# EVALUATION OF RESILIENT MODULUS OF SUBGRADE SOIL IN SELECTED LOCATIONS OF BANGLADESH

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**M. Engineering THESIS**

**DEPARTMENT OF CIVIL ENGINEERING**
**MILITARY INSTITUTE OF SCIENCE AND TECHNOLOGY**
**DHAKA, BANGLADESH**

**NOVEMBER 2022**

# EVALUATION OF RESILIENT MODULUS OF SUBGRADE SOIL IN SELECTED LOCATIONS OF BANGLADESH

SAUMIT KUMER NANDI (SN. 0419110001)

A Thesis Submitted in Partial Fulfillment of the Requirements for the
Degree of Master of Engineering in Civil Engineering

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By

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Approved as to style and content by the Board of Examination on 21 April 2022:

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|---|---|---|
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# EVALUATION OF RESILIENT MODULUS OF SUBGRADE SOIL IN SELECTED LOCATIONS OF BANGLADESH

## DECLARATION

I hereby declare that the study reported in this thesis entitled as above is my original work and has not been submitted before anywhere for any degree or other purposes. Further I certify that the intellectual content of this thesis is the product of my own work and that all the assistance received in preparing this thesis and sources have been acknowledged and cited in the reference Section.

Saumit Kumer Nandi

Department of Civil Engineering, MIST, Dhaka

# EVALUATION OF RESILIENT MODULUS OF SUBGRADE SOIL IN SELECTED LOCATIONS OF BANGLADESH

A Thesis

By

Saumit Kumer Nandi

## DEDICATION

Dedicated to my parents for supporting and encouraging me to believe in myself.

# ABSTRACT

In this thesis the study on the prediction of resilient modulus of subgrade soil based on index properties and moisture content is described. The study was mainly concerned with the effects of the variables such as percentage of silt and clay, maximum dry density, CBR and moisture content on resilient modulus. Several tests such as such as modified proctor compaction test, California bearing ratio test, Atterberg limit test, Grain size analysis and Specific Gravity tests were conducted on three types of subgrade soils. Three well-known resilient modulus prediction models were used to obtain resilient modulus for three selected subgrade soil samples. The test results indicated that the variables influence the resilient modulus are percentage of silt and clay, CBR, maximum dry density and optimum moisture content. Resilient modulus is increasing significantly with the increase in both CBR value and maximum dry density. However, it is ominously decreasing with the increase in both percentage of silt and clay and moisture content. Models that used for prediction of each subgrade soils fitted reasonably resilient modulus data with accuracy in terms of $R^2$. An empirical analysis was done for predicting resilient modulus that agreed with the experimental findings.

# ACKNOWLEDGEMENTS

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# LIST OF ABBREVIATION

| | |
|---|---|
| MEPDG | Mechanistic-Empirical Pavement Design Guide |
| $M_R$ | Resilient Modulus |
| ASTM | American Society for Testing and Materials |
| AASHTO | American Association of State Highway and Transportation Officials |
| USCS | Unified Soil Classification System |
| CBR | California Bearing Ratio |
| MDD | Maximum Dry Density |
| OMC | Optimum Moisture Content |
| PI | Plasticity Index |
| $C_U$ | Uniformity Coefficient |
| $C_C$ | The coefficient of curvature |
| LL | Liquid Limit |
| PL | Plastic Limit |
| SG#01 | Subgrade Soil Sample - 1 |
| SG#02 | Subgrade Soil Sample – 2 |
| SG#03 | Subgrade Soil Sample - 3 |
| MIST | Military Institute of Science & Technology |
| ECB | Engineering Construction Brigade |

# CHAPTER 1

# INTRODUCTION

## 1.1 Overview

Resilient modulus is a fundamental material property use to characterize pavement materials in flexible pavement design. In Bangladesh, this property is not used for flexible pavement design due to its complexity. This present study reports an evaluation of the resilient modulus of subgrade soil in selected locations of Bangladesh based on well-known resilient modulus prediction model. In addition, a comprehensive laboratory testing program have been conducted to investigate the factors affecting the resilient modulus of different subgrade soil in Bangladesh. A comparison between these results have been reviewed, studied and discussed to find the best possible model for optimum resilient modulus prediction with available subgrade soils in Bangladesh.

## 1.2 Preface

Although pavement design has gradually evolved from art to science, empiricism still plays an important role even up to the present day. The resilient modulus has been recognized as an important property that governs the performance of pavement materials. Resilient modulus expresses the elastic behavior of soil under cyclic traffic loading for Mechanistic Empirical design (Mousa et al., 2017). Over the last decade, resilient modulus has been gained attention in the world for effective pavement design. In order to overcome the scarcity, a simple and rapid method is essential to determine resilient modulus of subgrade soil. Also, the factors that affecting the resilient modulus has to be experimentally identify.

## 1.3 Resilient Modulus

The resilient modulus is the elastic modulus to be used with the elastic theory. It is well known that most paving materials are not elastic, but experience some permanent deformation after each load application. However, if the load is small compared to the strength of the material and is repeated for a large number of times, the deformation under each load repetition is nearly completely recoverable and can be considered elastic. Mechanistic Empirical pavement design methods has to be calibrated using specific pavement types, materials, specific local traffic and environmental conditions, which limit the possibility of using them, unless local calibration is conducted. In the Mechanistic Empirical Pavement Design Guide (MEPDG), a pavement system is analyzed by computing the structural responses (stresses, strains, and deflections) based on the mechanical properties of different pavement materials. Then, the pavement distresses are predicted by empirical models using the computed critical strains and deformations.

The proper characterization of subgrade soils is essential in the design and rehabilitation of pavement structures. The resilient modulus is used as a fundamental engineering property to describe stress–strain relationship of soil under cyclic loading. Resilient modulus is defined as the deviator stress divided by axial recoverable strain as shown in Equation (1.1).

$$M_R = \frac{\sigma d}{\epsilon r} \qquad 1.1$$

In which, $\sigma_d$ is the deviator stress, which is the axial stress in an unconfined compression test or the axial stress in excess of the confining pressure in a triaxial compression test. Because the applied load is usually small, the resilient modulus test is a nondestructive test and the same sample can be used for many tests under different loading and environmental conditions.

This study is required to determined resilient modulus based on resilient modulus prediction models for optimum flexible pavement design.

## 1.4 Applications

Subgrade materials are typically characterized by their resistance to deformation under load, which can be either a measure of their strength or stiffness.

Resilient modulus is an important engineering property that was used in mechanistic empirical pavement design. Resilient modulus calculation is a complex process that consume lot of time and effort. In this study, an experimental procedure have been performed to determine the variables that affects the resilient modulus of subgrade soil and some well-known were used to predict resilient modulus based on soil index properties and moisture content, Which will be applicable for any subgrade soil sample in context of Bangladesh for pavement design.

## 1.5 Objectives of the Study

The aim of this study was to Present the state of the art regarding the factors affecting the resilient modulus and the available resilient modulus predictive models for subgrade soil. Also, to determine the resilient modulus of three subgrade soil samples that are used for pavement construction in Bangladesh and compare between these models.
Considering these aspects, the present work is undertaken to study the following:

- To investigate the variables that affecting the resilient modulus of subgrade soil.
- To evaluate the resilient modulus of different subgrade soil for pavement construction in Bangladesh.
- To apply some of the well-known resilient modulus models exist in the literature to determine resilient modulus of subgrade soil.
- To do an empirical analysis with the prediction models result and laboratory tests result. Also, to determine the most accurate model for resilient modulus prediction of subgrade soil in Bangladesh.

## 1.6 Structure of the Thesis

The dissertation has been presented in five distinct chapters comprising different aspects of this study in Figure 1.1. The chapters included in this reports represent the evaluation of resilient modulus of subgrade soil in selected locations of Bangladesh, to analyze the application of research findings in context of Bangladesh.

**Chapter 1** represents introduction of project work including definition of resilient modulus, applications of the present work, objectives of the study and lastly the structure of the thesis.

**Chapter 2** comprises of a comprehensive literature review encompassing before research on resilient modulus and the prediction models with their outcome and Discussion.

**Chapter 3** contains analytical methods and experimental procedures employed in this study along with the fundamental principles underlying those.

**Chapter 4** deals with the experimental results of all the tests that were performed in the laboratory, correlation between different variables such as percentage of silt and clay, CBR, maximum dry density and moisture content with resilient modulus were executed, resilient modulus were calculated using well-known prediction model for different subgrade soil samples in selected locations of Bangladesh and finally a comparison were done between these results for determining suitable model for resilient modulus prediction.

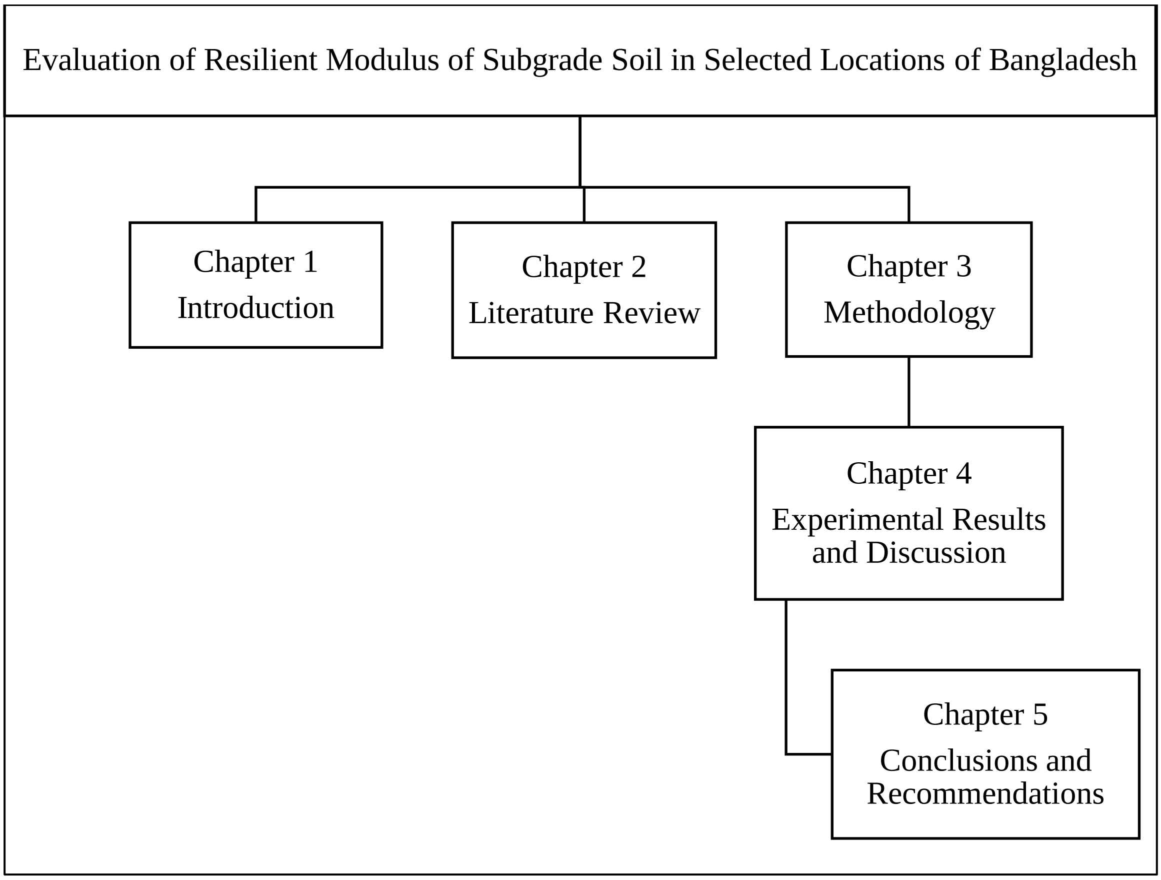

**Figure 1.1:** Structure of the Thesis

**Chapter 5** deals with overall conclusion and future scope of the work.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

Resilient modulus has been an important indicator used to reflect resilient behaviour of subgrade soils. The resilient response of pavement foundations has been found to depend on various variables.

Several experimental studies and research works have been done to characterize the resilient behavior of fine-grained subgrade soil which demonstrate a nonlinear, time dependent and elastoplastic response under traffic loading (Uzan, 1985; and Cabrera et al., 2012). The state conditions affecting resilient behaviour can be summarized as stress state including normal and deviator stress, loading state including frequency, magnitude of load and number of load repetitions.

Pavement foundation geomaterials i.e. fine-grained subgrade soils and unbound aggregates used in untreated base/subbase layers, exhibit nonlinear behavior under repeated wheel loads. This nonlinear behavior is commonly characterized by stress-dependent resilient modulus material models that need to be incorporated into finite element based mechanistic pavement analysis methods to predict more accurately the pavement resilient responses, such as stress, strain, and deformation. A traditional elasticity theories consider the response of subgrade soil as linear-elastic, which requires resilient modulus and Poisson’s ratio (Kim et al., 2009). Solid objects deform and become internally stressed due to prescribed loading conditions. It is a simplification of the more general nonlinear theory of elasticity and a branch of continuum mechanics.

Moisture content of subgrade soils will be subject to seasonal variation while climate change effects are likely to make the driest and wettest values more extreme. Moisture content showed direct correlation with resilient behaviour by (e.g.,) reducing effective particle friction and increasing compaction. When wetting and/or drying cycles are induced, whether by weather events or seasonal variations, these result in hysteretic moduli changes. Thus, it is necessary to incorporate moisture content or its effects into any resilient modulus prediction model.

Due to this reason, both engineering department and academic people have taken interest in this area. The following is a study according to similarity to the work done in this thesis. In this literature review emphasis is directed on:

- ✓ Overview of resilient modulus
- ✓ Overview of resilient modulus Bangladesh
- ✓ Index properties of soil
- ✓ Moisture content and Metric Suction
- ✓ Stress State
- ✓ Resilient modulus prediction models

## 2.2 Overview of Resilient Modulus

Resilient Modulus ($M_R$) is a fundamental material property used to characterize unbound pavement materials. It is a measure of material stiffness and provides a mean to analyze stiffness of materials under different conditions, such as moisture, density and stress level.

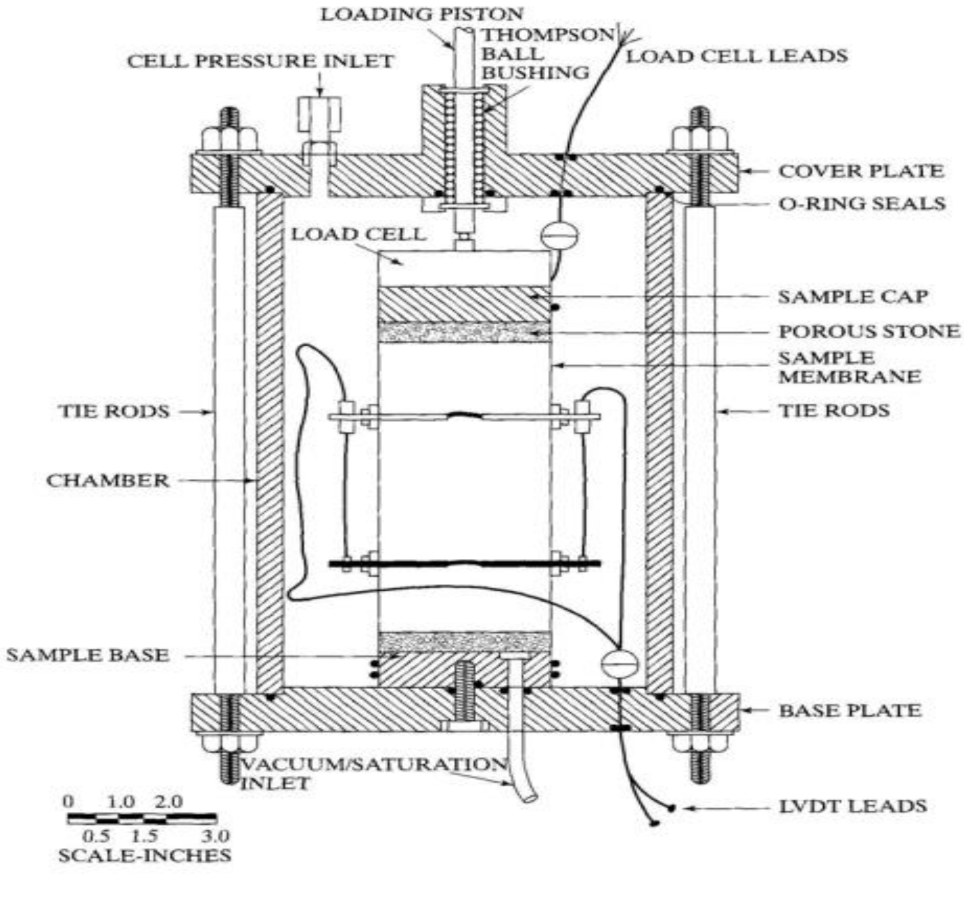

**Figure 2.1:** Triaxial cell for testing cylindrical specimens

Resilient modulus is determined using the repeated load triaxial test. The test applies a repeated axial cyclic stress of fixed magnitude, load duration and cycle duration to a cylindrical test specimen. While the specimen is subjected to this dynamic cyclic stress, it is also subjected to a static confining stress provided by a triaxial pressure chamber. It is essentially a cyclic version of a triaxial compression test; the cyclic load application is thought to more accurately simulate actual traffic loading. Figure 2.1 shows the triaxial cell for testing of cylindrical specimens.

## 2.3 Overview of Resilient Modulus Bangladesh

Resilient modulus is an important mechanical property widely used for the analysis and design of pavements. Therefore, the determination of the resilient modulus of pavement materials and subgrade soil is of vital importance for any mechanistically based design/analysis procedure for pavements. In Bangladesh, resilient modulus is neglected while designing and constructing of a new road or existing one. Few studies are performed in this important property and testing equipment are very rare. Bangladesh is invested huge money on road design, construction and maintenance but evaluation of resilient modulus is rare to find in unbound granular materials and subgrade soil. So, a revolution is required in the flexible pavement design for better value for money proposition in the road construction in Bangladesh.

## 2.4 Index Properties of Soil

Soil index properties are properties which facilitate identification and classification of soils for engineering purposes. The nature of some properties differs for coarse and fine-grained soils which is shown in Figure 2.2. Fine-grained (cohesive) soil index properties are consistency, clay and clay minerals content & water content.

One of soil index properties which describe non cohesive soils is particle size distribution. Soil that contains wide range of particle sizes is named well-graded. The opposite type of soil, which contains narrow range of particle sizes, is categorized as poorly graded. Well-graded soils can be more densely packed. Particle shape also influences how closely particles can be packed together. The density of soil (especially of coarse-grained) is the indication of strength and stiffness. The relative density is the ratio of the actual bulk density and the maximum possible density of the soil. Relative density is a good indicator of potential increases in density, and thus deformations that may occur under the different loads.

**Figure 2.2:** Different types of components of soil

Consistency is the resistance of soils to deformation and rupture. The unconfined compression strength is often used as an indication of consistency. In practice, the terms soft, medium, stiff, very stiff, and hard are applied to rate consistency of soil. This soil index property describes both cohesive and non-cohesive soils. Consistency at non-cohesive soil depends primarily on particle shape and size distribution, while at cohesive soils this property primarily depends on water content. Figure 2.3 shows the soil stages for different moisture content.

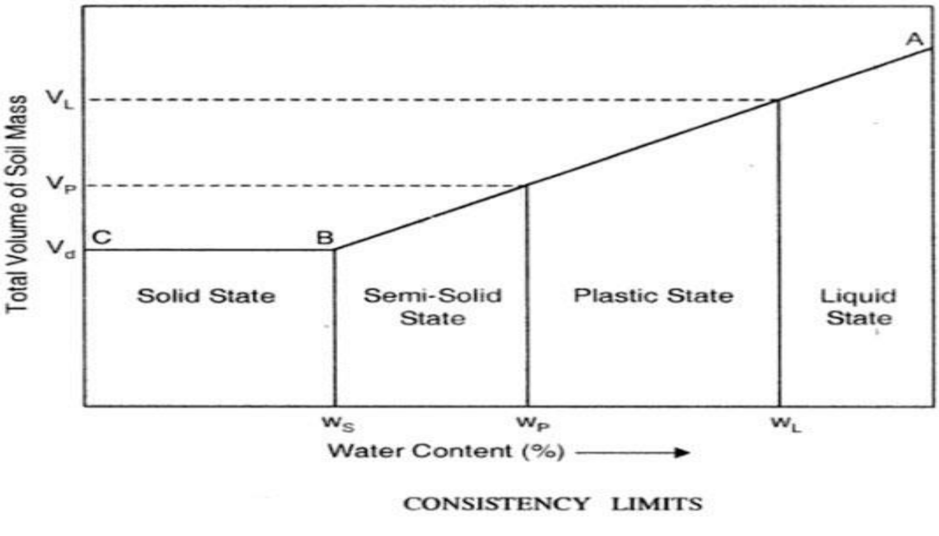

**Figure 2.3:** Different stages of soil at different water content

Clay and clay minerals content is important soil index characteristic for both coarse- and fine-grained soils. Clay minerals are fine-sized platy silicates which are highly plastic. Therefore, depending on percentage and type of clay minerals, clayey soils are less or more plastic.

Water content is very important soil index property of fine-grained soils since their behaviour largely changes with water concentration variations. According to Atterberg there are four states: liquid, plastic, semi-solid and solid. Marginal water contents that separate these states are known as Atterberg limits and these are: shrinkage (SL), plastic (PL) and liquid limit (LL). These limits have different values for different types of fine-grained soils.

The Unified Soil Classification gives each soil type a two-letter designation. For coarse grained soils, the first letter, either G for gravel or S for sand, refers to the dominant particle size in the soil. The second letter is either W, for well graded or P, for poorly graded. The second letter can also be M for silt or C for clay if coarse-grained soils contain more than 12% of silt or clay. The first letter of the designation for fine-grained soils is M or C (silt or clay). The second letter, either H (high) or L (low), refers to the plasticity of the soil.

Some studies investigated the effect of gradation, fines content, particle shape, liquid limit (LL), plasticity index (PI), coefficient of uniformity ($C_u$) and coefficient of curvature ($C_c$) on resilient modulus (Raad et al., 1992; Tian et al., 1998; and Hicks & Monismith, 1970).

## 2.5 Moisture Content and Metric Suction

Moisture content includes the effects of matric suction for unsaturated soil, a significant effect on the resilient modulus values of fine-grained subgrade soils. The moisture content and, consequently, matric suction vary periodically in subgrades in response to seasonal variation.

Numerous studies stated that the resilient modulus of subgrade soils fundamentally depends on moisture content in laboratory and in-situ condition (A. R. Gabr et al., 2012). Resilient modulus significantly influenced by moisture content (Hicks and Monismith, 1970). They demonstrated that a loss in modulus value was observed as the moisture content increases over the Optimum Moisture Content.

The pore pressure controls deformational behaviour as opposed to the level of saturation (Lekarp et al., 2000). An obvious diminishment of resilient modulus as well as Poisson's ratio (Lekarp et al., 2000) with the increase in moisture content, particularly at high level of saturation.

Thom and Brown (1987) demonstrated that moisture has some greasing impact on particles, and consequently builds an increase in the deformation of the aggregate structure with a loss in resilient modulus even without a generation of any pore water pressure.

While, Dawson et al. (1996) found that the stiffness of well-graded unbound granular materials underneath the optimum moisture content tends to increase with the decrease of moisture due to development of suction, then diminished with increasing the moisture content in the wet side of the compaction curve.

J. Ekblad (2008) investigated experimentally that the impact of water content on resilient behavior of different gradations by changing the maximum particle size and the grading shape. The author reasoned that for the loss of resilient modulus has been more articulated by increasing the water content in the higher stress levels.

Andrie et al. (2009) studied the effect of water content on both UGMs and subgrade soils. They observed that water content had little impact on the resilient modulus of base materials compared to the subgrade soils.

Azam et al. (2014) described that resilient modulus depends on matric suction. Studies showed that the matric suction has been appeared to be a vastly improved predictor of engineering behavior than moisture content (Khoury et al., 2009; Cary et al., 2011; and Azam et al., 2014).

