Sustainable and Environment-Friendly Utilization of Sludge and Eggshell in Soil Subgrade Stabilization

By

Aqsa Nisar

00000363906

Institute of Environmental Sciences and Engineering
School of Civil and Environmental Engineering
National University of Sciences and Technology
Sector H-12, Islamabad, Pakistan

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Submitted By

Aqsa Nisar

Registration Number 00000363906

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School of Civil and Environmental Engineering
National University of Sciences and Technology
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APPROVAL CERTIFICATE

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"Sustainable and Environment-Friendly Utilization of Sludge and Eggshell in Soil Subgrade Stabilization"

Submitted by

Mrs. Aqsa Nisar

has been found sufficient for the Masters of Science in Environmental Engineering requirement.

Supervisor: …………………………….
Dr. Muhammad Ali Inam
Assistant Professor
IESE, SCEE, NUST

Member: …………………………….
Dr. Musharib Khan
Assistant Professor
IESE, SCEE, NUST

Member: …………………………..
Dr. Zeshan
Associate Professor
IESE, SCEE, NUST

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Dr. Muhammad Ali Inam

Assistant Professor

Dated: ____________________

Head of Department: ________________

Date: ________________

Dean / Principal: ________________

Date: ________________

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Aqsa Nisar
00000363906

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To My Beloved Parents,

My Wonderful Husband

And Respectful Teachers

For their endless love, support, and encouragement

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I want to thank the academic staff at the IESE for their assistance and support throughout my postgraduate studies. I would like to thank Dr. Adnan Shah, for his continuous support and guidance throughout this tenure. Finally, I would want to express my deep appreciation and respect to my parents, husband, siblings, friends, and teachers for their support, as well as their prayers and well wishes for the successful completion of my research work.

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ABSTRACT

Subgrade stabilization of soil is an essential component for the construction of highways and pavements. However, significant quantity of soil stabilizers such as cement or sand or heavy rollers have been previously used to improve the strength of the soil. The utilization of traditional soil stabilization techniques may raise environmental concerns as well as require extensive resources. This abundant utilization of resources can be reduced by considering geotechnical management through efficient soil stabilization. Therefore, current research focuses on the effectiveness of eco-friendly additives (sludge and eggshell powder) at different percentages i.e., 2%, 4%, and 6%, by weight of clayey soil for subgrade stabilization. The soil sample was collected from Nandipur, Punjab, Pakistan. The results indicated that the maximum strength (California bearing ratio and unconfined compressive strength) of soil was achieved when 4% by weight of soil modifier was added. For the same weight percent of modifiers, the soil type changed from clayey (A-7-6) to silty soil (A-4) which is graded as poor to the fair category in the AASHTO classification system. Moreover, the group index of soil also decreased from 34 to 12, which means relatively less thick subgrade will be required hence, less compaction effort will be needed. Moreover, Artificial Neural Network was used to develop correlation between California bearing ratio (10, 30 and 56 blows) and other soil parameters for better prediction of soil properties after the addition of modifiers. Current study also evaluates the economic and environmental benefits of soil modifiers which resulted in reduction of approximately 17.42 million PKR and 71,282 Kg carbon dioxide emissions for two lane highway pavement with dimensions (500m x12m x 0.2m) and 1649.9 Kg/m^3 dry density of soil. This research will help develop sustainable, eco-friendly infrastructure and promote energy-efficient construction.

1. INTRODUCTION

Subgrade stabilization is one of the initial steps prior to any construction. The initial phase of any construction, particularly the road is the stabilization of the foremost layer of road known as subgrade. The soil stabilization is related to factors like durability and strength of soil Those affect the performance of subgrade. These factors are the quantitative values which are known as load bearing value, compressive and shear strength values. The better the bearing capacity of the soil is the more the soil is stabilized. When it comes to transportation engineering the stabilization for the subgrade focuses on low-cost compaction and materials without compromising the strength of soil. In some areas soil already has a good bearing capacity or good strength due to which very minimum efforts are required and, in some cases, only compaction can be enough but the places where the soil is weak stabilization needs a lot of effort and modifiers to improve its strength. Generally, the modifiers are the methods that are easily available by the site are considered but, in some cases, when the soil is very weak engineers need to opt for other materials or compaction methods which may not be economically friendly. Various soil modifiers like cement, lime, sand, rice husk ash, crushed aggregate, sludge, and molasses have been studied by the researchers and being used in several projects. Amongst these cement, lime, and sand I consider to be the traditional soil modifiers, but their production or extraction have always been our limitation due to environmental side effects of these. The stabilization of soil Maybe done chemically, biologically or by physical methods that depends upon the nature of the soil and the severity to improve its certain properties for engineering purposes. In case of subgrade the most go to methods are mechanical, cement, bitumen, and lime stabilization. In mechanical stabilization soil aggregate mixture is graded and is the only factor upon which the stability depends. This is also known as granular stabilization. Proportioning the soil aggregate mix followed by the compaction is the key principle of this stabilization. If the soil is merely clayey the addition of granular material having negligible fine particles improves its stability and enhances its strength. So, a proper proportion of granular materials when added to soil can improve its strength. But if the soil is already granular or it contains proportions of clay, salt, and sand and still possesses weak soil qualities the granular stabilization is no longer the solution instead other methods are opted. Cement stabilization is one of these methods that has been successful to stabilize granular soils where, cement sand motor or the cement soil mortar is prepared simply by adding cement to the soil followed by proper mixing and adequate moisture content. Other than cement lime is also used as it possesses pozzolanic properties, but it is only a factor for clay as clear consists of amorphous compounds and minerals why sand or other granular soil types do not. Bitumen is generally considered as a stabilizer when the water table is high, or the moisture content is more as bitumen is relatively waterproof making the subgrade layer retain its strength even in the presence of water. Moreover, bituminous material acts as a filler as well for the voids in the soil which again helps soil to protect from direct contact with water. The soil types including sand and gravel need a very small amount of bitumen material for its binding. In addition to these traditional methods researchers have been working on other materials that can be replaced while maintaining the strength of the soil. In today's world of sustainable construction researchers have been working on finding materials that are suitable for the environment. Several waste materials that were being dumped without being recycled or reused have been considered by the engineers for replacing several construction materials especially cement sand and aggregate. The main reason for replacing these materials has been the harmful environmental impacts on production or extraction of these on environment. Sludge and eggshell powder are the two waste materials studied in this research. In developing or underdeveloped countries, the disposal of waste material is a big issue and a matter of environmental concern. The production of sewage sludge is directly related to the increasing population in these countries whereas no proper disposal or treatment plants are available and, in this case, if these materials could be reused it will be a relief for environment as well. Similarly, eggs are the most commonly consumed food and the increase in population leads to an increased egg consumption. The more eggs are produced more eggshells are generated but their disposal is limited to agricultural uses which still leaves a huge amount of eggshell that do not have any proper treatment or disposal. Utilization of such materials in construction if they are capable enough of increasing the strength and replacing the traditional methods which apparently were not economically or environmentally much feasible will be a good lead to sustainable construction. So, Sludge and Eggshell powder are the two waste materials used in this research to find out if they could be a replacement option to other stabilizers.

