development of the soil's strength, particularly in stabilized soils where chemical reactions contribute to strength gain. The curing process can simulate the conditions the soil will experience in the field, leading to more accurate predictions of behaviour under load and ensures that all samples in a test batch are treated consistently, leading to repeatable and reliable results. The curing process is tailored based on the specific requirements of the UCS and CBR test, the type of soil, and the intended application of the test results. Proper curing is essential for achieving accurate, reliable, and meaningful UCS test outcomes. Initially, for UCS and CBR, curing was done for 14, 21 and 28 days. But it was observed that there was no appreciable change in the properties after 7 days and hence all the tests were confined to 7 days only. This longer curing period of 7 days allowed for the chemical reactions to occur, significantly increasing the strength of the sample. Before curing, the soil sample is typically compacted to the desired density using a mould and compaction tool. The moisture content is adjusted to achieve the optimal compaction, often based on the Proctor test results. After compaction, the sample is carefully extracted from the mould and trimmed to the standard dimensions required for the UCS test, typically maintaining a height-to-diameter ratio of 2:1. For the UCS test on a saturated or near-saturated soil sample, the curing process involves maintaining the sample in a moist environment. This can be done by wrapping the sample in plastic film or placing it in a sealed container to prevent moisture loss. Curing is usually conducted at a controlled temperature, often around 20°C to 25°C, and a controlled relative humidity (typically 95%

or higher). This is especially important for samples treated with stabilizers that require specific curing conditions to develop strength. When soil samples are treated with stabilizers curing can last from 7 days to several months. This longer curing period allows chemical reactions to occur, significantly increasing the strength of the sample. After curing, the sample handled carefully to avoid any disturbance or loss of moisture. Before testing, the sample were allowed to equilibrate to room conditions, especially if it was cured in a high-humidity.

5.4.1 Specific gravity with Terrazyme

The analysis of the effect of Terrazyme on specific gravity values was conducted, the results are presented in Table 5.2. An increase in specific gravity value was observed in comparison to untreated soil. The variation in values across different dosages is minimal, as illustrated in figure 5.2.

Table 5.2: Effect of Terrazyme on specific gravity.

Sr. No.	Dosage (ml)/100 ml of water	Specific Gravity (G)
1	Untreated	2.41
2	0.5	2.57
3	1.0	2.56
4	1.5	2.59
5	2.0	2.55
6	2.5	2.54

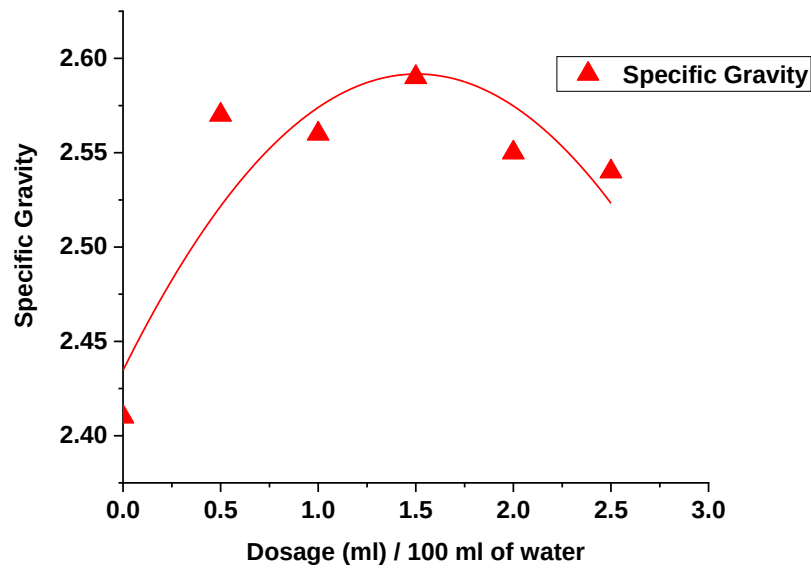


Figure 5.2: Specific gravity with Terrazyme.

5.4.2 Consistency limits of black cotton soil with Terrazyme

The analysis of the effect of Terrazyme on soil consistency revealed a decrease in consistency limits with the addition of Terrazyme. The liquid limit decreased by 22.51%, while the plastic limit decreased by 19.62%. Results are presented in Table 5.3. Figure 5.3 illustrates the change in the liquid limit and plastic limit with varying dosages of Terrazyme.

Table 5.3: Effect of Terrazyme on consistency of black cotton soil.

Sr. No.	Dosage (ml)/100 ml of water	Liquid Limit (LL) (%)	Plastic Limit (PL) (%)	Plasticity Index (PI) (%)
1	Untreated	62.20	45.20	17
2	0.5	54.37	40.12	14.25
3	1.0	50.51	36.33	14.18
4	1.5	48.53	38.22	10.31
5	2.0	48.32	37.57	10.75
6	2.5	48.20	37.43	10.77

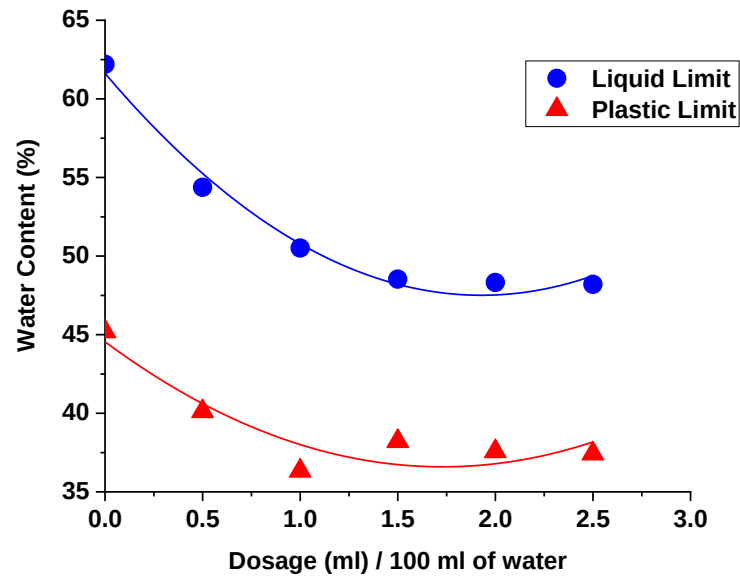


Figure 5.3: Consistency of BC soil with Terrazyme.