## 2.6 Stress State

The stress state is one of the most significant factor on the resilient modulus of subgrade soil and unbound granular material. It is a known fact that when stresses on a soil specimen are increased to a level higher than ever applied previously, plastic strains will occur (Seed et al., 1962; and Raymond et al., 1979). Therefore, the resilient modulus cannot be measured for such a cycle of loading. Stresses may be described broadly as either normal (spherical) stresses or shear (deviatoric) stresses. When discussing stress level, it is important to distinguish between normal stress level and shear stress level because normal and shear stresses produce some what differing effects on soil specimens (Fredlund et al., 1977; Drumm et al., 1990; and A. Nataatmadja and A. Parkin, 1989). When a specimen is overstressed by normal stress, plastic strains occur and bonds between particles are broken. However, bonds are reformed at a higher normal stress, and the net effect of having been loaded to a higher normal stress is that the specimen is now denser, stiffer, and stronger than it was previously (Mitchell et al., 1976). By contrast, when shear stress is raised to a level higher than ever before, plastic strains result in bonds breaking; either these bonds do not reform, or new bonds are formed that are typically weaker than previous bonds (Mitchell et al., 1976). Therefore, the net effect of increasing the shear stress to a new higher value is to produce a specimen that is softer and weaker than before. Overloading by shear is generally more damaging than overloading by normal stress.

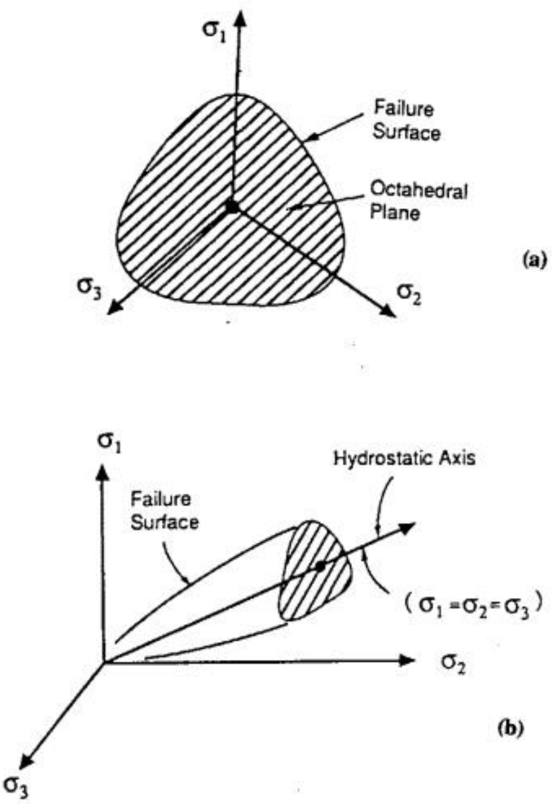

**Figure 2.4:** Soil failure surface

Thus the effect of shear stress elevation on the modulus is opposite to the effect of normal stress elevation (Fredlund et al., 1977). In the laboratory, separation of and distinction between shear and normal stresses are relatively easy. In the field, wheel loads produce both shear and normal stresses, and the predominant type of loading varies with the point of consideration within the pavement structure.

The measured modulus is sensitive to an increase in either normal or shear stress to levels higher than ever applied before because plastic strains are induced. However, when significant plastic strains occur, the resilient modulus cannot be measured in a straightforward manner because elastic and plastic strains must first be separated.

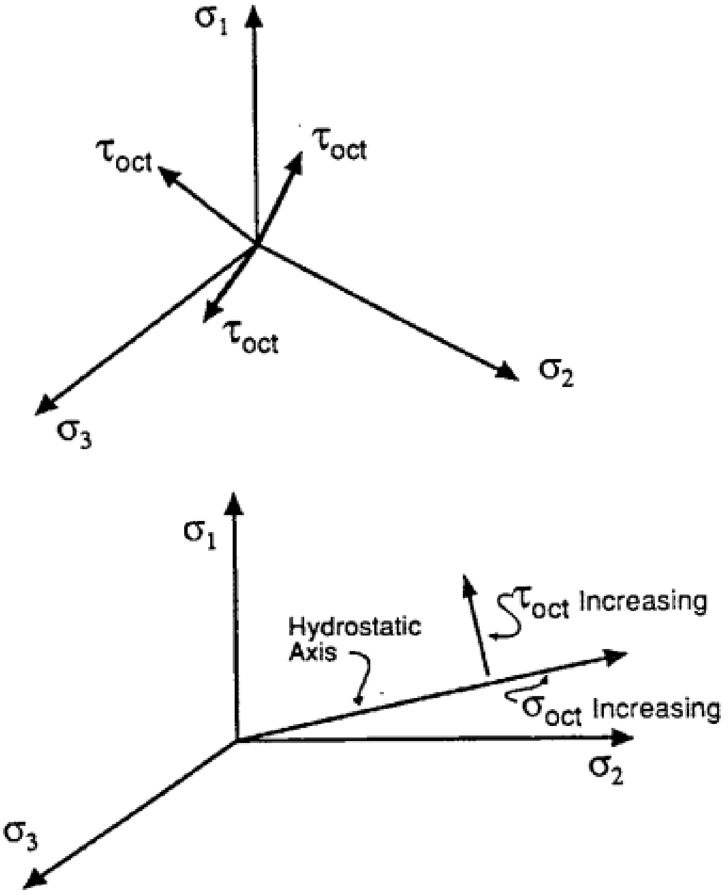

**Figure 2.5:** Three-dimensional stress space

A typical soil failure surface is shown in Figure 2.4. A projection of this failure surface in the more customary shear stress versus normal stress space would look like the Mohr Coulomb failure surface. Two perspectives of this failure surface are given in Figures 2.4 and corresponding to the perspectives shown in Figures 2.5 respectively.

It is possible to sketch a surface in stress space corresponding to the maximum stresses resulting from the maximum traffic loads plus the overburden stresses. As part of preconditioning the specimen, the AASHTO T274 procedure called for levels of both shear and normal stresses that are in most cases greater than those estimated to have been applied by in situ traffic loading.

Several studies have reported that resilient modulus of untreated unbound granular material is dependent on confining pressure and deviator stresses, which increases considerably with the increase of those stresses (Yoder and Witczak, 1975; Azam et al., 2013; Gabr et al., 2012; and Gabr et al., 2013).

Kolisoja (1998) reported that Poisson's ratio of unbound granular material increases with increasing deviator stress and decreasing confining pressure. Cabrera (2012) reported that resilient modulus decreased significantly with the increase in maximum cyclic stress amplitude. Results also showed that resilient modulus generally increases with the increase in confining pressure level.

## 2.7 Resilient Modulus Prediction Models

Different models have been developed to predict the resilient modulus of subgrade soils based on soil index properties and moisture content. The following subsections present most of the developed models found in the literature for predicting resilient modulus of fine-grained soils.

### 2.7.1 Models Based on Soil Index Properties

It is desirable to develop simple models for the estimation of resilient modulus based on the simple index properties to overcome the complexity of the resilient modulus test as well as the cost of testing, which requires expensive equipment and well trained technicians.

Many correlations were developed to predict resilient modulus depending on materials properties and soil characteristics such as CBR, Plasticity Index, Liquid Limit, water content, dry density, percentage of silt and clay, coefficient of curvature and coefficient of uniformity. The mechanistic empirical pavement design guide suggests that resilient modulus of fine-grained soils can be predicted using the following equation, can be written as follows:

$$M_R \text{ (psi)} = 3460.3 * CBR^{0.4187} \qquad 2.1a$$

Equation (2.1a) is a resilient modulus prediction model developed by Jaehun et al. (2009) which calculates resilient modulus based on CBR value.

Mechanistic Empirical pavement design guideline suggests a prediction model for determining resilient modulus for fine- grained soil. Heukelom and Klomp (1962) modified the model base on CBR value that shows in equation (2.1b) and equation (2.1c).

If materials CBR< 10%:

$$M_R \text{ (psi)} = 1500 * CBR \qquad 2.1b$$

If materials CBR> 10%:

$$M_R \text{ (psi)} = 2555 * CBR^{0.65} \qquad 2.1c$$

Rahim (2005) studied subgrade soil index properties to estimate resilient modulus for pavement design and developed correlations for fine-grained soil and coarse-grained soil as given in equation (2.1d) and equation (2.1e) as follows:

For fine-grained soil:

$$M_R \text{ (Mpa)} = 17.29 * [(\frac{\gamma dry}{Wc+1})^{2.18} + (\frac{P\#200}{100})^{-0.609}] \qquad 2.1d$$

For coarse-grained soil:

$$M_R \text{ (Mpa)} = 324.14 * [(\frac{\gamma dry}{Wc+1})^{0.8998} + (\frac{P\#200}{\text{Log CU}})^{0.4652}] \qquad 2.1e$$

Where, $\gamma_{dry}$ is the maximum dry density, $W_C$ is moisture content and P#200 is percentage of silt and clay.

### 2.7.2 Models Based on Moisture Content

Numerous models have been developed to consider the impact of moisture content or degree of saturation on resilient modulus. Among them a model was developed and compiled based on compacted fine-grained subgrade soils. Li and Selig (1994) predicted resilient modulus in terms of moisture content is shown in equation (2.2a).

$$M_R \text{ (Mpa)} = 0.98 - 0.28 * (W - W^{OPT}) + 0.29 * (W - W^{OPT})^2 \qquad 2.2a$$

Where, $W^{OPT}$ is the optimum moisture content and W is moisture content after test.

A universal model was developed base on moisture content for determining resilient modulus for both unbound granular materials and fine-grained soil (Andrie et al., 2009) as shows in equation (2.2b) and equation (2.2c).

For coarse-grained soils:

$$M_R\ (\mathrm{Mpa}) = 10^{a+\frac{b-a}{1+EXP(\beta+ks(S-Sopt))}}\ k_1p_a * (\frac{\theta}{P_a})^{k_2} * (\frac{\tau_{oct}}{p_a} + 1)^{k_3} \qquad 2.2b$$

For fine-grained soils:

$$M_R\ (\mathrm{Mpa}) = 10^{a+\frac{b-a}{1+EXP(\beta+kw(W-Wopt\_std))}}\ k_1p_a * (\frac{\theta}{P_a})^{k_2} * (\frac{\tau_{oct}}{p_a} + 1)^{k_3} \qquad 2.2c$$

Where, $K_S$= regression parameter for moisture and density effect, a is regression parameter at minimum of Log ($M_R/M_{Ropt}$), b is regression parameter at maximum of Log ($M_R/M_{Ropt}$),

β= Ln. ((-b)/a), S - $S_{opt}$ is the variation in degree of saturation, W is gravimetric moisture content, $W_{opt}$ gravimetric optimum moisture content corresponding to standard compaction and $K_W$ is a regression parameter.

A model was developed based on moisture content and stress state to predict resilient modulus (Garcia et al., 2015) which shows in equation (2.2d).

$$M_R\ (\mathrm{Mpa}) = e^{1.98-0.0714(W-Wopt)} * (\frac{\sigma_d}{\sigma_3})^{-0.2} \qquad 2.2d$$

Where, W= moisture content after testing.

### 2.7.3 Models Based on Stress State

Various researchers have developed different models to predicted resilient modulus depending on stresses for both coarse and fine-grained soil.

Hicks and Monismith (1971) developed a well-known k-θ model based on bulk stress which shows in equation (2.3a).

$$M_R = k_1\ (\theta)^{k_2} \qquad 2.3a$$

Where, $M_R$= resilient modulus, $k_1$ and $k_2$= regression coefficients, θ= bulk stress = ($\sigma_1$ + $\sigma_2$ + $\sigma_3$), $\sigma_1$= major principal stress, $\sigma_2$= intermediate stress and $\sigma_3$= minor principal stress. May and Witczak (1981) proposed a model that correlates the resilient modulus with the normalized measures of the mean stress and octahedral shear stress as shows in equation (2.3b).

$$M_R = k_0 * (\frac{\sigma_m}{P_a})^{k_1} * (\frac{\tau_{oct}}{\tau_{ref}})^{k_2} \qquad 2.3b$$

Where, $P_a$ = atmospheric pressure, $\sigma_m$ = mean normal stress = $((\sigma_1 + 2\sigma_3)/3)$, τoct = octahedral shear stress = $(\sqrt{2}/3)(\sigma_1 - \sigma_3)$, $\tau_{ref}$ = reference shear stress = $\frac{\sqrt{2}}{3} * q_f$; $q_f$ = peak shear strength = $(d + \sigma_m * \tan \beta)$; d and β are Druker-Prager failure parameters and $k_0$, $k_1$ and $k_2$ = regression parameters.

J. Uzan (1985) studied characterization of granular material where he developed a simple equation with the reference shear stress as shows in equation 2.3c.

$$M_R = k_1 p_a * (\frac{\theta}{P_a})^{k_2} * (\frac{\tau_{oct}}{p_a})^{k_3} \qquad 2.3c$$

Witczak (1981) added a shear stress term in equation (2.3c) and developed universal Witczak model which shows in equation 2.3d.

$$M_R = k_1 p_a * (\frac{\theta}{P_a})^{k_2} * (\frac{\tau_{oct}}{p_a} + 1)^{k_3} \qquad 2.3d$$

Rahim & George (2004) proposed two sets of models for predicting resilient modulus for coarse and fine-grained soils depending on stress state as described in equations 2.3e and equation 2.3f as follows.

For coarse-grained soils:

$$M_R = k_1 p_a * (\frac{\theta}{\sigma_d + 1} + 1)^{k_2} \qquad 2.3e$$

For fine-grained soils:

$$M_R = k_1 p_a * (\frac{\sigma_d}{\sigma_c + 1} + 1)^{k_2} \qquad 2.3f$$

Where, $\sigma_c$ = confining pressure and $K_1$, $K_2$ are regression model parameters.

# CHAPTER 3

# METHODOLOGY

## 3.1 Introduction

In this investigation, three typical subgrade soils was collected from three locations where road was constructed in Bangladesh. These materials were collected from purbachal express highway (300 ft.) project, widening and improvement of road from ECB circle to mirpur and construction of flyover at kalshi intersection project, padma bridge rail link project (PBRLP) respectively around Dhaka division, Bangladesh. modified proctor compaction test, California bearing ratio test, Atterberg limit test, Grain size analysis and Specific Gravity tests are performed. The soil samples are collected have tested at MIST's geotechnical laboratory and transportation laboratory. Soil samples have subjected to various laboratory tests according to American Society for Testing and Materials (ASTM) procedures. Resilient modulus are calculated by using the prediction models and linear regression coefficients are obtained for each investigated subgrade soil.  Their prediction accuracy are determined by using index properties of soil.

## 3.2 General Research Outline

The methodology adopted in this study is shown in the following diagram:

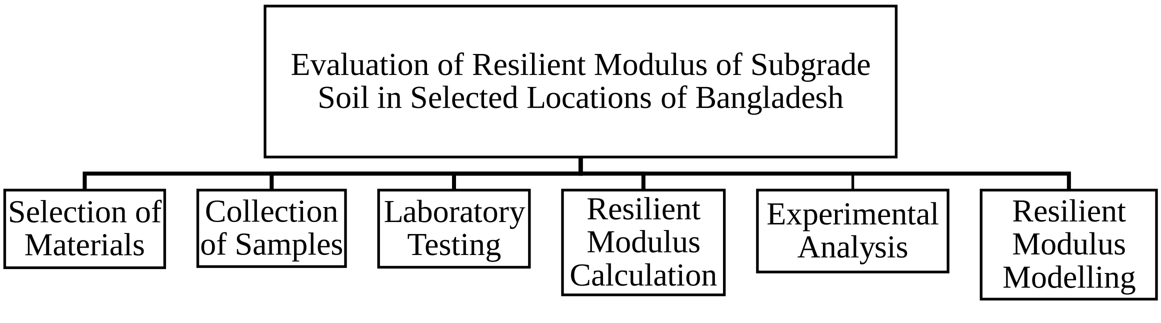

**Figure 3.1:** Procedure of this research

## 3.3 Research Survey

A survey program was carried out to find the best location from where we can collect the subgrade soil samples. Our actual plan was to collect samples around the country especially all types of subgrade soil. Due to covid-19 pandemic situation, it was difficult to collect samples from different locations of Bangladesh. So, we have selected following locations due to covid-19 pandemic situation.

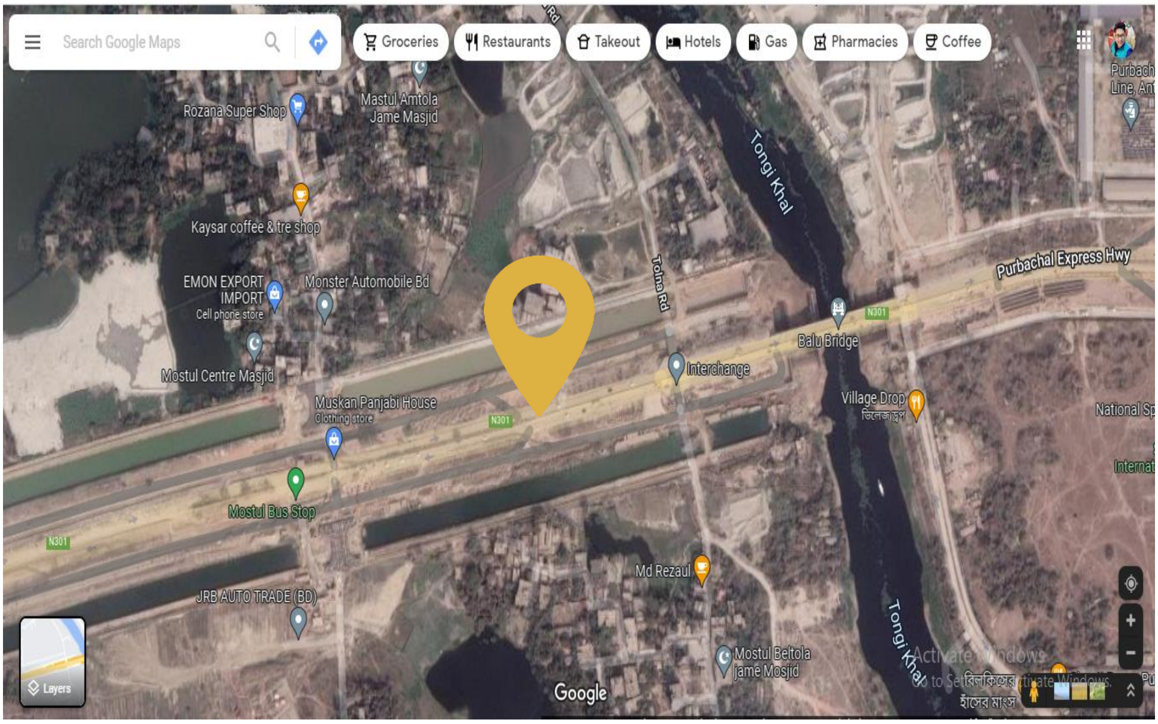

**Figure 3.2:** Collection Point of Subgrade Soil- 1

Figure 3.2 shows, purbachal express highway (300 ft.) collection point of subgrade soil- 1 location. Purbachal Expressway is a 12.5 kilometre long, eight-lane-wide avenue expressway in Dhaka, Bangladesh. This expressway connects Purbachal to eastern Dhaka. Development Project Proposal for the Purbachal new town was passed in 2005. In that proposal a eight-lane expressway was mentioned. But Rajdhani Unnayan Kartripakkha (RAJUK) started the expressway project with a four-lane road in 2013 because of fund shortage. Rajdhani Unnayan Kartripakkha (RAJUK) built the link road with Tk 300 crore. In 2015, Detailed Area Plan passed by Executive Committee of the National Economic Council . In that plan building 100-foot canal on both sides of the link road – from Kuril to the River Balu was mentioned with cost of Tk 5,287 crore. After completing the existing project,.The project was amended in November 2018 with plan to expanding the road into 8-lane expressway. The budget for the project was revised to Tk 10,330 crore. For the revision and canal the 300 feet road will be built as 235 feet. It has been decided to reconstruct the expressway by Bangladesh Army instead of Rajdhani Unnayan Kartripakkha (RAJUK). Under the project of 13 kilometre canal, 13 kilometre road, 39 kilometre walkway, four Iulups, 13 bridges over the canal, four expressway foot over bridges and five sluice gates are under construction. In addition to a pump house, 12 water bus stops and a 4.8 kilometre storm sewer line will be constructed. Keeping in mind the traffic management of next 40 years.

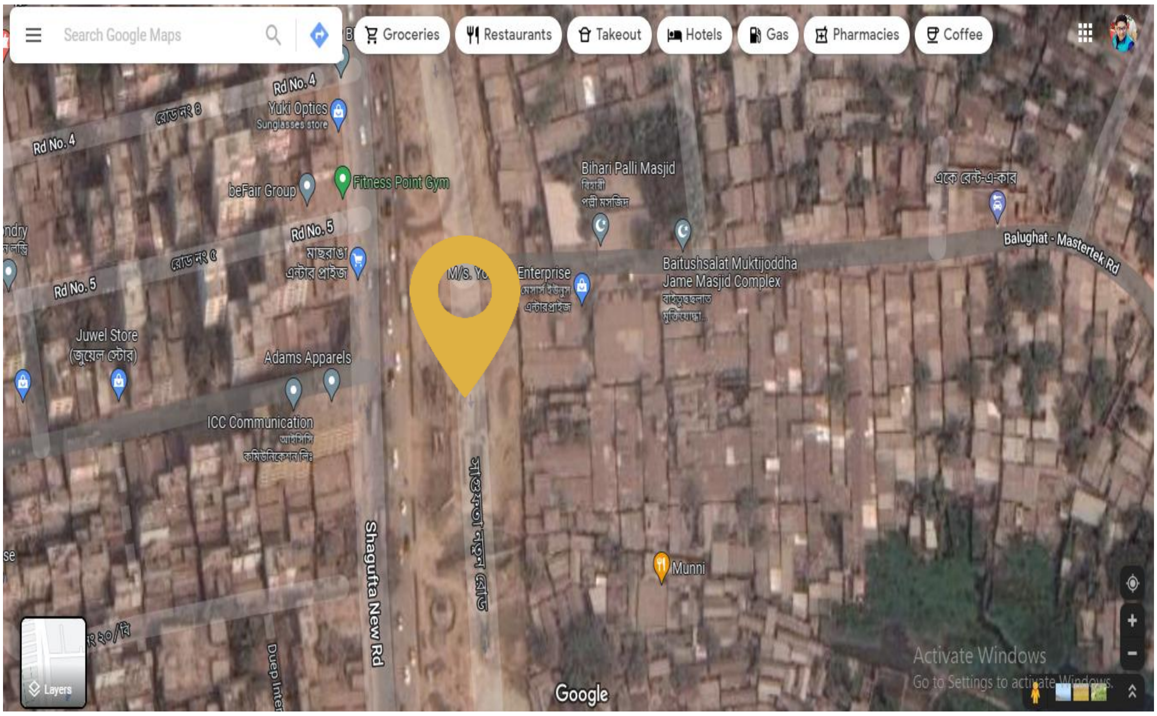

**Figure 3.3:** Collection Point of Subgrade Soil- 2

Figure 3.3 shows widening and improvement of road from ECB circle to Mirpur collection point of subgrade soil- 2 location.

The construction work is going on fast from Kalshi Road from the premises of Mirpur ECB. Many people think that this may be the metro rail route. In fact, the government has taken an initiative to construct a new flyover from the ECB Chattar to Kalshi border in Mirpur, Dhaka. Its total length will be around 0.85 Kilimeter. The road is also being expanded along with the flyover. It will improve road communication between Mirpur, Pallabi, Dhaka Cantonment, Uttara, Mohakhali and Rampura.