This study focuses on the economical soil stabilization using eco-friendly stabilizers for the pre-construction improvement of soil properties. The basic indicators like Atterberg's limit, California bearing ratio, and Unconfined Strength have been studied. Furthermore, considering an example of the motorway project section, the cost saving of fuel consumption has also been evaluated which will be an additional benefit to soil strength improvement and economical road construction. Therefore, the objectives are concluded as.

- Evaluation of municipal sludge and eggshell powder on soil subgrade stabilization.
- Assessment of physical and mechanical properties of soil after addition of modifier.
- Economic assessment and evaluation of environmental impact by replacing sewerage sludge and eggshells in soil subgrade

2. LITERATURE REVIEW

During the construction of road projects, soil stabilization is a process that consumes a lot of resources to be able to be utilized as a subgrade (Tizpa, Chenari et al. 2015, Alazigha, Indraratna et al. 2016, Soltani, Deng et al. 2017, Phummiphan, Horpibulsuk et al. 2018, Rajeswari, Naidu et al. 2018). Sometimes soil has a week bearing capacity and CBR values are an indicator for measurement of soil strength. Initial testing of soil provides details about the planning and designing of road projects (Aamir, Mahmood et al. 2019). These testing and calculation finally have an impact on cost planning and management of the projects. The link between the technical profile of existing soil and designing of future roads some time influence on project cost. The worldwide cost of different projects increased only because of that stabilization process and requirements (Aamir, Mahmood et al. 2019). So, the nature of the soil is important to be studied before design a road. Different countries have a major land with weak soil properties and require improvement during any construction project (Saberian and Rahgozar 2016, Jahandari, Toufigh et al. 2018). In developing countries due to varying soil conditions, high plastic clayey soil exists in abundance. Construction of highway or road design on such soil is a tough job. For any treatment done to stabilize soil ASTM D4609-08 (Testing, Soil et al. 2008),(Standard that helps to determine the effectiveness of admixture added for soil stabilization) is used. According to the standard and increase in unconfined compressive strength 345kpa (50 Psi) or more is to be achieved to say that an additive is an effective stabilizer. In addition to it, if the CBR of soil is increased to 10% or more, the additive is again beneficial for enhancing soil physical properties. In geotechnical engineering stabilization of soil is the first step for the construction of any structure. The stabilization is being done over the years by different methods, either by adding any materials to soil or by mechanical means which are selected based on depth. Some of the methods include preloading, removal and replacement of the weak soil layer, piles, stone columns, by compaction in rolling and introduction of several additives to the soil. The additives generally used are, cement, lime, gypsum, fly ash, nano chemicals, pond ash, blast furnace slag, waste tyre chips and powders (Lacuoture and Gonzalez 1995, Muntohar 2004, Basha, Hashim et al. 2005, Lin, Lin et al. 2007, Al-Malack, Abdullah et al. 2016, Kollaros and Athanasopoulou 2016, Yadav, Gaurav et al. 2017, Rajeswari, Naidu et al. 2018, Soltani, Deng et al. 2018). Physical properties of soil like cohesion, stability, durability, dry density unconfined compressive strength, California bearing ratio etc., are enhanced by these additions. There is a wide discussion on all these additives and the respective physical properties they improve on addition(Khabiri 2010, Wong, Hashim et al. 2013, Cong, Longzhu et al. 2014, Chemeda, Deneele et al. 2015, Rahgozar and Saberian 2015, Esaifan, Khoury et al. 2016, Esmaeili and Khajehei 2016, Rahgozar and Saberian 2016, Cheshomi, Eshaghi et al. 2017, Jahandari, Li et al. 2017, Saberian, Jahandari et al. 2017, Jahandari, Toufigh et al. 2018, Saberian and Khabiri 2018, Saberian, Mehrinejad Khotbehsara et al. 2018, Jahandari, Saberian et al. 2019). The methods described above can be costly while some of them might not be eco-friendly either in term of its addition to soil or its production (Saberian and Rahgozar 2016, Saberian and Khabiri 2018). As the population is increasing the need for urbanization has also increased due to which the production of chemicals especially cement is surging considerably and due to artificial manufacturing of additive including cement, certain harmful gasses, and other wastes are increasing. This is a serious environmental threat especially due to an increase in CO_2 emission that is also one of the major causes of global warming(Cao, Shen et al. 2016, Jahandari, Saberian et al. 2019). Some developed countries including Poland have taken step towards the eco-friendly stabilization of soil using waste material that is being dumped in certain ways, one such additive is RHA(Van Ruijven, Van Vuuren et al. 2016). According to research in(Shiravan 2014, Kwofie, Ngadi et al. 2017), it is briefed that CO_2 emissions of about 1 t/t are produced while cement is manufactured, on the other hand, RHA production emits 0.8 g/kg of CO2. Still, other additives are there which do not emit any carbon dioxide during their manufacture, for example, alum sludge, the additive used in this paper.

This study focuses on the economical soil stabilization using eco-friendly stabilizers for the pre-construction improvement of soil properties. The basics indicators like Atterberg's limit, California bearing ratio, and Unconfined Strength have been studied. Furthermore, considering an example of the motorway project section, the cost saving of fuel consumption has also been evaluated which will be an additional benefit to soil strength improvement and economical road construction.

2.1. SOIL STABILIZATION AND RESOURCE CONSUMPTION IN ROAD CONSTRUCTION

The soft grounds or clayey soils have always been a challenge for construction because of foundation problems (Mohamad, Razali et al. 2016). Generally soft grounds are avoided by engineers when selecting sites for construction. But because of rapid urbanization and increasing population the soft grounds can no more be neglected for construction purpose. It was reported by Department of Quaternary Geological Map of Malaysia in 2010, that along coastal plain maximum of area comprises of soft soil considered as organic or peat soil (Kaniraj and Joseph 2006). Similarly in Pakistan, Nandipur Punjab, an area situated in Province Punjab has a lot of clayey soil (Aamir, Mahmood et al. 2019).

