Predicting the consolidation settlement using the Compression Index and Coefficient of Consolidation based on sieve #40 and #200 in Pakistan

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(2024)

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A thesis submitted to the National University of Sciences and Technology, Islamabad,

in partial fulfillment of the requirements for the degree of

Master of Science in
Geotechnical Engineering

Thesis Supervisor: Dr. Badee Alshameri

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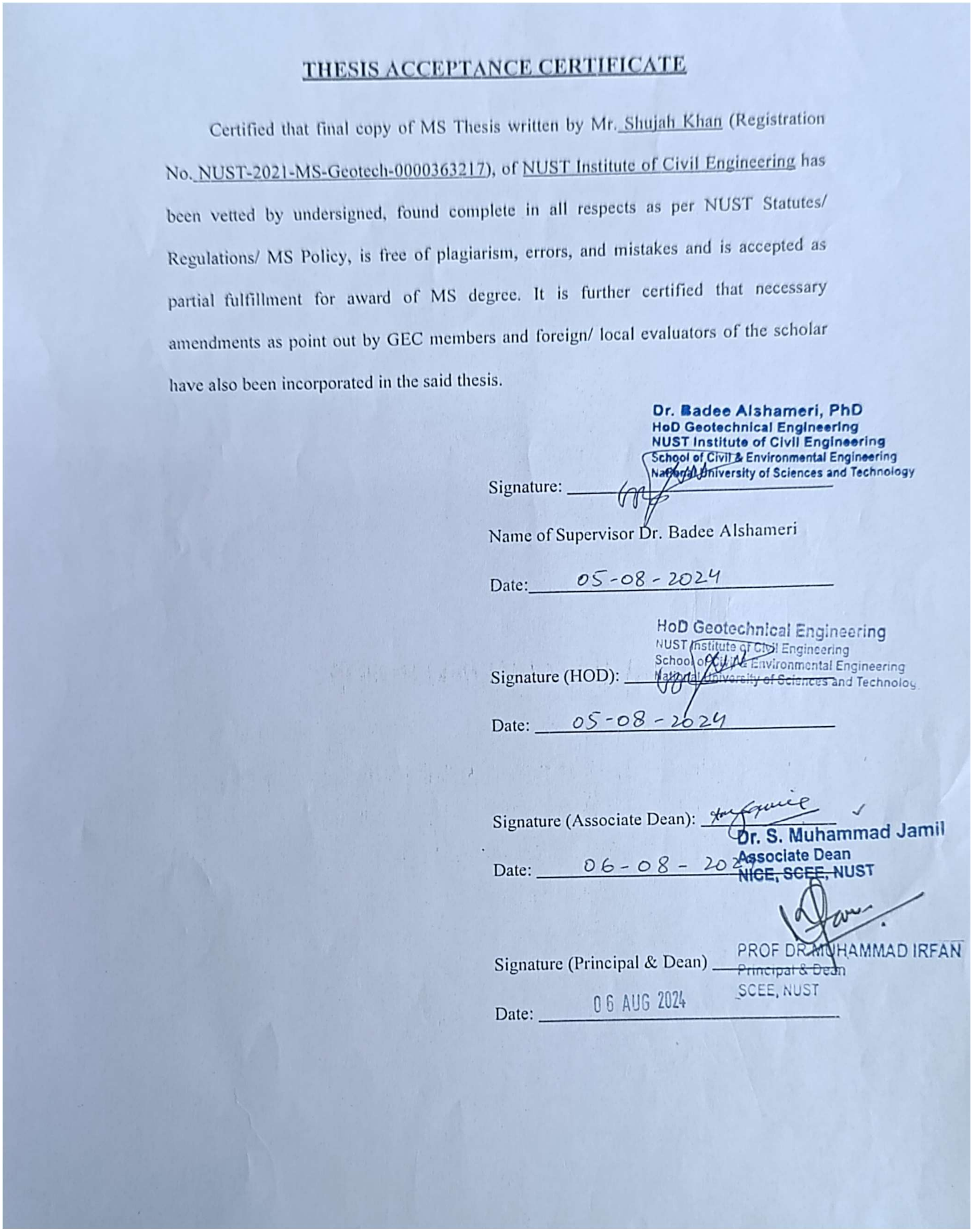

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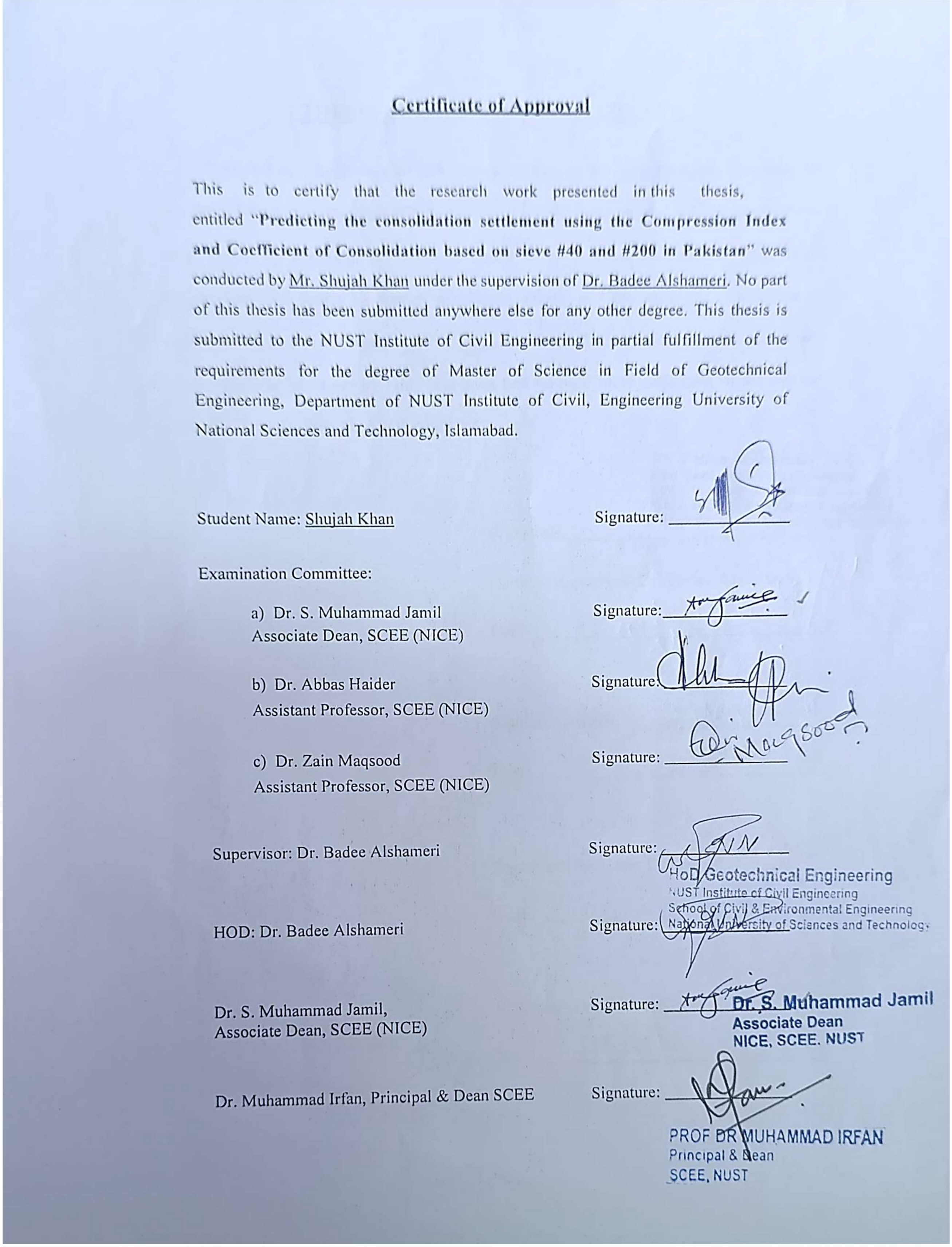

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DEDICATION

I dedicate this research to my beloved parents and family for their endless love, support, encouragement and prayers.

ACKNOWLEDGEMENTS

First and foremost, I would like to express my deepest gratitude to my supervisor, Dr. Badee Alshameri, Head of the Geotechnical Department, for his invaluable guidance, constant support, and encouragement throughout the course of my research. His profound knowledge, insightful suggestions, and unwavering commitment were instrumental in the successful completion of this thesis.

I am also sincerely thankful to my GEC members: Dr. Syed Muhammad Jamil, Dr. Zain Maqsood, and Dr. Abbas Haider. Their constructive feedback, critical analysis, and academic expertise have significantly enriched my research work.

A special thanks goes to Material Engineer Amjad Khan from the Frontier Works Organization (FWO) for providing the essential materials and resources needed for my laboratory tests. His assistance and cooperation were crucial to the practical aspects of this study.

I am immensely grateful to my parents for their unconditional love, constant prayers, and unwavering support throughout my academic journey. Their encouragement and belief in my abilities have been a source of inspiration and motivation. Without their sacrifices and understanding, this achievement would not have been possible.

Finally, I would like to acknowledge all my friends, colleagues, and everyone who has contributed to this research in one way or another. Your support and assistance have been greatly appreciated.

ABSTRACT

This study aims to develop empirical correlations for the compression index (Cc) and the coefficient of consolidation (Cv) with the liquid limit (LL) for soils from various locations in Pakistan. This research addresses the gap by offering a simpler, cost-effective method to estimate Cc and Cv based on LL, thereby reducing the need for extensive laboratory testing. Soil samples were collected from 100 different sites and subjected to comprehensive laboratory testing, including sieve analysis, hydrometer analysis, specific gravity determination, Atterberg limits, and consolidation tests using an Oedometer apparatus. A critical comparison was made between the liquid limits obtained from soils passing through sieve #40 and sieve #200, highlighting the impact of fine sand inclusion on LL values. Initially, 40 correlations were developed by exploring various soil index properties; however, only 4 correlations were retained due to the minimal impact of other parameters compared to the liquid limit on the compression index and coefficient of consolidation. Priliminary attempts to correlate Cc and Cv with multiple soil parameters through a multilinear regression model indicated high p-values, prompting a focus on LL as the sole predictor. The simplified model demonstrated statistical significance, with low p-values affirming the robustness of the correlations. To validate these findings, additional soil samples from 50 locations were analyzed, and the resultant percentage error for both Cc and Cv was found to be less than 1%, ensuring the reliability of the developed correlations. By comparing the results with past research, it was observed that previous models often overestimated or underestimated Cc and Cv values. This research offers more accurate and region-specific correlations, enhancing the understanding of soil compressibility characteristics in Pakistan.

Keywords: Atterberg Limits, Sieve # 40 and #200, Soil Compressibility, Compression Index (Cc), Coefficient of Consolidation (Cv), Multilinear Regression Model (MLR)

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LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

PI	Plasticity index
LL	Liquid Limit
PL	Plastic Limit
UCSC	Unified Soil Classification System
AASHTO	American Association of State Highway Transportation Official
ASTM	American Society for Testing and Materials
MLR	Multilinear Regression Analysis
Cc	Compression Index
Cv	Coefficient of Consolidation
Cr	Recompression Index
G	Gravel
S	Sand
M	Silt
C	Clay

CHAPTER 1: INTRODUCTION

1.1 General

A geotechnical assessment is required to ensure a safe and practical design before building any structure. This investigation includes both surface and subsurface site exploration. Inadequate knowledge of the soil compressibility, which is fundamental to the design of infrastructure and buildings, may result in construction faults that are expensive in terms of resources and effort (Shien et. al., 2018).

Evaluating the soil's compressibility properties is an essential step in selecting and designing an appropriate foundation system for construction. Two critical characteristics that affect soil compressibility, or its ability to reduce in volume under pressure, are the compression index (Cc) and the coefficient of consolidation (Cv). The compression index helps estimate the settlement of the soil due to primary consolidation, while the coefficient of consolidation predicts the time required for a certain amount of compression to occur (Skempton et al., 1944).

The compression index (Cc) is a critical parameter in geotechnical engineering, essential for predicting the primary consolidation settlement of clays. Derived from the oedometer test, Cc represents the slope of the void ratio versus the logarithm of effective stress curve, capturing soil compressibility under incremental loading. This parameter's importance lies in its ability to quantify the degree of volume reduction a soil undergoes under pressure, which is vital for foundation design and predicting settlement behavior in construction projects. Numerous studies have repeatedly demonstrated significant correlations between the compression index and several soil index properties, including liquid limit (LL), plasticity index (PI), and initial void ratio (e0). For example, (Skempton, 1944) established an empirical relationship $Cc=0.007(LL-10)$, which has been widely used to estimate Cc based on the liquid limit of the soil. Similarly, (Terzaghi and Peck, 1967) proposed a slightly different equation $Cc=0.009(LL-10)$, underscoring the dependence of soil compressibility on its liquid limit. Further studies have demonstrated that the natural water content and initial void ratio exhibit relatively linear correlations with the compression index, emphasizing the role of these state parameters in soil compressibility. For instance, research by (Lee et al., 2015) found that these parameters have a stronger influence on the recompression-compression indices in fully disturbed remolded soil samples (Kurnaz et al., 2016). Additionally, research on marine fine-grained soils by Kootahi and Moradi (2017) has shown that the compression index can be effectively evaluated using index tests, reinforcing the practical application of these correlations in geotechnical investigations (Shimobe et al., 2022).