Figure 3.4 shows Padma Bridge Rail Link Project (PBRLP) collection point of subgrade soil- 3 location. The Padma Bridge Rail Link project in Bangladesh is the largest infrastructure project and an outcome of the cooperation between the governments of China and Bangladesh. This railway line is an important passage connecting the east and west of Bangladesh for passenger and cargo transportation. The project management office has been actively fulfilling its corporate social responsibility in Bangladesh and doing their bits for the welfare of the people of this country ever since it has been mobilized to site on 3 July 2018.

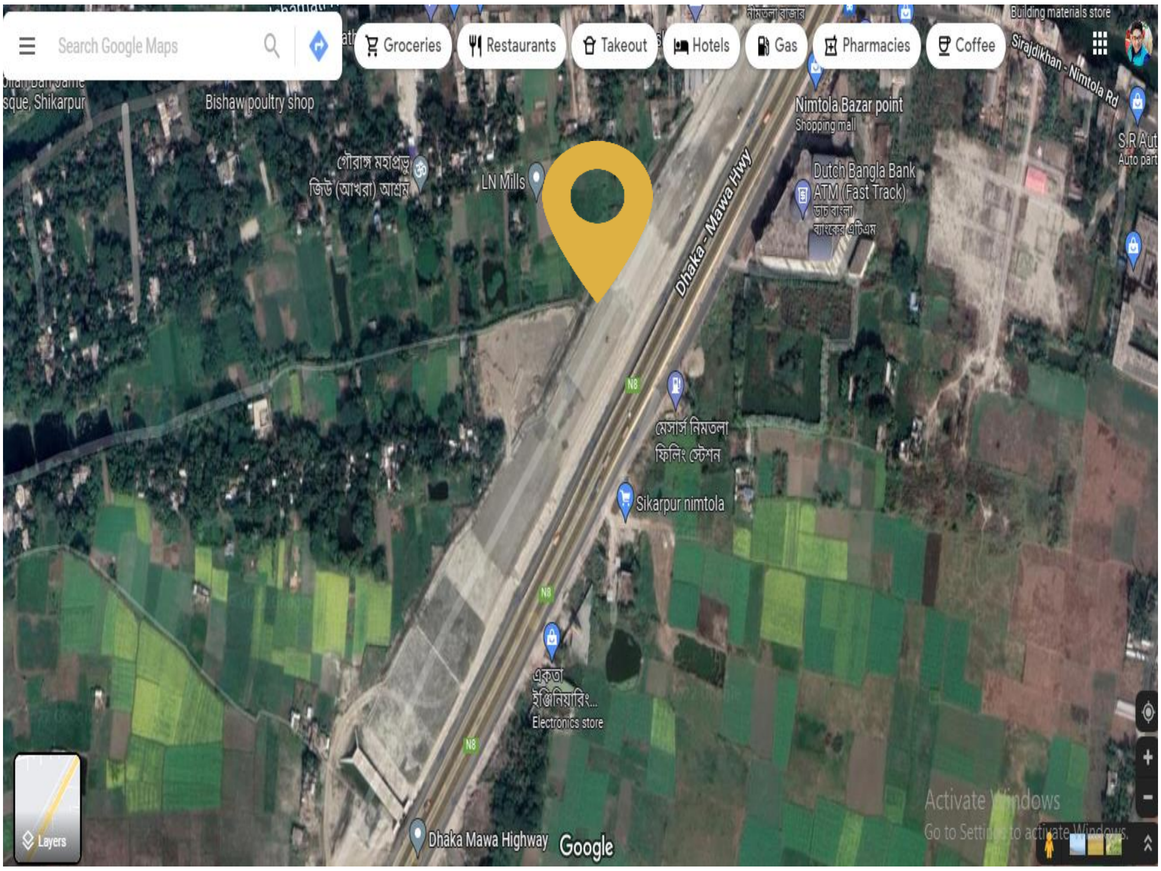

**Figure 3.4:** Collection Point of Subgrade Soil- 3

The project aims at constructing new railway track (approz. 169 Km) from Capital City Dhaka to Jashore via Padma Multipurpose Bridge to establish new Broad Gauge (BG) railway connectivity through south-west part of the country. Total Track length is 215.22 Km including loops and sidings and double lines.

## 3.4 Investigated Materials

The materials used in the research are three different subgrade soils from three different locations of Bangladesh. These materials are collected from various location where different infrastructures are constructing at present. It is important to do research to assist them for the optimum outcome from the existing project.

Table 3.1 shows that different locations of Bangladesh from where the subgrade soil samples were collected and were tested in the laboratory.

**Table 3.1:** Subgrade soil samples used in this study

| SL | Materials | Locations |
|---|---|---|
| SG#01 | Subgrade Soil - 1 | Purbachal Express Highway (300 ft.) Project |
| SG#02 | Subgrade Soil - 2 | Widening and improvement of road from ECB Circle to Mirpur and construction of flyover at Kalshi Intersection Project |
| SG#03 | Subgrade Soil - 3 | Padma Bridge Rail Link Project (PBRLP) |

## 3.5 Laboratory Tests

A list of laboratory tests have conducted on the investigated subgrade soil samples to determine the index soil properties. Lab testing included Particle Size Distribution (PSD), AASHTO classification, USCS classification, specific gravity, Atterberg limits, modified proctor compaction and CBR are performed.

Table 3.2 shows the laboratory tests methods that are applied in this study. Grain size analysis are done by ASTM D 7928 – 17. Atterberg limit test are accomplished by ASTM D 4318 – 17. Modified proctor compaction test are done by ASTM D 1557 – 12. California bearing ratio test are executed by ASTM D 1883 method and Specific Gravity test are done by ASTM D 854- 14 method.

**Table 3.2:** Tests and reference documents used in this study

| **Test No.** | **Name of the Test** | **Reference Documents** |
|---|---|---|
| 1 | Grain Size Analysis by Hydrometer | ASTM D 7928- 17 |
| 2 | Atterberg Limit | ASTM D 4318- 17 |
| 3 | Modified Proctor Compaction | ASTM D 1557- 12 |
| 4 | CBR | ASTM D 1883 |
| 5 | Specific Gravity | ASTM D 854- 14 |
| 6 | AASHTO Classification | AASHTO M 145- 91 |
| 7 | USCS Classification | ASTM D 2487 |

Soil is classified by AASHTO M 145 – 91 and ASTM D 2487 which is USCS classification method.

## 3.6 Selected Resilient Modulus Prediction Models

There are several models recommended by Mechanistic Empirical Pavement Design Guideline (MEPDG) based on soil index properties, moisture content and stress state to determine resilient modulus. For this study, three resilient modulus prediction models are selected as shown in Table 3.3.

**Table 3.3:** Selected models used in this study

| Model | Name of the Model | Equation |
|---|---|---|
| 1 | Jaehun et al. | 2.1a |
| 2 | Rahim | 2.1d |
| 3 | Li & Selig | 2.2a |

Here, Model - 1 is Jaehun et al. model developed in 2009 based on CBR. Model – 2 is Rahim model developed in 2007 based on index properties of soil and Model - 3 is developed by Li & Selig in 1994 based on moisture content.

## 3.7 Research Methods

### 3.7.1 Selection of Materials

Three different subgrade soil samples are selected in this study shows in Figure 3.5 to determined their index properties. These subgrade soil samples are used in various project in Dhaka division, Bangladesh. Currently, all these projects are ongoing and researches are performed by different authority to build quality infrastructure that brings optimum outcome.

**Figure 3.5:** Selected subgrade soil sample

## 3.7.2 Collection of Samples

In this study, all subgrade soil samples are collected from construction site. All three samples are collected as disturbed sample as shows in Figure 3.6 and they are carried at Military Institute of Science and Technology laboratory for testing.

**Figure 3.6:** Subgrade soil sample from construction site

## 3.7.3 Laboratory Testing

In this study, for three subgrade soil modified proctor compaction test, california bearing ratio test, Atterberg limit test, grain size analysis and specific gravity tests were performed. The soil samples collected have tested at MIST’s geotechnical laboratory and transportation laboratory. Soil samples have subjected to various laboratory tests according to ASTM procedures. Test results are recorded to prepare a summary sheet of the test results that are shown in Appendix - B. In Figure 3.7 shows laboratory testing of these materials.

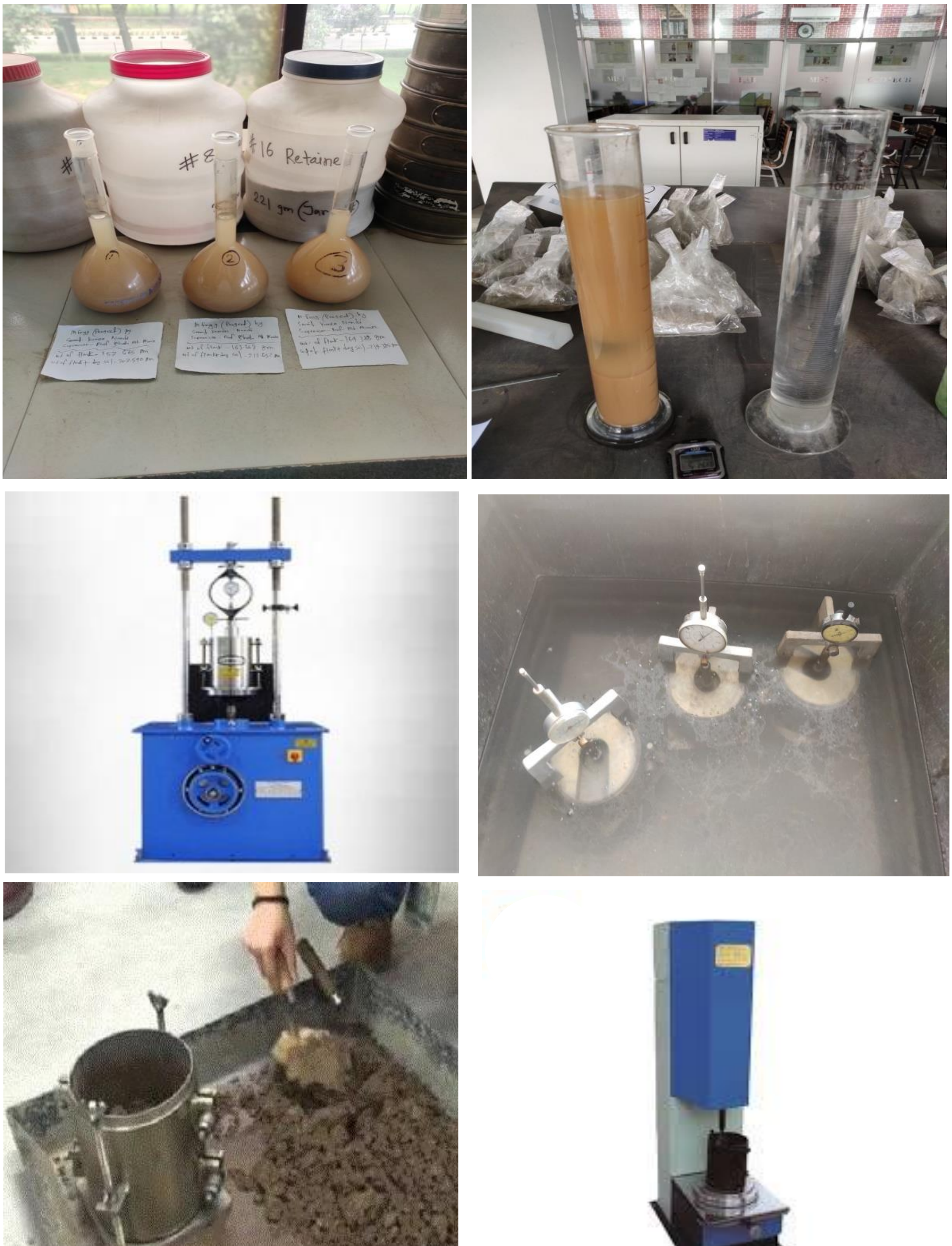

**Figure 3.7:** Laboratory tests of subgrade soil samples

### 3.7.4 Resilient Modulus Calculation

These tests are performed and resilient modulus is calculated by using three selected resilient modulus prediction model based on soil index properties and moisture content.

### 3.7.5 Experimental Analysis

An experimental analysis has done between resilient modulus determined from all selected models against the variables such as CBR, optimum moisture content, maximum dry density and percentage of silt and clay. The effect of these variables on resilient modulus of subgrade soil are evaluated.

### 3.7.6 Comparison of the Results

Using these prediction model's resilient modulus are calculated and their prediction accuracy are determined in terms of coefficient of determination, $R^2$ to find out suitable resilient modulus prediction model for subgrade soil in Bangladesh.

# CHAPTER 4

# EXPERIMENTAL RESULTS AND DISCUSSION

## 4.1 Introduction

This chapter deals with the experimental results performed in the laboratory in order to to evaluate resilient modulus by index properties of soil and moisture content. The details of this study has already been described in the last chapter. The test results were estimated from various laboratory investigations and their performance were analyzed. Moreover, an optimum resilient modulus prediction model estimated by using linear regression coefficients are presented in this chapter.

## 4.2 Grain Size Distribution Curves

Three subgrade soil samples collected from different locations and grain size distribution by hydrometer test are performed. The grain size distribution characteristics were obtained according to ASTM D7928 for all materials. The gradation curves for the samples are respectively as shown in Figure 4.1, 4.2 and 4.3.

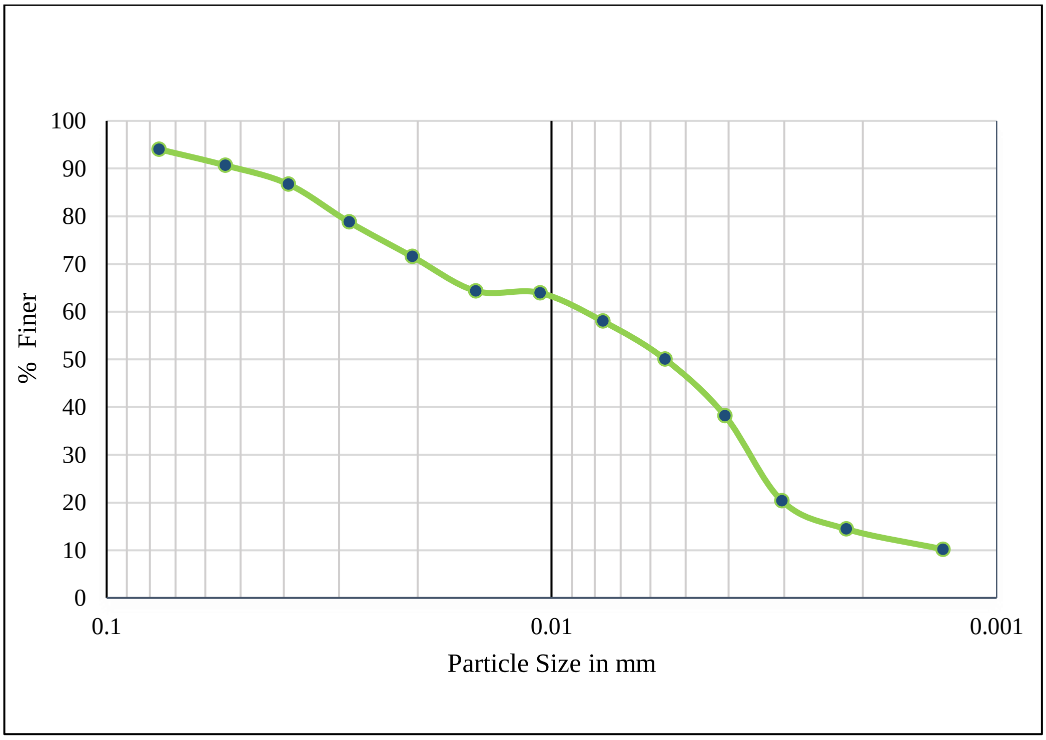

**Figure 4.1:** Particle size distribution for the investigated subgrade soil SG#01

Figure 4.1 is the subgrade soil - 1 grain size analysis curve where the soil is well graded. Well graded soil is a soil that contains particles of a wide range of sizes and has a good representation of all sizes from the No. 4 to No. 200 sieves.

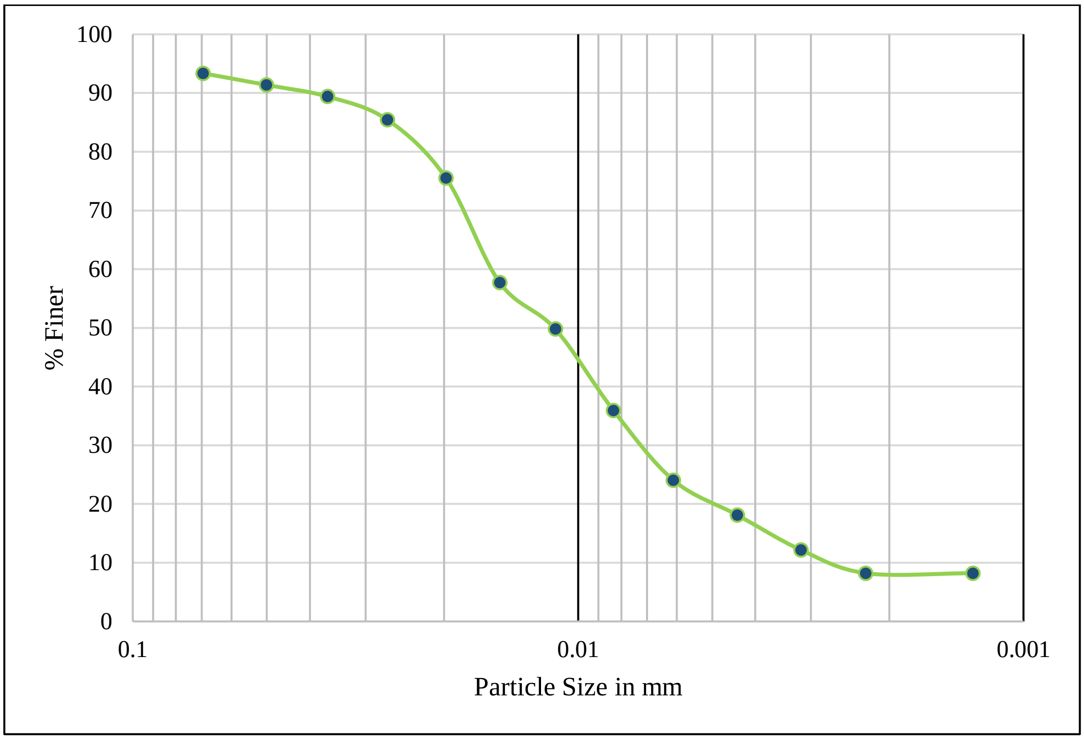

**Figure 4.2:** Particle size distribution for the investigated subgrade soil SG#02

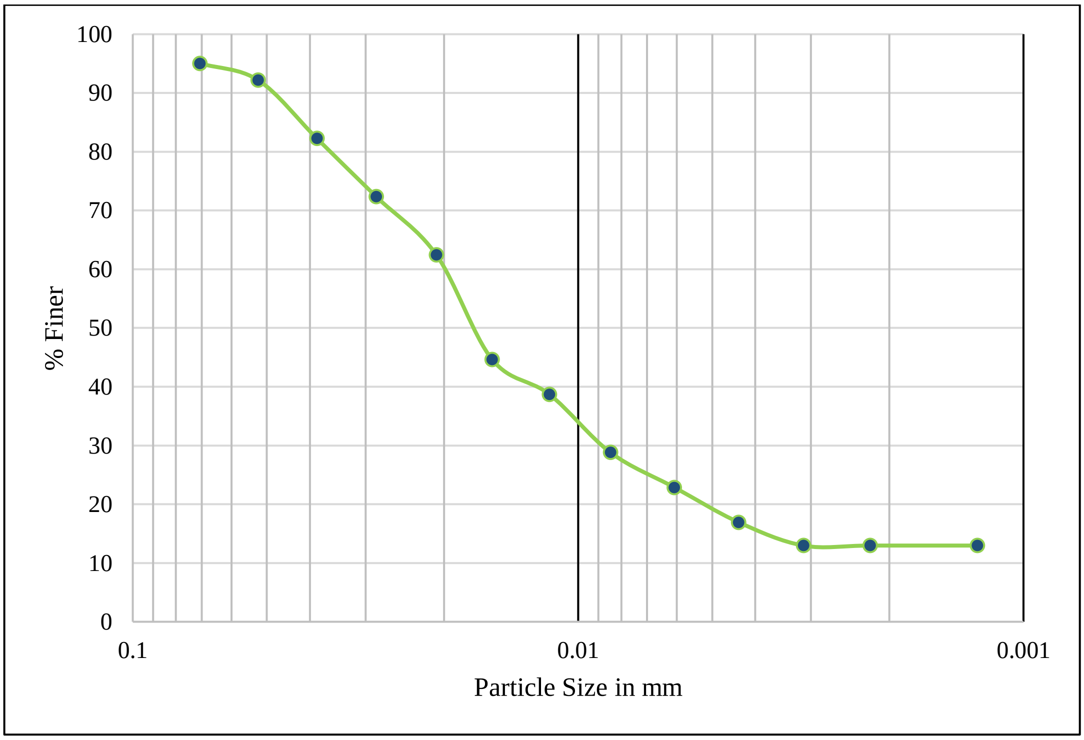

**Figure 4.3:** Particle size distribution for the investigated subgrade soil SG#03

Figure 4.2 is the subgrade soil - 2 grain size analysis curve where the soil is well graded. It contains particles of a wide range of sizes and has a good representation of all sizes. Here, the curve is not flat as Figure 4.1.

Figure 4.3 is the subgrade soil - 3 grain size analysis curve where the soil is well graded. All sizes of particles are presents here. The curve is flat as Figure 4.1.

## 4.3 Grain Size Distribution Characteristics

Grain size distribution by hydrometer test was performed and their soil characteristics was determined such as effective size ($D_{10}$), $D_{30}$, $D_{60}$, coefficient of uniformity ($C_u$), coefficient of curvature ($C_c$), percentage of silt and clay, specific gravity and soil type respectively. Table 4.1 encapsulates the particle size distribution characteristics of the materials including coefficient of uniformity ($C_u$), coefficient of curvature ($C_c$), % of silt and clay, $D_{10}$, $D_{30}$, $D_{60}$, specific gravity and soil type which as shows below.

**Table 4.1:** Particle size distribution characteristics of tested materials

| **Material** | **$D_{10}$** | **$D_{30}$** | **$D_{60}$** | **$C_u$** | **$C_c$** | **% Silt & Clay** | **Specific Gravity, Gs** | **USCS** |
|---|---|---|---|---|---|---|---|---|
| SG#01 | 0.0013 | 0.0036 | 0.00876 | 6.74 | 1.14 | 89 | 2.71 | CL |
| SG#02 | 0.0027 | 0.0072 | 0.01562 | 5.79 | 1.23 | 85 | 2.71 | CL |
| SG#03 | 0.0018 | 0.0088 | 0.0201 | 11.55 | 2.23 | 79 | 2.70 | CL |

For, Subgrade soil – 1, Subgrade soil – 2 and Subgrade soil – 3, $D_{10}$ are respectively 0.0013, 0.0027 and 0.0018. $D_{30}$ are 0.0036, 0.0072 and 0.0088 for three subgrade soil samples. $D_{60}$ are 0.00876, 0.01562 and 0.0201 for the selected soil samples. $C_u$ are 6.74, 5.79 and 11.55 and $C_C$ are 1.14, 1.23 and 2.23 respectively. Silt and clay percentages are 89, 85 and 79 respectively and Specific Gravity varies from 2.70 to 2,71.

## 4.4 Experimental Analysis

### 4.4.1 Effect of Material type and Fines Content on Resilient Modulus

The percentage of silt and clay provides an obvious effect on resilient modulus. The resilient modulus generally decreases when the amounts of fines increase.

In this study, three subgrade soil samples were collected from different locations and grain size analysis test by hydrometer are performed. Resilient modulus against percentage of silt and clay curve are shows in Figure 4.4, 4.5 and 4.6 respectively.