Plasticity index is the very important entity in black cotton soil analysis. Variation of plasticity index (PI) with dosage of Terrazyme is shown in figure 5.4. It was observed that the plasticity index decreased by 39.35%. It is because of Terrazyme, that interacts with soil minerals to modify clay particles, reducing their ability to retain water, especially in the adsorbed state. This results in an increase in the Plastic Limit (PL) and a decrease in the Liquid Limit (LL), resulting in a lower Plasticity Index (PI). Terrazyme also facilitates cation exchange by replacing weaker cations with stronger ones, improving particle aggregation and water absorption. It also reduces the swelling potential of expansive clays, such as montmorillonite, by breaking down their ability to absorb large amounts of water. Terrazyme also alters the soil's microstructure, promoting denser packing of particles, reducing void spaces that could hold water. Over time, Terrazyme-treated soils undergo chemical stabilization, leading to more stable soil particles less sensitive to changes in moisture content. The results show a reduction in the Plasticity Index (PI), increased structural integrity, and a net decrease in PI. This leads to improved workability during construction, reduced shrink-swell behaviour, and reduced economic benefits. By reducing the PI, Terrazyme helps transform problematic soils into more reliable construction materials, improving their engineering properties and long-term performance.

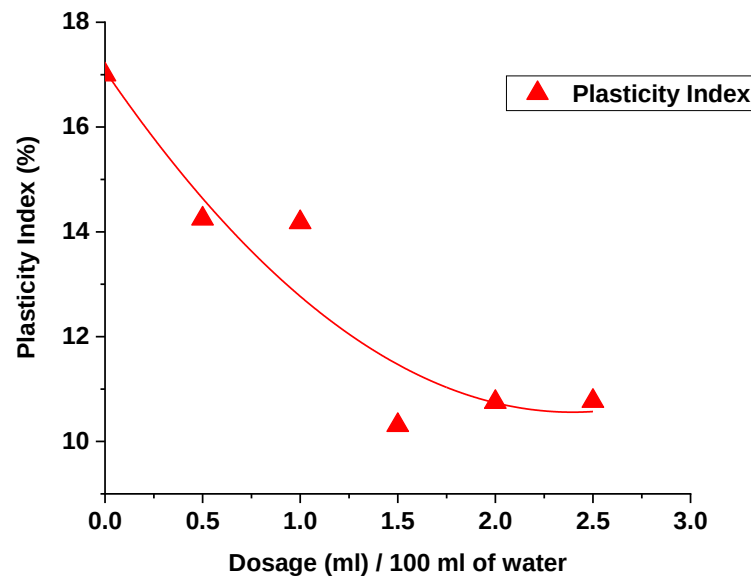


Figure 5.4: Plasticity index soil with Terrazyme.

5.4.3 Maximum dry unit weight and optimum moisture content of black cotton soil with Terrazyme

Standard Proctor tests were conducted on BCS samples that were treated with Terrazyme. The analysis of the effect of Terrazyme on maximum dry unit weight and OMC was conducted, the results are presented in Table 5.4. Figures 5.5 and 5.6 illustrate the variations in maximum dry unit weight and OMC, respectively, in relation to different dosages of Terrazyme. An increase of approximately 11.83% in maximum dry unit weight was noted, accompanied by a slight decrease in OMC. This is due to enhanced adhesion among particles, leading to the densification of soil because of Terrazyme action.

Table 5.4:Effect of Terrazyme on maximum dry unit weight.

Sr. No.	Dosage(ml)/ 100 ml of water)	Maximum Dry Unit Weight (kN/m ³)	Optimum Moisture Content (OMC) (%)
1	Untreated	16.90	13.00
2	0.5	17.20	12.50
3	1.0	17.30	12.00
4	1.5	18.90	12.00
5	2.0	18.50	12.50
6	2.5	18.20	12.50

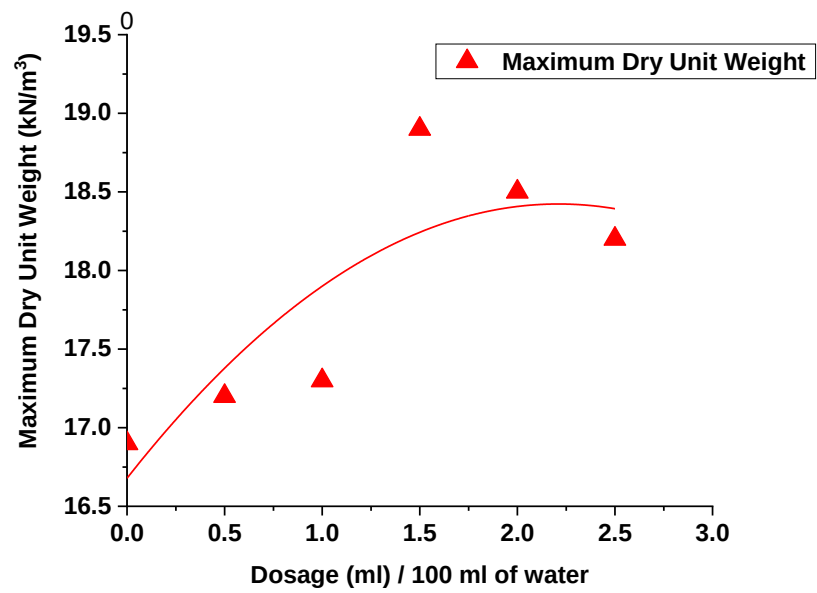


Figure 5.5: Maximum dry unit weight with Terrazyme.

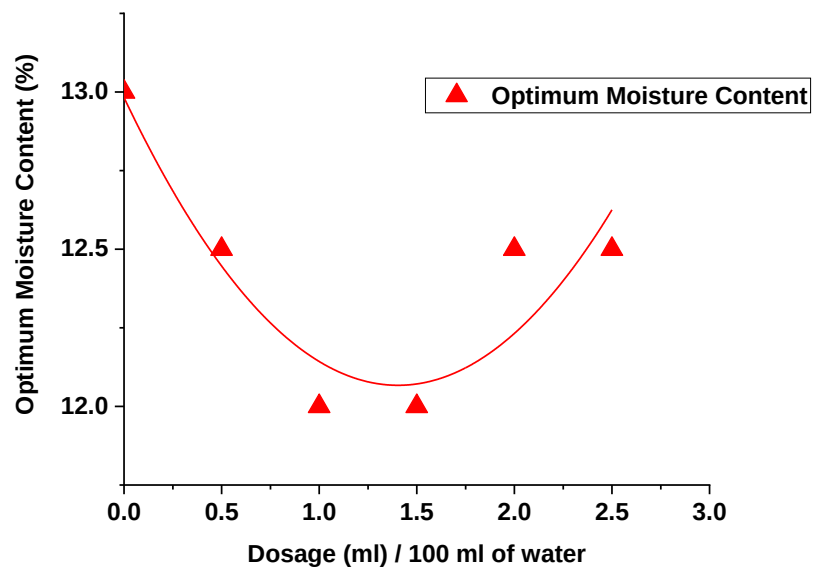


Figure 5.6: Optimum moisture content with Terrazyme.