One significant study applied MLR to predict the compressibility parameters of soils, demonstrating that soil properties such as the plasticity index and liquid limit significantly influence the compression index. The research emphasized that empirical models incorporating these properties could provide accurate predictions, supporting the design and analysis of geotechnical structures (Nagaraju et al., 2020). Moreover, further research has highlighted the effectiveness of combining multiple soil properties in MLR models to enhance prediction accuracy. These studies compared the performance of MLR models with other predictive techniques and found that MLR provides a straightforward and interpretable method for estimating Cc, making it a valuable tool in geotechnical engineering practice (Shimobe et al., 2023).

Terzaghi's classical one-dimensional consolidation theory initially introduced the coefficient of consolidation to predict the settlement of foundations subjected to vertical loading (Wang et. al., 2005). The soil's coefficient of consolidation is a significant engineering property that is crucial for the design and evaluation of geotechnical structures (Mittal et al., 2021). Grasping the coefficient of consolidation of soil is vital for performing settlement analysis on saturated fine-grained soils (Raju et al., 1995). It is mostly used to estimate the settlement in clay layers (Mittal et al., 2021). It can be determined in the labs, one-dimensional consolidation test using an Oedometer equipment can be used to determine the consolidation properties (Shien Ng et al., 2018) but it is a time-consuming and laborious process (Shukla et al., 2009). There have been several attempts to predict the values of the coefficient of consolidation using empirical correlation associated to the index properties, which is more quickly and easily (Jadhav, 2016). The soils' plasticity characteristics are vitally crucial in controlling the consolidation characteristics. The contribution of plasticity features in controlling compressibility characteristics was made by (Sridharan and Nagaraj, 2000), generally, as the liquid limit of soil increases, the coefficient of consolidation tends to decrease. To determine the settlement requirements for foundation design, the coefficient of consolidation, essential for predicting the settlement rate of structures constructed on cohesive soils, is determined using compression versus time test results (Shukla et. al., 2009). When a clayey specimen is being compressed in an Oedometer under pressure, Standard methods (Taylor, 1948) need the reasonably frequent measurement of compression dial gauges. Researchers have made attempts to suggest easier and more dependable ways for determining the coefficient of consolidation throughout the last five to six decades, research conducted by various scholars over the years, including Naylor et al. (1948), Scott (1961), Cour (1971), Parkin (1978), Sridharan and Rao (1981), Mikasa and Takada (1986), Pandian et al. (1994), Raju et al. (1995), Robinson and Allam (1996), and Singh (2005), has contributed significantly to our understanding of soil properties. Moreover, existing correlations typically account for only one or two parameters, while compressibility is influenced by a range of other factors. For example, two soils with identical liquid limit values may exhibit different compressibility behaviors, additionally, it is not possible to apply empirical correlations to all regions and soil types to find consolidation parameters (Solanki, 2009).

The objective of this study is to examine the compression index (Cc) and coefficient of consolidation (Cv) for soil samples obtained from different regions in Pakistan. Through comprehensive laboratory testing, including Atterberg limits and Oedometer tests, empirical correlations were developed to establish relationships between Cc and Cv with the liquid limit (LL) of soils passing sieve #40 and #200. These correlations are intended to provide a robust framework for predicting soil compressibility and settlement behavior, leveraging fundamental soil index properties. By enhancing the understanding and predictive accuracy of these parameters, the study seeks to contribute valuable insights into geotechnical engineering practices essential for safe and efficient infrastructure development in Pakistan's diverse soil conditions.

1.2 Reason / Justification for Research

Predicting settlement rates and the time required for soil compression is vital for ensuring the durability of structures built on compressible soil layers. Nevertheless, conventional approaches for measuring the compression index (Cc) and coefficient of consolidation (Cv) of soil through Oedometer tests are resource-intensive and time-consuming. Utilizing empirical correlations offers a quicker and more accessible alternative, especially when correlated with soil index properties. Existing correlations often lack generalizability across diverse regions and soil types; soils with similar liquid limits can exhibit significantly varied compressibility characteristics. Furthermore, previous research predominantly focuses on particle sizes passing sieve #40, overlooking the impact of finer particles (< 0.075mm) passing sieve #200. This study addresses these gaps by comparing the behavior of soil particles passing sieve #40 and sieve #200 in Pakistan. By developing region-specific empirical correlations, particularly for particle sizes typically excluded from standard tests, the research aims to enhance the precision and applicability of geotechnical predictions. This approach not only advances foundation design practices but also contributes to a deeper understanding of soil mechanics, essential for sustainable infrastructure development in Pakistan.

1.3 Research Objectives

The primary objectives of this research are outlined below:

1. To experimentally assess the Atterberg limits (for materials passing through sieves #40 and #200), Compression Index (Cc), and Coefficient of Consolidation (Cv) for soil samples collected from different locations across Pakistan.
2. To establish empirical correlations for Cc and Cv for soils passing sieve #40 and #200, assessing their influence on soil behavior.
3. To evaluate the consistency and applicability of developed correlations across different soil types and regions through comparison with existing studies.

1.4 Scope and Methodology

This study aims to explore the compression index (Cc) and coefficient of consolidation (Cv) of soil samples gathered from various regions throughout Pakistan. The study emphasizes the impact of particle size by comparing soil samples passing sieve #40 and sieve #200. Empirical correlations between Cc, Cv, and the liquid limit (LL) will be developed to enhance the accuracy of geotechnical predictions.

Soil samples will be collected from various sites across Pakistan, ensuring representation of different geological conditions. Samples will be sieved to classify into fractions passing sieve #40 and sieve #200 for subsequent testing. The liquid limit (LL) and plastic limit (PL) will be measured following established standard procedures for samples passing sieve #40 and sieve #200. The Cc and Cv will be determined from One-dimensional consolidation tests. Empirical correlations between Cc, Cv, and LL will be developed separately for soil passing sieve #40 and sieve #200 based on experimental data. The compressibility characteristics of soil particles passing sieve #40 and sieve #200 will be compared to evaluate the influence of particle size on soil behavior. Developed empirical correlations will be compared with existing studies to assess consistency and applicability across different soil types and regions. The reliability and robustness of developed empirical correlations will be validated using additional data collected from 50 locations across Pakistan, ensuring broader applicability.

1.5 Research Outcomes

The findings of this study aim to significantly improve the understanding and predictive accuracy of soil compressibility characteristics in Pakistan. By developing empirical relationships between the compression index (Cc) and the coefficient of consolidation (Cv), and liquid limit (LL) for soils passing sieve #40 and sieve #200, This study seeks to offer a more precise and efficient approach for predicting soil settlement behavior. The findings will facilitate more reliable foundation design and infrastructure development by addressing the variations in soil behavior due to particle size differences. Additionally, the validation of these correlations using data from diverse locations across Pakistan will ensure their robustness and applicability across various soil types and regions. This research will contribute to the body of knowledge in geotechnical engineering, offering valuable insights for both academic research and practical applications in construction and infrastructure projects.

1.6 Thesis Outlines

The structure of this thesis is organized as follows:

Chapter 1

Highlights the general introduction, reasons/justification for research, research objectives, and the scope and methodology of the research work.

Chapter 2

Represents a detailed previous literature reviews, relevant to the research work.

Chapter 3

Explains the materials and procedures utilized to carry out the research project.

Chapter 4

Reports the findings and conclusions from the research work.

Chapter 5

Summarizes the findings and a few significant suggestions derived from the investigation.

CHAPTER 2: LITERATURE REVIEW

2.1 General

In geotechnical engineering, understanding soil behavior under various conditions is crucial for designing stable and efficient structures. The compression index (Cc) and the coefficient of consolidation (Cv) are essential parameters that characterize soil compressibility and its consolidation behavior. Empirical correlations between these parameters and basic soil properties like the liquid limit (LL) offer a practical alternative to extensive laboratory testing. This literature review delves into the development of such correlations, with a focus on their application to soils in Pakistan.

2.2 Consolidation of Soils

Consolidation refers to the process through which soil volume decreases as excess pore pressures are dissipated (Ho et al., 2015). Soil consolidation refers to the rate of volume change of soils with time in response to a change in pressure (Barnes, 2014). Soft soils like clay are made up of fine particles, with the spaces between these particles often occupied by water. In soil mechanics, this condition is described as a saturated or partially saturated porous medium. The deformation of such porous media depends upon the stiffness of the porous material (Verruijt, 1984). When a saturated compressible fine-grained soil layer is loaded with pressure intensity, elastic settlement happens instantaneously. Due to the significantly lower hydraulic conductivity (permeability) of clay compared to sand, the excess pore water pressure induced by loading dissipates slowly over an extended period. Consequently, the volume change associated with consolidation in soft clay soils may persist long after the initial (or elastic) settlement has occurred (Das, 2019a).

2.3 Theory of One Dimensional Consolidation

Karl Terzaghi has contributed his assumption about the theory of consolidation on the development of classical soil mechanics. Many Geotechnical engineers use Terzaghi's theory to solve soil mechanics problems. The assumptions outlined by Terzaghi (1943) are as follows:

1. The loading is one-dimensional, with both settlement and water flow occurring vertically.
2. Compressibility remains constant.
3. Permeability is constant.
4. Flow is governed by Darcy's law.
5. Secondary compression is not considered.
6. Deformations are minor, allowing for strain calculations based on the original, undeformed geometry.
7. The soil is assumed to be saturated and uniform.

Terzaghi's theory relies on several simplifying assumptions, which can result in significant inaccuracies when applied to practical problems, particularly those involving soft clays. One major limitation is the assumption that the coefficient of consolidation remains constant throughout the consolidation process (Abbasi et al., 2007).

2.4 Principle of Consolidation

When a soil mass experiences applied pressure, its volume reduces, similar to other materials. The soil's property that causes this volume reduction under compressive load is referred to as soil compressibility. Vertical compression of soils under increased pressure can result from one or more of the following factors (Tefera & Leikun, 1999).

1. Compression of the solid material, which typically contributes minimally to overall compression under normal loading conditions.
2. Compression of pore fluid, which is relevant when air fills the pores but is negligible when the pores are fully saturated with water.
3. Decrease in pore space due to the expulsion of pore fluid, which is the primary factor contributing to the overall compression.

This occurs because soil is a two-phase material, consisting of soil particles and pore fluid, typically groundwater. When water-saturated soil is exposed to increased pressure, the high volumetric stiffness of the water relative to the soil matrix initially absorbs the pressure change without altering its volume, resulting in excess pore water pressure (Barnes, 2014).

2.5 Phase of Consolidation

Three phases of soil take place during the compression of fine-grained soils. The phases are as follows (Rahim, 2008).

1. **Initial Compression** – This phase involves a relatively rapid reduction in volume upon loading, primarily due to the expulsion and compression of air trapped in the soil pores.
2. **Primary Consolidation** – This phase represents the principal compression process, driven by the expulsion of pore water and the dissipation of excess pore pressure.

3. **Secondary Compression** – Following the dissipation of excess pore pressure, the soil continues to compress at a gradually decreasing rate. This ongoing compression, known as secondary consolidation, is a complex process believed to result from adjustments in the soil's internal structure to accommodate increased effective stress.

2.6 Factors Affecting the Rate of Consolidation

The total settlement of a structure supported by clay consists of both immediate and consolidation settlements. For clay soils, consolidation settlement typically exceeds immediate settlement. Factors affecting the consolidation settlement of a clay layer under normal loading conditions include the degree of saturation (S), the void ratio (e) of the soil prior to excavation, the amount of overburden (σo) that has been removed, the degree of rebound, and the intensity of loading (σ) from the construction of the superstructure (Phanikumar & Amrutha, 2014).

2.6.1 Permeability

The rate at which pressure dissipates is influenced by how quickly fluid moves through the soil's pores (voids), which is determined by the soil's permeability (Kaliakin, 2017). During soil compression, porosity decreases, resulting in reduced space for pore water. Although pore water can be expelled from the soil, in clays, the rate of expulsion depends on the soil's permeability (Verruijt, 2018). Radhika et al. (2020) and Shukla et al. (2009) argued that the compressibility of clays is primarily due to the expulsion of water (i.e. Permeability) between soil particles and the rearrangement of particles into new positions to achieve higher densities. In addition to the above, Hawlader et al. (2002) have studied the effect of permeability on the rate of consolidation using vertical drains.

(Laskar & Pal, 2017a) also concluded that the rate of soil consolidation is significantly influenced by anisotropic water flow. As pore-water flow restrictions increase, the consolidation rate decreases.

2.6.2 Stress History

The results of an exhaustive consolidation testing program revealed that consolidation of soil is stress-dependent rather than constant values (Elkateb, 2018a). And in addition to this, stress history has a crucial role in determining the consolidation behavior of soft clays, with only a few models that can quantify its impact (Ma et al., 2013). Phanikumar & Amrutha (2014) also concluded that for a given degree of saturation, both the rate and magnitude of initial compression increase with higher overburden pressure (σo).

2.6.3 Surcharge Pressure

The compressibility of a soil mass refers to its tendency to reduce in volume under pressure and is described by soil compression characteristics such as the coefficient of compressibility and the compression index (Singh & Noor, 2012). Laskar & Pal (2017b) have investigated the impact of surcharge on the three dimensional consolidation of soils and observed that as surcharge pressure increases on the surrounding soil of consolidating soil, the surrounding soil becomes denser. The increase in soil density reduces both the lateral displacement of consolidating soil particles and the lateral movement of pore water. As a result, higher surcharge pressure on the surrounding soil leads to a reduction in both compressibility and the rate of consolidation in a three-dimensional context. Researchers have observed that the compression indices and coefficient of consolidation for soils such as silty-sand with clay and silty-clay tend to decrease gradually with increasing surcharge pressure. Additionally, the coefficient of consolidation is influenced by changes in permeability and volume compressibility, which result from variations in effective stress as consolidation progresses (Abbasi et al., 2007). Farzi (2017) shows that the variations in pressure applied to the soil significantly affect the performance of stabilizers. Generally, the methods of wet and dry mixing impact the coefficient of volume compressibility and, subsequently, the settlement. This researcher noted that as the effective pressure on the stabilized sample increases, the coefficient of compressibility decreases.