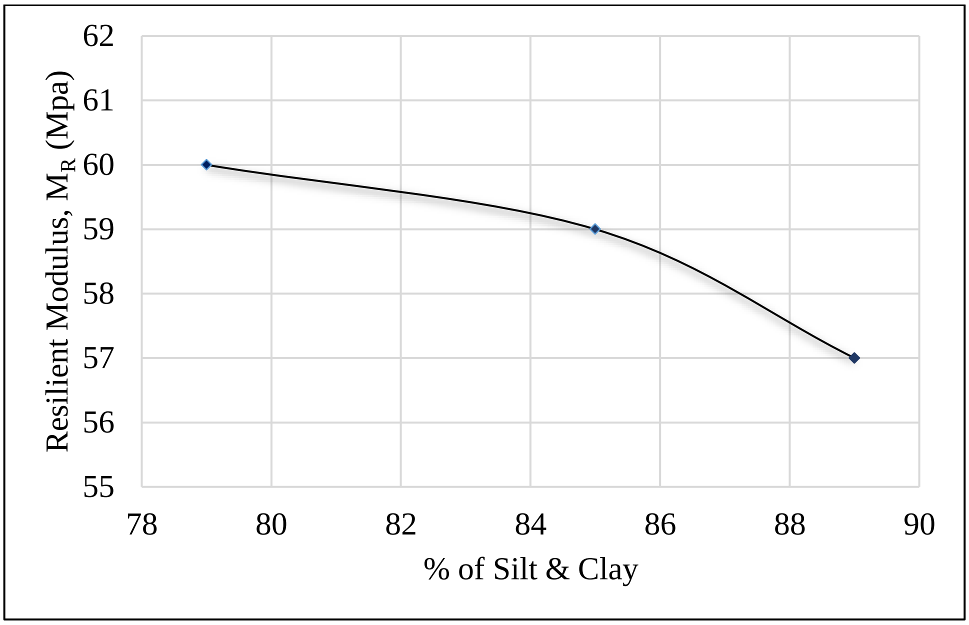

**Figure 4.4:** A graph $M_R$ (calculated using model-1) against % of silt & clay

Resilient modulus estimated from model – 1 give linear curve against percentage of silt and clay that indicates resilient modulus decreases when percentage of silt and clay increases as shown in Figure 4.4.

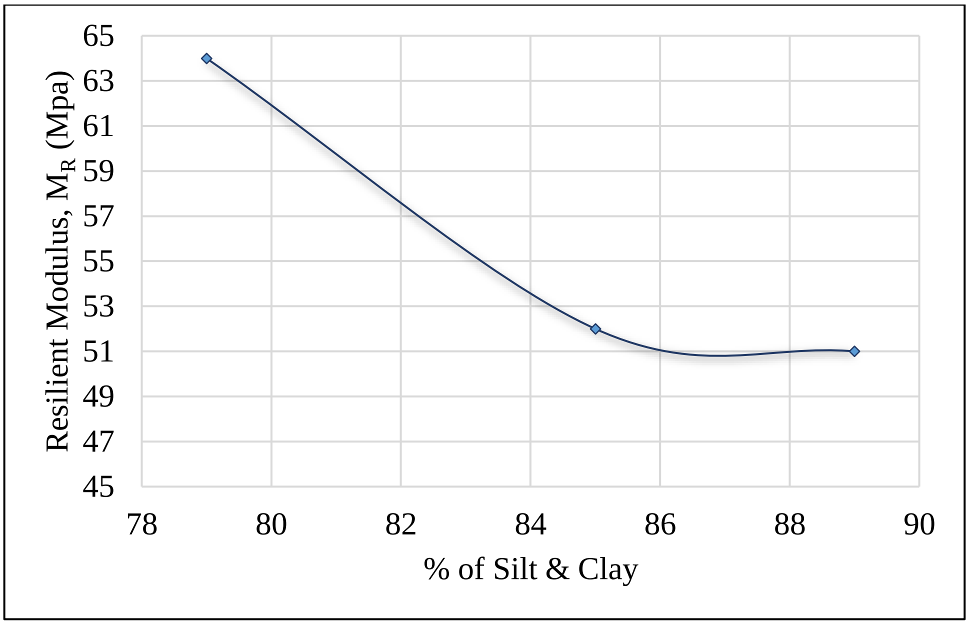

**Figure 4.5:** A graph $M_R$ (calculated using model-2) against % of silt & clay

Resilient modulus estimated from model – 2 give linear curve against percentage of silt and clay that indicates resilient modulus decreases when percentage of silt and clay increases as shown 4.5.

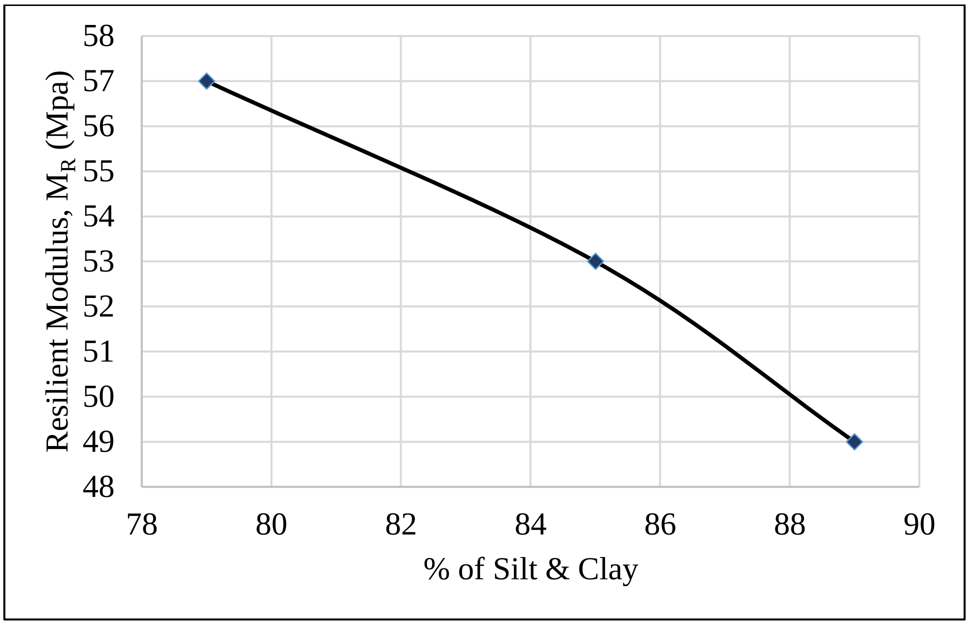

**Figure 4.6:** A graph $M_R$ (calculated using model-3) against % of silt & clay

Resilient modulus estimated from model – 3 give linear curve against percentage of silt and clay that indicates resilient modulus decreases when percentage of silt and clay increases as shown in Figure 4.6.

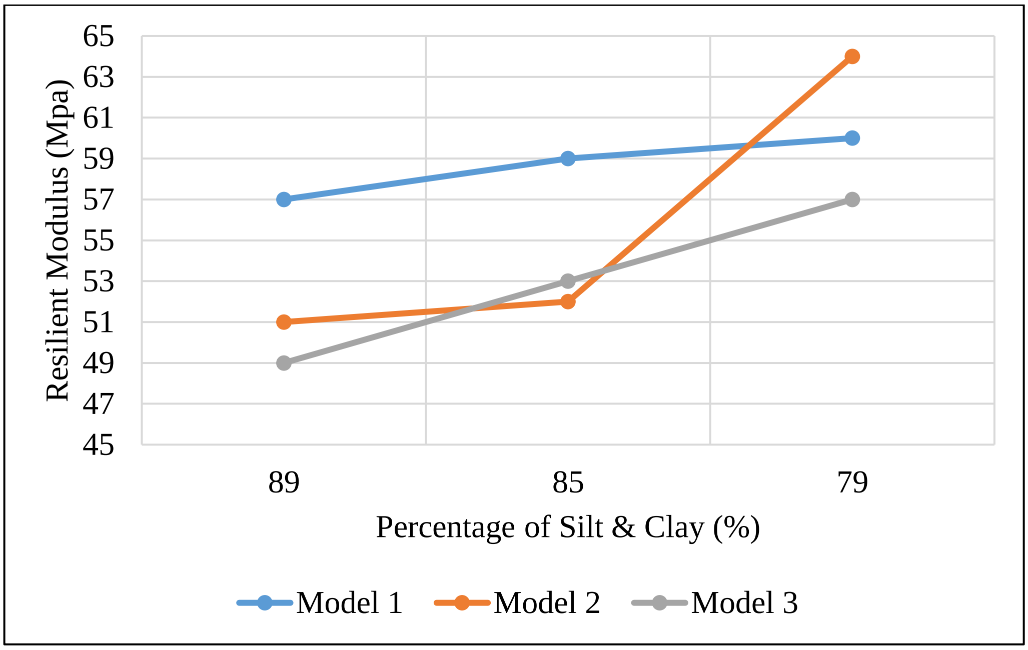

**Figure 4.7:** Comparison between selected models against % of Silt & Clay

Silt and clay percentage is an important variable that shows resilient modulus decreasing when percentage of silt and clay increasing for all the three models as shown in Figure 4.7.

### 4.4.2 Effect of Moisture Content on Resilient Modulus

Moisture content of subgrade soil has been found to affect the resilient response characteristics. The resilient behavior may be affected significantly where decreases steadily as the moisture content increases. In this study, Three subgrade soil samples were collected from different locations and modified proctor test are performed to determine optimum moisture content and maximum dry density. Here, some figures are shown between resilient modulus against optimum moisture content and shows in figure 4.8, 4.9 and 4.10 respectively. In these Figure 4.8, 4.9 and 4.10 for all three models, resilient modulus decreasing when optimum moisture content increasing. This result agrees with many researchers (Adu – Osei, 2001; Lekarp et al., 2000; and Azam et al., 2013) who studied the behavior of subgrade soil, have all reported a notable dependence of resilient modulus on moisture content, with the modulus decreasing with growing saturation level.

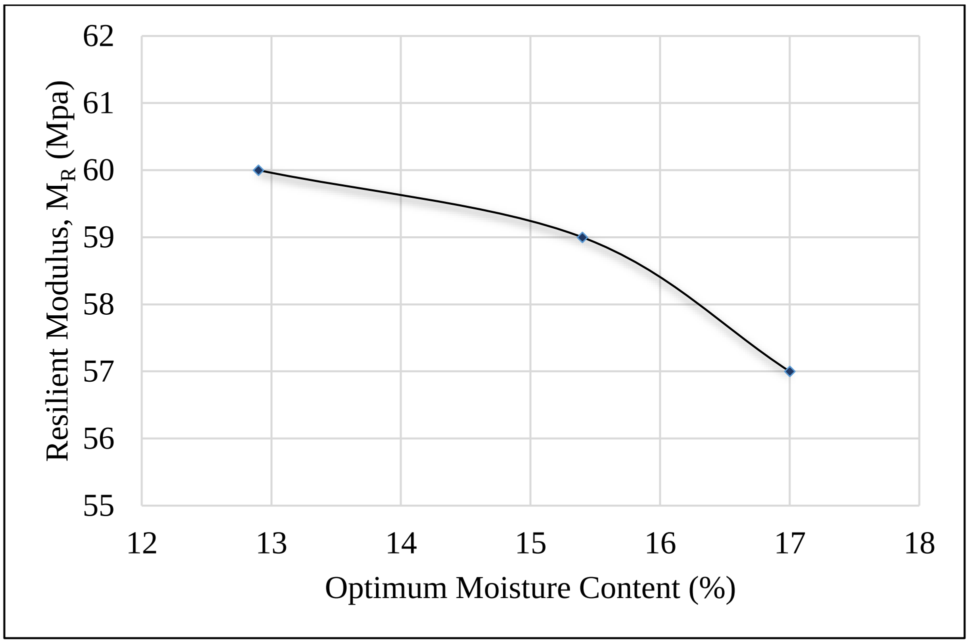

**Figure 4.8:** A graph $M_R$ (calculated using model-1) against OMC

Resilient modulus estimated from model – 1 give linear curve against optimum moisture content that indicates resilient modulus decreases when optimum moisture content increases as shown in Figure 4.8.

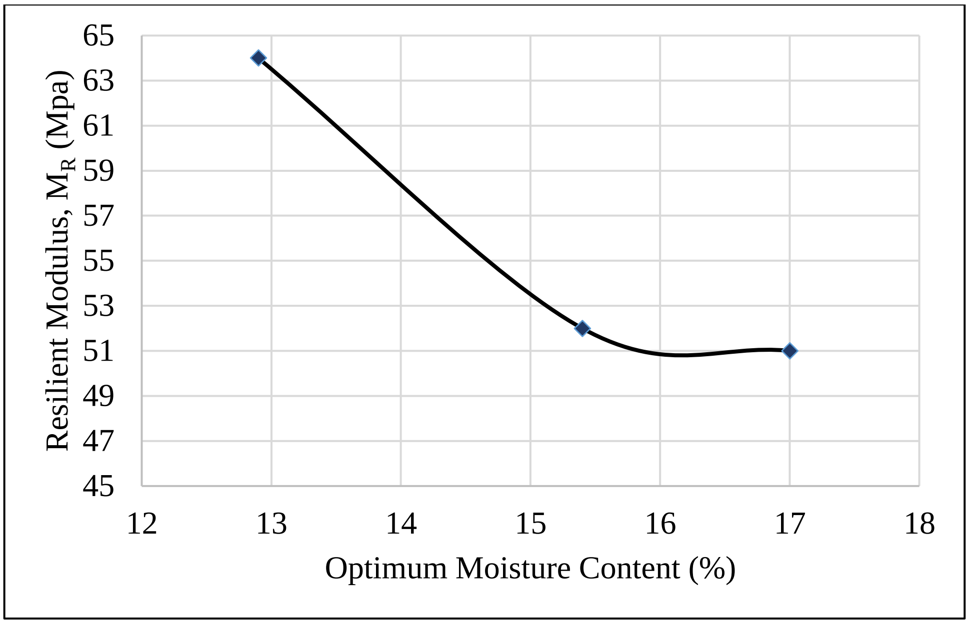

**Figure 4.9:** A graph $M_R$ (calculated using model-2) against OMC

Resilient modulus estimated from model – 2 give linear curve against optimum moisture content that indicates resilient modulus decreases when optimum moisture content increases as shown in Figure 4.9.

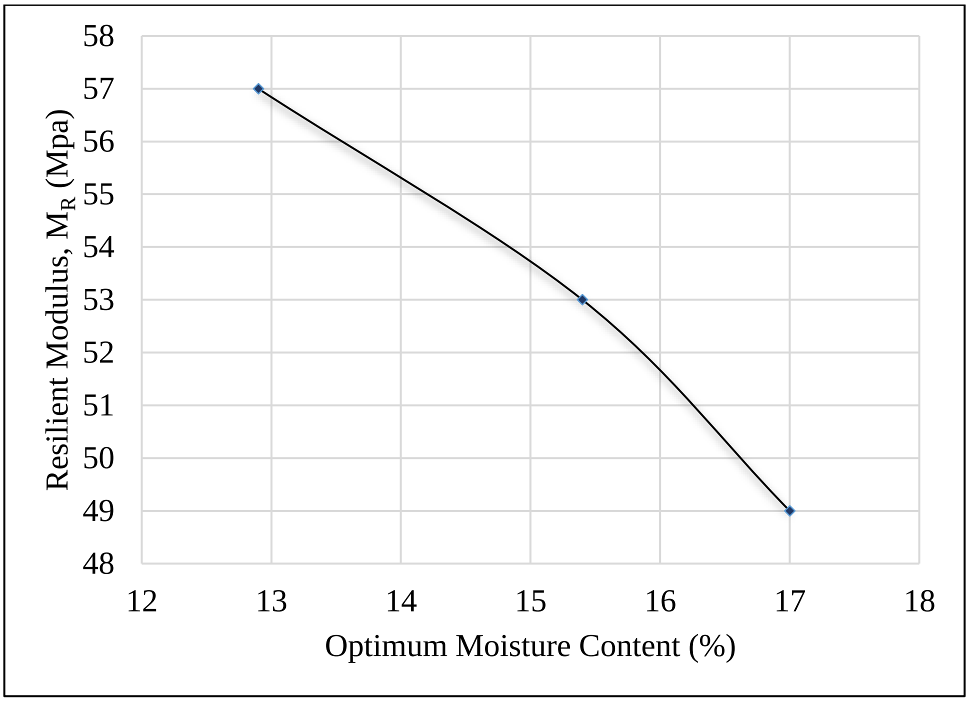

**Figure 4.10:** A graph $M_R$ (calculated using model-3) against OMC

Resilient modulus estimated from model – 3 give linear curve against optimum moisture content that indicates resilient modulus decreases when optimum moisture content increases as shown in Figure 4.10.

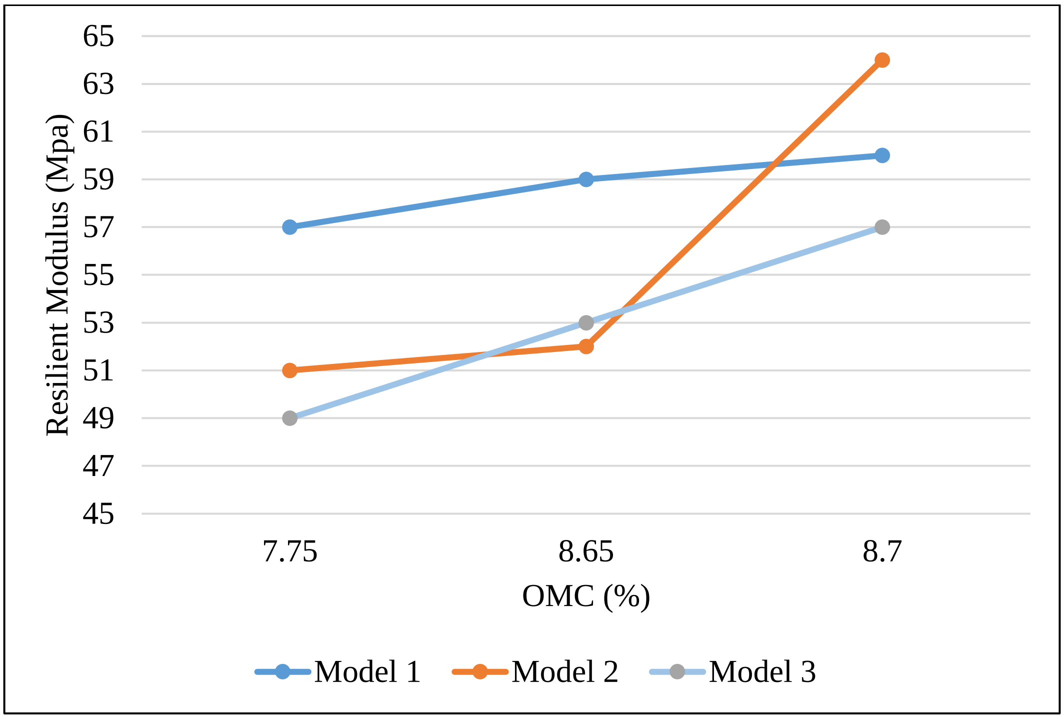

**Figure 4.11:** Comparison between selected models against OMC

Optimum moisture content is a vital variable that shows resilient modulus decreasing when optimum moisture content increasing. Figure 4.11 showing a comparison between resilient modulus determined from selected models against optimum moisture content.

### 4.4.3 Effect of Dry Density on Resilient Modulus

Maximum dry density of subgrade soil also has relation with resilient modulus. The resilient behavior increases gradually as the maximum dry density increases. In this study, modified proctor test has been performed to determine maximum dry density.

Resilient modulus estimated from model – 1 give linear curve against maximum dry density that indicates resilient modulus increases when maximum dry density increases as shown in Figure 4.12

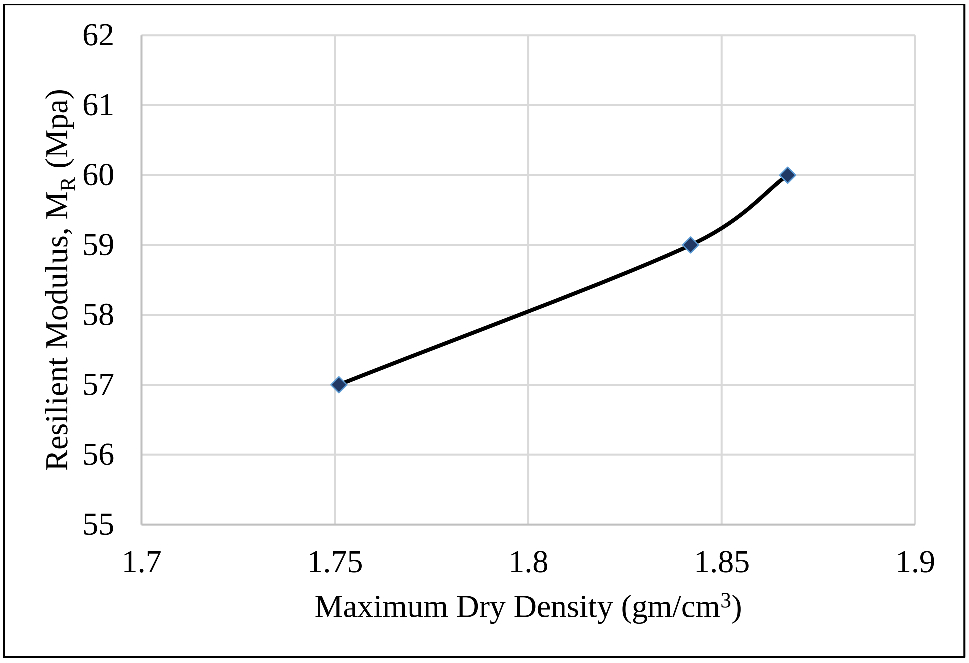

**Figure 4.12:** A graph $M_R$ (calculated using model-1) against MDD

Resilient modulus estimated from model – 2 give linear curve against maximum dry density that indicates resilient modulus increases when maximum dry density increases as shown in Figure 4.13.

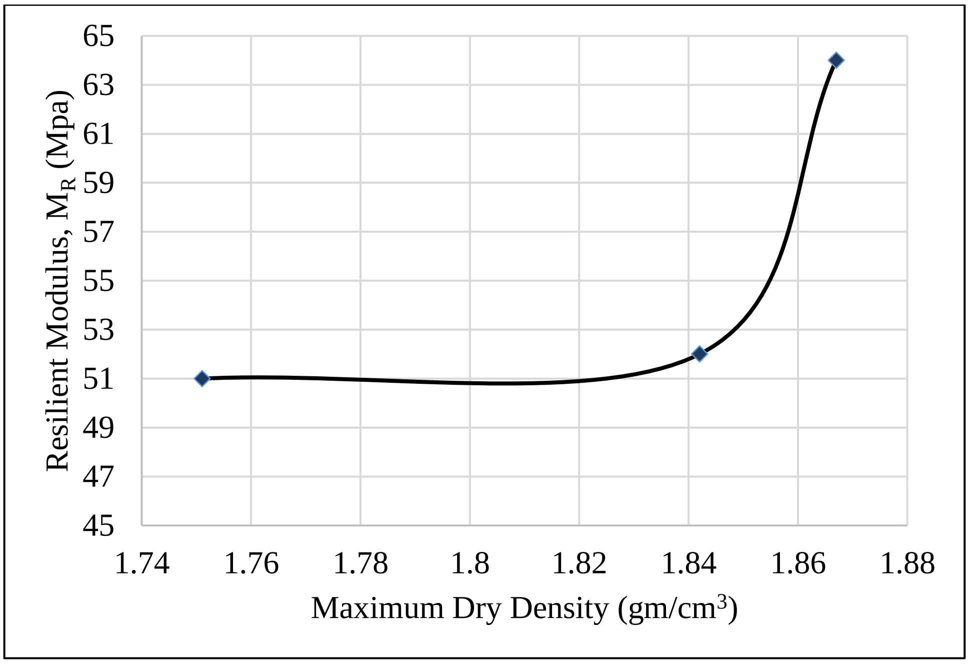

**Figure 4.13:** A graph $M_R$ (calculated using model-2) against MDD

Resilient modulus estimated from model – 3 give linear curve against maximum dry density that indicates resilient modulus increases when maximum dry density increases as shown in Figure 4.14.