Currently, the improvisation of ground is being carried out by several different methods. These method include replacement of problematic soil after excavating it, compacting soil for its densification also known as mechanical modification, reduction of water table also termed as dewatering or hydraulic modification, stabilization of soil with addition of some admixtures, electro-osmosis i.e. electrical modification method, modification of soil by thermal affects etc. (Raju and Daramalinggam 2012, Mathew and Sasikumar 2017, Zahri and Zainorabidin 2019).

In order to improve the strength of week soil several stabilizers have been in use amongst which cement is one of the most widely used stabilizer for improving the strength of soil. In 20th century cement was first used as a stabilizing agent (Azzam 2014). But still, the oldest stabilizer is lime which was being used for the purpose even before cement (Qingquan, Qing et al. 2004). Followed by lime and cement some other binders have also been used for stabilization and those include fly ash, slag, gypsum, kiln dust, bituminous materials, and stone dust (Naeini and Ghorbanali 2010, Borthakur and Singh 2014, Marto, Latifi et al. 2014, Mirzababaei, Arulrajah et al. 2017). The most commonly used stabilizers include fly ash, lime and cement (Yong and Ouhadi 2007, Al-Jabban, Knutsson et al. 2017, Talib and Noriyuki 2017). Unfortunately, a few of these stabilizers generate a negative impact on the environment and directly or indirectly are reported by occupational health safety (Indraratna, Athukorala et al. 2013). The negative effects generated are because of excessive omission of CO2. As per research done by Alyeldeen and Kitazumi 2017 (Ayeldeen and Kitazume 2017), production of cement is followed by ton of production of carbon dioxide. Another research concluded that 8% of the total production of carbon dioxide is because of cement industry (Andrew 2018). Generally these traditional stabilizers required more time for curing and a large quantity of stabilizer too (Yong and Ouhadi 2007, Naeini and Ghorbanali 2010). The reason behind the prolonged curing time is because of the pozzolanic reactions which generally take 28 days for completion (Teja, Suresh et al. 2015). Quantity of material and time are the two factors that affect construction cost. Some studies even concluded that the traditional stabilizer results in brittle behavior of the soil because of which it shall be effected easily by seismic activities (Chen, Dai et al. 2010). This may increase the probability of unsound foundation and may result in structure failure. Other then the mentioned issues the addition of traditional stabilizer often increase soils' pH value, effecting ground water and reducing the fertility of soil (Nalbantoglu and Tuncer 2001, Vinod, Indraratna et al. 2010, Indraratna, Athukorala et al. 2013).

The stabilizers are being classified on several bases including dominant chemical basic (Qingquan, Qing et al. 2004).In addition to traditional additives some other additives have also been tested and used i.e. enzymes, resin, acids, liquid polymer, ions silicate, and lignin derivatives (Kassim, Hamir et al. 2005, Hafez, Sidek et al. 2008, Horpibulsuk, Rachan et al. 2010). Stabilizers not being used traditionally generally overcome disadvantages of traditional stabilizers. Still the research work and developmental plans for enhancing and improving the soft ground is being continued. The geotechnical engineers have to work hard to come across the most appropriate techniques to deal with problems of the soft ground. This paper explains affect of an admixture (Alum Sludge) selected for stabilization of soil.

3. MATERIALS AND METHODS

Initially, the research work started after a thorough study of the soil and waste materials. After the selection of waste materials, the source for soil, sludge, and eggshells was decided. The materials were eventually collected and transported to the laboratory which was oven dried, crushed, and followed by the physical and mechanical properties testing of soil as per ASTM or AASHTO standards