2.6.4 Layer Thickness

An increase in the thickness of the soil layer results in a reduced total head gradient during the pore water expulsion phase. This also implies a larger volume of water that needs to be expelled, both of which contribute to a slower rate of consolidation. Miao et al. (2010) show the impact of layer thickness on the rate of consolidation can be analyzed using one-dimensional consolidation solutions for a double-layered soil profile. The researcher concludes that reducing the thickness of the lower sublayer accelerates the rate of consolidation. This is anticipated because a thinner soil layer decreases the equivalent drainage path in the two-layered system.

2.7 Compressibility Characteristics

The compressibility characteristics of soil are critical parameters in geotechnical engineering, affecting the design and analysis of foundation, embankment, and other geotechnical structure. Two primary indicators of soil compressibility are the coefficient of consolidation (Cv) and the compression index (Cc). The compression index is utilized to estimate the extent of settlement that will occur due to consolidation under the application of external load (Sridharan & Nagaraj, 2000). The coefficient of consolidation (Cv) indicates the rate at which soil undergoes consolidation when subjected to loading, crucial for predicting settlement rates over time. Cv is influenced by the soil's permeability and compressibility characteristics (Skempton et al., 1944).

The compression index (Cc), defined as the slope of the linear portion of the void ratio (e) versus the logarithm of effective pressure (log p) relationship, is widely used for predicting settlement. It is commonly assumed that the e-log p curve is linear in the higher pressure range, allowing Cc to be considered a constant (Sridharan & Gurtug, 2005). Suneel et al. (2008) have demonstrated the compressibility characteristics of soils, including the compression index (Cc), recompression index (Cr), and secondary compression index (Ca), based on initial porosity from four marine deposits, as determined by Oedometer tests. Badmus (2001) shows that the most influenced parameter by the parent rock is the coefficient of compressibility followed by the amount of fines, plasticity index and specific gravity.

2.8 One Dimensional Consolidation Laboratory Test

Although the size of the consolidation ring cell may vary somewhat, the standard one-dimensional consolidation test is typically performed on saturated specimens that are approximately 25.4 mm thick and 63.5 mm in diameter (Das, 2019b). The soil specimen is placed inside a metal ring, with porous stones positioned at both the top and bottom. A lever arm is used to apply the load (P) to the specimen, and compression is measured using a micrometer dial gauge. The load is typically increased by a factor of two every 24 hours. Throughout the test, the specimen is kept submerged in water (Das, 2019b).

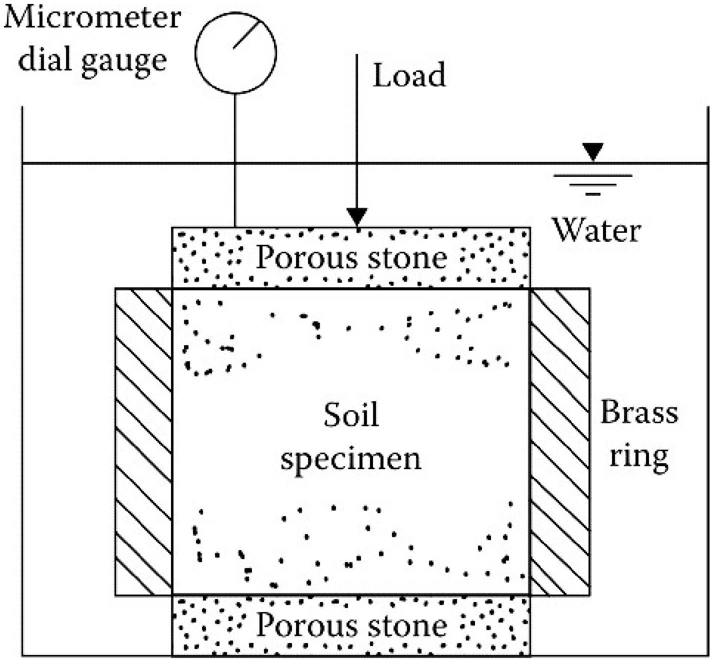

Figure 1: Incremental load consolidation test apparatus (Das, 2019)

2.9 Conventional Incremental Loading test

The conventional incremental loading (CIL) test, commonly well-known as the Oedometer test, is a fundamental procedure in geotechnical engineering used to evaluate the compressibility and consolidation properties of soils. This test involves positioning a soil specimen within a rigid confining ring and applying a sequence of incremental vertical loads while permitting lateral deformation. Each load increment is maintained until primary consolidation is considered complete, typically inferred from time-rate of settlement curves (Lambe & Whitman, 1969). The resulting data are used to construct void ratio versus effective stress plots, from which key parameters such as the compression index (Cc) and the coefficient of consolidation (Cv) can be determined. The CIL test is invaluable for predicting soil settlement and analyzing the stability of earth structures (Head, 1994). Despite its widespread use, the test has limitations, including the assumption of one-dimensional consolidation and the potential for sample disturbance affecting the results (Terzaghi, Peck, & Mesri, 1996). Recent studies continue to refine the method and explore its applications in different soil types and conditions, emphasizing the importance of accurate parameter determination for effective geotechnical design (Craig, 2004).

2.9.1 Compression Index (Cc)

The compression index (Cc) is a crucial parameter in geotechnical engineering that quantifies the compressibility of soil under one-dimensional loading conditions. It is obtained from the slope of the curve representing the void ratio versus the logarithm of effective stress obtained during consolidation testing, typically using an oedometer test (Lambe & Whitman, 1969). The compression index provides insight into how much a soil sample will compress when subjected to an increase in effective stress, which is vital for predicting settlement in structures such as foundations and embankments. Empirical correlations, such as those developed by Skempton (1944), have shown that Cc is significantly influenced by soil properties such as the liquid limit (LL) and plasticity index (PI). Further research by Bowles (1984) expanded these correlations, making them widely used in geotechnical practice to estimate soil compressibility based on readily available soil properties.

$$Cc = \frac{\Delta e}{log(\frac{p_1}{p_0})} \tag{1}$$

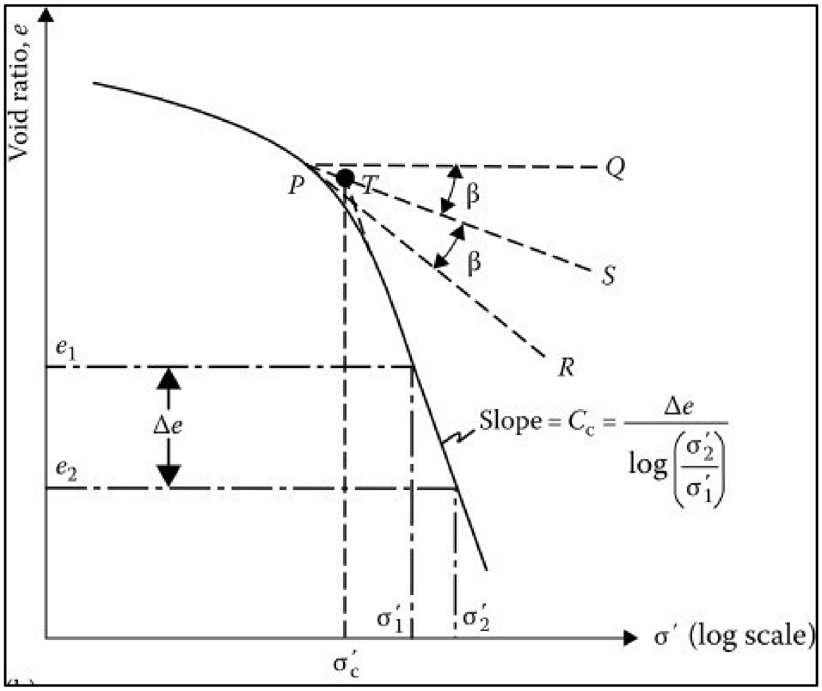

Figure 2: e versus log σ′ plot for determination of Cc (Das, 2019).

2.9.2 *Coefficient of Consolidation (Cv)*

The coefficient of consolidation (Cv) is a parameter that characterizes the rate at which soil undergoes consolidation under a specific load, playing a critical role in predicting the time-dependent settlement of structures. Cv is influenced by both the soil's permeability and compressibility characteristics, making it a complex parameter to determine accurately (Mesri & Choi, 1985). Typically derived from oedometer test data, Cv is calculated based on the time rate of settlement and the variation in void ratio during consolidation. Research by Yin and Graham (1996) highlighted that while there is a general relationship between Cv and the compression index (Cc), significant variability can occur due to local soil conditions and mineralogical differences. This variability underscores the importance of site-specific investigations to obtain accurate Cv values.

2.9.3 Methods for Determining Coefficient of Consolidation

The methods used to determine the coefficient of consolidation are as follows;

2.9.3.1 Casagrande Method (Logarithm Time Fitting)

The Casagrande method, also known as the logarithm of time fitting method, is a widely used technique for defining the coefficient of consolidation (Cv) from oedometer test data. This method involves plotting the settlement data on a semi-logarithmic graph, where the time (t) is plotted on the logarithmic scale, and the settlement (δ) is plotted on the arithmetic scale. The coefficient of consolidation is then determined by identifying two key points on the curve: the point of 90% consolidation (t90) and the point of 50% consolidation (t50). The time for 90% consolidation (t90) is used to calculate Cv using the following formula:

$$C_v = \frac{0.197 \times H_d^2}{t_{90}} \tag{2}$$

Where H_d is the drainage path length, typically half the specimen height for double drainage conditions (Casagrande, 1938; Lambe & Whitman, 1969). This method provides a practical and relatively straightforward approach to estimating Cv from consolidation test data.

2.9.3.2 Taylor Square Root Method

The Taylor square root method is another commonly used technique for defining the coefficient of consolidation. This method involves plotting the settlement data on a graph where the settlement (δ) is plotted against the square root of time (√t). A straight line is fitted to the initial portion of the data, and the point of 90% consolidation (t90) is identified from the intersection of this line with the settlement curve. The coefficient of consolidation is determined using the formula:

$$C_v = \frac{\pi \,.\, H_d^2}{4 \,.\, t_{90}} \tag{3}$$

Where Hd is the drainage path length (Taylor, 1948). The Taylor square root method is particularly useful for soils with rapid initial consolidation and provides a robust estimate of Cv for a variety of soil types.

2.9.3.3 Coefficient of the Volume Change (mv)

The coefficient of volume change (mv) is a parameter that quantifies the change in volume per unit increase in effective stress. It is an important factor in the calculation of Cv, particularly in the context of settlement predictions. The coefficient of volume change is given by:

$$m_v = \frac{\Delta e}{\Delta \sigma' .\, (1+e_0)} \tag{4}$$

Where Δe represents the change in void ratio, Δσ′ denotes the change in effective stress, and e0 is the initial void ratio (Terzaghi et al., 1996). The coefficient of consolidation (Cv) can then be related to mv through the soil's permeability (k) and the unit weight of the water (γw).

$$C_v = \frac{k}{m_v \,.\, \gamma_w} \tag{5}$$

2.10 Previous Studies of Compression Index and Coefficient of Consolidation

A significant amount of research has been carried out on the compression index (Cc) and the coefficient of consolidation (Cv), which are vital parameters in soil mechanics for understanding soil compressibility and consolidation behavior. Skempton (1944) was among the first to establish a relationship between Compression index and the soil properties such as the liquid limit, noting that Cc tends to increase with higher LL values. This empirical correlation has been foundational in geotechnical engineering, providing a basis for estimating Cc from easily measurable soil properties. Further refining these relationships, Bowles (1984) expanded the scope of empirical correlations to include other properties like the plasticity index (PI), making them more versatile for different soil types.

In parallel, studies on Cv have focused on its variability and the factors affecting it. Mesri and Choi (1985) provided a comprehensive review of the factors influencing Cv, emphasizing the importance of soil permeability and initial void ratio. Their research highlighted that Cv is not only dependent on intrinsic soil properties but also on external conditions such as loading rates and boundary conditions during consolidation testing. Yin and Graham (1996) further investigated the relationship between Cv and Cc, revealing that while a general trend exists, significant variability can arise due to differences in soil mineralogy and structure. This variability necessitates site-specific investigations to accurately determine Cv for precise settlement predictions.