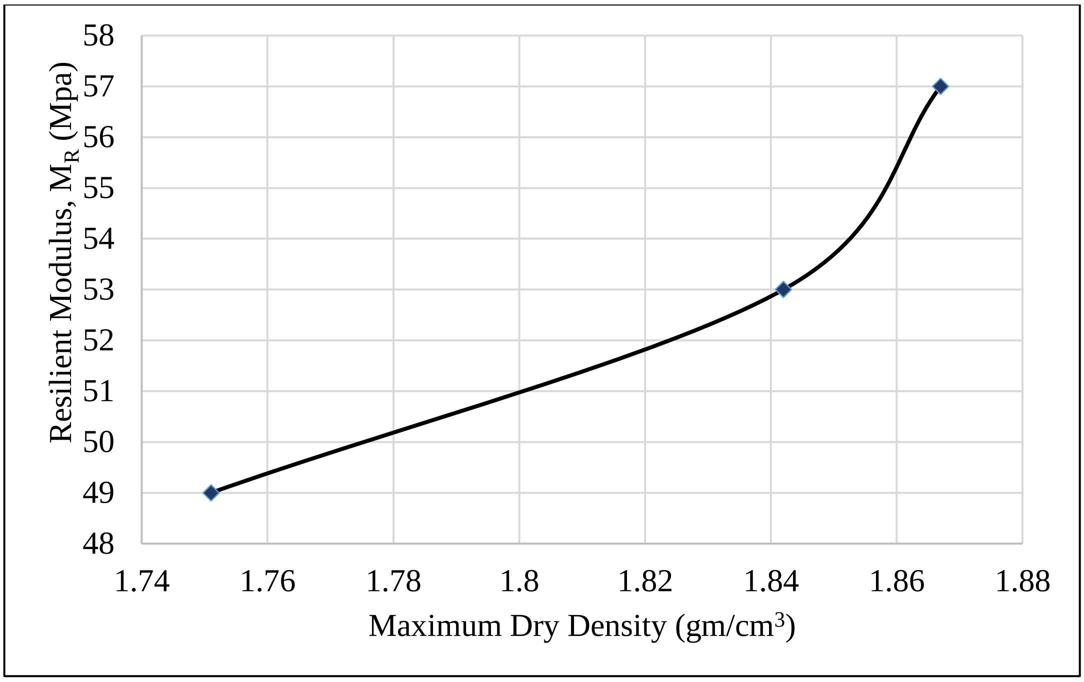

**Figure 4.14:** A graph $M_R$ (calculated using model-3) against MDD

Resilient modulus notable dependent on maximum dry density as shows resilient modulus increasing when maximum dry density increasing. A comparison between resilient modulus determined from selected models against maximum dry density as shown in Figure 4.15.

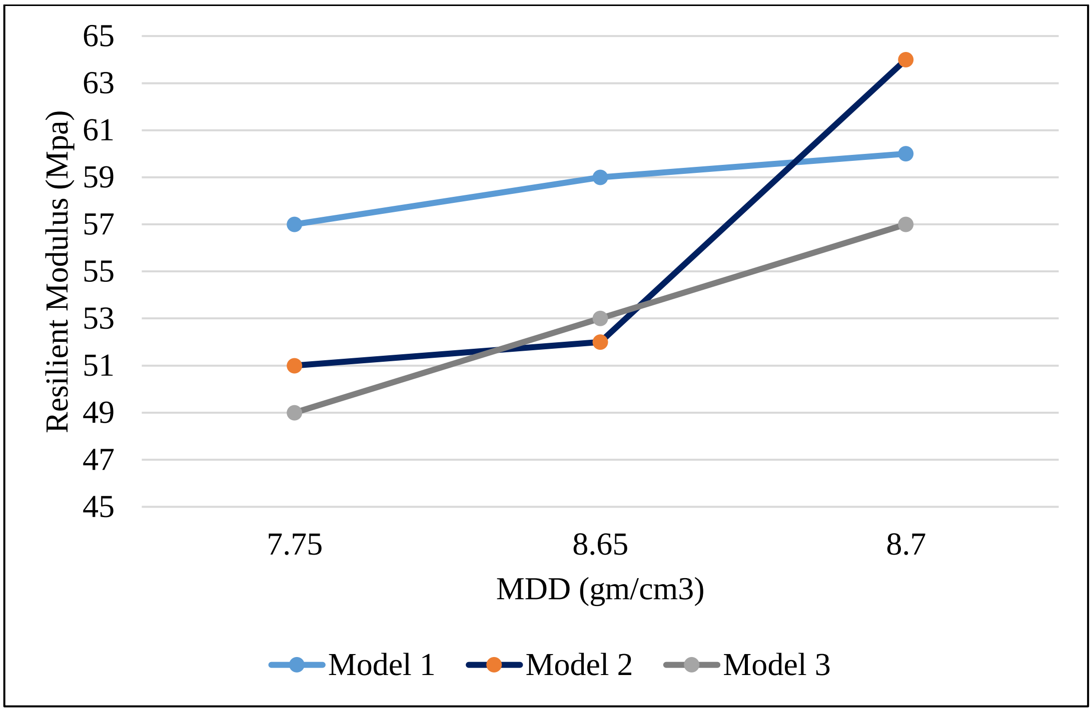

**Figure 4.15:** Comparison between selected models against MDD

### 4.4.4 Correlation between Resilient Modulus and CBR

The subgrade soil is more sensitive to the change in the CBR. This may be indicating that the resilient modulus of subgrade soil is extremely improved with increasing CBR value.

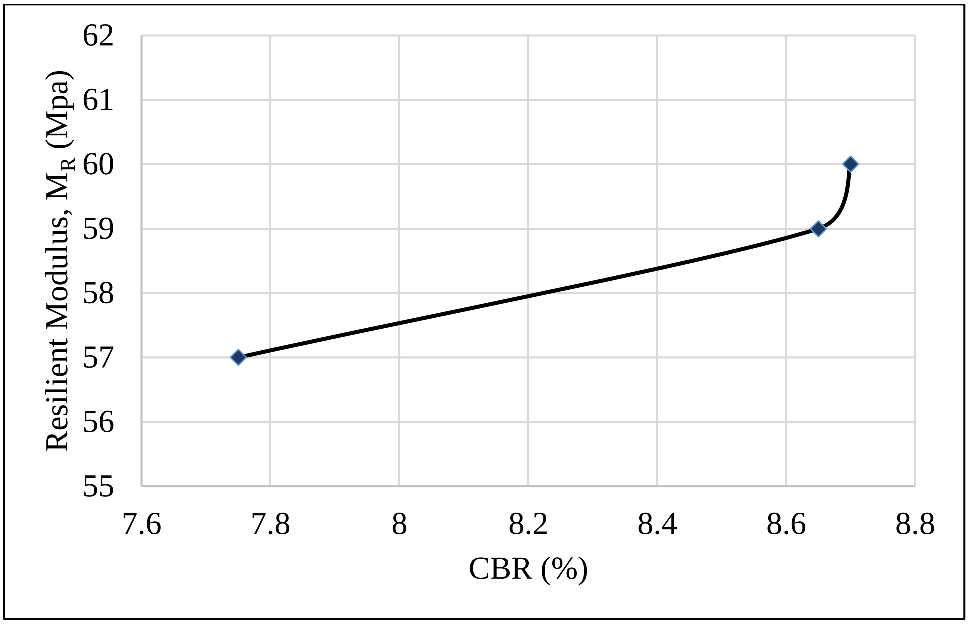

**Figure 4.16:** A graph $M_R$ (calculated using model-1) against CBR

In this study, three subgrade soil samples were collected from different locations and California bearing ratio tests are performed to determine CBR value. Resilient modulus estimated from model – 1 give linear curve against maximum CBR value that indicates resilient modulus increases when CBR value increases as shown in Figure 4.16.

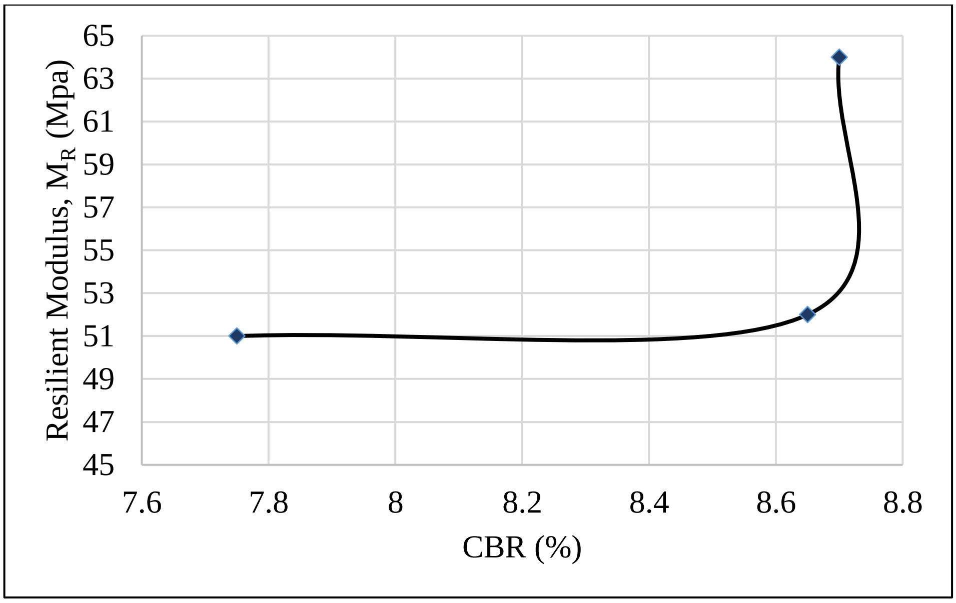

**Figure 4.17:** A graph $M_R$ (calculated using model-2) against CBR

Resilient modulus estimated from model – 2 give linear curve against maximum CBR value that indicates resilient modulus increases when CBR value increases as shown in Figure 4.17.

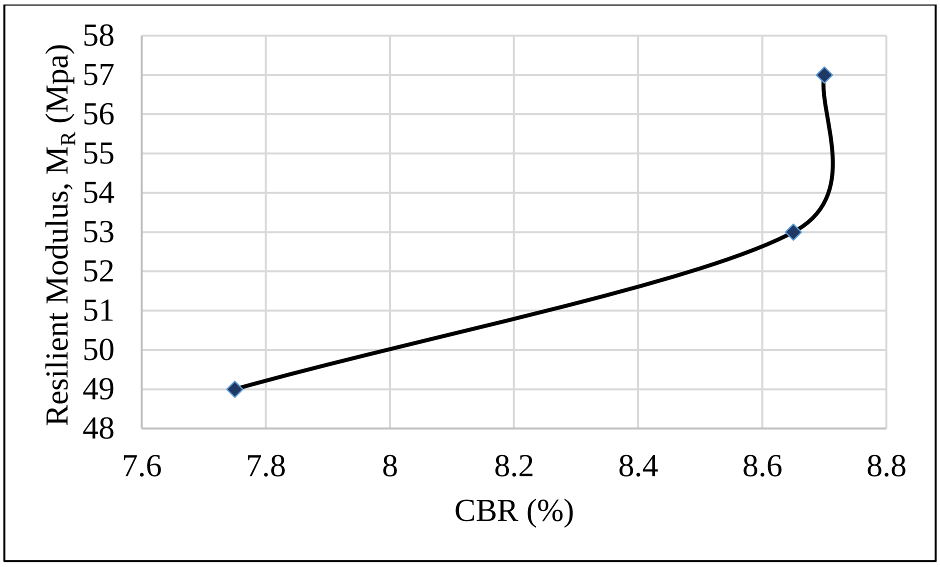

**Figure 4.18:** A graph $M_R$ (calculated using model-3) against CBR

Resilient modulus estimated from model – 3 give linear curve against maximum CBR value that indicates resilient modulus increases when CBR value increases as shown in Figure 4.18.

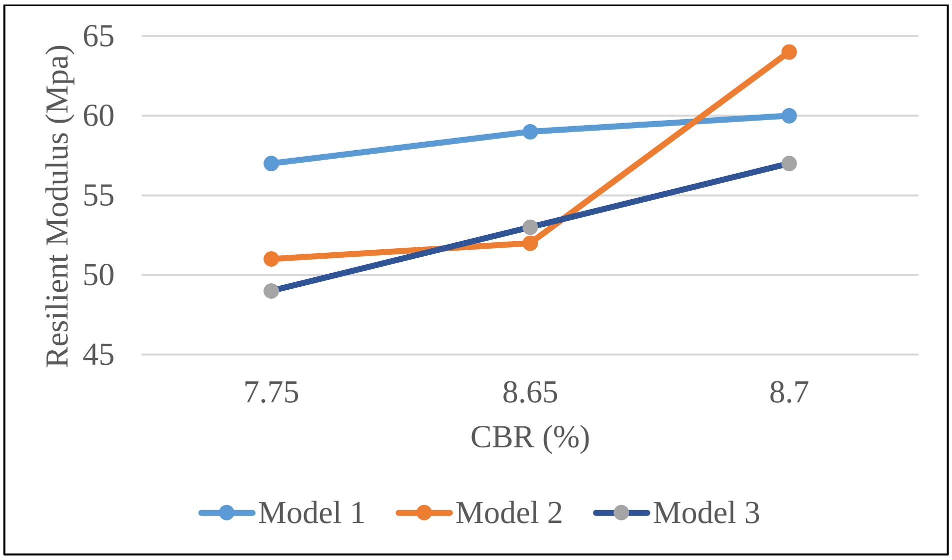

**Figure 4.19:** Comparison between selected models against CBR

A comparison between resilient modulus determined from selected models against CBR that shows resilient modulus increasing as CBR value increasing in Figure 4.19.

## 4.5 Laboratory Test Results of Investigated Materials

The testing program have been conducted on the investigated subgrade soil to determine the basic engineering properties that are summarized in Table 4.2.

**Table 4.2:** Required engineering properties of the investigated subgrade soil

| Material | Proctor test ASTM D 1557 | | Atterberg limits ASTM D 4318 | | | CBR (4 days Soaked) ASTM D 1883 | USCS Classification | Soil Classification AASHTO M 145 |
|---|---|---|---|---|---|---|---|---|
| | MDD, g/ cm$^3$ | OMC, % | LL, % | PL, % | PI, % | % | | |
| SG# 01 | 1.751 | 17 | 33.5 | 17.6 | 15.9 | 7.75 | CL | A-6 |
| SG# 02 | 1.842 | 15.4 | 34.8 | 21.3 | 13.5 | 8.65 | CL | A-6 |
| SG# 03 | 1.867 | 12.9 | 38 | 24.1 | 13.9 | 8.70 | CL | A-6 |

Here, MDD= Maximum Dry Density; OMC= Optimum Moisture Content; CL= Inorganic Clay; USCS= unified Soil Classification System respectively.

In this table 4.2, for these three subgrade soil samples several tests are performed to identify basic soil properties. These tests are modified proctor compaction test using ASTM D 1557, atterberg limit test using ASTM D 4318, CBR test using ASTM D 1883 etc. Soil classification are categorized using Unified Soil Classification System (USCS) and American Association of State Highway and Transportation Officials (AASHTO) based on ASTM D 2487 and AASHTO M 145 respectively.

For these following samples maximum dry density is determined as 1.751, 1.842 and 1.867 gm/cm$^3$ for SG#01, SG#02 and SG#03 respectively.

Atterberg limit test was performed for three subgrade soil samples and their liquid limit, plasticity limit and plasticity index are determined. Liquid limit is 33.5, 34.8 and 38 for SG#01, SG#02 and SG#03 respectively.

Four days soaked CBR test was performed for three subgrade soil samples and their CBR values are 7.75, 8.65 and 8.70 for SG#01, SG#02 and SG#03 respectively.

Based on these following results, soil is classified as Low plasticity clays (CL) using Unified Soil Classification System (USCS) and soil is classified as plastic clay soil 75% or more of which usually passes the #200 sieve using American Association of State Highway and Transportation Officials (AASHTO).

## 4.6 Resilient Modulus Estimation

Some of the well-known published models in the literature was applied such as Jaehun et al., Rahim and Li and Selig models to predict resilient modulus of subgrade soils. Jaehun et al. was recommended resilient modulus prediction model based on CBR value, which is presented in Equation (2.1a) were used to predict resilient modulus for each material. Rahim was suggested a model based on index properties of soil, which is presented in Equation (2.1d) were used to predict resilient modulus for each material. Li and Selig was recommended resilient modulus prediction model based on moisture content, which is written in Equation (2.2a) were used to predict resilient modulus for each material.

**Table 4.3:** Resilient Modulus determined from Equation (2.1a)

| Soil Types | Resilient Modulus (Mpa) |
|---|---|
| SG#01 | 57 |
| SG#02 | 59 |
| SG#03 | 60 |

Table 4.3 shows that resilient modulus of SG#01, SG#02 and SG#03 are 57, 59 and 60 mpa respectively determined by using Equation (2.1a).

**Table 4.4:** Resilient Modulus determined from Equation (2.1d)

| Soil Types | Resilient Modulus (Mpa) |
|---|---|
| SG#01 | 51 |
| SG#02 | 52 |
| SG#03 | 64 |

Table 4.4 shows that resilient modulus of SG#01, SG#02 and SG#03 are 51, 52 and 64 mpa respectively determined by using Equation (2.1d).

**Table 4.5:** Resilient Modulus determined from Equation (2.2a)

| Soil Types | Resilient Modulus (Mpa) |
|---|---|
| SG#01 | 49 |
| SG#02 | 53 |
| SG#03 | 57 |

Table 4.5 shows that resilient modulus of SG#01, SG#02 and SG#03 are 49, 53 and 57 mpa respectively determined by using Equation (2.2a).

## 4.6.1 Resilient modulus modelling

Resilient modulus are calculated by using well-known prediction models used for subgrade soils, which are collected from selected locations of Bangladesh. The Jaehun et al., Rahim and Li & Selig models, which are presented in Equation (2.1a, 2.1d and 2.2a) respectively were used to predict resilient modulus for each material. Table 4.6 presents the regression constants for each material. Resilient modulus prediction accuracy in terms of coefficient of determination, $R^2$ for subgrade soil was fair to excellent for all the three equations. Resilient modulus against CBR value shows $R^2$ value 0.92 means 92% accuracy of predicting resilient modulus as shows in Figure 4.20.

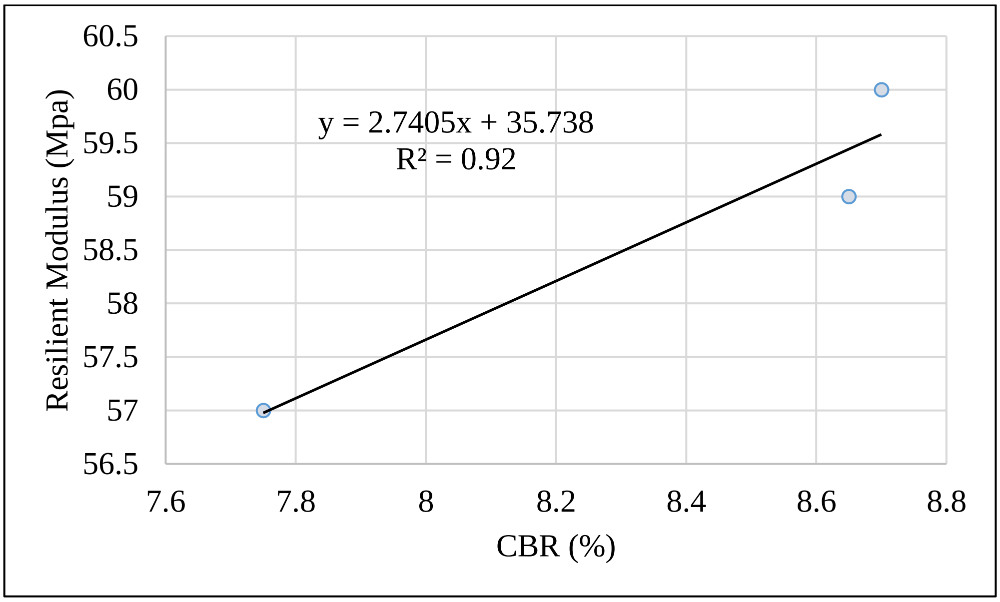

**Figure 4.20:** The variation of resilient modulus predicted from model- 1 with CBR

Resilient modulus against Maximum Dry Density shows $R^2$ value 0.52 means 52% accuracy of predicting resilient modulus as shows in Figure 4.21.

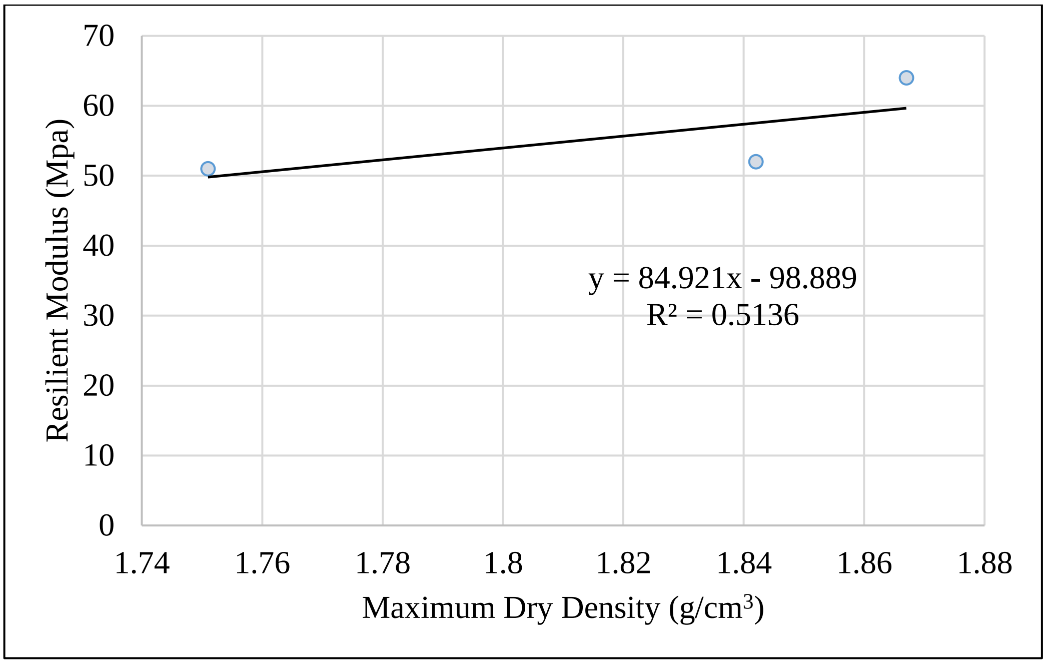

**Figure 4.21:** The variation of resilient modulus predicted from model- 2 with MDD

Resilient modulus against Optimum Moisture Content shows $R^2$ value 0.98 means 98% accuracy of predicting resilient modulus as shows in Figure 4.22.