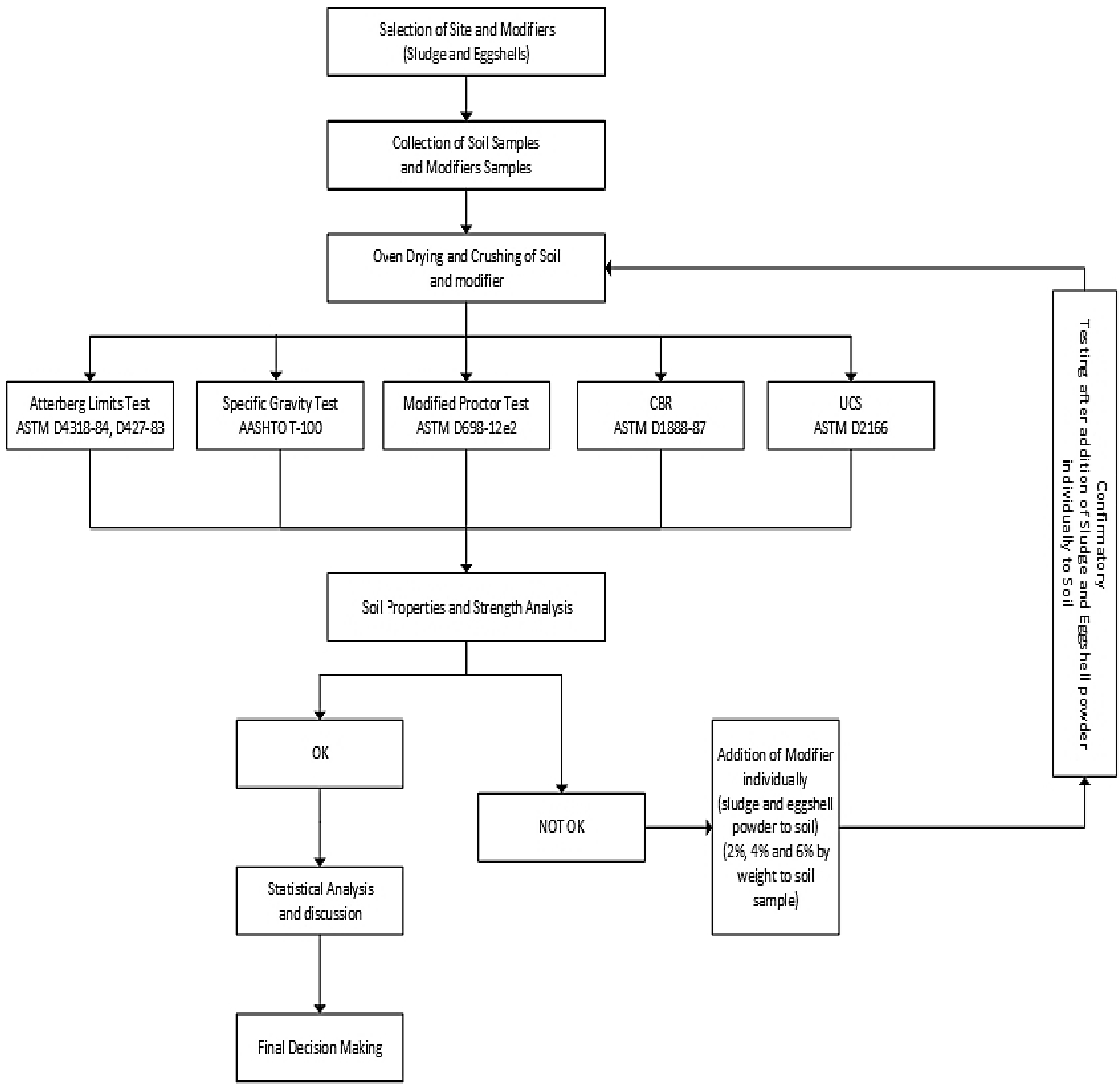


Figure 1 Basic flowchart of research methodology

3.1. SOIL COLLECTION

The soil sample was collected from a small town near Gujranwala more precisely known as Nandipur located in upper Punjab, Pakistan. The soil was selected based on previous literature and studies done on the soil according to which the soil had weak properties. The textural properties of soil already indicate its clayey nature and due to weak soil, the part of the land has no construction or agricultural use. The soil sample was collected from a depth of one meter approximately. The soil was oven-dried before any testing.

Figure 2 Satellite image of soil site

3.2. SLUDGE COLLECTION

Sludge was obtained from a wastewater treatment plant located in the I-9 sector, Islamabad, Pakistan. The treatment plant is operated by the capital development authority (CDA). The sludge was sun-dried and then oven dried. The oven-dried sludge was then crushed into a fine powder that could pass sieve#100 completely and partially pass sieve#200 as well.

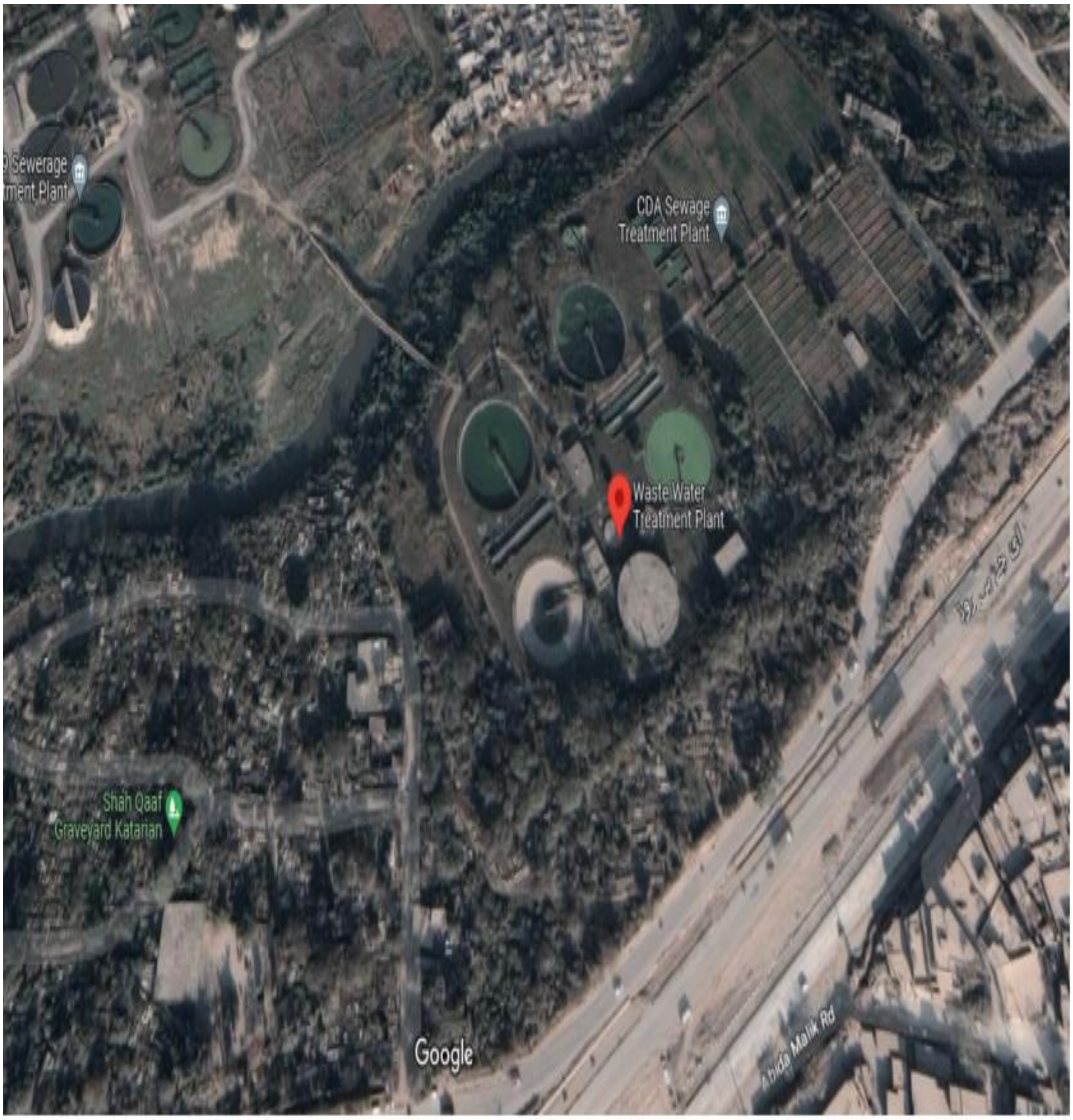


Figure 3 Satellite image of sludge site

3.3. EGGSHELL COLLECTION

Bakeries and hotels are among the main consumers of eggs. Shangrilla hotels and bakery is a food chain that has several outlets in Multan (Punjab, Pakistan). The eggshells were collected from one of the outlets of Shangrilla known as Shangrilla Cuisine hotel and bakery in Multan. On daily basis, an average of about ten to twenty kilograms of eggshells were collected. These eggshells were then oven-dried for twenty-four hours. Once dried these were then crushed into a fine powder that could pass sieve#100 and partially pass sieve#200 as well.

Figure 4 Satellite image for eggshell site

3.4. SAMPLE PREPARATION

The soil, sludge, and eggshell powder were oven dried for 24 hours at 110 ± 5°C each. After the drying process, the materials were crushed and sieved separately through sieve numbers 100 and 200. Sludge and eggshell were added to the soil separately by 2%, 4%, 6%, and 8% by weight. Each test was done first on soil without any percentage of modifier i.e., sludge and eggshells and after the addition of modifier, the samples were tested again.