2.10.1 Compression index

Parameters such as the compression index, derived from consolidation tests, are used to estimate settlement for normally consolidated soils. When it is not feasible to conduct these tests, various alternative methods are explored to obtain these parameters without performing the consolidation test (Alptekin & Taga, 2019). These alternative methods are regression analyses for index properties of the soil and numerical models based on Artificial Neural Network (ANN) methods. Most researchers have developed a correlation for compression index with a single parameters including the liquid limit, plasticity index, natural moisture content, and void ratio. Skempton (1944), is the first person to develop a correlation between compression index and liquid limit for remolded clays as:

$$C_c = 0.007(L.L - 10) \tag{6}$$

Table 1: Summary of the Correlations of Cc Developed by Past Researchers

Author	Region	Number of samples	L.L ranges	Correlation
Hamza Güllü et al. (2016)	Baghdad	69 fine grained	32% to 62%	C_C=0.00454LL – 0.01246
Kok Shien Ng et al. (2018)		5 remolded cohesive soil samples	29% to 46%	C_C=0.0062LL + 0.0165
Kumar K et al. (2016)	6 different regions of India	Fine-grained soils (CH)	63% to 70%	C_C=0.001(LL) – 0.013
Puri et al. (2018)	North India	1053 locations (state of Haryana)		C_C=(0.0092LL) – 0.1091 [LL≤29.25] C_C=(0.0017LL) + 0.1235 [29.25< LL <37.35] C_C=(0.0064LL) – 0.0523 [LL ≥37.35]
Solanki, C. H. (2012)	10 regions in Gujarat, India	135 literature data	30% to 60%	C_C=0.0061LL – 0.0024
Sridharan and Nagaraj (2000)		10 soil samples	30% to 60%	C_C=0.008 (LL – 12)
Vinod P. and Bindu J. (2010)	Kerala in India	18 highly plastic soil samples	70.8% to 276.3%	C_C=0.0055 (LL – 1.8364)
Slamet W. and Abdelazim I. (2012)	Pontianak, Indonesia	20 samples from 10 boreholes	17.1% to 62.46%	C_C=0.01706 LL – 0.02209
Zaman et al. (2017)	Bangladesh	14 undisturbed clay samples	33.7% to 67.1%	C_C=0.01 (LL – 13.61)
Binod Tiwari and Beena Ajmera (2012)	Japan	82 different natural samples		C_C=0.0075(LL) [Activity < 1] C_C=0.012(LL) [Activity > 1]

Table 2: Continue

Author	Region	Number of samples	L.L ranges	Correlation
Ayşen Lav and Atilla Ansal (2001)	Türkiye	300 soil specimens	23% to 166%	$C_C=0.006\,(LL + 1)$ $C_C=0.007LL - 0.029$ (NC)
Gil Lim Yoon et al. (2004)	3 different regions of Korea	1200 marine clay samples	23% to 120.2%	$C_C=0.012(LL + 16.4)$, South coast $C_C=0.011(LL - 6.36)$, East coast $C_C=0.01(LL - 10.9)$, West coast
Akayuli and Ofosu (2013)	Kumasi in Ghana	90 soil samples	14.6% to 67.6%	$C_C=0.004LL - 0.03$
Kumar, Jain, et al. (2016)	16 different regions of Bhopal, India	23 samples	41.3% to 140.5%	$C_C=0.0067\,(LL) - 0.0364$
Laskar and Pal (2012)	regions of India	3 samples		$C_C=0.0046(LL - 1.39)$
McCabe et al. (2014)	fine-grained soils of Ireland	61 soil samples	32% to 199%	$C_C=0.0118LL - 0.2443$
Nesamatha and Arumairaj (2015)	Coimbatore, India	5 soil samples	66.2% to 77.8%	$C_C=0.002LL - 0.127$
Rashed et al. (2017)	Sulaymaniyah, Iraq	54 undisturbed soil samples	35.5% to 65.2%	$C_C=0.006LL - 0.1$
Al-Ameri and Al-Kahdaar (2010)	Ammarah, Iraq	40 different locations	22% to 62%	$C_C=0.00556LL$
Shaikh et al. (2014)	Khulna, Bangladesh		29% to 68%	$C_C=0.011LL - 0.102$
Kootahi and Moradi (2017)	different locations worldwide	500 marine clay samples		$C_C=-0.096 + 0.012LL$
Ara S et al. (2021)	Chattagram city	8 undisturbed soil samples		$C_C=0.0046LL + 0.2324$

2.10.1.1 Research Gaps of Existing Correlation Equations

In geotechnical engineering, the index properties of soil are not constant throughout the world. The major reason for this variation is the mineralogical variation. Since correlation equations of compression index are developed based on index properties, the range of predicted values of Cc also varies. This indicates that compressibility parameter correlation equations should be developed for a specified soil type and mineralogical content.

In other cases, some of the existing equations are developed for a specific region and are not able to be applicable in other regions. In most correlation equations, the natural moisture content is used as a predictor variable. However, natural moisture content is not a consistent value. It does not quantify the compressibility parameters meaningfully. The value of natural moisture content is variable throughout the season.

2.10.2 Coefficient of Consolidation

The coefficient of consolidation (Cv) is a fundamental parameter in geotechnical engineering that describes the rate at which soil consolidates under load, influencing the time-dependent settlement of structures. Early foundational work by Casagrande and Carillo (1944) provided essential theoretical frameworks for understanding Cv, emphasizing its dependence on soil permeability and compressibility. Their research introduced methods for determining Cv from consolidation test data, which remain widely used today. Building on this foundation, Mesri and Choi (1985) conducted a comprehensive review of factors affecting Cv, highlighting the significant influence of initial void ratio and soil permeability on consolidation behavior. They emphasized that Cv is not a fixed property but varies with changes in effective stress and void ratio, necessitating careful interpretation of test results.

Further contributions to the understanding of Cv include studies by Lambe and Whitman (1969), who discussed the variability of Cv across different soil types and conditions, suggesting that empirical correlations require local calibration for accurate predictions. Yin and Graham (1996) investigated the relationship between Cv and other soil properties such as the compression index (Cc), concluding that while there is a general trend linking these parameters, significant variability exists due to differences in soil mineralogy and structure. Their findings underscored the importance of site-specific investigations to accurately determine Cv. These studies collectively emphasize the complexity of Cv as a parameter and the necessity for ongoing research and refinement of empirical methods to improve the predictability and reliability of consolidation behavior in diverse geotechnical contexts.

Table 3: Summary of the Correlations of Cv Developed by Past Researchers

Author	**Region**	**Number of samples**	**Correlation**	**R^2 value**
Kassou et al. (2017)			$C_V=26.917LL - 2.57$	
Asma Y. and Abbas F. (2011)	Central and Southern Iraq	280 undisturbed silty clay	$C_V=4258LL^{-1.758}$	0.721
Devi et al.	Manipur Valley (India)	5 undisturbed samples	$C_V=-4x10^{-9}\ LL + 4x10^{-7}$	0.8298
Solanki's (2012)	10 regions in Gujarat, India	135 literature data	$C_V= 108\ LL^{-6.7591}$	0.9156
Kok Shien Ng et al. (2018)		5 remolded cohesive soil samples	$C_V=0.7519 - 0.0102LL$	0.8608

2.11 Summary

The literature review emphasizes the importance of understanding soil compressibility characteristics, especially the compression index and coefficient of consolidation, for effective foundation design. Foundational research by Terzaghi and Peck (1967) and Skempton (1944) established empirical correlations between Cc and soil index properties like the liquid limit (LL), which have become standard in geotechnical engineering.

Research has shown strong correlations between the liquid limit and plasticity index (PI) with Cc, aiding in the prediction of settlement behavior. Skempton's empirical relationship ($Cc = 0.007*(LL - 10)$) and Terzaghi and Peck's variation ($Cc = 0.009*(LL - 10)$) highlight the predictive value of the liquid limit. Additionally, studies by Kootahi and Moradi (2017) and Shimobe et al. (2022) have validated the use of index tests for estimating Cc, demonstrating practical applications in geotechnical assessments.

The coefficient of consolidation (Cv), introduced by Terzaghi’s classical theory of one-dimensional consolidation, is crucial for predicting settlement rates in cohesive soils. Traditional Oedometer tests are time-consuming, leading researchers to explore quicker, empirical methods. Studies by Sridharan and Nagaraj (2000), Mittal et al. (2021), and others have examined the influence of soil plasticity on Cv, noting that Cv generally decreases with higher liquid limits. Despite numerous empirical correlations, creating universally applicable models remains challenging due to regional and soil type variations.

This research addresses gaps in the literature by investigating the compressibility characteristics of soils passing different sieve sizes (#40 and #200) in Pakistan. By developing and validating new empirical correlations tailored to Pakistan's diverse soil conditions, this study aims to provide more accurate tools for predicting soil behavior and improving foundation design practices.

CHAPTER 3: MATERIALS AND METHODOLOGY

3.1 General

This chapter outlines the methodology employed to accomplish the research objectives. Following an extensive literature review of previous studies and academic articles relevant to the research topic, a detailed framework was devised. This framework encompassed all necessary procedures, including sample collection and the execution of various laboratory tests such as Sieve Analysis, Hydrometer Analysis, Specific Gravity determination, Atterberg Limits for plasticity evaluation, and the Oedometer test to ascertain Consolidation Parameters.

3.2 Research Framework

This thesis aimed to meet the research objectives while maintaining efficiency in effort and resources, and ensuring precision and accuracy in measurements. The key elements of the research framework include:

1. Collection of soil samples from different locations of Pakistan.
2. Conducting various laboratory tests, which include:
    a) Sieve Analysis: Measure the grain size distribution of the soil.
    b) Hydrometer Analysis: Analyze the finer fraction of the soil.
    c) Specific Gravity: Measure the Specific Gravity of the soil.
    d) Atterberg Limits: Determine the liquid limit (LL), plastic limit (PL), and plasticity index (PI) of the soil for sieve # 40 and sieve # 200.
    e) Oedometer test: Conduct Oedometer tests to find the compression index and coefficient of consolidation.

3. Compare LL of Sieve #40 vs. Sieve #200: Compare the liquid limit values obtained from different sieve sizes.
4. Develop Multilinear Regression Model: Create a model to correlate Cc and Cv with various soil parameters.
5. Data Validation of developed correlation with Additional 50 Locations: Collect more data from 50 locations to validate the model.
6. Compare Results with Past Studies: Compare the developed correlations with those from previous research.
7. Conclusion: Summarize the findings and implications of the research.

When conducting laboratory work, the following considerations are crucial:

1. Ensure all equipment, tools, and test apparatus are properly calibrated before use.
2. Exercise utmost care throughout all laboratory procedures and tests.
3. Document all activities and reports meticulously to guarantee the accuracy of all data and figures.
4. Maintain a presence during the execution of all laboratory tests and procedures.
5. Verify measurement and scale accuracy by repeating tests if any uncertainties in the results arise.

3.3 Flow Chart for Research Work

The flow chart for this research provides a comprehensive visual representation of the sequential steps involved in the study. It outlines the entire process, from the initial phase of problem identification and sample collection to laboratory testing, data analysis, model development using machine learning techniques, and the final validation and application of the predictive models. The detailed flow chart for this research is shown below.

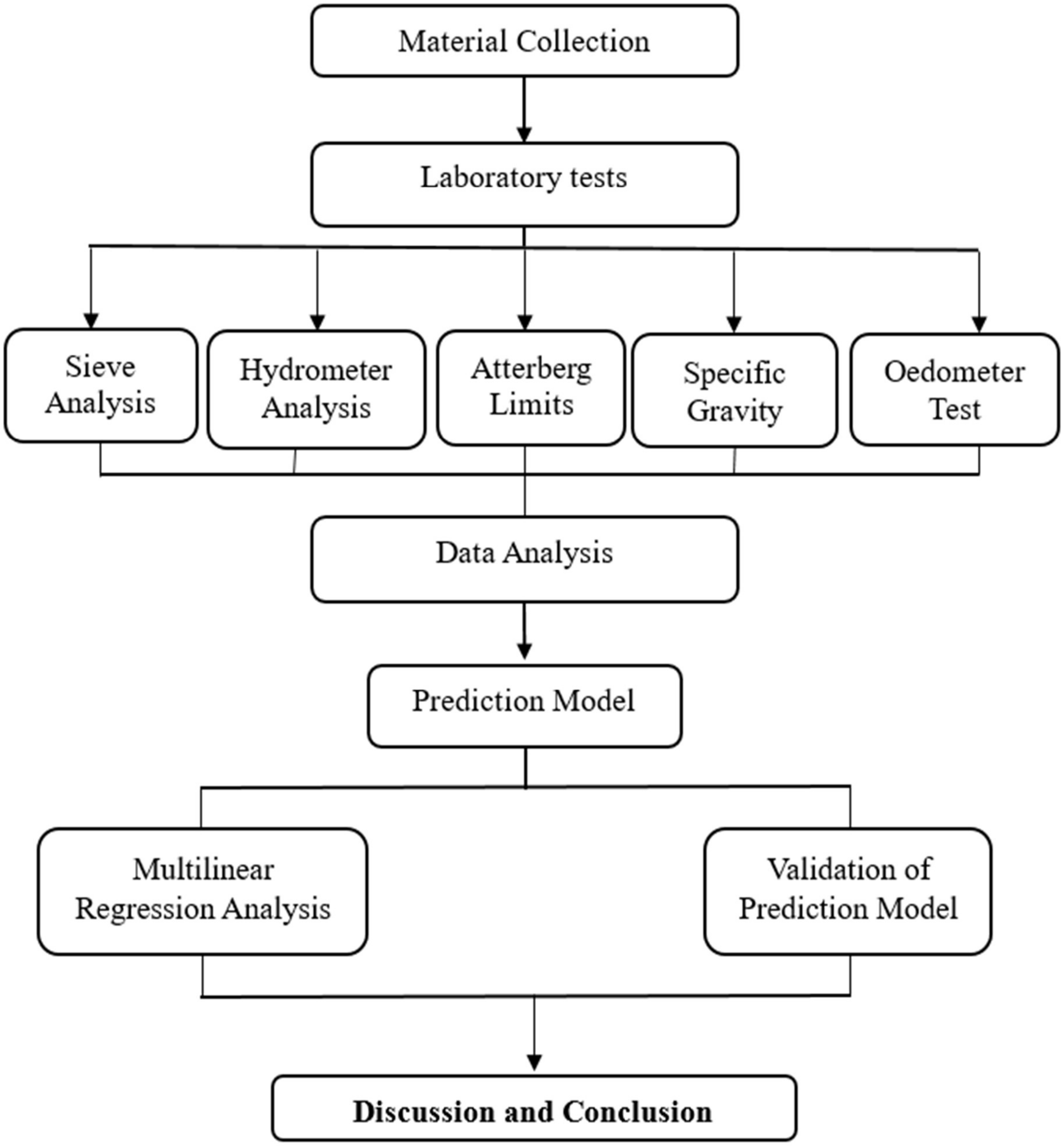

Figure 3: Flow chart of the research

3.4 Samples Collection

A total of one hundred soil samples were gathered from various locations across Pakistan. These undisturbed samples were collected using Shelby tube samplers and as box samples. To preserve their original state and natural water content, the samples were sealed with wax. The coordinates of each sample location were recorded and plotted on a shape file of Pakistan.