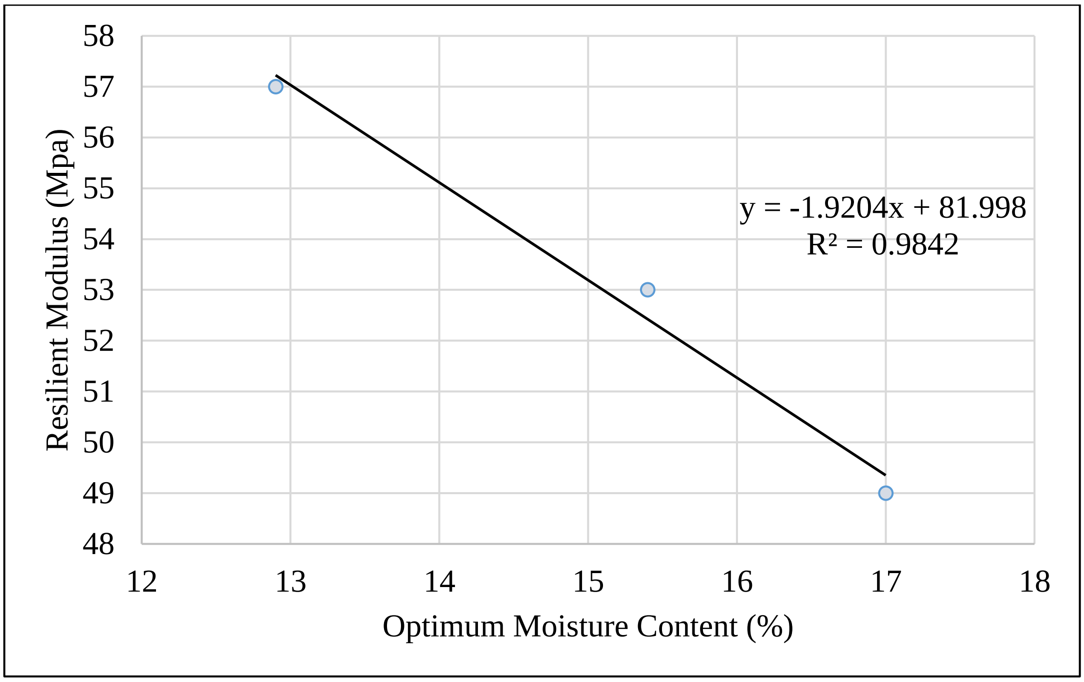

**Figure 4.22:** The variation of resilient modulus predicted from model- 3 with OMC

In this figures, linear regression relationship has been developed between resilient modulus predicted from predicted models and soil index properties and moisture content. Figure 4.20, 4.21 and 4.22 present the prediction of the resilient modulus for all the three subgrade soils, respectively using Equation (2.1a, 2.1d and 2.2a) along with the values of the regression coefficients.

**Table 4.6:** Regression coefficients and prediction accuracy of different models

| Model | m | c | $R^2$ | Prediction Accuracy (%) | Classification |
|---|---|---|---|---|---|
| Jaehun et al. | 2.74 | 35.74 | 0.92 | 92 | Excellent |
| Rahim | 84.92 | -98.9 | 0.51 | 51 | Fair |
| Li & Selig | -1.92 | 81.9 | 0.98 | 98 | Excellent |

It can be seen that equation (2.1a) gave excellent fit with $R^2$ of 0.92, which mean it is provided 92% accuracy of predicting resilient modulus. However, Equation (2.1d) was predicted resilient modulus with $R^2$ of 0.52, which is 52% provided fair result. It is clear from the Figure 4.18 that Equation (2.2a) gave excellent fit with $R^2$ of 0.98, which provided optimum prediction accuracy of 98% with these investigated materials.

Among these three models two are predicted resilient modulus with more than 90% accuracy. This is because pavement subgrade soil is dependent on CBR value and moisture content and these are very important parameters for flexible pavement design. Model focus on these parameters are given optimum prediction accuracy than other parameters.

# CHAPTER 5

# CONCLUSION AND RECOMMENDATIONS

## 5.1 Introduction

Resilient modulus of three different subgrade soil samples has been determined using three well-known resilient modulus prediction models in the context of Bangladesh. Also, the variables that affecting the resilient modulus of subgrade soil are identified and the results are presented in previous chapters. The summery of the results and the conclusions drawn and the recommendations for further study are presented in this chapter.

## 5.2 Limitations of the study

This study has made an attempt to determine the variables that effect resilient modulus of subgrade soil in Bangladesh. It has developed a methodology for predicting resilient modulus of subgrade soil. It has also proposed models that has the optimum prediction accuracy in the context of Bangladesh. This research has been done based on limited subgrade soil samples with some selected resilient modulus prediction models.

## 5.3 Conclusion

The experimental and mathematical analysis has been undertaken in present study. Resilient modulus have been calculated using soil index properties and moisture content with three well-known resilient modulus prediction models with three different subgrade soil samples in Bangladesh. Based on the literature review presented in this paper and the engineering properties of the subgrade soil, the following conclusions are drawn as presented below:

a) There are many variables that influence the behavior of fine-grained soils. These factors are density, gradation, fines content, grain size, particle shape, strength of soil and moisture content. Resilient modulus is mostly influenced by gradation and the amount of moisture content in the soil.

b) Several tests was conducted on three types of subgrade soils in order to determine resilient modulus based on index properties of soil and moisture content. Resilient modulus is increasing significantly with the increase in both CBR value and maximum dry density. However, resilient modulus is ominously decreasing with the increase in both percentage of silt and clay and moisture content.

c) Three well-known resilient modulus prediction models was used to investigate obtain resilient modulus for three selected subgrade soil samples and a comparison between them was done. Models that used for prediction of each subgrade soils fitted reasonably resilient modulus data with accuracy in terms of $R^2$ varied from fair to excellent or 51% to 98%. Among them Li and Selig model provided optimum prediction accuracy of 98% proving that it can be used as a general model for predicting resilient modulus in context of Bangladesh.

## 5.4 Recommendations

Due to lack of sufficient experimental facilities, the following study is carried out on three subgrade soil samples and soil index properties. However, the following recommendations are made to extend present research further in future:

a) A similar study can be conducted using unbound granular materials such as surface, base, subbase and so on.

b) To do study involving subgrade soil from all over Bangladesh.

c) To explore the stress state factor such as confining pressure and deviator stresses on the resilient modulus of unbound granular materials and subgrade soils of Bangladesh.

d) To use all well-known resilient modulus models for predicting resilient modulus.

e) To perform repeated load triaxial test in order to determine resilient modulus values and compare them with these models data with regression coefficients.

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# APPENDIX- A

Calculation of resilient modulus from three well- known resilient modulus prediction models for three different subgrade soils which are collected from selected locations of Bangladesh are shown below:

**Model 1:**

$M_R$ (psi) = $3460.3*CBR^{0.4187}$

Here,

CBR = California bearing ratio (%)

$M_R$ = Resilient Modulus (psi)

SG#01: $M_R = 3460.3*7.75^{0.4187}$ = 8155.76 psi = 56.25 Mpa = 57 Mpa.

SG#02: $M_R = 3460.3*8.65^{0.4187}$ = 8539.70 psi = 58.89 Mpa = 59 Mpa.

SG#03: $M_R = 3460.3*8.70^{0.4187}$ = 8560.33 psi = 59.04 Mpa = 60 Mpa.

**Model 2:**

$M_R$ = 17.29 * $[(\frac{\gamma dry}{Wc+1})^{\mathbf{2 \cdot 18}} + (\frac{P\#200}{100})^{\mathbf{-0 \cdot 609}}]$

Here,

$\gamma_{dry}$ = Dry Density (KN/m$^3$)

$W_c$ = Moisture Content (%)

P#200 = Percentage of Silt & Clay (%)

$M_R$ = Resilient Modulus (mpa)

SG#01: $M_R$ = 17.29 * $[(\frac{17.17}{12+1})^{\mathbf{2 \cdot 18}} + (\frac{89}{100})^{\mathbf{-0 \cdot 609}}]$ = 50.27 Mpa = 51 Mpa.

SG#02: $M_R$ = 17.29 * $[(\frac{18.06}{12.5+1})^{\mathbf{2 \cdot 18}} + (\frac{85}{100})^{\mathbf{-0 \cdot 609}}]$ = 51.70 Mpa = 52 Mpa.

SG#03: $M_R$ = 17.29 * $[(\frac{18.31}{11+1})^{\mathbf{2 \cdot 18}} + (\frac{79}{100})^{\mathbf{-0 \cdot 609}}]$ = 63.40 Mpa = 64 Mpa.

**Model 3:**

$M_R = 0.98 – 0.28 * (W – W^{OPT}) + 0.29 * (W – W^{OPT})^2$

Here,

$W_{OPT}$ = Optimum Moisture Content (%)

W = Moisture Content after Test (%)

$M_R$ = Resilient Modulus (mpa)

SG#01: $M_R = 0.98 - 0.28 * (30.25 – 17) + 0.29 * (30.25 – 17)^2$ = 48.18 Mpa = 49 Mpa.

SG#02: $M_R = 0.98 - 0.28 * (29.16 – 15.4) + 0.29 * (29.16 – 15.4)^2$ = 52.04 Mpa = 53 Mpa.

SG#03: $M_R = 0.98 - 0.28 * (27.29 – 12.9) + 0.29 * (27.29 – 12.9)^2$ = 57.00 Mpa = 57 Mpa.

# APPENDIX- B

Test result data are given here as follows:

**Test Name: Wash sieve to determine percentage of silt and clay.**

| Sample | Total soil sample, $W_T$ (gm) | Weight retained, $W_R$ (gm) | Percentage retained, $W_R$ (%) | Percentage of silt & clay (%) |
|---|---|---|---|---|
| 1 | 101.280 | 10.984 | 11 | 89 |
| 2 | 105.480 | 15.53 | 15 | 85 |
| 3 | 100 | 20.53 | 21 | 79 |

**Test Name: Specific Gravity Test.**

**For, Sample - 1**

| No | Bottle No | Wt of bottle, $W_P$ (gm) | Wt of bottle + dry soil, $W_{PS}$ (gm) | Wt of dry soil, $W_O$ (gm) | Wt of bottle + soil + water, $W_B$ (gm) | Wt of bottle + water, $W_A$ (gm) | Tem, $T^OC$ | Specific gravity of water at $T^OC$ | Specific gravity of soil, $G_S$ $\frac{W_O \times G_T}{W_O + (W_A - W_B)}$ |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 157.565 | 207.540 | 49.975 | 685.6 | 654.6 | 23 | 0.9976 | 2.63 |
| 2 | 2 | 163.667 | 213.652 | 49.985 | 691.9 | 660.1 | 23 | 0.9976 | 2.74 |
| 3 | 3 | 164.388 | 214.385 | 49.997 | 692.8 | 660.8 | 23 | 0.9976 | 2.77 |

$G_S = \frac{GS1+GS2+GS3}{3} = \frac{2.63+2.74+2.77}{3} = 2.713 = 2.71$

**For, Sample - 2**

| No | Bottle No | Wt of bottle, $W_P$ (gm) | Wt of bottle + dry soil, $W_{PS}$ (gm) | Wt of dry soil, $W_O$ (gm) | Wt of bottle + soil + water, $W_B$ (gm) | Wt of bottle + water, $W_A$ (gm) | Tem, $T^O C$ | Specific gravity of water at $T^O C$ | Specific gravity of soil, $G_S$ $\frac{W_O \times G_T}{W_O + (W_A - W_B)}$ |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 157.568 | 207.869 | 50.301 | 687.67 | 656.7 | 32 | 0.9951 | 2.59 |
| 2 | 2 | 163.720 | 214.413 | 50.693 | 694.87 | 662.5 | 32 | 0.9951 | 2.75 |
| 3 | 3 | 164.393 | 215.365 | 50.972 | 695.95 | 663.2 | 32 | 0.9951 | 2.78 |

$G_S = \frac{GS1+GS2+GS3}{3} = \frac{2.59+2.75+2.78}{3} = 2.709 = 2.71$

**For, Sample - 3**

| No | Bottle No | Wt of bottle, $W_P$ (gm) | Wt of bottle + dry soil, $W_{PS}$ (gm) | Wt of dry soil, $W_O$ (gm) | Wt of bottle + soil + water, $W_B$ (gm) | Wt of bottle + water, $W_A$ (gm) | Tem, $T^O C$ | Specific gravity of water at $T^O C$ | Specific gravity of soil, $G_S$ $\frac{W_O \times G_T}{W_O + (W_A - W_B)}$ |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 158.165 | 208.668 | 50.503 | 695.84 | 664.58 | 29 | 0.9960 | 2.62 |
| 2 | 2 | 163.669 | 214.139 | 50.470 | 707.01 | 674.94 | 29 | 0.9960 | 2.73 |
| 3 | 3 | 164.410 | 214.625 | 50.215 | 706.32 | 674.16 | 29 | 0.9960 | 2.77 |

$G_S = \frac{GS1+GS2+GS3}{3} = \frac{2.62+2.73+2.77}{3} = 2.705 = 2.71$

**Test Name: Grain size analysis by hydrometer**

**For, Sample – 1**

Hydrometer no: 152H, Zero correction: -0.5, Meniscus correction: 0.5.

| **T (min)** | **Room Tem, °C** | **Actual hydro. Red., $R_a$** | **Reading after meniscus correction, R = $R_a$-$C_m$** | **Effective depth, L (cm)** | **K** | **D in cm = $K\sqrt{(\frac{L}{t})}$** | **$C_t$** | **a** | **$R_C$ = $R_a$- $C_z$± $C_t$** | **P (%)** |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.25 | 24 | 46 | 45.5 | 8.85 | 0.0128 | 0.0763 | +1.00 | 0.99 | 47.5 | 94.05 |
| 0.5 | 25 | 44 | 43.5 | 9.15 | 0.0127 | 0.0542 | +1.30 | 0.99 | 45.8 | 90.69 |
| 1 | 25 | 42 | 41.5 | 9.5 | 0.0127 | 0.0391 | +1.30 | 0.99 | 43.8 | 86.73 |
| 2 | 25 | 38 | 37.5 | 10.15 | 0.0127 | 0.0286 | +1.30 | 0.99 | 39.8 | 78.81 |
| 4 | 26 | 34 | 33.5 | 10.8 | 0.0125 | 0.0206 | +1.65 | 0.99 | 36.2 | 71.58 |
| 8 | 27 | 30 | 29.5 | 11.45 | 0.0124 | 0.0148 | +2.00 | 0.99 | 32.2 | 64.35 |
| 15 | 30 | 28 | 27.5 | 11.8 | 0.0120 | 0.0106 | +3.80 | 0.99 | 32.3 | 63.96 |
| 30 | 30 | 25 | 24.5 | 12.3 | 0.0120 | 0.0077 | +3.80 | 0.99 | 29.3 | 58.02 |
| 60 | 30 | 21 | 20.5 | 12.95 | 0.0120 | 0.0056 | +3.80 | 0.99 | 25.3 | 50.10 |
| 120 | 30 | 15 | 14.5 | 13.9 | 0.0120 | 0.0041 | +3.80 | 0.99 | 19.3 | 38.22 |
| 240 | 30 | 6 | 5.5 | 15.4 | 0.0120 | 0.0031 | +3.80 | 0.99 | 10.3 | 20.40 |
| 480 | 30 | 3 | 2.5 | 15.9 | 0.0120 | 0.0022 | +3.80 | 0.99 | 7.3 | 14.46 |
| 1440 | 26 | 3 | 2.5 | 15.9 | 0.0125 | 0.0013 | +1.65 | 0.99 | 5.2 | 10.20 |

**For, Sample – 2**

Hydrometer no: 152H, Zero correction: -2.5, Meniscus correction: 0.5.

| T (min) | Room Tem, $^{O}$C | Actual hydro. Red., Ra | Reading after meniscus correction, R = Ra-Cm | Effective depth, L (cm) | K | D in cm = $K\sqrt{(\frac{L}{t})}$ | $C_t$ | a | $R_C$ = $R_a$-$C_z$± $C_t$ | P (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.25 | 26 | 50.5 | 50 | 7.7 | 0.0125 | 0.0696 | +1.65 | 0.99 | 47.2 | 93.36 |
| 0.5 | 26 | 50 | 49.5 | 8 | 0.0125 | 0.0501 | +1.65 | 0.99 | 46.2 | 91.38 |
| 1 | 26 | 48 | 47.5 | 8.5 | 0.0125 | 0.0365 | +1.65 | 0.99 | 45.2 | 89.40 |
| 2 | 26 | 44 | 43.5 | 9.15 | 0.0125 | 0.0268 | +1.65 | 0.99 | 43.2 | 85.44 |
| 4 | 26 | 39 | 38.5 | 10 | 0.0125 | 0.0198 | +1.65 | 0.99 | 38.2 | 75.54 |
| 8 | 26 | 30 | 29.5 | 11.45 | 0.0125 | 0.0150 | +1.65 | 0.99 | 29.2 | 57.72 |
| 15 | 26 | 26 | 25.5 | 12.1 | 0.0125 | 0.0113 | +1.65 | 0.99 | 25.2 | 49.80 |
| 30 | 26 | 19 | 18.5 | 13.25 | 0.0125 | 0.0083 | +1.65 | 0.99 | 18.2 | 35.40 |
| 60 | 26 | 13 | 12.5 | 14.25 | 0.0125 | 0.0061 | +1.65 | 0.99 | 12.2 | 24.06 |
| 120 | 26 | 10 | 9.5 | 14.75 | 0.0125 | 0.0044 | +1.65 | 0.99 | 9.2 | 18.12 |
| 240 | 26 | 7 | 6.5 | 15.25 | 0.0125 | 0.0032 | +1.65 | 0.99 | 6.2 | 12.18 |
| 480 | 26 | 5 | 4.5 | 15.55 | 0.0125 | 0.0023 | +1.65 | 0.99 | 4.2 | 8.22 |
| 1440 | 26 | 5 | 4.5 | 15.55 | 0.0125 | 0.0013 | +1.65 | 0.99 | 4.2 | 8.22 |

**For, Sample – 3**

Hydrometer no: 152H, Zero correction: -0.5, Meniscus correction: 0.5.

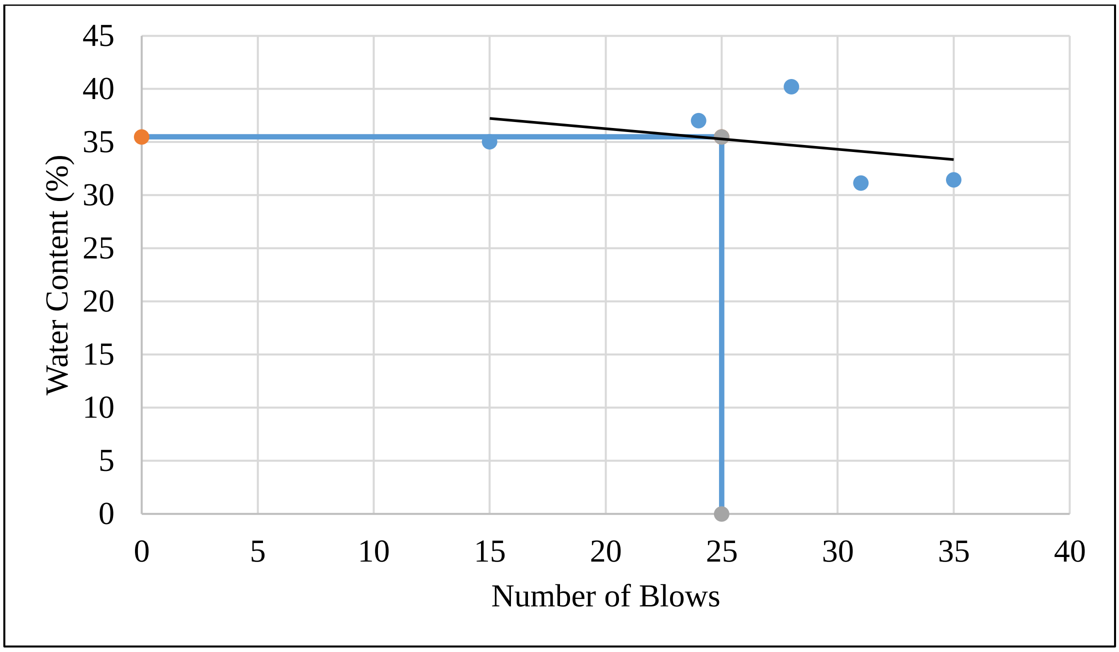
| T (min) | Room Tem, $^{O}$C | Actual hydro. Red., Ra | Reading after meniscus correction, R = Ra-Cm | Effective depth, L (cm) | K | D in cm = $K\sqrt{(\frac{L}{t})}$ | $C_t$ | a | $R_C = R_a - C_z \pm C_t$ | P (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.25 | 29 | 48 | 47.5 | 8.5 | 0.0121 | 0.0707 | +3.05 | 0.99 | 51.6 | 95.04 |
| 0.5 | 29 | 43 | 42.5 | 9.3 | 0.0121 | 0.0523 | +3.05 | 0.99 | 46.6 | 92.17 |
| 1 | 29 | 38 | 37.5 | 10.15 | 0.0121 | 0.0386 | +3.05 | 0.99 | 41.6 | 82.27 |
| 2 | 29 | 33 | 32.5 | 11 | 0.0121 | 0.0284 | +3.05 | 0.99 | 36.6 | 72.37 |
| 4 | 29 | 28 | 27.5 | 11.8 | 0.0121 | 0.0208 | +3.05 | 0.99 | 31.6 | 62.47 |
| 8 | 29 | 19 | 18.5 | 13.25 | 0.0121 | 0.0156 | +3.05 | 0.99 | 22.6 | 44.65 |
| 15 | 29 | 16 | 15.5 | 13.75 | 0.0121 | 0.0116 | +3.05 | 0.99 | 19.6 | 38.71 |
| 30 | 29 | 11 | 10.5 | 14.6 | 0.0121 | 0.0085 | +3.05 | 0.99 | 14.6 | 28.81 |
| 60 | 29 | 8 | 7.5 | 15.1 | 0.0121 | 0.0061 | +3.05 | 0.99 | 11.6 | 22.87 |
| 120 | 29 | 5 | 4.5 | 15.55 | 0.0121 | 0.0044 | +3.05 | 0.99 | 8.6 | 16.93 |
| 240 | 29 | 3 | 2.5 | 15.9 | 0.0121 | 0.0031 | +3.05 | 0.99 | 6.6 | 12.97 |
| 480 | 29 | 3 | 2.5 | 15.9 | 0.0121 | 0.0022 | +3.05 | 0.99 | 6.6 | 12.97 |
| 1440 | 29 | 3 | 2.5 | 15.9 | 0.0121 | 0.0013 | +3.05 | 0.99 | 6.6 | 12.97 |

**Test Name: Atterberg limit test.**

**For, Sample – 1**

Liquid Limit (LL)

| No | Can | Wt of can, $W_C$ (gm) | Wt of can + wet sample, Wc+Ww+Ws (gm) | Wt of can+dry soil, Wc+Ws (gm) | Wt of dry soil, Ws (gm) | Wt of water, Ww (gm) | Moisture content, W(%) | No of blow, N |
|---|---|---|---|---|---|---|---|---|
| 1 | Viii | 15.102 | 56.972 | 46.120 | 31.018 | 10.87 | 35.05 | 15 |
| 2 | T-6 | 16.356 | 56.693 | 47.037 | 30.681 | 9.66 | 31.47 | 35 |
| 3 | iii | 16.507 | 71.301 | 58.286 | 41.779 | 13.02 | 31.15 | 31 |
| 4 | 6 | 17.094 | 54.933 | 45.637 | 28.543 | 9.30 | 32.57 | 27 |
| 5 | 5 | 17.800 | 55.161 | 46.095 | 28.295 | 9.07 | 32.04 | 19 |



From graph, for 25 blows: LL = 33.5%.