5.4.4 California bearing ratio value of black cotton soil with Terrazyme

California bearing ratio value tests were conducted on BCS treated with Terrazyme. The effect of Terrazyme on CBR value was analyzed, results are tabulated in Table 5.5.

Table 5.5: Effect of Terrazyme on CBR value.

Sr. No.	Dosage(ml)/ 100 ml of water	California bearing ratio value(CBR) (%)
1	Untreated	3.55
2	0.5	4.20
3	1.0	4.44
4	1.5	4.80
5	2.0	4.62
6	2.5	4.28

The curing period is the most critical aspect when using Terrazyme; thus, the impact of Terrazyme on the CBR value with curing was examined, and the findings are shown in Table 5.6. Figure 5.7 illustrates the fluctuation in CBR values with several dosages of Terrazyme, both with and without the curative effect. After seven days of curing with a Terrazyme dose of 1.5 ml per 100 ml of water, the CBR value improved by 76.32%. The findings demonstrated the potential of Terrazyme as a stabilizing enzyme for use in various civil engineering applications, particularly in the treatment of BCS.

Table 5.6: Effect of Terrazyme on CBR value on curing.

Sr. No.	Dosage(ml)/ 100 ml of water	California bearing ratio value(CBR) (%)	
Curing period (days)		0	07
1	Untreated	3.55	3.80
2	0.5	4.20	4.59
3	1.0	4.44	5.10
4	1.5	4.80	6.70
5	2.0	4.62	6.10
6	2.5	4.28	5.60

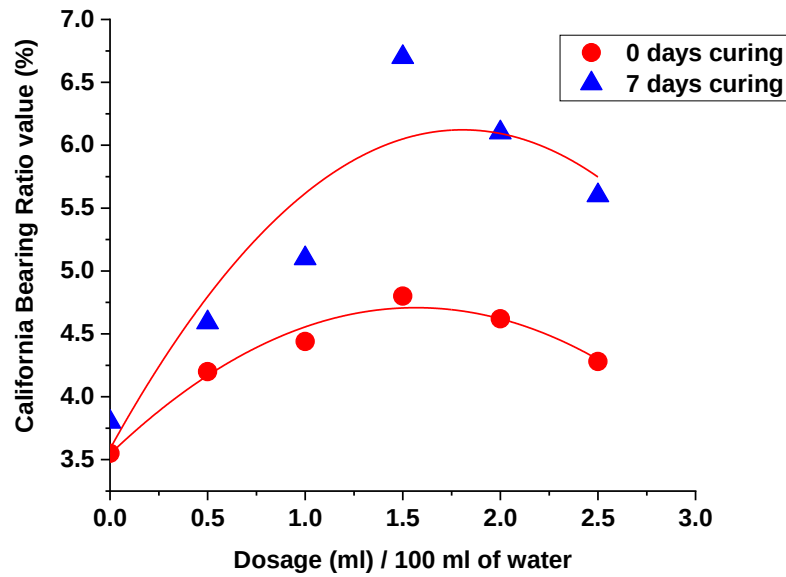


Figure 5.7:California bearing ratio value with Terrazyme.

5.4.5Unconfined compression strength of black cotton soil with Terrazyme

Unconfined compressive strength tests were performed on BCS treated with Terrazyme. The impact of Terrazyme on UCS values was examined, and the findings are shown in Table 5.7. Figure 5.8 illustrates the variation in unconfined compressive strength corresponding to various Terrazyme doses, both with and without curing. It was observed that the UCS increased by 57.89% with a Terrazyme dose of 1.5 ml per 100 ml of water after 7 days of curing. The optimal dosage of Terrazyme for stabilising black cotton soil is 1.5 ml per 100 ml of water. The incorporation of Terrazyme enhances soil strength, particularly evident after seven days of curing.

Table 5.7:Effect of Terrazyme on unconfined compression strength on curing.

Sr. No.	Dosage(ml)/ 100 ml of water	Unconfined compression strength (UCS) (kN/m ²)	
		Curing period (days)	007
1	Untreated	64.45	71.12
2	0.5	82.30	86.30
3	1.0	86.20	90.71

4	1.5	89.30	112.22
5	2.0	87.13	110.18
6	2.5	80.65	104.30

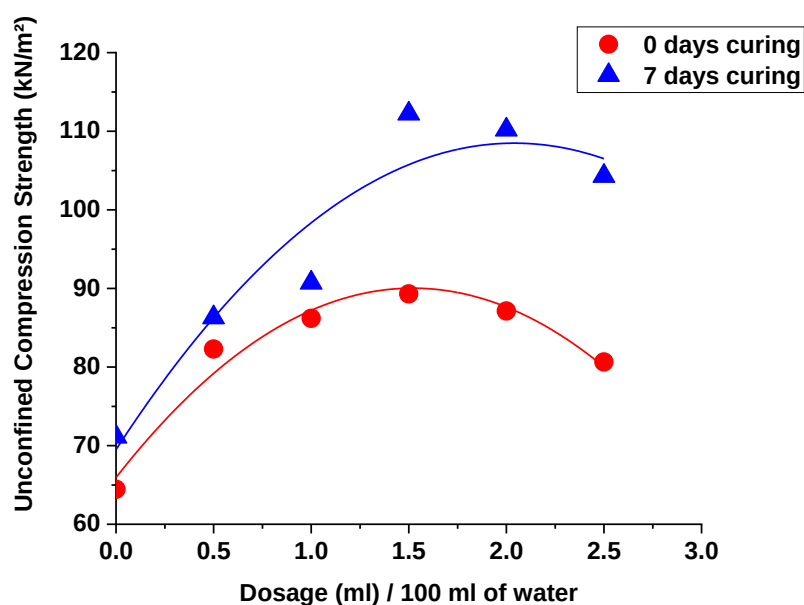


Figure 5.8: Unconfined compression strength with Terrazyme.