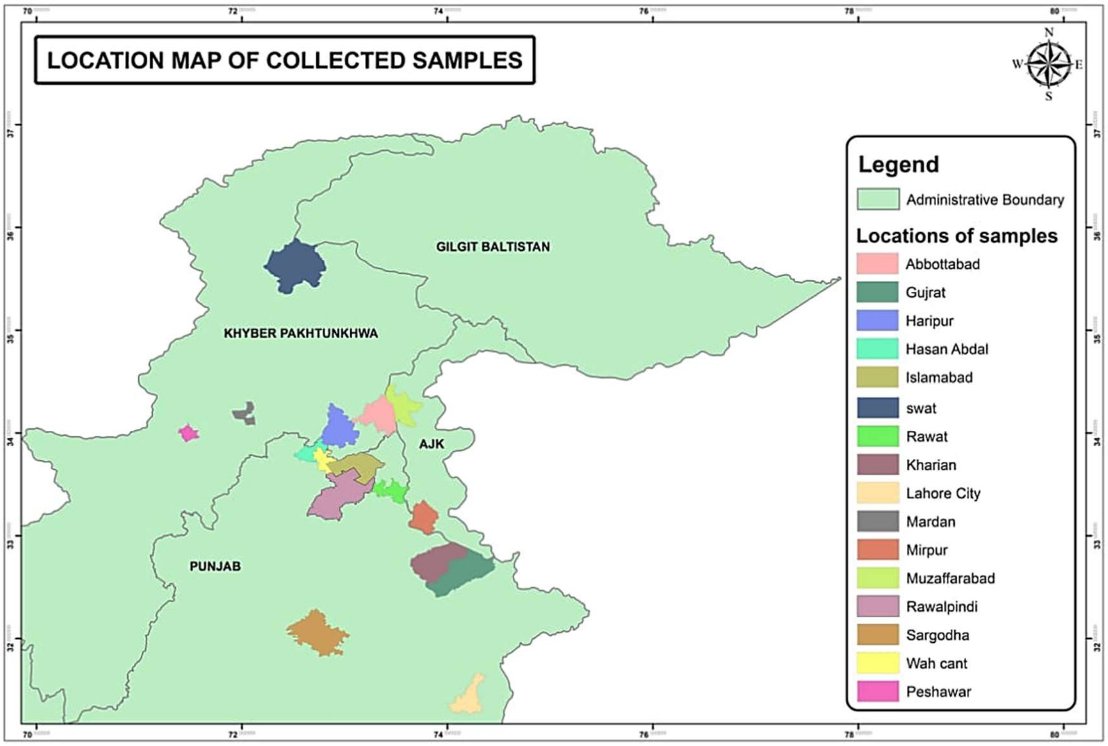

Figure 4: Location Map of Collected Samples

Figure 5: Sample Collection

The table below lists the number of soil samples collected from various cities, along with their geographical coordinates.

Table 4: Soil Samples Collected from Various Cities with their Geographical Coordinates

City Name	Number of Samples	Coordinates
Abbottabad	**5**	34°09'37.99"N 73°14'47.99"E
Gujrat	**5**	32°34'39.0"N 74°04'48.0"E
Haripur	**5**	33°59'24.0"N 72°56'10.0"E
Hassan Abdal	**8**	33°48'10.0"N 72°41'33.0"E
Islamabad	**8**	33°43'47.08"N73° 5'32.10"E
Swat	**5**	35°12'16.0"N 72°25'14.0"E
Rawat	**7**	33°31'27.0"N 73°10'41.0"E
Kharian	**5**	32°49'20.0"N 73°51'24.0"E
Lahore	**8**	31°32'59.0"N 74°20'37.0"E
Mardan	**5**	34°11'36.99"N72° 2'53.67"E
Mirpur	**5**	33°11'55.0"N 73°44'50.0"E
Muzaffarabad	**5**	34°22'59.0"N 73°28'00.0"E
Rawalpindi	**8**	33°36'00.0"N 73°02'00.0"E
Sargodha	**5**	32°05'60.0"N 72°40'50.0"E
Wah Cantt	**8**	33°44'50.0"N 72°47'21.0"E
Peshawar	**7**	34°00'00.0"N 71°34'00.0"E

3.5 Experimental Work

This section outlines the detailed procedures and methodologies for each laboratory test conducted as part of this research.

3.5.1 Natural Water Content of Soil

The natural water content test is followed by the ASTM D2216 that calculate the amount of the water present in soil sample without applying any external force or altering its natural condition. This measurement is crucial as it provides a baseline for further soil testing and helps in understanding the initial moisture state of the soil. The apparatus typically includes an electronic balance for accurate weighing of soil samples, an oven for drying samples, and a desiccator for cooling and storing dried samples.

To determine the natural water content of soil, a representative soil sample was initially weighed to record its initial weight (W1). Subsequently, the sample was placed in an oven set at a controlled temperature of 105°C ± 5°C and dried until it reached a constant weight. Upon completion of drying, the sample was removed from the oven and allowed to cool inside a desiccator to prevent moisture absorption from the surrounding environment. After cooling, the sample was re-weighed (W2). The natural water content was then calculated using the formula:

$$\text{Natural Water Content (\%)} = \frac{W1-W2}{W2} \times 100 \tag{7}$$

This procedure was crucial for accurately determining the moisture content of the soil sample, providing foundational data for subsequent geotechnical analyses.

Figure 6: Oven used to find Natural Water Content of Soil

3.5.2 *Sieve Analysis*

Sieve analysis is performed according to ASTM D422 that determines the particle size distribution of a soil sample by dividing it into fractions using a series of sieves with progressively smaller mesh sizes. This test helps in understanding soil classification, suitability for different engineering applications, and behavior under load. The apparatus consists of a set of sieves with mesh sizes ranging from coarse to fine, a mechanical sieve shaker, an electronic balance, and necessary tools for handling and weighing soil samples.

To conduct sieve analysis, a representative soil sample was first weighed. The sample was then passed through a series of sieves arranged in a series, with the largest sieve at the top and the smallest at the bottom. Sieves were shaken either mechanically or by hand for a specified duration to separate the soil particles by size. After shaking, the soil retained on each sieve was carefully weighed. The percentage of soil passing through and retained on each sieve was calculated based on the initial sample weight. This data was used to plot a grain size distribution curve, which illustrates the distribution of particle sizes within the soil sample. Parameters including the uniformity coefficient and the coefficient of gradation were determined from the grain size distribution curve, providing valuable information about the soil's particle size distribution and its suitability for various engineering applications. This procedure ensured accurate characterization of the soil's grain size distribution.

Figure 7: Arrangement of sieve descending order according to Mesh sizes

3.5.3 Hydrometer Analysis

Hydrometer analysis is followed by ASTM D422 that determines the particle distribution of fine grained soils (particles passing sieve #200) using a hydrometer. This test complements sieve analysis by providing accurate results for finer particles. The apparatus includes a hydrometer with calibrated readings, a sedimentation cylinder, a mechanical stirrer for dispersing soil samples, and an electronic balance for precise measurement of soil and water quantities.

To perform hydrometer analysis, a soil sample was initially dispersed in water to suspend fine particles. The suspension was allowed to settle for a specified period to ensure adequate separation. Density measurements of the suspension were then taken at timed intervals using a hydrometer. These measurements enabled determination of the settling rate of the soil particles in the suspension. This was subsequently calculated using sedimentation analysis techniques, applying principles such as Stokes' Law to relate settling velocities to particle sizes. This comprehensive procedure facilitated accurate assessment of the soil's particle size distribution.

Hydrometer analysis is critical for characterizing fine-grained soils, assessing soil behavior, and designing soil mixes for construction and environmental applications.

Figure 8: Hydrometer Analysis of Soil

3.5.4 Specific Gravity of Soil

The specific gravity test is followed by ASTM D854 determines the ratio of the density of a soil solids to the density of water. This property is important for calculating various soil mechanics parameters, such as void ratio, porosity, and degree of saturation. The apparatus includes an electronic balance for weighing samples in air and water, a container filled with water for immersion, and a desiccator for drying samples.

To determine the specific gravity of soil, a soil sample was first weighed in air to obtain its weight (W1). The sample was then suspended in water and weighed again while fully submerged to record its underwater weight (W2). The specific gravity of the soil was calculated using the formula:

$$\text{Specific Gravity}=\frac{\text{Weight in Air}}{\text{Weight in Air-Weight in Water}} \tag{8}$$

This procedure provide a measure of density of the soil solids relative to water, essential for evaluating soil compaction and void spaces accurately.

Specific gravity is used to assess soil compaction, permeability, and strength characteristics, as well as in calculating soil water content and density.

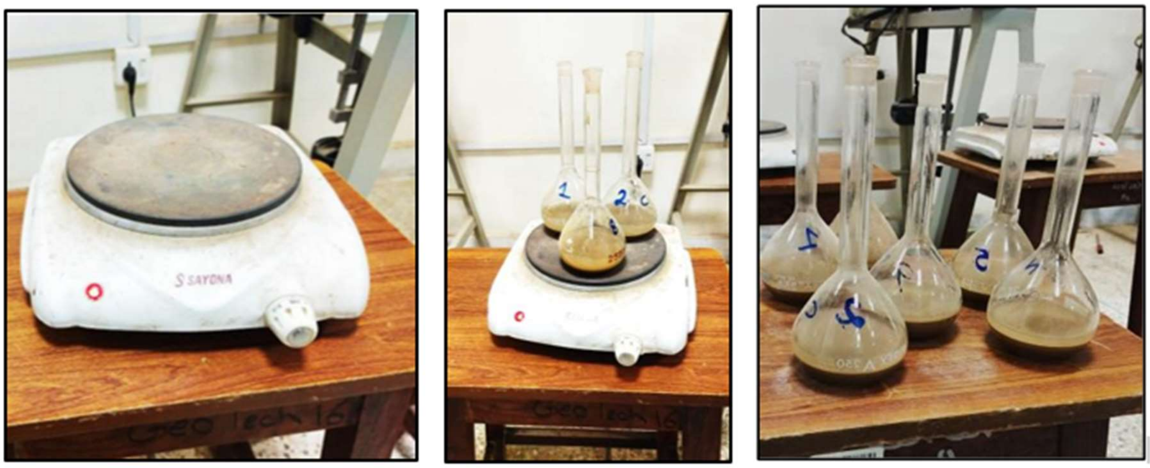

Figure 9: Specific Gravity test

3.5.5 Atterberg Limits

The Atterberg limits test using the Casagrande apparatus was conducted using ASTM D4318 to evaluate the plasticity characteristics of fine-grained soils. This test is pivotal in geotechnical engineering for determining key parameters such as the liquid limit (LL), plastic limit (PL), and plasticity index (PI). The purpose of this test was to precisely define the boundaries between different states of soil consistency, aiding in soil classification and engineering design assessments. The Casagrande apparatus, comprising a brass cup and grooving tool, provided a controlled environment for measuring these limits.

During the procedure, soil samples were incrementally mixed with water until achieving a uniform paste consistency for LL testing. The cup was then subjected to standardized drops, and the number of drops required for the groove to close over a set distance determined the LL. For PL determination, soil samples were kneaded to form threads, which were rolled into a specific diameter and rolled out on a glass plate until they crumbled. The moisture content at which the thread began to crumble defined the PL. Subsequently, the plasticity index (PI) was calculated as the difference between LL and PL as follows;

$$\mathrm{P.I} = \mathrm{L.L} - \mathrm{P.L} \tag{9}$$

The significance of these results lies in their utility for precise soil characterization, essential for geotechnical investigations and foundation design. By understanding the plasticity characteristics of soils, engineers can make informed decisions regarding construction materials and methods, ensuring the stability of infrastructure projects.

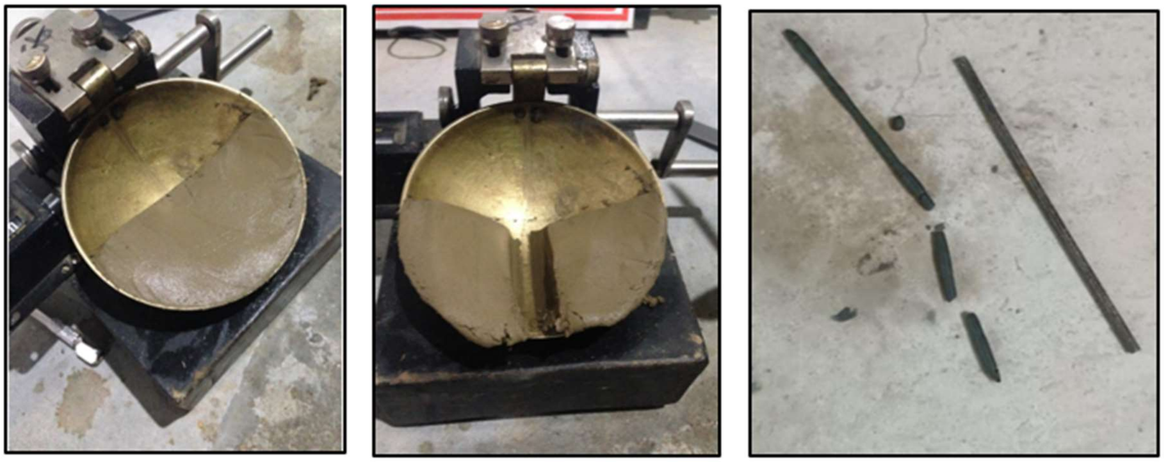

Figure 10: Atterberg limit test using casagrande method

3.5.6 One Dimensional Consolidation Test

The One Dimensional Consolidation (ODC) test is followed by ASTM D2435 that is crucial geotechnical test designed to determine the consolidation characteristics of soils under controlled conditions. The purpose of this test is to evaluate how much a soil sample consolidates under a specified load over time, simulating the process soils undergo in the field under building foundations or embankments. The test apparatus typically consists of a consolidometer, which houses the soil sample in a confined space and allows for the application of a vertical stress.