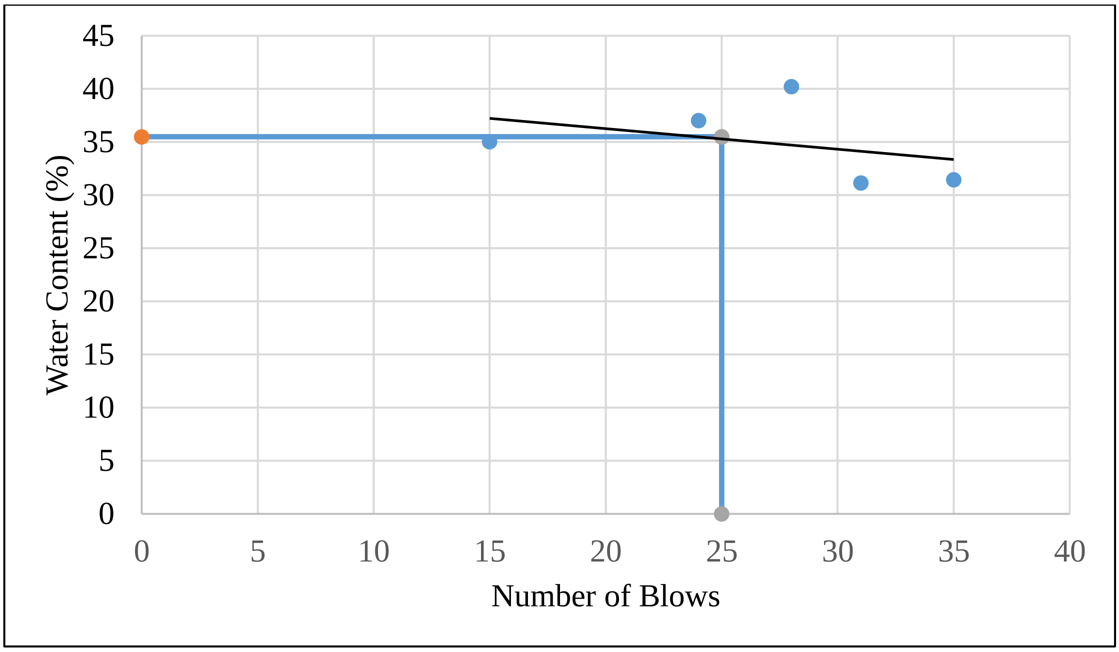
Plastic Limit (PL)

| No | Can | Wt of can, WC (gm) | Wt of can + wet sample, Wc+Ww+Ws (gm) | Wt of can+dry soil, Wc+Ws (gm) | Wt of dry soil, Ws (gm) | Wt of water, Ww (gm) | Moisture content, W(%) | Average Plastic Limit, PL |
|---|---|---|---|---|---|---|---|---|
| 1 | 3 | 20.30 | 36.63 | 33.81 | 13.59 | 2.74 | 20.15 | 17.6 |
| 2 | 2 | 17.32 | 27.75 | 26.04 | 10.43 | 1.75 | 16.44 |  |
| 3 | 4 | 11.17 | 28.95 | 26.87 | 12.78 | 2.08 | 16.31 |  |

**For, Sample – 2**

Liquid Limit (LL)

| No | Can | Wt of can, Wc (gm) | Wt of can + wet sample, Wc+Ww+Ws (gm) | Wt of can+dry soil, Wc+Ws (gm) | Wt of dry soil, Ws (gm) | Wt of water, Ww (gm) | Moisture content, W(%) | No of blow, N |
|---|---|---|---|---|---|---|---|---|
| 1 | 105 | 30 | 51 | 46.5 | 16.5 | 4.5 | 27.3 | 33 |
| 2 | 93 | 29.4 | 50.5 | 45.5 | 16.1 | 5 | 31.1 | 29 |
| 3 | 95 | 28.8 | 53.6 | 47.1 | 18.3 | 6.5 | 35.5 | 22 |
| 4 | 98 | 25.1 | 58.5 | 49.1 | 24 | 9.4 | 39.2 | 15 |
| 5 | 91 | 27.6 | 54.1 | 46.9 | 19.3 | 7.2 | 37.5 | 18 |



From graph, for 25 blows: LL = 34.8%.

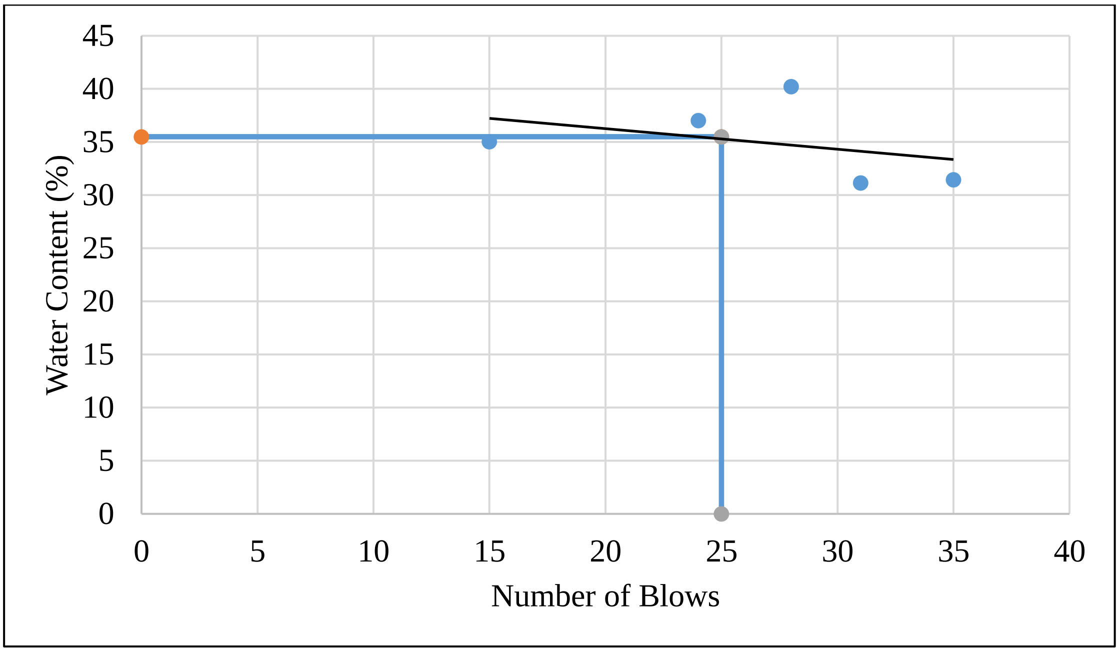
Plastic Limit (PL)

| No | Can | Wt of can, WC (gm) | Wt of can + wet sample, Wc+Ww+Ws (gm) | Wt of can+dry soil, Wc+Ws (gm) | Wt of dry soil, Ws (gm) | Wt of water, Ww (gm) | Moisture content, W(%) | Average Plastic Limit, PL |
|---|---|---|---|---|---|---|---|---|
| 1 | 102 | 29.8 | 51.1 | 47.4 | 17.6 | 3.7 | 21 | 21.3 |
| 2 | 107 | 29.6 | 48.8 | 45.4 | 15.8 | 3.4 | 21.4 | |
| 3 | 100 | 29.4 | 50.8 | 47 | 17.6 | 3.8 | 21.5 | |

**For, Sample – 3**

Liquid Limit (LL)

| No | Can | Wt of can, Wc (gm) | Wt of can + wet sample, Wc+Ww+Ws (gm) | Wt of can+dry soil, Wc+Ws (gm) | Wt of dry soil, Ws (gm) | Wt of water, Ww (gm) | Moisture content, W(%) | No of blow, N |
|---|---|---|---|---|---|---|---|---|
| 1 | S-6 | 22.63 | 49.21 | 41.68 | 19.05 | 7.53 | 39.54 | 15 |
| 2 | 1 | 15.32 | 54.62 | 43.83 | 28.51 | 10.8 | 37.85 | 20 |
| 3 | 7 | 15.58 | 50.19 | 40.84 | 25.26 | 9.35 | 37.03 | 24 |
| 4 | T-4 | 12.04 | 51.79 | 40.39 | 28.35 | 11.40 | 40.21 | 28 |
| 5 | 4-5 | 17.27 | 52.09 | 43.56 | 26.29 | 8.53 | 32.44 | 32 |



From graph, for 25 blows: LL = 38%.

Plastic Limit (PL)

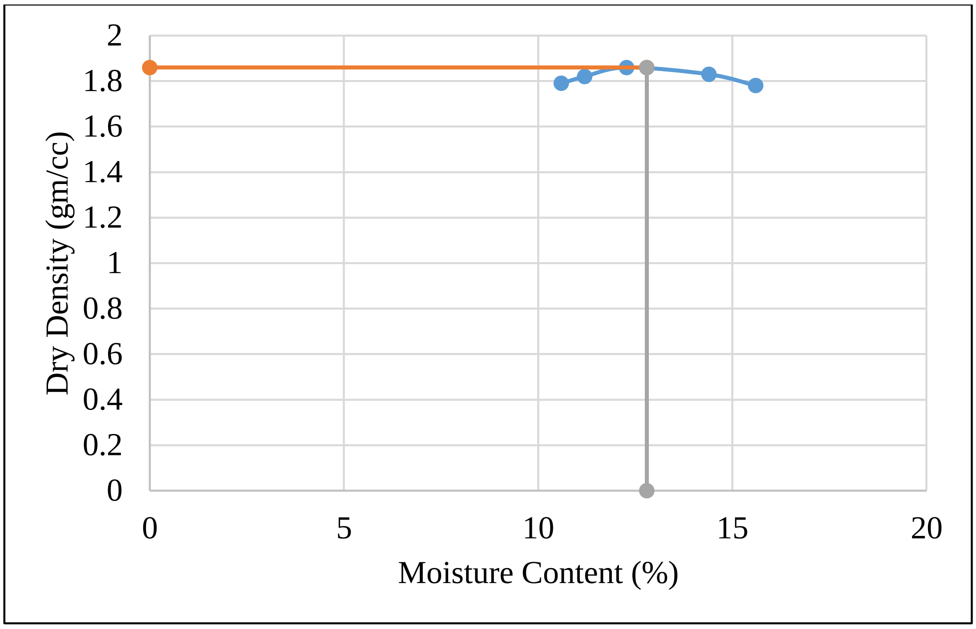
| No | Can | Wt of can, WC (gm) | Wt of can + wet sample, Wc+Ww+Ws (gm) | Wt of can+dry soil, Wc+Ws (gm) | Wt of dry soil, Ws (gm) | Wt of water, Ww (gm) | Moisture content, W(%) | Average Plastic Limit, PL |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 27.2 | 47.1 | 42.87 | 15.7 | 4.2 | 26.61 | 24.10 |
| 2 | 4-3 | 23.9 | 39.5 | 36.43 | 12.5 | 3.2 | 25.52 | |
| 3 | S-4 | 23.6 | 39.9 | 37.17 | 13.6 | 2.7 | 20.17 | |

**Test Name: Modified Proctor Compaction test.**

**For, Sample – 1**

Mold dia: 4’’, Mold volume: 944 cm$^3$, Method A: 5 layers and 25 blows.

| No | Can | Wt of can, Wc (gm) | Wt of can + wet sample, Wc+ Ww+ Ws (gm) | Wt of can+ dry soil, Wc+ Ws (gm) | Wt of dry soil, Ws (gm) | Wt of water, Ww (gm) | Moisture content, W(%) | Wt of mold, gm | Wt of mold+compacted soil, W gm | Wt of compacted soil | Wet density | Dry density |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 17.3 | 51.4 | 48.6 | 31.3 | 2.5 | 7.96 | 4357 | 5953 | 1595 | 1.7 | 1.5 |
|  | 2 | 16.4 | 50.6 | 48.1 | 31.7 | 2.6 |  |  |  |  |  |  |
| 2 | 3 | 16.7 | 53.3 | 50.2 | 33.5 | 3.1 | 8.86 | 4357 | 6031 | 1673 | 1.8 | 1.6 |
|  | 4 | 23.1 | 66.2 | 62.8 | 39.7 | 3.4 |  |  |  |  |  |  |
| 3 | 5 | 23.6 | 77.4 | 72.01 | 48.4 | 5.4 | 11.2 | 4357 | 6096 | 1738 | 1.8 | 1.7 |
|  | 6 | 21.5 | 79.8 | 73.9 | 52.4 | 5.9 |  |  |  |  |  |  |
| 4 | 7 | 16 | 77.8 | 70.9 | 54.9 | 6.9 | 12.83 | 4357 | 6163 | 1805 | 1.9 | 1.7 |
|  | 8 | 15.4 | 67.9 | 61.8 | 46.4 | 6.1 |  |  |  |  |  |  |
| 5 | 9 | 19.5 | 77.5 | 69.8 | 50.3 | 7.5 | 15.68 | 4357 | 6234 | 1877 | 1.9 | 1.8 |
|  | 10 | 15 | 92.2 | 81.7 | 66.7 | 10 |  |  |  |  |  |  |
| 6 | 11 | 18 | 82.1 | 71.5 | 52.6 | 11 | 19.33 | 4357 | 6099 | 1741 | 1.7 | 1.5 |
|  | 12 | 23.6 | 107.3 | 94.1 | 70.5 | 13 |  |  |  |  |  |  |

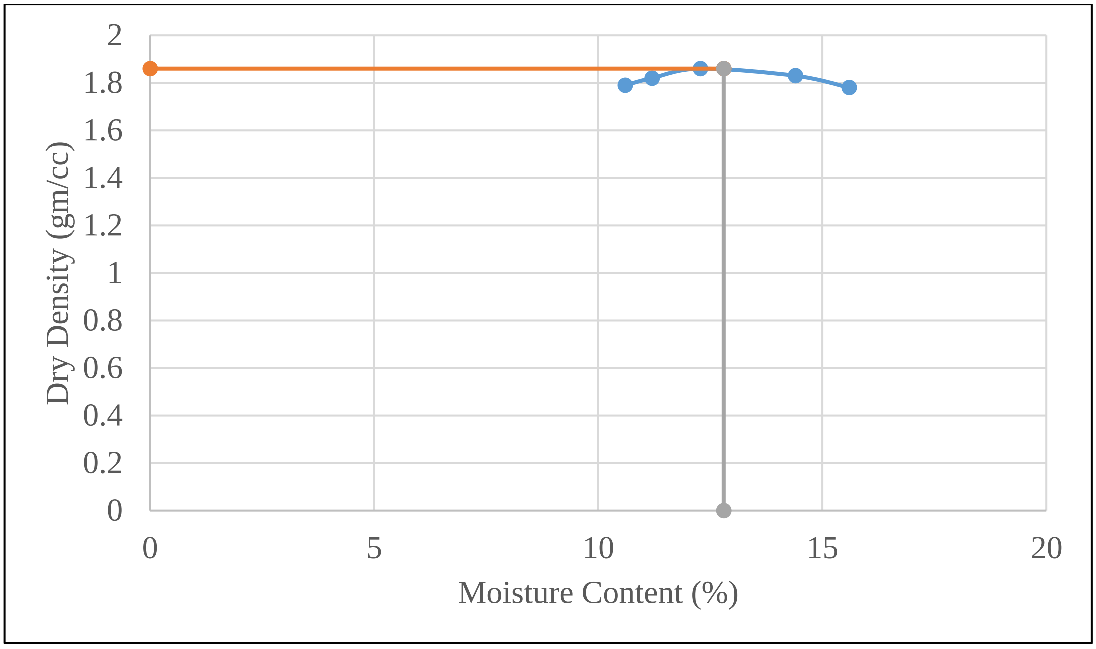


From graph, MDD: 1.751 gm/cm$^3$ and OMC: 17%.

**For, Sample – 2**

Mold dia: 4'', Mold volume: 944 $cm^3$ , Method A: 5 layers and 25 blows.

| **No** | **Can** | **Wt of can, Wc (gm)** | **Wt of can + wet sample, Wc+Ww+Ws (gm)** | **Wt of can+ dry soil, Wc+ Ws (gm)** | **Wt of dry soil, Ws (gm)** | **Wt of water, Ww (gm)** | **Moisture content, W(%)** | **Wt of mold, gm** | **Wt of mold +compacted soil, W gm** | **Wt of compacted soil** | **Wet density** | **Dry density** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 11 | 31.5 | 188.3 | 172.8 | 141.3 | 15.5 | 11 | 3096 | 4887 | 1791 | 1.89 | 1.71 |
| 2 | 12 | 28.8 | 144.9 | 131.6 | 102.8 | 13.3 | 12.9 | 3096 | 4997 | 1901 | 2.01 | 1.78 |
| 3 | 54 | 27.1 | 166 | 147.7 | 120.6 | 18.3 | 15.2 | 3096 | 5097 | 2001 | 2.12 | 1.84 |
| 4 | 7 | 31.3 | 175.8 | 154.7 | 123.4 | 21.1 | 17.1 | 3096 | 5095 | 1999 | 2.13 | 1.81 |
| 5 | 55 | 31.3 | 188.4 | 163.4 | 132.1 | 25 | 18.9 | 3096 | 5046 | 1950 | 2.1 | 1.74 |

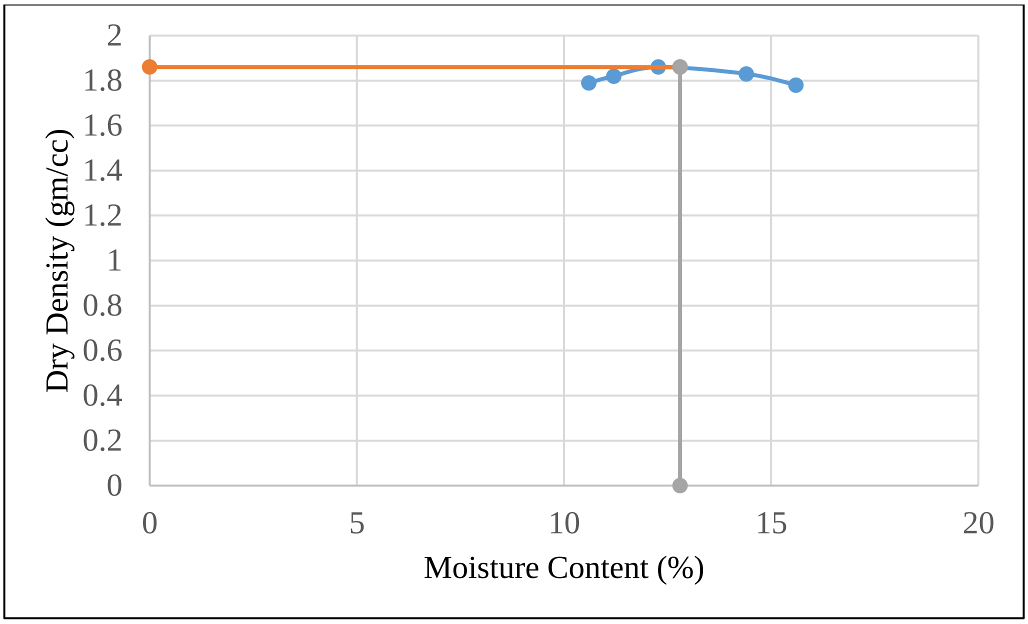


From graph, MDD: 1.842 gm/cm$^3$ and OMC: 15.4%.

**For, Sample – 3**

Mold dia: 4’’, Mold volume: 944 $cm^3$ , Method A: 5 layers and 25 blows.

| No | Can | Wt of can, Wc (gm) | Wt of can + wet sample, Wc+Ww+Ws (gm) | Wt of can+ dry soil, Wc+ Ws (gm) | Wt of dry soil, Ws (gm) | Wt of water, Ww (gm) | Moisture content, W(%) | Wt of mold, gm | Wt of mold +compacted soil, W gm | Wt of compacted soil | Wet density | Dry density |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | viii | 15.1 | 88.8 | 81.8 | 66.7 | 7.07 | 10.6 | 4358 | 6227 | 1869 | 1.98 | 1.79 |
| 2 | T-6 | 16.4 | 74.6 | 68.7 | 52.4 | 5.87 | 11.2 | 4358 | 6271 | 1912 | 2.03 | 1.82 |
| 3 | iii | 16.5 | 69.9 | 63.2 | 46.7 | 5.73 | 12.3 | 4358 | 6323 | 1965 | 2.08 | 1.86 |
| 4 | 5 | 17.8 | 75.3 | 68.1 | 50.3 | 7.24 | 14.4 | 4358 | 6329 | 1971 | 2.09 | 1.83 |
| 5 | S-6 | 22.6 | 68.6 | 62.3 | 39.7 | 6.19 | 15.6 | 4358 | 6302 | 1943 | 2.06 | 1.78 |



From graph, MDD: 1.867 gm/cm$^3$ and OMC: 12.9%.

**Test Name: California Bearing Ratio Test**

**For, Sample – 1**

MDD: 1.751 gm/ cc, OMC: 17%, Soaking period: 96 hours & Volume of Mould: 2123 $cm^3$

| No Of Blows | Mould No | Wt of mould +base plate, M1 gm | Wt of mould+compacted soil, M2 gm | Wt of compacted soil, W3 gm | Wet density, Dw | Container no | Wt of can, Wc gm | Wt of can+soil, Ww+ Wc+ Ws gm | Wt of can+ dry soil, Wc+ Ws gm | Moisture Content % | Dry Density |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 | 1 | 6300 | 10368 | 4068 | 1.916 | 6 | 15.7 | 118.24 | 102.58 | 17.6 | 101.67 |
| 25 | 2 | 6650 | 10950 | 4300 | 2.025 | 554 | 15.6 | 126.81 | 109.91 | 17.9 | 107.17 |
| 56 | 3 | 5800 | 10156 | 4356 | 2.052 | BH-1 | 16.5 | 121.49 | 106.02 | 17.3 | 109.16 |

| No of Blows | | 10 | | | 25 | | | 56 | |
|---|---|---|---|---|---|---|---|---|---|
| Mould | | 1 | | | 2 | | | 3 | |
| Penetration (mm) | Gauge Reading x | Load kn | Corrected load, kn | Gauge Reading x | Load kn | Corrected load, kn | Gauge Reading x | Load kn | Corrected load, kn |
| 0.64 | 5 | 0.43 | | 4 | 0.37 | | 5 | 0.43 | |
| 1.27 | 7 | 0.54 | | 9 | 0.67 | | 8 | 0.60 | |
| 1.91 | 9 | 0.66 | | 11 | 0.77 | | 10 | 0.72 | |
| 2.54 | 11 | 0.77 | 0.77 | 12 | 0.83 | 1 | 11 | 0.77 | 1.2 |
| 3.18 | 13 | 0.89 | | 15 | 1.00 | | 13 | 0.89 | |
| 3.81 | 15 | 1.00 | | 18 | 1.18 | | 15 | 1.00 | |
| 4.45 | 18 | 1.17 | | 20 | 1.29 | | 17 | 1.12 | |
| 5.08 | 24 | 1.53 | 1.53 | 24 | 1.53 | 1.60 | 19 | 1.24 | 1.80 |
| 7.62 | 29 | 1.82 | | 27 | 1.70 | | 25 | 1.58 | |

For, 10 blows;

CBR @ 2.54 mm = (.77/13.44) X 100 = 5.73%

CBR @ 5.08 mm = (1.53/20.06) X 100 = 7.63%

For, 25 blows;

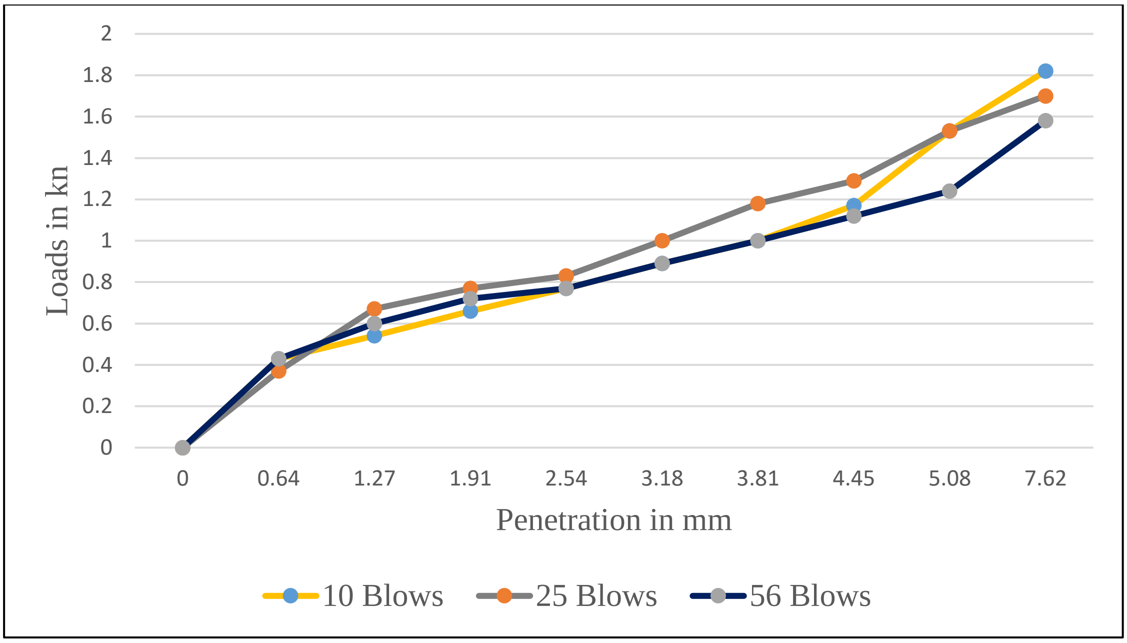
CBR @ 2.54 mm = (1/13.44) X 100 = 7.44%

CBR @ 5.08 mm = (1.60/20.06) X 100 = 7.98%

For, 56 blows;