Figure 5 Oven drying of soil, sludge, and eggshell powder

3.5. SIEVE ANALYSIS

Sieve analysis is the first step toward the classification of soil. This is used to determine soils' particle size distribution. The soil gradation helps to predict the engineering properties of soil. Wet sieve analysis was done as more than 50% of the soil passed through sieve #200 which according to USCS means that the soil was clayey or silty. The soil after sieving was oven dried and weighed (ASTM 2007).

3.6. ATTERBERG LIMITS

Atterberg limits are the moisture content percentages used to identify the soil type especially according to the AASHTO standard of soil classification. These limits include shrinkage limit, plastic limit, liquid limit, and plasticity index. Amongst these, the liquid limit and plastic limit are the most critical parameters to classify soil according to AASHTO standards. The test is performed according to ASTM D4318 (Standard 2010).

The liquid limit test is carried out on a Casagrande apparatus in which a soil sample with adequate moisture content is added and a groove with dimensions of 2mm width from the bottom and 11mm width from the top is cut. The height of the grove cut is about 8mm. The blows are repeated until the soil from both sides of the groove meets at any point. The sample is then weighed before and after oven drying to calculate the moisture content i.e., liquid limit, and a graph is plotted between the number of blows and water content. The moisture content at twenty-five blows from the graph plotted is said to be the liquid limit of soil. This test was carried out with and without the addition of modifiers for 0%, 2%, 4%, 6%, and 8%.

The plastic limit test is the next Atterberg limit that is determined by rolling out a ball of soil into a thread till an approximate diameter of 3mm. The point at which the soil thread breaks or crumbles tends to be the moisture content at which soil reaches its plastic limit. This is calculated by weighing wet soil thread and then weighing it after oven drying it for 24 hours at 100 ^{o}C. The soil threads were made without the modifier and with 2%, 4%, 6, and 8% of the modifier (i.e., sludge and eggshell powder).

The plasticity index is calculated then simply by subtracting the plastic limit of the soil from the liquid limit of the soil.

3.7. SOIL CLASSIFICATION

The soil classification is done based on grain size and Atterberg limit i.e., liquid limit and plasticity index of soil. The engineering properties of soil can be predicted by either of the two soil classification systems.

3.7.1. AASHTO CLASSIFICATION SYSTEM

This is the soil classification system that was introduced by the American association of state highway and transportation officials and is used as a guiding tool for soil engineering properties. The soil type is classified according to the grain size, plastic limit, liquid limit, and plasticity index of the soil. The soil is categorically divided into coarse to fine soil grading from A1 to A7. Soil from A1 to A3 category is coarse and does not pass through sieve #200. Whereas the soil categories from A4 to A7 demonstrate fine soil type which passes through sieve #200 and is classified further on basis of Atterberg limits.

AASHTO SOIL CLASSIFICATION

GENERAL CLASSIFICATION	GRANULAR MATERIALS (35% OR LESS PASSING 0.075 SIEVE)							SILT-CLAY MATERIALS (MORE THAN 35% PASSING 0.075 SIEVE)			
GROUP CLASSIFICATION	A–1		A–3	A–2				A–4	A–5	A–6	A–7–5 A–7–6
	A–1–a	A–1–b		A-2-4	A-2-5	A-2-6	A-2-7				
SIEVE ANALYSIS, PERCENT PASSING:											
2.00 mm (No. 10)	≤ 50	–	–	–	–	–	–	–	–	–	–
0.425 mm (No. 40)	≤ 30	≤ 50	≥ 51	–	–	–	–	–	–	–	–
0.075 mm (No. 200)	≤ 15	≤ 25	≤ 10	≤ 35	≤ 35	≤ 35	≤ 35	≥ 36	≥ 36	≥ 36	≥ 36
CHARACTERISTICS OF FRACTION PASSING 0.425 SIEVE (No. 40):											
LIQUID LIMIT	–		–	≤ 40	≥ 41	≤ 40	≥ 41	≤ 40	≥ 41	≤ 40	≥ 41
PLASTICITY INDEX *	6 max		NP	≤ 10	≤ 10	≥ 11	≥ 11	≤ 10	≤ 10	≥ 11	≥ 11
USUAL TYPES OF CONSTITUENT MATERIALS	STONE FRAGMTS, GRAVEL, SAND		FINE SAND	SILTY OR CLAYEY GRAVEL AND SAND				SILTY SOILS		CLAYEY SOILS	
GENERAL RATING AS A SUBGRADE	EXCELLENT TO GOOD							FAIR TO POOR			

*Plasticity index of A-7-5 subgroup is equal to or less than LL-30. Plasticity index of A-7-6 subgroup is greater than LL-30.
NP = Non-plastic (use "0"). Symbol "–" means that the particular sieve analysis is not considered for that classification.

Figure 6 AASHTO Classification table (AASHTO. 2011)

3.7.2. UNIFIED SOIL CLASSIFICATION SYSTEM

USCS divides soil into two majors initially based on particle size. If 50% of the soil particles are coarser enough not to pass through sieve #200, the soil is categorized on further sieve analysis. If 50% of particles retain sieve #4 size, then it is classified under the category of gravel. Whereas 50% of the particles passing sieve #4 and retaining on sieve #200 are catered as sandy soil. The soil that passes through sieve #200 is termed fine-grained soil. The further classification of soil into silt or clay is done based on the liquid limit of the soil.

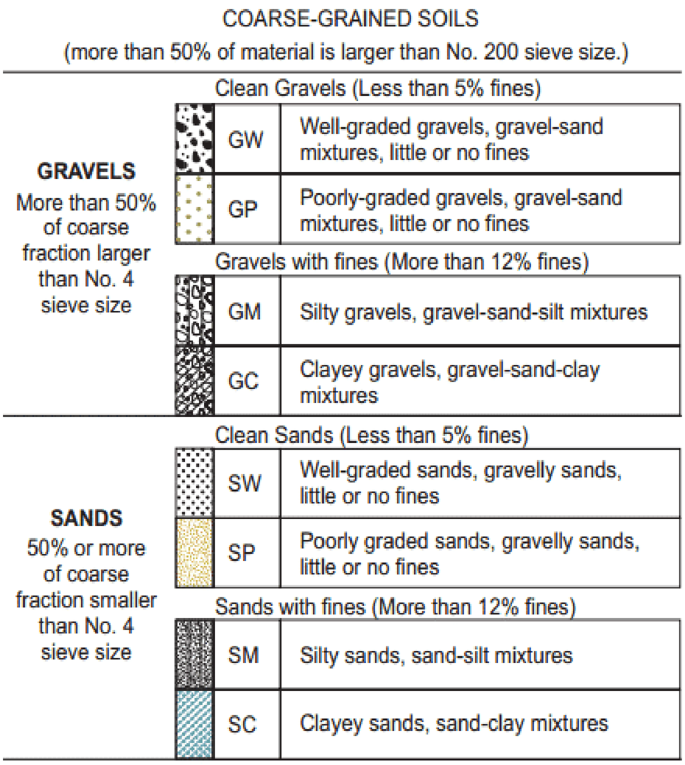


Figure 7 USCS chart for coarse soil (Standard 2011)

FINE-GRAINED SOILS
(50% or more of material is smaller than No. 200 sieve size.)