5.5 Xanthan gum as additive

Xanthan gum, a polysaccharide produced by the bacterium *Xanthomonas campestris* through fermentation, has emerged as a versatile biopolymer in soil improvement applications. Its unique rheological and biochemical properties make it an attractive additive for enhancing soil stability, permeability, and resistance to erosion. The increasing interest in sustainable and environmentally friendly solutions in geotechnical engineering has catalyzed research into xanthan gum's efficacy as a soil modifier. Xanthan gum consists of a cellulose backbone with trisaccharide side chains, imparting high molecular weight and excellent water solubility. The polymer's ability to form highly viscous solutions even at low concentrations is critical for its soil applications. It is stable across a wide pH range, 4–11, and can withstand temperatures up to 120°C without significant degradation, which enhances its utility in various soil environments. Additionally, xanthan gum exhibits pseudoplastic behavior which facilitates its effective interaction with soil

particles by reducing interparticle friction while maintaining structural integrity (García-Ochoa et al., 2000).

5.5.1 Mechanism of soil stabilization by Xanthan gum

Xanthan gum enhances soil cohesion by forming a biopolymeric network that binds soil particles together. This binding occurs as the polymer adsorbs onto particle surfaces via hydrogen bonding, electrostatic interactions, and van der Waals forces. The result is a gel-like matrix that enhances interparticle bonding and reduces the mobility of soil particles (Chang et al., 2021). When introduced to porous soils, Xanthan gum reduces permeability by clogging pore spaces with its gel matrix. This property is particularly beneficial in applications like landfill liners, embankments, and agricultural practices to minimize water loss and improve water retention (Yang et al., 2019). Studies have shown that Xanthan gum-treated soils exhibit a reduction in hydraulic conductivity by up to 80%, depending on the concentration and soil type. Xanthan gum improves the resistance of soil to erosion by wind and water. The polymer forms a surface crust that stabilizes the topsoil layer, preventing detachment and transportation of particles under erosive forces. This characteristic is especially advantageous in regions prone to desertification or high rainfall, where soil conservation is critical (Tayebi et al., 2020). The addition of xanthan gum to soil significantly enhances its shear strength. By binding particles, the polymer increases soil resistance to deformation and compaction under load. This property is vital for geotechnical applications such as road construction, embankments, and slope stabilization. In field different methods were employed for application of Xanthan gum as a stabilizer, In Surface Stabilization, xanthan gum solutions are sprayed onto exposed soil surfaces to form a protective crust. This approach is commonly used to control dust and surface erosion in arid and semi-arid regions. Also, In-Situ Mixing of Xanthan gum powder or solution can be mechanically mixed into the soil to achieve stabilization. This technique is used for improving the load-bearing capacity and reducing the permeability of soil layers. Injection methods are generally utilized in case of deeper soil stabilization; Xanthan gum solutions are injected into subsurface layers. This technique is particularly effective for reducing permeability in porous soils and enhancing their structural properties. Xanthan gum is biodegradable, non-toxic, and derived from renewable resources, making it an environmentally sustainable alternative to traditional chemical soil additives such as cement and lime. Unlike these conventional methods, Xanthan gum contributes to lower

greenhouse gas emissions and aligns with green engineering practices. (Hataf et al., 2021). Figure 5.9 shows the typical appearance of the Xanthan gum powder.



Figure 5.9: Xanthan gum powder.

Experimental programs have been conducted to analyze the efficiency of the Xanthan gum in soil improvement based on various laboratory tests. BCS samples collected from the second borehole by manual auger boring behind D-Mart, near Rankala, Phulewadi Road, Kolhapur, were treated with Xanthan gum. Sampling was done up to a depth of 4.75 m in four different layers; hence, soil from 4.0 m below ground level was considered for all tests. Characterization of soil was done, and soil was treated with different dosages, i.e., 0.2, 0.4, 0.6, 1.0, 1.5, and 2.0 percent of the weight of soil. The impact of Xanthan gum on maximum dry unit weight, optimum moisture content, unconfined compressive strength, and unsoaked California bearing ratio was assessed and documented. The treated soil was then allowed to cure for 7 days to facilitate the efficient stabilization. Samples were typically cured under controlled temperature and humidity to simulate field conditions.

5.5.2 Maximum dry unit weight and optimum moisture content of black cotton soil with Xanthan gum

Standard Procter tests were conducted on BCS mixed with Xanthan gum. The effect of Xanthan gum on the maximum dry unit weight of soil was analyzed, and results were tabulated in Table 5.8. Also, figure 5.10 shows variation of maximum dry unit weight with

different dosages of Xanthan gum, and figure 5.11 shows variation of OMC. It was observed that there is a 13.61% increase in maximum dry unit weight at a 1.5% dosage of Xanthan gum with marginal reduction in OMC values.

Table 5.8: Effect of Xanthan gum on maximum dry unit weight and optimum moisture content.

Sr. No.	Dosage (%) of weight of soil sample	Maximum Dry Unit Weight (kN/m ³)	Optimum Moisture Content (OMC) (%)
1	Untreated	16.90	13.00
2	0.2	16.92	12.50
3	0.4	17.20	12.50
4	0.6	18.02	12.00
5	1.0	18.33	12.00
6	1.5	19.20	12.00
7	2.0	18.56	12.00

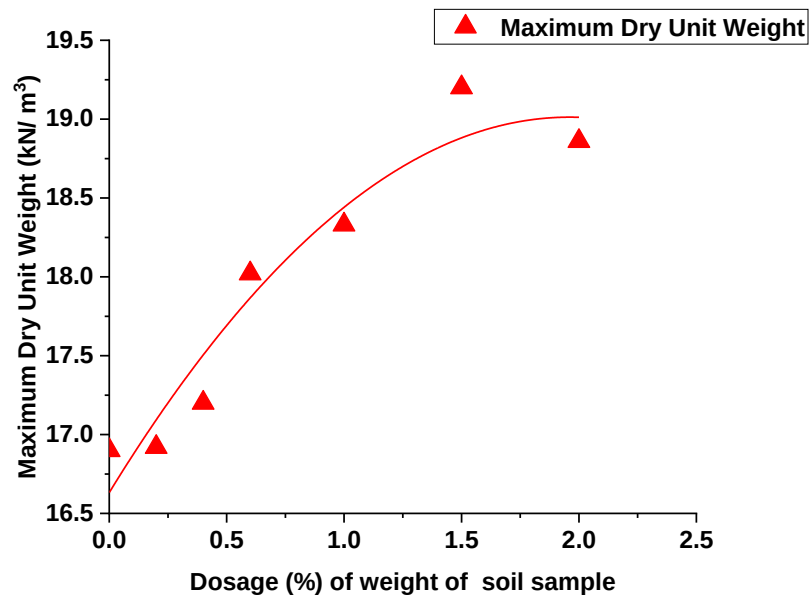


Figure 5.10: Maximum dry unit weight with Xanthan gum.