CBR @ 2.54 mm = (1.20/13.44) X 100 = 8.93%

CBR @ 5.08 mm = (1.80/20.06) X 100 = 8.97%



From graph, CBR = 7.75%

**For, Sample – 2**

MDD: 1.842 gm/ cc, OMC: 15.4%, Soaking period: 96 hours & Volume of Mould: 2123 cm$^3$

| No Of Blows | Mould No | Wt of mould +base plate, M1 gm | Wt of mould+compacted soil, M2 gm | Wt of compacted soil, W3 gm | Wet density, Dw | Container no | Wt of can , Wc gm | Wt of can+soil, Ww+Wc+Ws gm | Wt of can+dry soil, Wc+Ws gm | Moisture Content % | Dry Density |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 | 1 | 6300 | 10316 | 4010 | 1.889 | 2 | 27.8 | 141.95 | 127.75 | 14.2 | 103.21 |
| 25 | 2 | 6650 | 10898 | 4248 | 2.001 | 3 | 36.6 | 152.43 | 136.63 | 15.8 | 107.83 |
| 56 | 3 | 5800 | 10324 | 4524 | 2.130 | 4 | 28.9 | 144.65 | 128.95 | 15.7 | 114.94 |

| No of Blows | 10 | | | 25 | | | 56 | | |
|---|---|---|---|---|---|---|---|---|---|
| Mould | 1 | | | 2 | | | 3 | | |
| Penetration (mm) | Gauge Reading x | Load kn | Corrected load, kn | Gauge Reading x | Load kn | Corrected load, kn | Gauge Reading x | Load kn | Corrected load, kn |
| 0.64 | 4 | 0.37 | | 3 | 0.31 | | 6 | 0.48 | |
| 1.27 | 7 | 0.54 | | 8 | 0.60 | | 11 | 0.77 | |
| 1.91 | 10 | 0.72 | | 12 | 0.83 | | 15 | 1.00 | |
| 2.54 | 13 | 0.89 | 0.93 | 15 | 1.00 | 1.06 | 17 | 1.12 | 1.17 |
| 3.18 | 15 | 1.00 | | 17 | 1.12 | | 19 | 1.24 | |
| 3.81 | 18 | 1.18 | | 20 | 1.29 | | 23 | 1.47 | |
| 4.45 | 21 | 1.35 | | 23 | 1.47 | | 25 | 1.58 | |
| 5.08 | 24 | 1.53 | 1.69 | 25 | 1.58 | 1.73 | 27 | 1.70 | 1.79 |
| 7.62 | 26 | 1.64 | | 27 | 1.70 | | 29 | 1.82 | |

For, 10 blows;

CBR @ 2.54 mm = (0.93/13.44) X 100 = 6.93%

CBR @ 5.08 mm = (1.69/20.06) X 100 = 8.43%

For, 25 blows;

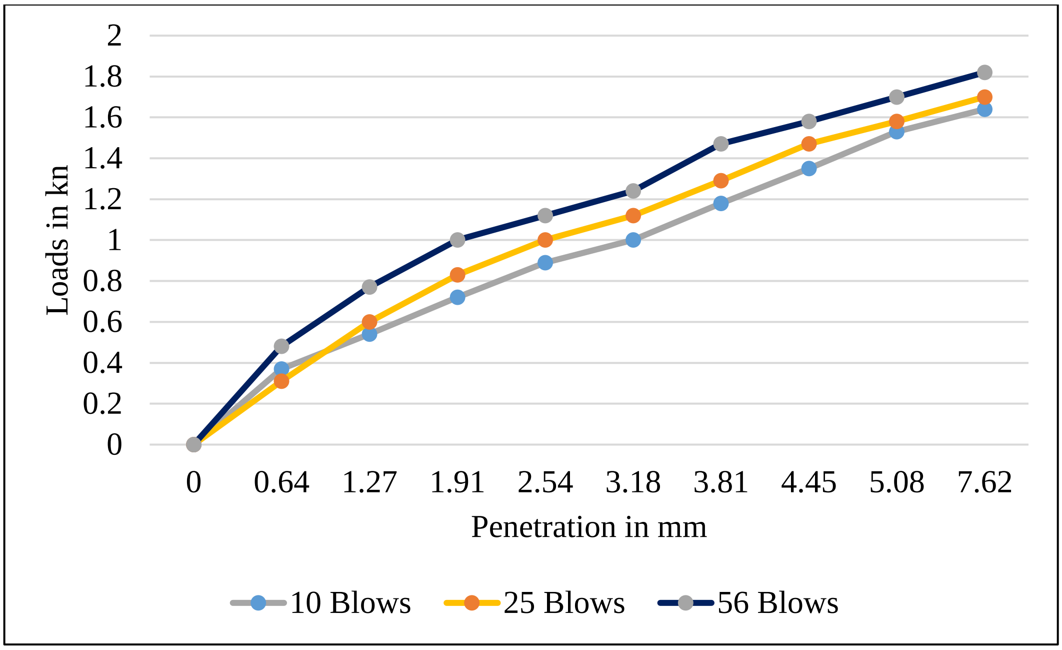
CBR @ 2.54 mm = (1.06/13.44) X 100 = 7.92%

CBR @ 5.08 mm = (1.73/20.06) X 100 = 8.61%

For, 56 blows;

CBR @ 2.54 mm = (1.17/13.44) X 100 = 8.69%

CBR @ 5.08 mm = (1.79/20.06) X 100 = 8.94%



From graph, CBR = 8.65%

**For, Sample – 3**

MDD: 1.867 gm/ cc, OMC: 12.9%, Soaking period: 96 hours & Volume of Mould: 2123 cm$^3$

| No Of Blows | Mould No | Wt of mould +base plate, M1 gm | Wt of mould+compacted soil, M2 gm | Wt of compacted soil, W3 gm | Wet density, Dw | Container no | Wt of can, Wc gm | Wt of can+soil, Ww+ Wc+ Ws gm | Wt of can+ dry soil, Wc+ Ws gm | Moisture Content % | Dry Density |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 | 1 | 6300 | 10270 | 3970 | 1.870 | viii | 15.1 | 128.20 | 115.10 | 13.1 | 103.15 |
| 25 | 2 | 6650 | 11219 | 4569 | 2.152 | T-6 | 16.4 | 129.76 | 116.36 | 13.4 | 118.44 |
| 56 | 3 | 5800 | 10836 | 5036 | 2.372 | iii | 16.5 | 129.31 | 116.51 | 12.8 | 131.23 |

| No of Blows | 10 | | | 25 | | | 56 | | |
|---|---|---|---|---|---|---|---|---|---|
| Mould | 1 | | | 2 | | | 3 | | |
| Penetration (mm) | Gauge Reading x | Load kn | Corrected load, kn | Gauge Reading x | Load kn | Corrected load, kn | Gauge Reading x | Load kn | Corrected load, kn |
| 0.64 | 3 | 0.31 | | 7 | 0.54 | | 9 | 0.66 | |
| 1.27 | 8 | 0.60 | | 11 | 0.77 | | 11 | 0.77 | |
| 1.91 | 12 | 0.83 | | 15 | 1.00 | | 15 | 1.06 | |
| 2.54 | 14 | 0.95 | 1.01 | 17 | 1.12 | 1.13 | 18 | 1.18 | 1.21 |
| 3.18 | 17 | 1.12 | | 20 | 1.29 | | 20 | 1.29 | |
| 3.81 | 19 | 1.24 | | 25 | 1.58 | | 23 | 1.47 | |
| 4.45 | 24 | 1.53 | | 27 | 1.70 | | 28 | 1.76 | |
| 5.08 | 26 | 1.64 | 1.68 | 29 | 1.82 | 1.83 | 30 | 1.87 | 1.89 |
| 7.62 | 31 | 1.93 | | 34 | 2.11 | | 36 | 2.22 | |

For, 10 blows;

CBR @ 2.54 mm = (1.01/13.44) X 100 = 7.53%

CBR @ 5.08 mm = (1.68/20.06) X 100 = 8.36%

For, 25 blows;

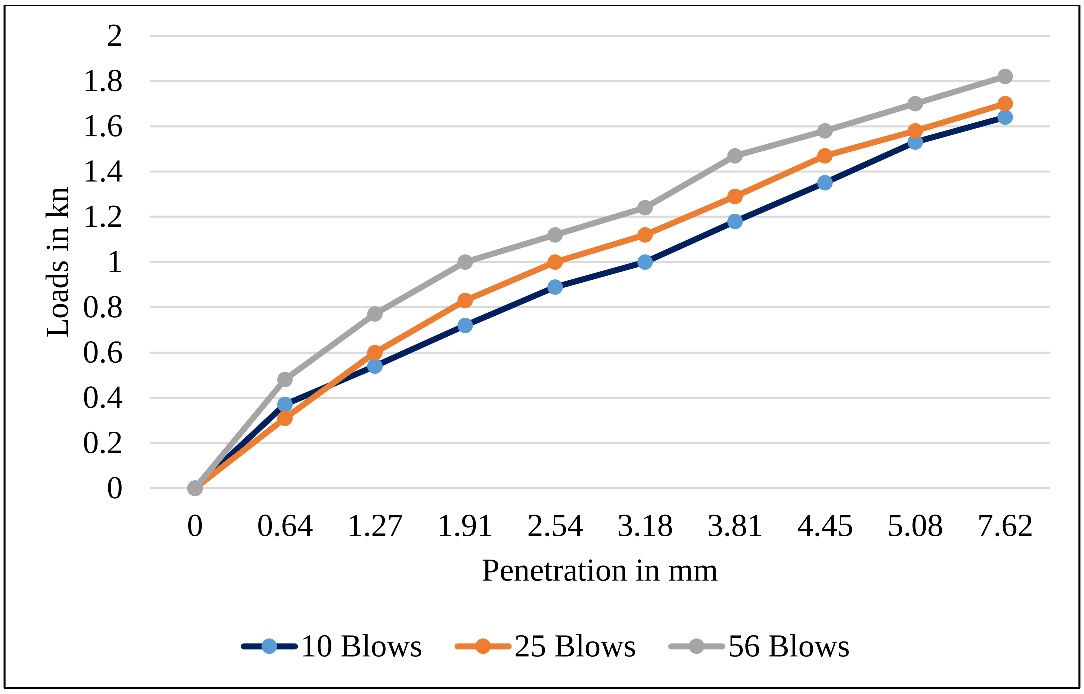
CBR @ 2.54 mm = (1.13/13.44) X 100 = 8.44%

CBR @ 5.08 mm = (1.83/20.06) X 100 = 9.14%

For, 56 blows;

CBR @ 2.54 mm = (1.21/13.44) X 100 = 8.96%

CBR @ 5.08 mm = (1.89/20.06) X 100 = 9.43%



From graph, CBR = 8.70%

# APPENDIX- C

American Association of State Highway and Transportation Officials Chart:

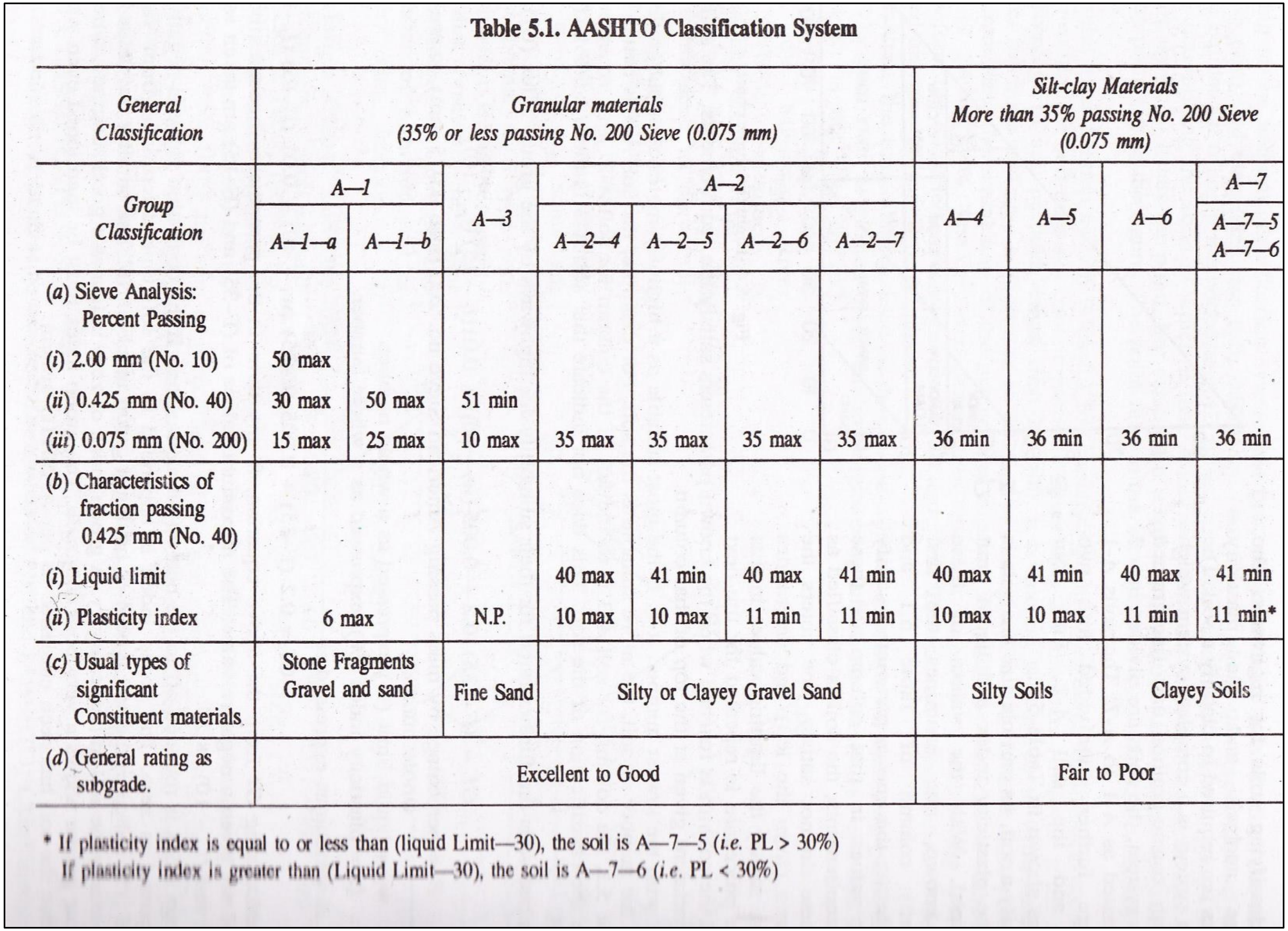
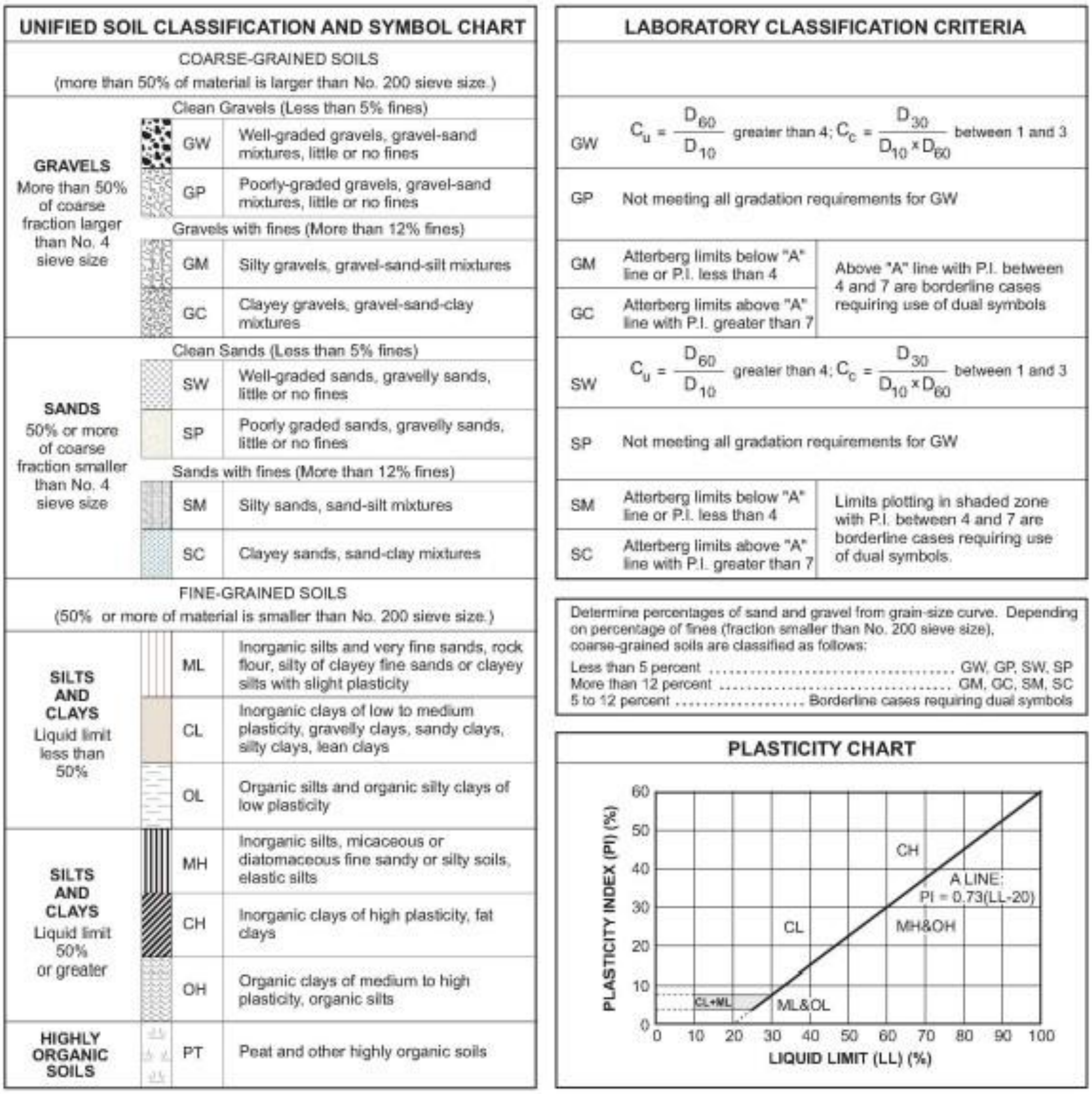


**Table 5.1. AASHTO Classification System**

| *General Classification* | *Granular materials (35% or less passing No. 200 Sieve (0.075 mm)* | | | | | | | *Silt-clay Materials More than 35% passing No. 200 Sieve (0.075 mm)* | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Group Classification* | *A—1* | | *A—3* | *A—2* | | | | *A—4* | *A—5* | *A—6* | *A—7* |
| | *A—1—a* | *A—1—b* | | *A—2—4* | *A—2—5* | *A—2—6* | *A—2—7* | | | | *A—7—5*<br>*A—7—6* |
| (*a*) Sieve Analysis: Percent Passing | | | | | | | | | | | |
| (*i*) 2.00 mm (No. 10) | 50 max | | | | | | | | | | |
| (*ii*) 0.425 mm (No. 40) | 30 max | 50 max | 51 min | | | | | | | | |
| (*iii*) 0.075 mm (No. 200) | 15 max | 25 max | 10 max | 35 max | 35 max | 35 max | 35 max | 36 min | 36 min | 36 min | 36 min |
| (*b*) Characteristics of fraction passing 0.425 mm (No. 40) | | | | | | | | | | | |
| (*i*) Liquid limit | | | | 40 max | 41 min | 40 max | 41 min | 40 max | 41 min | 40 max | 41 min |
| (*ii*) Plasticity index | 6 max | | N.P. | 10 max | 10 max | 11 min | 11 min | 10 max | 10 max | 11 min | 11 min* |
| (*c*) Usual types of significant Constituent materials | Stone Fragments Gravel and sand | | Fine Sand | Silty or Clayey Gravel Sand | | | | Silty Soils | | Clayey Soils | |
| (*d*) General rating as subgrade. | Excellent to Good | | | | | | | Fair to Poor | | | |

* If plasticity index is equal to or less than (liquid Limit—30), the soil is A—7—5 (*i.e.* PL > 30%)
If plasticity index is greater than (Liquid Limit—30), the soil is A—7—6 (*i.e.* PL < 30%)

Unified Soil Classification System Chart:



### UNIFIED SOIL CLASSIFICATION AND SYMBOL CHART

| | | |
|---|---|---|
| COARSE-GRAINED SOILS<br>(more than 50% of material is larger than No. 200 sieve size.) | | |
| **GRAVELS**<br>More than 50% of coarse fraction larger than No. 4 sieve size | Clean Gravels (Less than 5% fines) | |
| | GW | Well-graded gravels, gravel-sand mixtures, little or no fines |
| | GP | Poorly-graded gravels, gravel-sand mixtures, little or no fines |
| | Gravels with fines (More than 12% fines) | |
| | GM | Silty gravels, gravel-sand-silt mixtures |
| | GC | Clayey gravels, gravel-sand-clay mixtures |
| **SANDS**<br>50% or more of coarse fraction smaller than No. 4 sieve size | Clean Sands (Less than 5% fines) | |
| | SW | Well-graded sands, gravelly sands, little or no fines |
| | SP | Poorly graded sands, gravelly sands, little or no fines |
| | Sands with fines (More than 12% fines) | |
| | SM | Silty sands, sand-silt mixtures |
| | SC | Clayey sands, sand-clay mixtures |
| FINE-GRAINED SOILS<br>(50% or more of material is smaller than No. 200 sieve size.) | | |
| **SILTS AND CLAYS**<br>Liquid limit less than 50% | ML | Inorganic silts and very fine sands, rock flour, silty of clayey fine sands or clayey silts with slight plasticity |
| | CL | Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays |
| | OL | Organic silts and organic silty clays of low plasticity |
| **SILTS AND CLAYS**<br>Liquid limit 50% or greater | MH | Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts |
| | CH | Inorganic clays of high plasticity, fat clays |
| | OH | Organic clays of medium to high plasticity, organic silts |
| **HIGHLY ORGANIC SOILS** | PT | Peat and other highly organic soils |

### LABORATORY CLASSIFICATION CRITERIA

| | | |
|---|---|---|
| GW | $C_u = \frac{D_{60}}{D_{10}}$ greater than 4; $C_c = \frac{D_{30}}{D_{10} \times D_{60}}$ between 1 and 3 | |
| GP | Not meeting all gradation requirements for GW | |
| GM | Atterberg limits below "A" line or P.I. less than 4 | Above "A" line with P.I. between 4 and 7 are borderline cases requiring use of dual symbols |
| GC | Atterberg limits above "A" line with P.I. greater than 7 | |
| SW | $C_u = \frac{D_{60}}{D_{10}}$ greater than 4; $C_c = \frac{D_{30}}{D_{10} \times D_{60}}$ between 1 and 3 | |
| SP | Not meeting all gradation requirements for GW | |
| SM | Atterberg limits below "A" line or P.I. less than 4 | Limits plotting in shaded zone with P.I. between 4 and 7 are borderline cases requiring use of dual symbols. |
| SC | Atterberg limits above "A" line with P.I. greater than 7 | |

Determine percentages of sand and gravel from grain-size curve. Depending on percentage of fines (fraction smaller than No. 200 sieve size), coarse-grained soils are classified as follows:

Less than 5 percent ...................................... GW, GP, SW, SP
More than 12 percent .................................... GM, GC, SM, SC
5 to 12 percent .................... Borderline cases requiring dual symbols

### PLASTICITY CHART