SILTS AND CLAYS 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 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

Figure 8 USCS chart for fine soil (Standard 2011)

3.8. SPECIFIC GRAVITY

The specific gravity test was done under test standard AASHTO T100 . The test is done using the pycnometer. Porosity and voids of soil are the factors that are related to specific gravity. The specific gravity of soil ranges from 2.6 to 2.8. The specific gravity of coarse soil is greater than that of fine soil.

3.9. MODIFIED PROCTOR TEST

The modified proctor test is an improved version of the standard proctor test and is designated in AASHTO test standards as D-1557 and T-180. The test is performed to calculate the maximum dry density and optimum moisture content of the soil. The test is performed in a mold of volume that is approximately 1 / 13.33 ft^3. The soil is compacted into five layers. Each layer is hammered with 25 blows. The height of the fall is 18 inches while the hammer weighs about 10 lbs. This high compaction force results in an increase in the dry unit weight of soil which is indirectly related to the optimum moisture content required for compacting the soil.

3.10. CALIFORNIA BEARING RATIO TEST

California bearing ratio test is used to determine the stress for a soil sample which is inhibited by a plunger of diameter about 50mm and at a rate of 1.25mm/min. this is calculated in percentage and is measured in correspondence to the same penetration in a standard material. The test is designated under AASHTO standard T 193-99 or ASTM D4429 (D 2016). There are two methods for calculating CBR i.e., 1-point CBR and 3-point CBR. The more accurate and widely used CBR method is the 3-point CBR. In the three-point CBR method, the CBR is calculated for varying numbers of blows for each specimen i.e., 10 blows, 30 blows, and 56 blows. The soil is compacted in five layers with a respective number of blows for each sample. This test was performed on the soil before adding any modifier to it and after adding 2%, 4%, and 6% of sludge as well as eggshell powder separately to the soil. CBR is then calculated against 0.1- and 0.2-inches penetration of the plunger. The depth at which more CBR is recorded is taken as the California bearing ratio percentage of the soil sample. This is a strength evaluation for the subbase and subgrade of soil based on load penetration.

3.11. UNCONFINED COMPRESSIVE STRENGTH TEST

Undrained and unconsolidated shear strength of soil determined indirectly by unconfined compressive strength test. The test is performed on an unconfined compacted cylinder of soil that is put under a compressive strength test. The point at which this soil cylinder fails under compressive loading is termed unconfined compressive strength. The experimental setup constitutes the compression device and dials gauge for load and deformation. The test is performed under the ASTM D2166 standard (Standard 2009). This is a strength test of soil when compressed uniaxially without any confined boundary of a container or membrane.

3.12. ARTIFICIAL NEURAL NETWORK

Artificial Neural Network (ANN) is a statistical tool that competently relates inputs and outputs in a system by complex mathematical nonlinear process and is abbreviated as artificial neural network (Sabat 2013). The neural network weight is changed in the modeling system as per assumptions and model convergence for progressive self-training by adding new data to the system. ANN is based on the idea on idea of the human brain and the nervous system operates in parallel relating almost every bit like neurons (Song, Li, Dai, & Liu, 2011). ANN works on groups of interconnected nodes which are input parameters put in the analysis model. For analysis of this research every circular node, and each layer illustrates a neuron and a line means the connection of the output of one node to the input of another. In consideration of the basic properties of soil and the impact of parameters like modifier type (MT) (eggshell or sludge), modifier percentage (M%) (percentage by weight of modifier added to the soil), the specific gravity of soil, liquid limit, plastic limit, maximum dry density, optimum moisture content, and soil classification according to AASHTO has been taken as input variables and the output variables considered are California bearing ratio percentage at different blows i.e., 10 blows, 30 blows, and 56 blows.