During the test, the sample was subjected to incremental vertical loads, and the resulting settlements were measured over time. From these measurements, two key parameters were derived: the Compression Index (Cc) and the Coefficient of Consolidation (C_v).

The compression index (C_c) quantifies the compressibility of a soil under vertical loading. It is derived from the relationship between void ratio and effective stress obtained through oedometer consolidation tests and was calculated using the formula;

$$C_C = \frac{\log e_2 - \log e_1}{\log\ _1 - \log \sigma_2} \tag{10}$$

Where e1 and e2 were void ratios at initial and final states, and σ1 and σ2 were the corresponding effective stresses.

The coefficient of consolidation (C_v) measures the rate at which soil consolidates under applied load. It provides information on the time required for a soil layer to achieve a certain degree of consolidation and was determined using the formula;

$$C_V = \frac{0.848 \times H_{dr}^2}{t_{90}} \tag{11}$$

Where the t_{90} value represents the time it takes for a soil sample to undergo 90% of its total consolidation settlement under a constant vertical load and H is the thickness of the soil sample. These parameters were crucial for predicting settlement behavior in structures and for designing foundations to ensure stability and safety over the long term.

Figure 11: Oedometer test for Cc and Cv

CHAPTER 4: RESULTS AND DISCUSSION

4.1 General

This chapter presents the findings from the tests conducted, including sieve analysis, hydrometer analysis, Atterberg limits, specific gravity, and consolidation parameters for one hundred soil samples. A Multilinear regression model was developed for the compression index and the coefficient of consolidation, with input parameters such as Clay %, Silt %, L.L 40 %, P.I 40 %, L.L 200 %, P.I 200 %, and Gs. To validate the developed correlations, additional data were collected from 50 different locations in Pakistan, ensuring the reliability and robustness of the correlations.

4.2 Sieve Analysis

A sieve analysis was performed on one hundred soil samples to assess their grain size distribution. The test adhered to the ASTM D422 standard. The analysis revealed a high fine content in the soil, with a significant proportion of silt and clay, and a comparatively lower gravel content.

4.3 Hydrometer Analysis

Hydrometer analysis was conducted to classify the fine content present in the soil, following the ASTM D422 standard. The hydrometer analysis revealed that the soil's clay content exceeded its silt content, indicating a higher proportion of very fine particles. This higher clay content can significantly influence the soil's plasticity, compressibility, and hydraulic conductivity, which are critical factors in geotechnical engineering.

4.4 Atterberg Limits

The Atterberg limit test was performed on the soil samples passing through sieve #40 and sieve # 200. The results indicate that the liquid limit measured from material passing through sieve #200 is significantly higher than that from sieve #40, attributing this difference to the finer particles' greater water retention capacity. This discrepancy suggests that the soil classification based on the Unified Soil Classification System (USCS) will be influenced by the Atterberg limits determined from the finer particles passing through sieve #200. Tables 4 and 5 present the Atterberg limit statistics for materials passing through sieve #40 and sieve #200, respectively.

Table 5: Statistics of Atterberg based on Sieve #40

Statistic	**Liquid Limit ($L.L_{40}$)**	**Plastic Limit ($P.L_{40}$)**	**Plasticity Index ($P.I_{40}$)**
Minimum	18.00	10.00	4.00
Maximum	33.60	22.70	13.25
Mean	28.47	19.38	9.09
Median	29.00	20.00	9.13
Standard Deviation	3.15	2.00	1.73

Table 6: Statistics of Atterberg based on Sieve #200

Statistic	**Liquid Limit ($L.L_{200}$)**	**Plastic Limit ($P.L_{200}$)**	**Plasticity Index ($P.I_{200}$)**
Minimum	22.79	13.21	5.75
Maximum	38.55	25.83	15.05
Mean	33.31	22.60	10.72
Median	33.91	23.15	10.86
Standard Deviation	3.17	1.98	1.81

Graphs depicting L.L$_{40}$ vs P.I$_{40}$ and L.L$_{200}$ vs P.I$_{200}$ were generated to visualize the relationships between liquid limit (L.L) and plasticity index (P.I) for soil passing through sieve #40 and sieve #200.

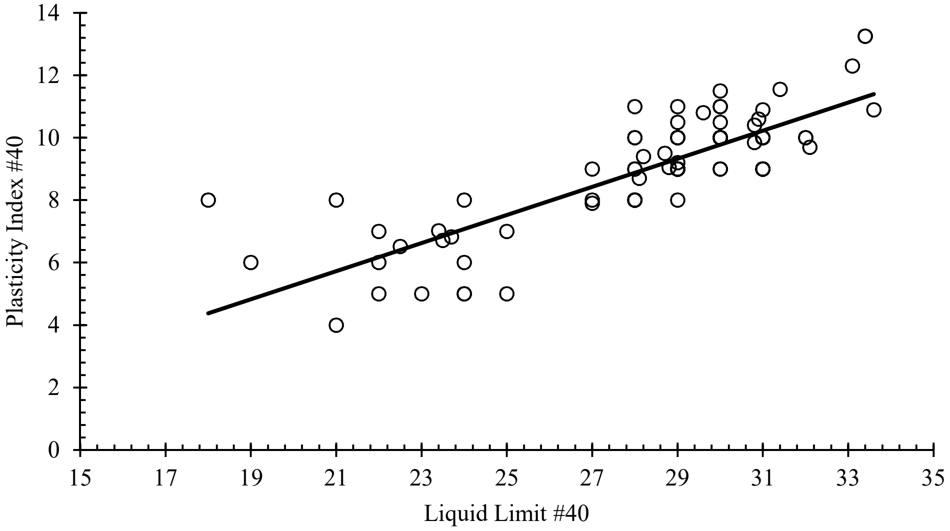

Figure 12: Liquid Limit$_{40}$ vs. Plasticity Index$_{40}$

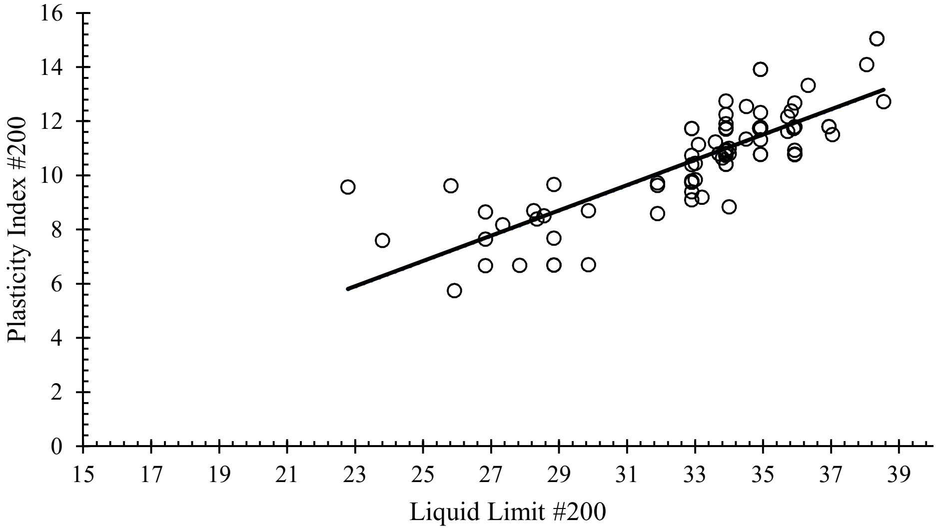

Figure 13: Liquid Limit$_{200}$ vs. Plasticity Index$_{200}$

A comparison graph was plotted to illustrate the difference between L.L40 and L.L200 values, clearly indicating that L.L200 values are significantly higher than those of L.L40. The lower L.L40 values are attributed to the presence of fine sand in the soil, as per the Unified Soil Classification System. It is possible to switch the soil type from CL to MH or CL to CH.

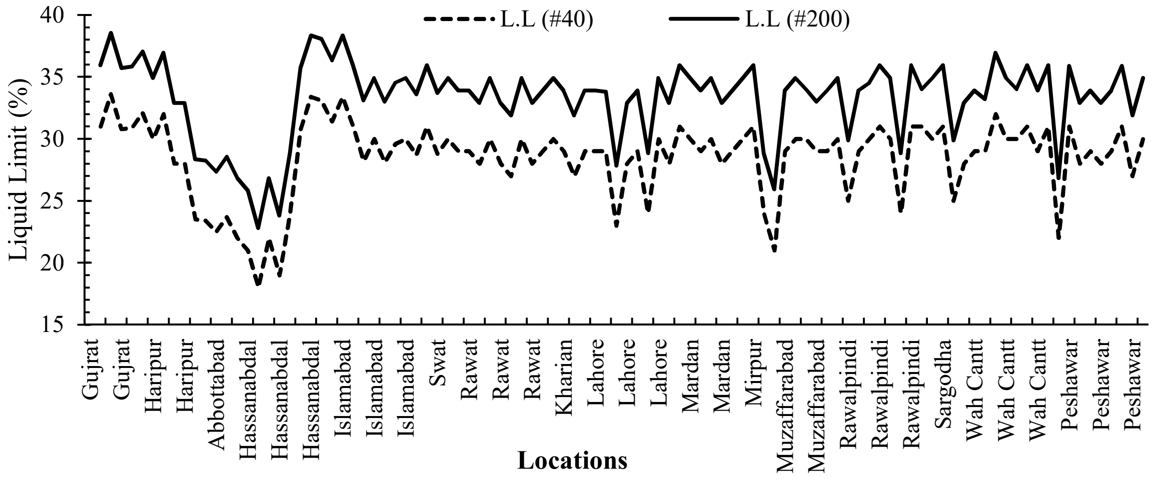

Figure 14: Comparison graph for $L.L_{40}$ and $L.L_{200}$

4.5 Specific Gravity

The specific gravity values obtained for soil from one hundred locations fall within the typical range for clays. The testing was conducted according to ASTM D854 standards. Graph below shows the Specific Gravity values against number of locations;

4.6 Oedometer Test

An Oedometer test was conducted following the ASTM D2435 standard to determine the soil's consolidation characteristics. From this test, the Compression Index and Coefficient of Consolidation were obtained. Graphs were plotted between L.L vs. Cc and Cv.

4.7 Liquid Limit and Compression Index

Graphs were plotted to illustrate the relationship between the Liquid Limit for soil passing sieve #40 (L.L$_{40}$) and the Compression Index (Cc), as well as between the Liquid Limit for soil passing sieve #200 (L.L$_{200}$) and the Compression Index (Cc). The graph for L.L$_{40}$ vs. Cc shows an R-squared value of 0.8994, while the graph for L.L$_{200}$ vs. Cc shows an R-squared value of 0.8873.

4.7.1 Liquid Limit $_{(\#40)}$ vs. Compression Index

The graph below illustrates the relationship between the Liquid Limit (#40) and the Compression Index, highlighting how variations in the liquid limit affect the soil's compressibility.

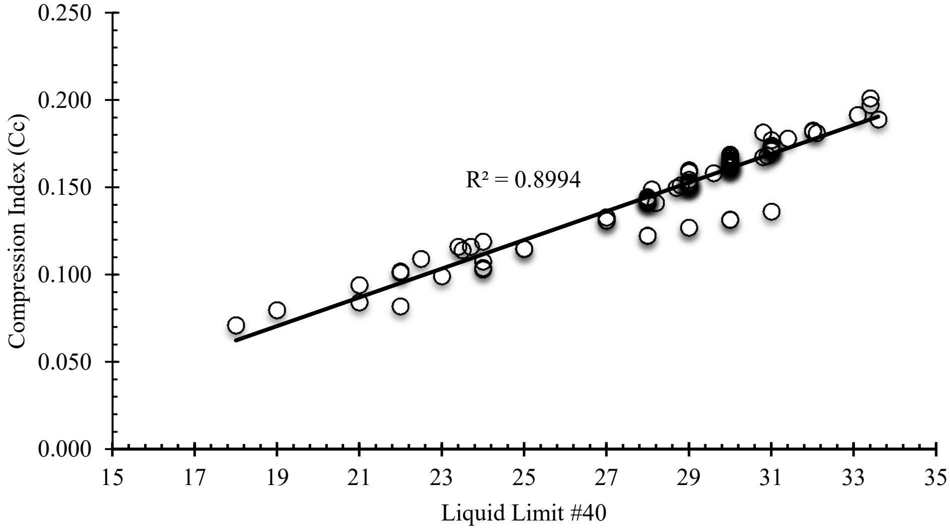

Figure 15: L.L$_{40}$ vs. Compression Index

4.7.2 *Liquid Limit* $_{(\#200)}$ *vs Compression Index*

The graph below illustrates the relationship between the Liquid Limit (#200) and the Compression Index, highlighting how variations in the liquid limit affect the soil's compressibility.