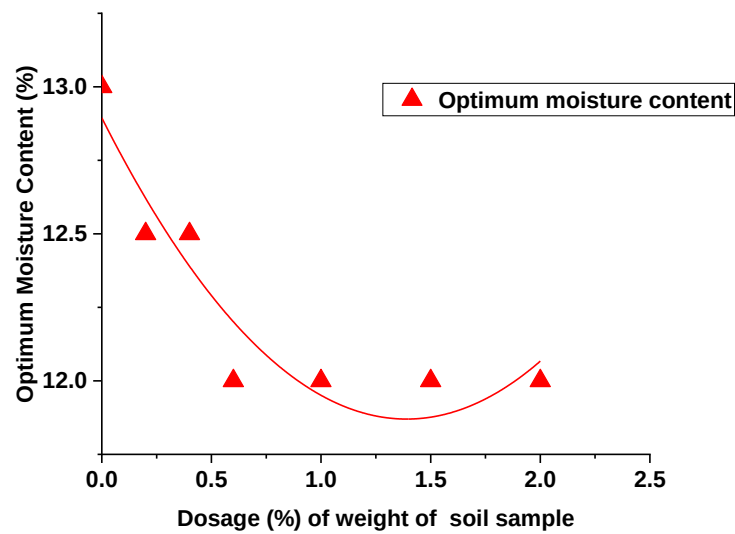


Figure 5.11: Optimum moisture content with Xanthan gum.

5.5.3 California bearing ratio value of black cotton soil with Xanthan gum

The effect of Xanthan gum on the CBR of soil was analyzed, and results were tabulated in Table 5.9. Also, figure 5.12 shows the variation of CBR value with different dosages of Xanthan gum; this effect is more predominant with curing. After 7 days of curing, the CBR value increased by 89.47% compared to untreated BCS.

Table 5.9: Effect of Xanthan gum on California bearing ratio value.

Sr. No.	Dosage (%) of weight of	California bearing ratio	
	soil sample	value(CBR) (%)	
Curing period (days)		0	07
1	Untreated	3.55	3.80
2	0.2	3.68	3.90
3	0.4	3.88	4.30
4	0.6	4.5	5.89
5	1.0	5.65	7.20
6	1.5	5.38	6.56
7	2.0	4.96	6.23

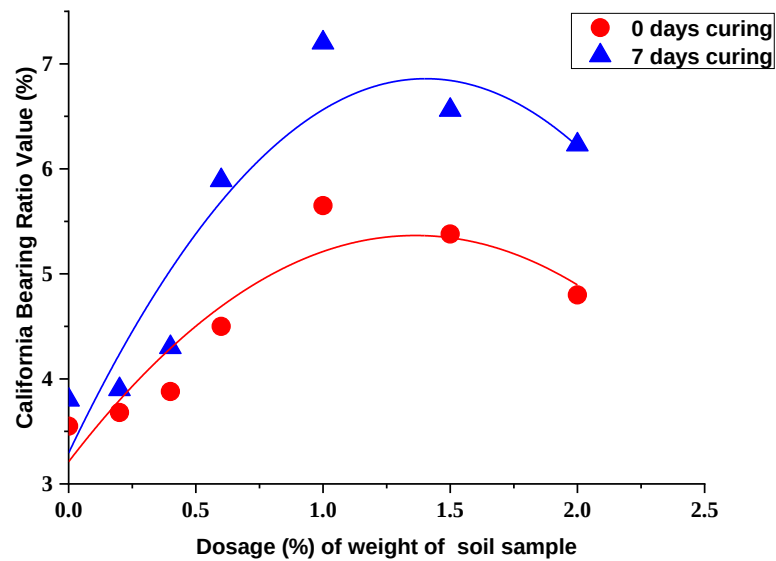


Figure 5.12:California bearing ratio value with Xanthan gum.

5.5.4 Unconfined compression strength of black cotton soil with Xanthan gum

The effect of Xanthan gum on UCS value was analyzed, and results were tabulated in Table 5.10. Also, figure 5.13 shows the variation of UCS with different dosages of Xanthan gum. It was observed that the UCS of BCS increased by 149.30% when mixed with a 1% dosage of Xanthan gum. This occurs because there is direct interaction between fine particles and Xanthan gum strands due to electrically charged clay particles, and Xanthan gum bridges the gap between distant particles, enhancing particle alignment and strength improvement.

Table 5.10: Effect of Xanthan gum on unconfined compression strength.

Sr. No.	Dosage (%) of weight of soil sample	Unconfined compression strength (UCS) (kN/m ²)	
		0	07
	Curing period (days)		
1	Untreated	64.45	71.12
2	0.2	78.55	90.42
3	0.4	90.50	98.52
4	0.6	98.30	120.40
5	1.0	110.00	177.30

6	1.5	108.20	156.43
7	2.0	106.33	152.89

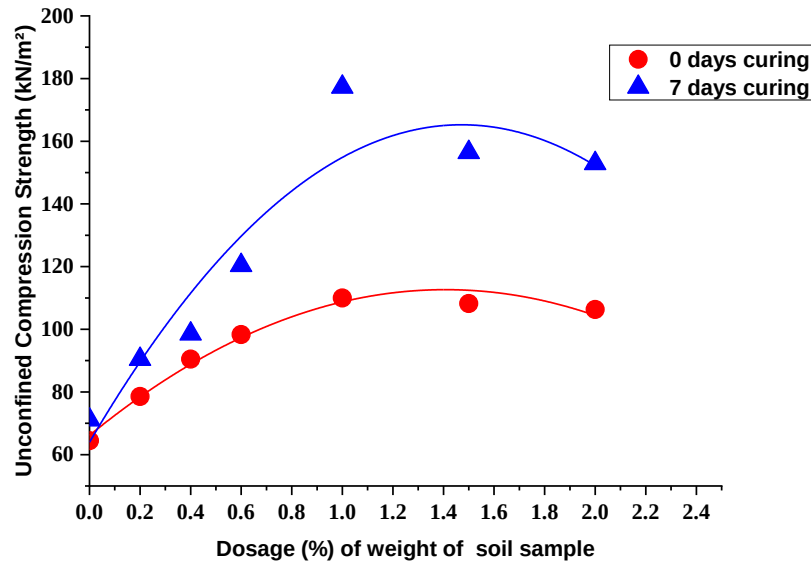


Figure 5.13: Unconfined compression strength with Xanthan gum.