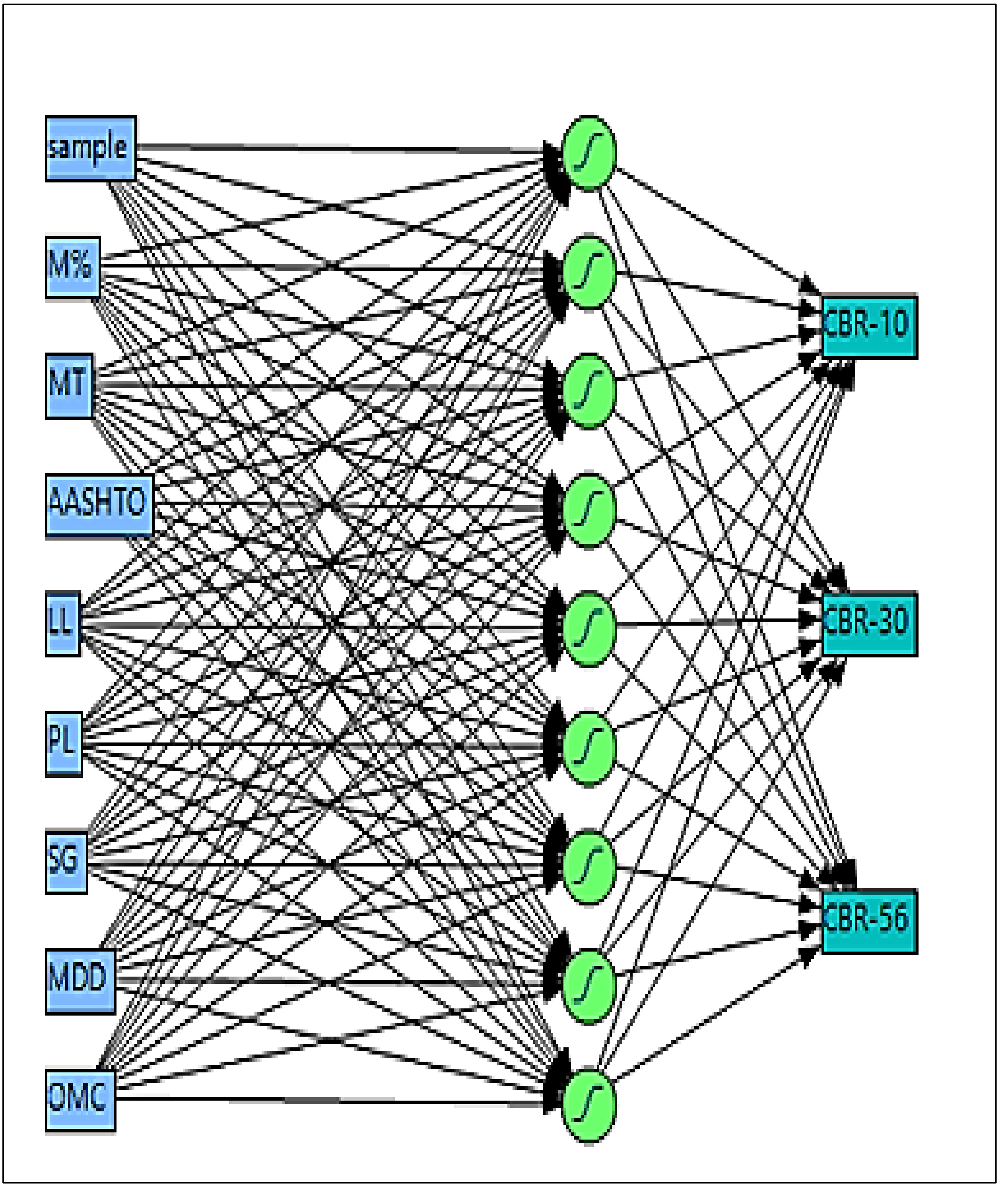


Figure 9 Artificial neural network chart

The model is established and evaluated as per the testing mechanism of its accuracy, prediction power, and precision. The three parameters, relationship coefficient, root mean square error (RMSE), and coefficient of determination (R^2) are developed to deduce the analytical capacity of the developed model (Siddique et al., 2011). The following table displays the approximate parameters and likelihood of the California Bearing Ratios (CBR) (10, 30, and 56 blows) regarding soil compaction. Data was leaped using the K-folded mechanism and divided into five segments. The estimated parameters and prediction of 3-point CBR, (10, 30, and 56 blows) is shown in the following table regarding soil compaction. The division of data was done in five segments according to the K folded mechanism; so, training data sample was 34 whereas validation samples were 6. The value of regression (R^2) should be nearest to 1, this is basically the highest level of accuracy for a developed model.

4. RESULTS AND DISCUSSION

This chapter displays and discusses the results of testing. The following table summarizes the soil index properties as well as the optimum moisture content and maximum dry density of the soil.

Table 1 Summary of physical properties of soil w.r.t. sludge

Sludge %	**0%**	**2%**	**4%**	**6%**
AASHTO	A-7-6	A-7-6	A-4	A-7-5
Liquid Limit	56.15	50.67	42.66	36.63
Plastic Limit	20.31	20.78	22.12	26.44
MDD lb./ft3	102.89	113.62	116.33	100.26
OMC %	11.24	13.48	14.49	16.89

Table 2 Summary of physical properties of soil w.r.t. eggshell powder

Eggshell powder%	**0%**	**2%**	**4%**	**6%**
AASHTO	A-7-6	A-7-6	A-4	A-4
Liquid Limit	56.15	53.73	50.21	45.45
Plastic Limit	20.31	27.88	29.20	34.98
MDD lb/ft3	102.88	115.91	119.96	106.16
OMC %	11.24	13.18	16.11	17.94

4.1. SIEVE ANALYSIS

Sieve analysis of Nandipur soil was done prior adding any modifier to it for classification of the soil. The sieve analysis performed was wet sieve analysis. Sieves were arranged in descending order of sieve size i.e. 4.76mm, 2.36mm, 1.18mm, 0.425mm, 0.3mm, 0.15mm, and 0.075mm. The percentage passing of soil particles by weight was recorded and a logarithmic graph is generated as the particle size of soil exhibits uniformity due to very similar shape of grain size curve despite the varying size fraction of particles of soil.

The graph below is plotted between percentage of passing soil by weight on y-axis and sieve sizes in millimeters on x-axis.