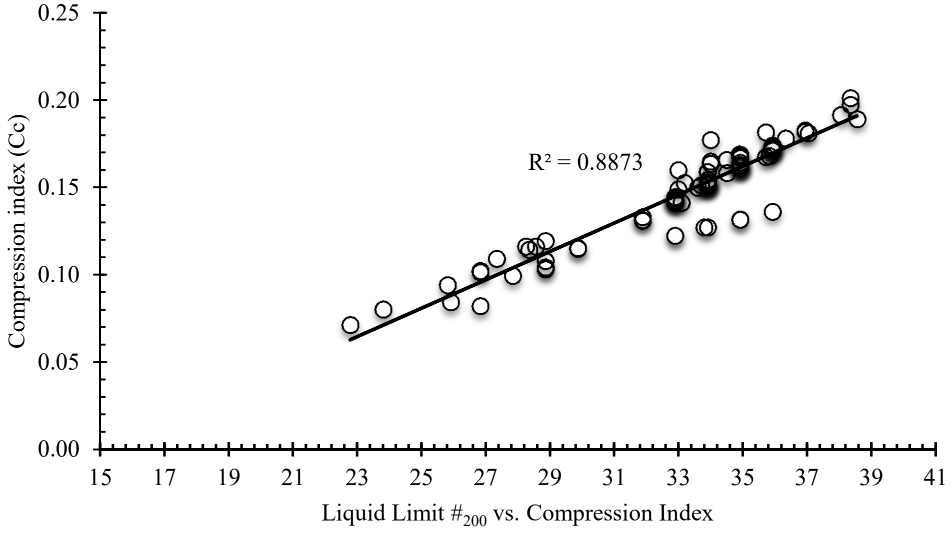

Figure 16: L.L200 vs. Compression Index

4.8 Liquid Limit and Coefficient of Consolidation

Graphs were plotted to illustrate the relationship between the Liquid Limit for soil passing sieve #40 (L.L40) and the Coefficient of Consolidation (Cv), as well as between the Liquid Limit for soil passing sieve #200 (L.L200) and the Coefficient of Consolidation (Cv). The graph for L.L40 vs. Cv demonstrates an R-squared value of 0.816, while the graph for L.L200 vs. Cv shows an R-squared value of 0.8072. These graphs are presented below.

4.8.1 *Liquid Limit* $_{(\#40)}$ *vs. Coefficient of Consolidation*

The graph below depicts the correlation between the Liquid Limit (sieve #40) and the Coefficient of Consolidation, showing how changes in the liquid limit influence the compressibility of the soil.

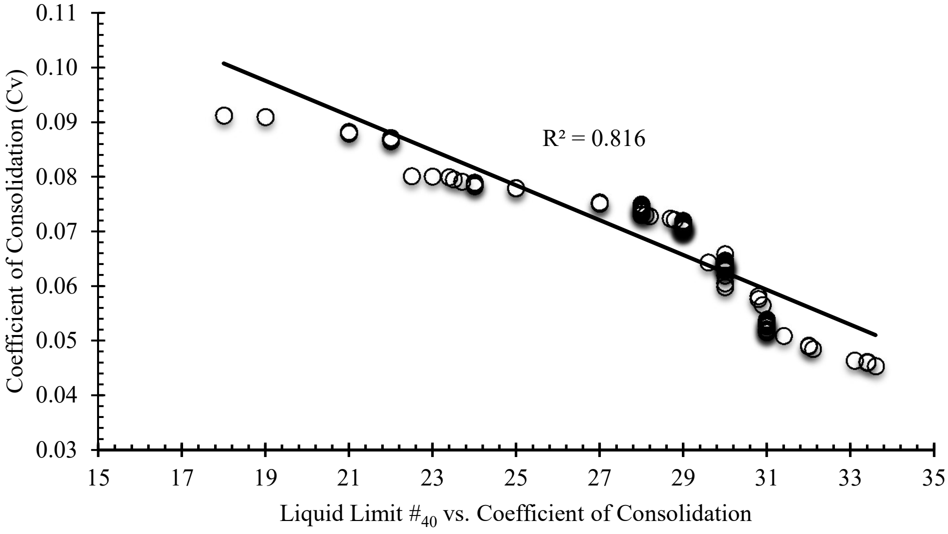

Figure 17: L.L40 vs. Coefficient of Consolidation

4.8.2 Liquid Limit $_{(\#200)}$ vs Coefficient of Consolidation

The graph below illustrates the link between the Liquid Limit (#200) and Coefficient of Consolidation, highlighting how variations in the liquid limit affect the soil's compressibility.

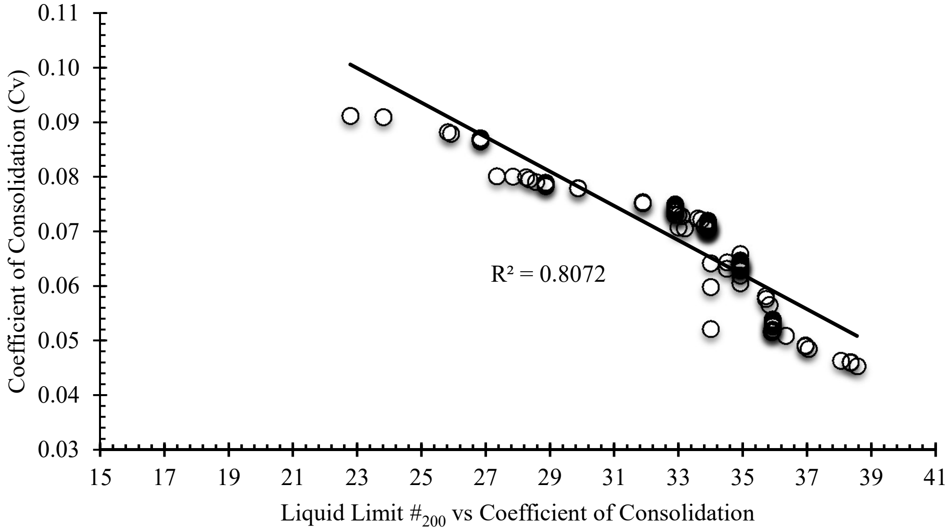

Figure 18: Graph for L.L$_{200}$ vs. Coefficient of Consolidation

4.9 Development of Prediction Model

Empirical correlations are crucial for predicting soil behavior without the need for extensive laboratory testing, which can be time-consuming, labor-intensive, and costly. Determining values of the Compression Index (Cc) and the Coefficient of Consolidation (Cv) from the Oedometer test exemplifies this challenge. To address this, prediction models were developed using a multilinear regression approach. In this study, the most significant and relevant inputs for the prediction model were identified as the Atterberg limits for sieve #40 and sieve #200, the clay content, the silt content, and the specific gravity.

4.9.1 Multilinear Regression Model (MLR)

A multiple linear regression model was developed to determine the Compression Index (Cc) and the Coefficient of Consolidation (Cv) more efficiently, as experimental evaluation can be quite time-consuming. To achieve accurate predictions, the model incorporated the Atterberg limits for soil passing through sieve #40 and sieve #200, as well as the clay content, silt content, and specific gravity as independent variables. The table below provides a detailed statistical summary of these soil characteristics, based on data from 100 soil samples used to train the prediction model.

Table 7: Statistics of Input for Validation of Cc and Cv Model

Predictors	Minimum	Maximum	Mean	Median	Standard Deviation
Clay %	11	57	45.62	50	10.4
Silt %	7	46	31.65	34	7.4
L.L 40 %	18.0	33.6	28.5	29.0	3.2
P.I 40 %	4	13.3	9.1	9.13	1.7
L.L 200 %	22.8	38.6	33.3	33.91	3.2
P.I 200 %	5.8	15.1	10.7	10.86	1.8
Gs	2.4	2.8	2.7	2.66	0.1

The primary assumption of multiple regression is that the relationship between the independent variables (IVs) and the dependent variables (DVs) can be represented by a straight line. Additionally, the assumption of normality specifies that the distribution of residuals should be normal. A histogram can confirm this by showing that the residuals are centered on zero, indicating an optimal residual distribution. Furthermore, when a prediction model is homoscedastic, the residuals exhibit a constant variance with respect to the values of the dependent variables.

4.10 Regression Summary

The table below presents a comprehensive summary of the regression analysis for the compression index and coefficient of consolidation based on soil passing sieve #40 and soil passing sieve # 200. This regression analysis includes the correlations between Cc and Cv with various soil parameters, detailing the R-square value and predicted R-square for each correlation. The R-square value indicates the proportion of variance in the dependent variable (Cc or Cv) that can be explained by the predictor variable, while the predicted R-square provides a measure of how well the regression model is likely to perform with new data. This summary allows for a clear understanding of the strength and predictive power of each correlation developed.

4.10.1 Regression Summary Based on Sieve # 40

The section includes two tables summarizing the regression analyses and correlations developed for the Compression Index and the Coefficient of Consolidation for materials passing through Sieve #40.

Table 8: Regression Summary of Cc based on sieve #40

Regression Analysis	**Regression Equation**	**R-square**	**Predicted R-square**
Cc versus L.L$_{40}$, P.I4$_{0}$, Clay, Silt, Gs	Cc= -0.0943 + 0.007430 L.L$_{40}$ + 0.001558 P.I$_{40}$ - 0.000109 Clay + 0.000341 Silt + 0.0042 Gs	91%	90%
Cc versus L.L$_{40}$, P.I$_{40}$, Clay, Silt	Cc= -0.08310 + 0.007417 L.L$_{40}$ + 0.001601 P.I$_{40}$ - 0.000118 Clay + 0.000352 Silt	91%	90%
Cc versus L.L$_{40}$, P.I$_{40}$, Clay, Gs	Cc= -0.1012 + 0.007463 L.L$_{40}$ + 0.001545 P.I$_{40}$ + 0.000106 Clay + 0.0069 Gs	91%	90%
Cc versus L.L$_{40}$, Clay, Silt, Gs	Cc= -0.1115 + 0.008108 L.L$_{40}$ - 0.000070 Clay + 0.000336 Silt + 0.0081 Gs	90%	90%
Cc versus L.L$_{40}$, P.I$_{40}$	Cc= -0.07887 + 0.007390 L.L$_{40}$ + 0.001853 P.I$_{40}$	90%	90%
Cc versus L.L$_{40}$	Cc= -0.086 + 0.0082 L.L$_{40}$	90%	90%
Cc versus L.L$_{40}$, P.I$_{40}$, Clay	Cc= -0.08285 + 0.007444 L.L$_{40}$ + 0.001615 P.I$_{40}$ + 0.000101 Clay	91%	90%
Cc versus L.L$_{40}$, P.I$_{40}$, Gs	Cc= -0.0924 + 0.007403 L.L$_{40}$ + 0.001808 P.I$_{40}$ + 0.0051 Gs	90%	90%
Cc versus L.L$_{40}$, Gs	Cc= -0.1097 + 0.008212 L.L$_{40}$ + 0.0091 Gs	90%	89%
Cc versus L.L$_{40}$, Clay, Gs	Cc= -0.1182 + 0.008135 L.L$_{40}$ + 0.000141 Clay + 0.0107 Gs	90%	89%

Table 9: Regression Summary of Cv based on sieve #40

Regression Analysis	Regression Equation	R-square	Predicted R-square
Cv versus $L.L_{40}$, $P.I_{40}$, Clay, Silt, Gs	$Cv= 0.1539 - 0.003231\ L.L_{40} + 0.000268\ P.I_{40} + 0.000216\ Clay - 0.000463\ Silt + 0.00293\ Gs$	84%	82%
Cv versus $L.L_{40}$, $P.I_{40}$, Clay, Silt	$Cv= 0.16175 - 0.003240\ L.L_{40} + 0.000298\ P.I_{40} + 0.000210\ Clay - 0.000455\ Silt$	84%	82%
Cv versus $L.L_{40}$, $P.I_{40}$, Clay	$Cv= 0.16142 - 0.003274\ L.L_{40} + 0.000279\ P.I_{40} - 0.000074\ Clay$	82%	80%
Cv versus $L.L_{40}$, $P.I_{40}$	$Cv= 0.15851 - 0.003235\ L.L_{40} + 0.000105\ P.I_{40}$	82%	80%
Cv versus $L.L_{40}$	$Cv= 0.158 - 0.0032\ L.L_{40}$	82%	81%
Cv versus $L.L_{40}$, $P.I_{40}$, Gs	$Cv= 0.1570 - 0.003233\ L.L_{40} + 0.000100\ P.I_{40} + 0.00056\ Gs$	82%	80%
Cv versus $L.L_{40}$, Gs	$Cv= 0.1561 - 0.003189\ L.L_{40} + 0.00078\ Gs$	82%	80%
Cv versus $L.L_{40}$, Clay, Gs	$Cv= 0.1601 - 0.003152\ L.L_{40} - 0.000068\ Clay + 0.00002\ Gs$	82%	80%
Cv versus $L.L_{40}$, Clay, Silt, Gs	$Cv= 0.1510 - 0.003114\ L.L_{40} + 0.000223\ Clay - 0.000464\ Silt + 0.00360\ Gs$	84%	82%
Cv versus $L.L_{40}$, $P.I_{40}$, Clay, Gs	$Cv= 0.1633 - 0.003276\ L.L_{40} + 0.000286\ P.I_{40} - 0.000074\ Clay - 0.00070\ Gs$	82%	80%

4.10.2 Regression Summary Based on Sieve # 200

This includes two tables summarizing the regression analyses and correlations developed for the Compression Index (Cc) and the Coefficient of Consolidation (Cv) for materials passing through Sieve #200.