5.6 Practical limitations of bio-stabilization and cost analysis

While bio-stabilization using additives such as Terrazyme and Xanthan gum has demonstrated promising improvements in soil strength and environmental compatibility, its practical application is constrained by several factors. These include variability in soil response depending on mineralogy and moisture content (Sahoo et al., 2019), challenges in achieving uniform mixing on-site (Patel & Desai, 2021), and sensitivity to curing conditions. Additionally, although Terrazyme may offer long-term durability benefits, the initial material and application costs, especially in remote or large-scale projects, can outweigh those of traditional stabilizers (Ramesh & Venkataraman, 2018). A thorough cost-benefit analysis is essential to determine feasibility in specific engineering contexts.

5.6.1 Material variability

Both Terrazyme and Xanthan gum exhibit inherent variability due to differences in source materials and production processes. For Terrazyme, enzyme concentration and activity can vary between batches and manufacturers, affecting performance consistency in field applications (Suresh Kumar and Ramesh, 2013). Similarly, the rheological and binding

properties of Xanthan gum can vary with fermentation conditions, bacterial strains, and purification methods (Chang et al., 2016).

5.6.2 Shelf-life and storage conditions

Terrazyme, while stable in sealed containers, may degrade over time if exposed to air or high temperatures, reducing its effectiveness. Manufacturers recommend storage under cool and dry conditions, with a typical shelf-life of 12–24 months (Chauhan & Sahu, 2017). Xanthan gum, being hygroscopic, requires airtight storage to prevent premature gelling or microbial contamination. Its shelf-life can exceed 2 years in powder form but is significantly reduced once hydrated.

5.6.3 Cost-benefit analysis

While both materials are marketed as eco-friendly alternatives, their economic viability depends on project scale and soil conditions. Terrazyme shows significant cost savings in road construction, reducing material transport and compaction effort. Studies report up to 20–30% cost reduction in road subgrade projects (Sherwood, 2001).Xanthan gum, although effective in small-scale or erosion-prone applications, may be less cost-efficient for large-volume stabilization due to the high unit cost of the polymer and potential need for reapplication in moist environments. Therefore, a careful cost-benefit analysis based on site-specific conditions is essential prior to large-scale deployment. Table 5.11 shows comprehensive Cost-Benefit Analysis comparing Terrazyme and Xanthan gum with conventional soil stabilizers as lime and cement when used in soil stabilization. This analysis includes cost per unit, application rate, labour and equipment need, performance factors, and long-term economic and environmental benefits.

Table 5.11: Cost-benefit analysis and detail comparison withconventional stabilizers.

Parameter	Terrazyme	Xanthan Gum	Lime	Cement
Material Cost (INR/kg)	160 - 240	800 - 1000	10 - 20	7–13
Typical Application Rate	150 - 200 ml/m³ (≈0.3 kg/m³)	2 - 4 kg/m³	3 - 10% by weight	5 - 12% by weight
Cost per m³	₹10 - ₹20	₹1650 - ₹3300	₹200 - ₹400	₹350 - ₹750

Parameter	Terrazyme	Xanthan Gum	Lime	Cement
(Material Only)				
Total Cost/m ³ in INR	₹78 - ₹130	₹1745 - ₹3493	₹345 - ₹580	₹495 - ₹980
Labour& Equipment	Low (simple spraying/mixing)	Low–Medium (hydration/mixing)	Medium (rotovating, curing)	High (mixing, curing, compaction)
Strength Gain (CBR%)	2x - 7x (long-lasting)	2x - 4x (depends on soil type)	2x - 6x	3x - 7x
Durability	High (moisture resistant)	Medium (biodegradable; reapplication needed in wet cycles)	High	High
Time to Achieve Full Strength	1-7 days	1 - 7 days	7 - 28 days	7 - 28 days
Environmental Impact	Very low (organic, biodegradable)	Very low (biopolymer, decomposes safely)	Moderate (alkaline leaching, CO ₂ during production)	High (energy- intensive, high CO ₂ emissions)
Shelf-Life	12 - 24 months (dry, sealed)	12 - 24 months (powder form)	Indefinite (if dry)	Indefinite (if dry)
Recommended Uses	Road subgrades, clayey soils	Erosion control, sand stabilization, temporary works	Expansive soils, embankments	Pavement layers, high-load areas
Total Life- Cycle Cost (estimated)	Low (due to reduced maintenance and fuel)	Medium–High (reapplication possible)	Medium	Medium–High (depending on curing control and cracking)

It is observed that the Terrazyme is cost-effective in large-scale applications road construction and foundation strata stabilization due to its low dosage, durability, and

reduced maintenance costs. Xanthan gum, while more expensive upfront, is suitable for sensitive environments or temporary/erosion-prone areas, but may require reapplication in humid or rainy climates. Lime and cement, though cheaper by weight, require higher quantities, more intensive labor, and have larger environmental footprints. Therefore, the use of Terrazyme and xanthan gum represents a promising step toward sustainable soil stabilization.

5.6.4 Long-term effects and environmental implications

In case of Terrazyme, as a soil stabilizer, its long-term performance has been shown in several studies to enhance soil strength and reduce plasticity over extended periods due to the enzymatic breakdown and rearrangement of clay minerals, resulting in a denser and more water-resistant matrix. Terrazyme is a non-toxic product, posing minimal risk to soil and groundwater ecosystems. However, long-term monitoring is essential to fully confirm its environmental neutrality under diverse soil and climatic conditions.

For Xanthan gum, long-term stability is influenced by microbial activity and soil pH. Studies indicate that Xanthan gum-treated soils can retain improved mechanical properties for long duration. Its compatibility with plant growth and low ecotoxicity as advantages in environmentally sensitive areas. In the present investigation, samples experienced a 7-day curing period. Several samples were also cured for 14 and 28 days during the first testing phase. It was noted that after 7 days of curing, the samples achieve considerable strength, with further improvements being relatively small and minimal. This also demonstrates that enzymatic and polymeric actions remain consistent, with no loss in strength.

5.7 Summary

This study focuses on enhancing the properties of BCS, particularly its maximum dry unit weight, CBR, and UCS. Various stabilizing agents have been employed in the past to improve soil characteristics. Researchers have explored the use of industrial and agricultural by-products, recycled materials, and other cementitious substances in combination with locally available stabilizers. In this research, two specific additives, Terrazyme and Xanthan gum, were applied to improve BCS properties. The soil was treated with different dosages of these additives, and their effects were analyzed after a curing period of seven days. The results indicate that both additives effectively enhance the properties of BCS, with their impact becoming more significant over time with curing.

Bio-stabilization with Terrazyme and Xanthan gum offers eco-friendly soil improvement but faces practical challenges such as variable soil response, mixing difficulties, and sensitivity to curing. Both materials show variability due to production differences and have specific storage requirements affecting shelf life. Terrazyme is cost-effective for large-scale projects like road construction due to low dosage and durability, while Xanthan gum suits smaller, sensitive, or erosion-prone sites but at higher cost and possible need for reapplication. Compared to conventional stabilizers like lime and cement, Terrazyme and Xanthan gum provide environmental benefits and potentially lower life-cycle costs. Long-term studies indicate Terrazyme improves soil strength and durability with minimal environmental risks, and Xanthan gum maintains strength with good ecological compatibility, though monitoring is advised.

Chapter 6

Conclusion

6.1 Conclusion

Based on the literature survey, sampling programme, laboratory tests and result analysis, to summarize the current work, the important conclusions that follow may be drawn:

1. Subsurface investigations carried out in various locations across Kolhapur city, Maharashtra, reveal that expansive black cotton soil predominantly exists up to a depth of approximately 5.0 meters below the existing ground level. Detailed stratigraphic profiling indicates a transition to soft murrum or weathered limestone strata beyond this depth in several sampling sites. Notably, in proximity to the Panchaganga River, the vertical extent of black cotton soil exceeds 5.0 meters, suggesting deeper depositional environments or alluvial influences. Additionally, observations near the Rankala Lake area confirm the presence of groundwater at an average depth of approximately 4.75 meters, indicating a relatively shallow water table which may influence the geotechnical behavior of the underlying expansive soil layer. These findings are critical for foundation design and ground improvement strategies in the region.

2. Particle size distribution analysis, conducted through hydrometer due to the fine-grained nature of the soil, because more than 90% of soil is finer than 75 microns, confirmed the predominance of silt and clay-sized fractions across all sampling locations. Gravel content was negligible, and sand was present in only minor proportions, with medium sand varying from approximately 1% to 8%. At the Line Bazar site, clay content showed a notable decrease from 48.54% at 1.5 m depth to 30.71% at 3.5 m depth. At the Rankala borehole, a similar reduction in clay fraction was recorded, falling from 52.0% at 2.0 m to 22.0% at 4.0 m depth. Conversely, silt content exhibited an increasing trend with depth, ranging from 44% to 65%, indicating a vertical textural variation in subsurface stratigraphy. The results suggest that the subsurface soils in the study area are predominantly fine-grained, with a silt-dominated matrix and a decreasing trend in clay content with depth, which may significantly influence the geotechnical behaviour of the deposits.

3. The study classified soil samples based on their plasticity chart. Some samples, from 1.5m depth, were classified as silt of high plasticity (MH), while others were classified as clay of high plasticity (CH). A few samples were found in the intermediate plasticity zone, with a liquid limit between 35% to 50% and PI above the 'A line', indicating a clay of intermediate plasticity (CI).
4. The field density and moisture content increase with the depth. The liquid limit is maximum in the zone of 0.5m to 1.5m below GL. Plastic limit decreases with the depth. Shrinkage limit was minimum in the zone of 1.5m to 2.0m below GL. The maximum dry unit weight increases, and OMC decreases with the depth. Cohesion decreases with the depth, and the angle of internal friction increases with the depth; it is due to the reduction in clay content in subsequent layers. About 95% of the soil is finer than 75 microns in the zone of 0.5 to 2.0m, and finer particles decreased with depth in some percentage.
5. Dry unit weight ranges from 10.45 to 14.80 kN/m². Highest value of liquid limit, plastic limit and shrinkage limit was 65.40%, 51.71% and 16% respectively. Highest value of maximum dry unit weight with light compaction and California bearing ratio value was achieved up to 17.20 kN/m² and 4.60% respectively. Unconfined compression strength was ranges from 62.20 to 68.95 kN/m².
6. FESEM is used in this investigation to determine the grain size of soil particles. FESEM analysis was carried out with scales ranging from 5µm to 500nm for samples recovered from the Rankala site bore hole up to a depth of 4.0m. Based on FESEM analysis, the grain size was determined to be 0.503 µm. The FESEM image of untreated black cotton soil at 50,000× magnification reveals a highly flocculated microstructure, typical of montmorillonitic clay. The flake-like morphology and disordered particle arrangement indicate weak interparticle bonding and high water adsorption and swelling potential. The rough surface texture and dispersed structure suggest a lack of cementation or binding agents, indicating poor engineering properties like low shear strength, high plasticity, and volumetric instability under moisture variations. These microstructural characteristics suggest the need for stabilization interventions.
7. XRD analysis reveals that, BCS is predominantly composed of montmorillonite (45.4%), kaolinite (44.3%), and a smaller portion of illite (10.3%). These clay minerals have different properties that significantly affect the soil's behaviour. Montmorillonite is a highly expansive clay mineral with high shrink-swell capacity, making soils highly

reactive to moisture changes. Its layered silicate structure is supported by high Si and O content, while kaolinite is a non-expanding clay with a relatively stable structure. Kaolinite's higher Al and moderate Si content contribute to low plasticity and moderate cohesion, improving workability. Illite, a moderately reactive clay intermediate between kaolinite and montmorillonite, stabilizes its structure by holding layers together. The dominance of montmorillonite makes BCS highly plastic, moisture-sensitive, and prone to swelling and shrinkage. Kaolinite adds stability and reduces excessive plasticity. Illite, although minor, contributes strength and structural consistency due to its potassium content. BCS is highly moisture-sensitive and structurally unstable, making it unsuitable for direct construction without stabilization. Chemical or biological treatments like Terrazyme or Xanthan Gum are recommended to improve its engineering performance.