Table 10: Regression Summary of Cc based on sieve #200

Regression Analysis	Regression Equation	R-square	Predicted R-square
Cc versus L.L$_{200}$, P.I$_{200}$, Clay, Silt, Gs	Cc= -0.1425 + 0.007731 L.L$_{200}$ + 0.000622 P.I$_{200}$ - 0.000026 Clay + 0.000294 Silt + 0.0070 Gs	89%	88%
Cc versus L.L$_{200}$, P.I$_{200}$, Clay, Silt	Cc= -0.1241 + 0.007724 L.L$_{200}$ + 0.000658 P.I$_{200}$ - 0.000040 Clay + 0.000311 Silt	89%	88%
Cc versus L.L$_{200}$, P.I$_{200}$, Clay	Cc= -0.1240 + 0.007745 L.L$_{200}$ + 0.000681 P.I$_{200}$ + 0.000154 Clay	89%	88%
Cc versus L.L$_{200}$, P.I$_{200}$	Cc= -0.1186 + 0.007732 L.L$_{200}$ + 0.000872 P.I$_{200}$	89%	88%
Cc versus L.L$_{200}$	Cc= -0.123 + 0.00814 L.L$_{200}$	89%	88%
Cc versus L.L$_{200}$, P.I$_{200}$, Gs	Cc= -0.1374 + 0.007737 L.L$_{200}$ + 0.000839 P.I$_{200}$ + 0.0072 Gs	89%	88%
Cc versus L.L$_{200}$, Gs	Cc= -0.1443 + 0.008126 L.L$_{200}$ + 0.0083 Gs	89%	88%
Cc versus L.L$_{200}$, Clay, Gs	Cc= -0.1541 + 0.008041 L.L$_{200}$ + 0.000167 Clay + 0.0101 Gs	89%	88%
Cc versus L.L$_{200}$, Clay, Silt, Gs	Cc= -0.1481 + 0.008015 L.L$_{200}$ - 0.000019 Clay + 0.000296 Silt + 0.0079 Gs	89%	88%
Cc versus L.L$_{200}$, P.I$_{200}$, Clay, Gs	Cc= -0.1484 + 0.007751 L.L$_{200}$ + 0.000632 P.I$_{200}$ + 0.000159 Clay + 0.0092 Gs	89%	88%

Table 11: Regression Summary of Cv based on sieve #200

Regression Analysis	Regression Equation	R-square	Predicted R-square
Cv versus L.L$_{200}$, P.I$_{200}$, Clay, Silt, Gs	Cv= 0.1663 - 0.003145 L.L$_{200}$ + 0.000138 P.I$_{200}$ + 0.000202 Clay - 0.000448 Silt + 0.00352 Gs	83.09%	80.70%
Cv versus L.L$_{200}$, P.I$_{200}$, Clay, Silt	Cv= 0.17560 - 0.003148 L.L$_{200}$ + 0.000156 P.I$_{200}$ + 0.000195 Clay - 0.000440 Silt	83.05%	81.03%
Cv versus L.L$_{200}$, P.I$_{200}$, Clay	Cv= 0.17549 - 0.003176 L.L$_{200}$ + 0.000123 P.I$_{200}$ - 0.000079 Clay	81.25%	79.29%
Cv versus L.L$_{200}$, P.I$_{200}$	Cv= 0.17271 - 0.003170 L.L$_{200}$ + 0.000024 P.I$_{200}$	80.73%	79.04%
Cv versus L.L$_{200}$	Cv= 0.173 - 0.00316 L.L$_{200}$	81%	80%
Cv versus L.L$_{200}$, P.I$_{200}$, Gs	Cv= 0.1698 - 0.003169 L.L$_{200}$ + 0.000019 P.I$_{200}$ + 0.00111 Gs	80.73%	78.72%
Cv versus L.L$_{200}$, Gs	Cv= 0.1696 - 0.003160 L.L$_{200}$ + 0.00114 Gs	80.73%	79.49%
Cv versus L.L$_{200}$, Clay, Gs	Cv= 0.1741 - 0.003120 L.L$_{200}$ - 0.000077 Clay + 0.00027 Gs	81.24%	79.68%
Cv versus L.L$_{200}$, Clay, Silt, Gs	Cv= 0.1651 - 0.003082 L.L$_{200}$ + 0.000203 Clay - 0.000448 Silt + 0.00372 Gs	83.07%	81.44%
Cv versus L.L$_{200}$, P.I$_{200}$, Clay, Gs	Cv= 0.1752 - 0.003176 L.L$_{200}$ + 0.000122 P.I$_{200}$ - 0.000079 Clay + 0.00009 Gs	81.25%	78.95%

4.11 Correlation Used for Prediction

After developing the correlations, statistical analysis revealed that the p-values for the correlations between the compression index and coefficient of consolidation with liquid limits L.L40 and L.L200 were less than 0.05. This indicates that L.L40 and L.L200 have a statistically significant influence on Cc and Cv, respectively, meaning these variables significantly affect the soil's compressibility and consolidation characteristics.

Conversely, correlations developed with other parameters such as silt content, clay content, specific gravity (Gs), and plasticity index (P.I) yielded p-values greater than 0.05. This suggests that these variables do not have a statistically significant effect on Cc and Cv.

Variables with p-values less than 0.05 are typically retained in statistical models as they are considered to make a significant contribution to explaining the variability observed in the dependent variables (Cc and Cv). The correlations retained for further analysis are summarized in the table below.

Table 12: Correlations Retained in Statistical Model

Regression Analysis	Correlation Developed	R-square	Predicted R-square
C_c versus $L.L_{40}$	$C_c = -0.08580 + 0.008225\ L.L_{40}$	89.94%	89.54%
C_v versus $L.L_{40}$	$C_v = 0.15812 - 0.003187\ L.L_{40}$	81.60%	80.68%
C_c versus $L.L_{200}$	$C_c = -0.12277 + 0.008139\ L.L_{200}$	88.73%	88.31%
C_v versus $L.L_{200}$	$C_v = 0.17259 - 0.003158\ L.L_{200}$	80.72%	79.81%

4.12 Data Validation

Validation is a critical step to assess the reliability and robustness of the correlations developed. By comparing the developed correlations with additional data, we can demonstrate their effectiveness and general applicability. To validate the developed empirical correlations, an additional set of soil samples was collected from 50 different locations across Pakistan. These samples were subjected to the same laboratory tests.

The data validation process has demonstrated that the developed empirical correlations between Cc, Cv, and LL are both reliable and robust. The comparison between the predicted values and experimental results showed the percentage error for both the compression index (Cc) and the coefficient of consolidation was less than 1%. The high level of agreement between the predicted and observed values confirms the effectiveness of these correlations in predicting the compressibility characteristics of soils.

4.13 Comparison with Past Researchers

Comparison graphs have been plotted to illustrate the differences between the experimental and predicted results for soils passing sieve #40 and sieve #200, alongside results from previous researchers. These graphs provide a visual representation of how our experimental and predicted values align with or differ from the findings of past studies. By examining these graphs, we can better understand the accuracy of our models and the variations in results reported by different researchers. The graphs are presented below to facilitate a clearer comparison and understanding of the observed differences.

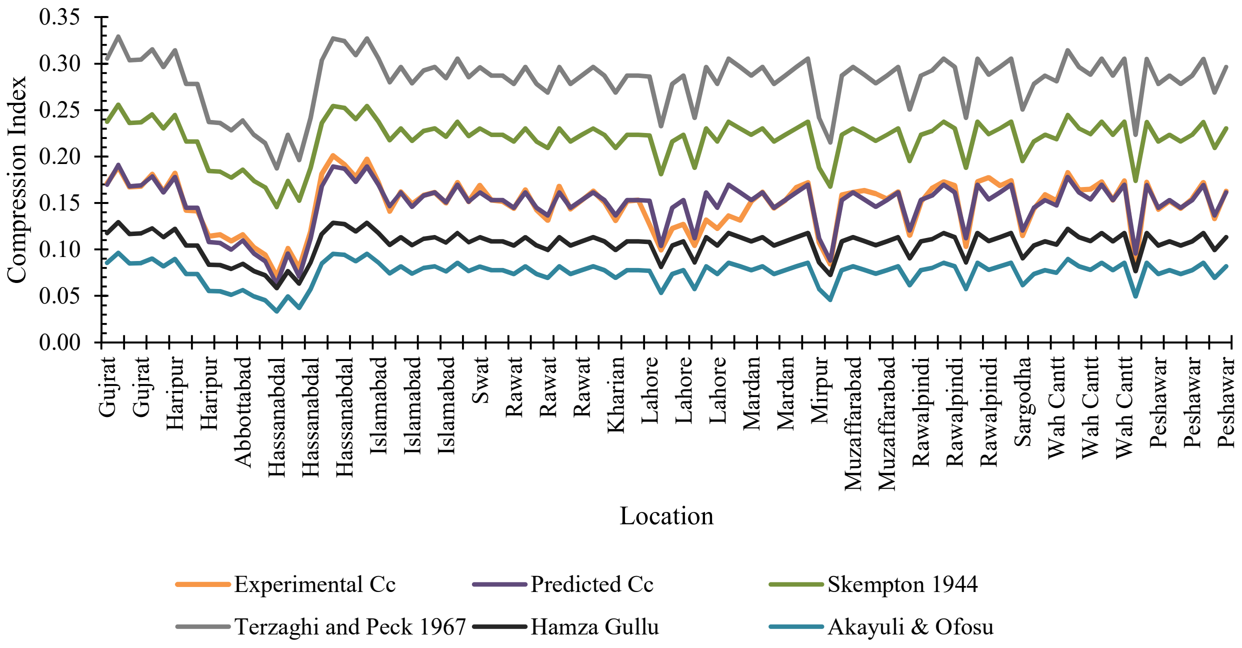

Figure 19: Comparison of Experimental and Predicted Cc with Past Researchers

When comparing the experimental and predicted values of the compression index (Cc) with findings from previous researchers, it is evident that our experimental and predicted values align closely, demonstrating the accuracy of our correlations.

However, discrepancies were observed when comparing with other researchers' findings. For instance, Skempton 1944, Terzaghi and Peck 1967 overestimated the compressibility values, suggesting that his model did not fully capture the specific characteristics of soils in Pakistan. Similarly, Hamza Gullu and Akayulu Ofosu underestimated the compressibility values for soils in this region, indicating a regional variation that his model did not account for accurately.

These variations highlight that soils with the same liquid limit can exhibit different compressibility characteristics based on regional differences. This suggests that while the liquid limit is a critical factor in determining soil compressibility, other local factors and soil properties may also play a significant role. Therefore, it is essential to consider regional calibration when applying empirical correlations for soil behavior predictions.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

This research focused on developing empirical correlations for the compression index (Cc) and the coefficient of consolidation (Cv) with the liquid limit (LL) for soils from various locations across Pakistan. The study involved collecting undisturbed soil samples from 100 different sites and performing a series of geotechnical laboratory tests, including sieve analysis, hydrometer analysis, specific gravity tests, Atterberg limits, and consolidation tests using the Oedometer apparatus.

One of the key aspects of this study was comparing the Atterberg limits, particularly the liquid limit (LL), for soil passing through sieve #40 and sieve #200. This comparison revealed that LL values obtained from soil passing through sieve #200, which only contains silt and clay, are more representative of the actual soil behavior as they exclude fine sand present in samples passing through sieve #40.

Using the results from these tests, multilinear regression models were initially applied to correlate Cc and Cv with various soil parameters such as LL, plasticity index (PI), clay percentage, silt percentage, and specific gravity (Gs), 40 correlations were developed by exploring various soil index properties; however, only 4 correlations were retained due to the minimal impact of other parameters compared to the liquid limit on the compression index and coefficient of consolidation. However, the high p-values indicated that these predictors were not significant. A simplified model using only LL as the predictor was then developed, yielding statistically significant results with low p-values.

The correlations developed in this study are crucial because the Oedometer test is both time-consuming and costly. These correlations provide a simpler means of estimating Cc and Cv based on LL, which is particularly useful for the geotechnical characterization of soils in Pakistan. Notably, this study is among the first to develop such correlations specifically for the Pakistan region, addressing the variability in soil behavior that can occur even with similar LL values across different regions.

The validity of the developed correlations was tested by collecting additional data from 50 locations across Pakistan. The resulting percentage error for both Cc and Cv was found to be less than 1%, demonstrating the reliability and robustness of these correlations. When comparing these results with those of past researchers, it was observed that some previous studies overestimated or underestimated Cc and Cv values. This further underscores the importance of region-specific correlations in accurately predicting soil compressibility characteristics.

These correlations provide a valuable tool for geotechnical engineers, reducing the need for extensive and expensive laboratory testing while ensuring reliable and accurate soil behavior predictions. The findings of this study not only contribute to the existing body of knowledge but also offer practical solutions tailored to the specific geotechnical conditions of Pakistan.

5.2 Recommendations

To further validate the developed empirical correlations for Cc and Cv with LL, it is recommended to expand the study to include soil samples from a wider range of geographical locations across Pakistan. This will ensure a more comprehensive understanding of regional variations in soil behavior and enhance the generalizability of the findings.

It is advisable to compare the developed empirical correlations with predictions from advanced machine learning models, such as Artificial Neural Networks (ANN) and

Support Vector Machines (SVM). These models can potentially offer more accurate predictions by capturing nonlinear relationships between soil properties.

Given the regional specificity of soil behavior, future studies should consider the impact of regional climatic conditions, such as temperature and precipitation, on soil compressibility characteristics. Understanding these effects can enhance the predictive accuracy of the models for different climatic zones within Pakistan.

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