8. EDX analysis was performed on samples taken at two distinct depths in Ramnagar, 1.5m and 3.5m. It was observed that at Ramnagar site, SiO_2 content is predominant in the soil. Iron oxide is also found in appreciable quantities.

9. Regression analysis is identified as statistical tool for development of correlations of black cotton soil properties. Based on experimental analysis correlations were developed by using CurveExpert 1.4 module. After developing data base of soil characterization, empirical correlations were developed for variation of CBR with liquid limit and MDD, UCS with PI, FSI with activity (A) of soil, plastic limit with specific gravity, etc. The five regression models for black cotton soil show high reliability and predictive strength, with correlation coefficients equal to 0.95, P-values less than 0.05, and calculated F-value exceeding the tabulated F-value. These models explain significantly more variation than unexplained variation, confirming their effectiveness in analyzing black cotton soil behaviour.

10. Additives were utilized for improvement of BCS collected from second bore hole behind D-Mart, near Rankala, Phulewadi road, Kolhapur. Effect of curing period also taken into consideration and samples were cured for 07 days before every test. Both the additives are improving properties of BCS; this effect is prominent with curing.

11. Terrazyme as admixture was analyzed on the basis of different laboratory tests. The tests were conducted are specific gravity, plastic limit, liquid limit, standard Proctor test, CBR and UCS. Soil was treated with different Terrazyme dosages, i.e., 0.5 ml, 1.0 ml, 1.5 ml, 2.0 ml, and 2.5 ml per 100 ml of water, to determine the optimal amount for

stabilization. It was found that the consistency limits were decreed with addition of Terrazyme. Plasticity index was also decreased by 39.35%. A 12% increase in maximum dry unit weight was observed. After seven days of curing with a dosage of 1.5 ml per 100 ml of water, the CBR value increased by 76%. Additionally, UCS value increased by 57.79% with 1.5 ml per 100 ml of water dose, after 07 days of curing. It was found that the optimum Terrazyme dose for stabilizing black cotton soil is 1.5 ml per 100 ml of water.

12. Xanthan gum was added as an admixture to BCS with different doses, such as 0.2, 0.4, 0.6, 1.0, 1.5, and 2.0 percent of weight of soil. At a 1.5% dosage, the maximum dry unit weight increased by 13.60%. A seven-day period of 1.0% dosage curing resulted in an 89.47% increase in the CBR value. Additionally, after 7 days of cure with an 1.0% dosage, UCS increased by 149.30%. It was found that the optimum dosage of Xanthan gum for stabilizing BCS is 1.0% of weight of soil.

6.2. Contribution from the present research work

In the present research work, a detailed mapping of geotechnical characteristics of BCS in the entire Kolhapur city was done up to 4.5 m depth below ground level, which is below the zone of influence or unstable zone, which is generally 3 to 4 m. In this study, a comprehensive analysis of the geotechnical properties of black cotton soil (BCS) across Kolhapur city was conducted, focusing on depths up to 4.5 meters below the ground surface. This depth was selected as it extends beyond the typical unstable zone, which is usually within 3 to 4 meters.

The database of geotechnical properties and the correlations developed will be very useful to the designs in depth of foundations on BCS. Improvement in properties of BCS using bio enzymes and natural adhesive presented in the research helps in determining the type and dosage of stabilizers for improving geotechnical properties of BCS.

6.3 Scope of future work

The laboratory investigations, characterization, and improvement of black cotton soil in the current research demand further studies for the investigation of deeper strata to investigate the overall stratification of the study area. The study could be further expanded to explore the following areas:

1. Black cotton soil is highly sensitive to moisture fluctuations, leading to significant volumetric changes. Further research should systematically examine the influence of varying natural moisture content depth wise, particularly during monsoon and dry seasons, on the physicochemical and mechanical properties of both untreated and stabilized BCS. Such studies would improve the prediction of field performance under cyclic wetting and drying conditions.
2. By integrating field and laboratory data from multiple depths, it will be possible to develop empirical design models and regression-based correlations for key geotechnical parameters such as California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), swelling pressure, and shrinkage limit, with respect to depth, moisture content, and degree of stabilization.
3. Long-term field monitoring and durability studies are essential to evaluate the aging behaviour, leachability, biodegradation, and environmental compatibility of bio-stabilized BCS over time. These investigations would aid in validating the sustainability and performance reliability of bio-based soil stabilizers under diverse climatic and loading scenarios. Also, the SEM & XRD analysis could've been performed for soil and additive mixture to study the bonding characteristics and reason for strength enhancement at micro and nano level.
4. Incorporating machine learning and finite element modelling techniques could provide predictive capabilities for stabilized BCS behaviour under different loading and environmental conditions. AI-based models trained on expanded datasets could support rapid assessment and decision-making for infrastructure planning in expansive soil regions.

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PUBLICATIONS

Following research papers are published/ under review related to this research work,

1. International journals:

Sr. No.	Title	Author	Name of Journal	Status
1	Characterization of Black Cotton Soil in Kolhapur Region	Chavan, G. and Savoikar,P.	Indian Geotechnical Journal, vol. 53, pp-1454-1467, 2023 https://doi.org/10.1007/s40098-023-00766-9 Springer Nature Publication Scopus Indexed, ESCI (Impact factor: 1.4)	Published
2	Use of Bio-enzymes and Natural Adhesives for Improvement of Geotechnical Properties of Black Cotton Soils	Chavan, G. and Savoikar,P.	International Journal of Geo-Engineering Springer Nature Publication Scopus Indexed, Q1 (Impact factor: 7.1)	under review

2. International conferences:

Sr. No.	Title	Author	Name of Conference	Status
1	Sustainable techniques for improvement of black cotton soils	Chavan, G. and Savoikar,P.	ISC-HSFEA-2023:4th InternationalSustainability Conference on HEALTH Safety Fire and Environmental Advances, UPES, Dehradun,India, October 30-	published

			31, 2023.	
			Springer Book Chapter:	
			Proceedings of Indian	
			Geotechnical Conference 2018,	
2	Development of Rapid Moisture Meter for Soil Laboratory and Field Testing.	Chavan, G. and Savoikar, P.	Bengaluru also, in, Springer Nature- lecture notes in Civil Engg. (LNCE Vol. 85), 2020.	published
3	Empirical Correlations for Characterization of Black Cotton Soil in Kolhapur City	Chavan, G. and Savoikar, P.	Sixteenth Asian regional Conference on Soil Mechanics and Geotechnical Engineering, TICC Taipei, Taiwan, 2019.	published