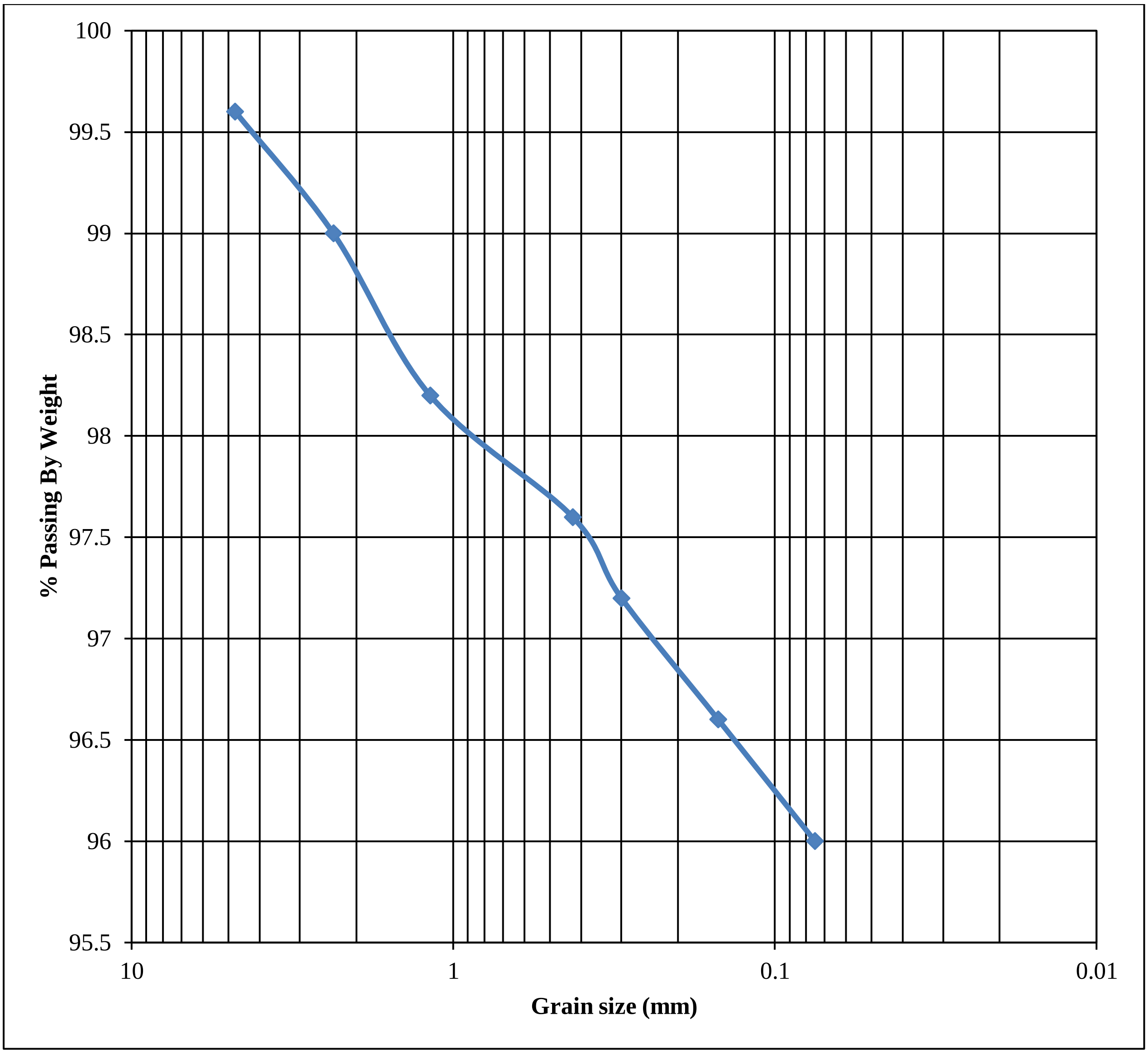


Figure 10 Sieve analysis graph

4.2. ATTERBERG LIMITS

Atterberg limits were calculated separately for sludge and eggshell powder. in the case of sludge, it was observed that as the percentage of sludge increased in the soil tell the 4% the liquid limit of the soil gradually decreased whereas the plastic limit of the soil gradually increased hence there was an increase in the plasticity index of the soil as well. Similarly, for eggshell powder again the liquid limit started to decrease as the percentage of actual powder was increased in the soil whereas the plastic limit of the soil increased which again led to an increase in the plasticity index value of the soil. this increase in plasticity index and decrease in liquid limit changes the soil categorization in AASHTO. The following tables illustrate the liquid limit, the plastic limit, and the plasticity index values for different percentages of sludge and eggshells for each repeated tests done with same percentages.

Table 3 Atterberg limits with and without addition of sludge to soil

Sample	**Sludge%**	**LL**	**PL**	**PI**
1	0%	58.12	20.61	37.51
2	0%	54.23	19.22	35.01
3	0%	56.10	21.11	34.99
1	2%	50.53	20.77	29.76
2	2%	49.68	20.36	29.32
3	2%	51.61	21.19	30.42
1	4%	42.89	21.72	21.17
2	4%	44.69	22.51	22.18
3	4%	40.14	22.14	18.00
1	6%	34.98	28.14	6.84
2	6%	37.01	26.03	10.98
3	6%	36.32	25.54	10.78

Table 4 Atterberg limits with and without the addition of eggshell Powder to soil

Sample	Eggshell powder%	LL	PL	PI
1	0%	55.33	21.22	34.11
2	0%	57.02	19.71	37.31
3	0%	56.12	20.01	36.11
1	2%	54.85	29.46	25.39
2	2%	53.54	26.39	27.15
3	2%	52.72	27.83	24.89
1	4%	48.97	30.19	18.78
2	4%	51.03	29.33	21.70
3	4%	50.63	28.37	22.26
1	6%	46.21	36.35	9.86
2	6%	44.38	33.76	10.62
3	6%	45.76	34.81	10.95

4.3. SPECIFIC GRAVITY

Finer soils have higher specific gravity value than the coarse soil. The soil sample without any additive added to it had specific gravity value of about 2.71. This means that soil was highly porous and had organic content added to it. On addition of sludge and eggshell powder to the soil the specific gravity gradually decreased which means that the particles changed its type from finer to coarser side.

Table 5 Specific gravity of soil with and without modifier

Modifier	0%	2%	4%	6%
Sludge	2.71	2.68	2.63	2.58
Eggshells Powder	2.71	2.64	2.59	2.55

4.4. SOIL CLASSIFICATION

As described in the methodology soil was classified according to AASHTO standards. The soil passing through sieve#200 was more than 50% which was a clear indication of soil being clayey as per AASHTO standards and as well as USCS. The materials added to the soil were oven dried and crushed into fine powder. The sludge powder or eggshell powder that passed through sieve#100 or #200 was only used to make soil specimens. As the modifiers were very fine but still percentage retaining on sieve#200 and passing through sieve #200 both were used the soil slightly changed its characteristic. Initially, the soil layers in the A-7-6 category in AASHTO standards, which means that the soil may depict poor engineering properties and is highly plastic soil.

In the case of sludge, after sludge was crushed, sieved, and mixed 2%,4%, and 6% by weight with the soil. The soil type initially remained A-7-6 despite the addition of 2% sludge but the soil category changed from A-7-6 to A-4 when 4% of the sludge was added to the soil, which means it shifted from poor to the fair type of soil as per AASHTO. The soil type changed from clayey to silty soil. But, as the percentage of crushed sludge added to soil increased from 4% to 6%, the soil type changed to A-5 from A-4, which means the soil type shifted to less silty soil.

For eggshell powder, the eggshells were oven dried, crushed, sieved, and mixed 2%, 4%, and 6% by weight to the soil. Initially, after a 2% addition of eggshell powder to the soil type did not change i.e., it remained A-7-6 category which meant it was clayey soil. Whereas, when the eggshell powder percentage increased in the soil to 4% and 6%, the soil type shifted from A-7-6 to A-4, which lies in the category of silty soil as a better soil type than the A-7-6 soil.

4.5. MODIFIED PROCTOR TEST

The Modified Proctor test was performed on sludge and eggshell powder each individually. The soil sample was prepared by adding different percentages of sludge and eggshell powder to it i.e., 2%, 4%, and 6%. The graph between dry density and moisture content is plotted below for both modifiers i.e., sludge and eggshell powder. The dry density of the soil increased from 102.8 lb./ft^3 to approximately 116.3 lb./ft^3 with the addition of 4% sludge to the soil. While the optimum moisture content of soil increased from 11.24% to 14.49% at the same percentage of sludge. Likewise in the addition of eggshell powder again results were similar, as dry density increased to 119.96 lb./ft^3 on 4% addition. Whereas the moisture content increased to 16% approximately for the 4% addition of eggshell powder.

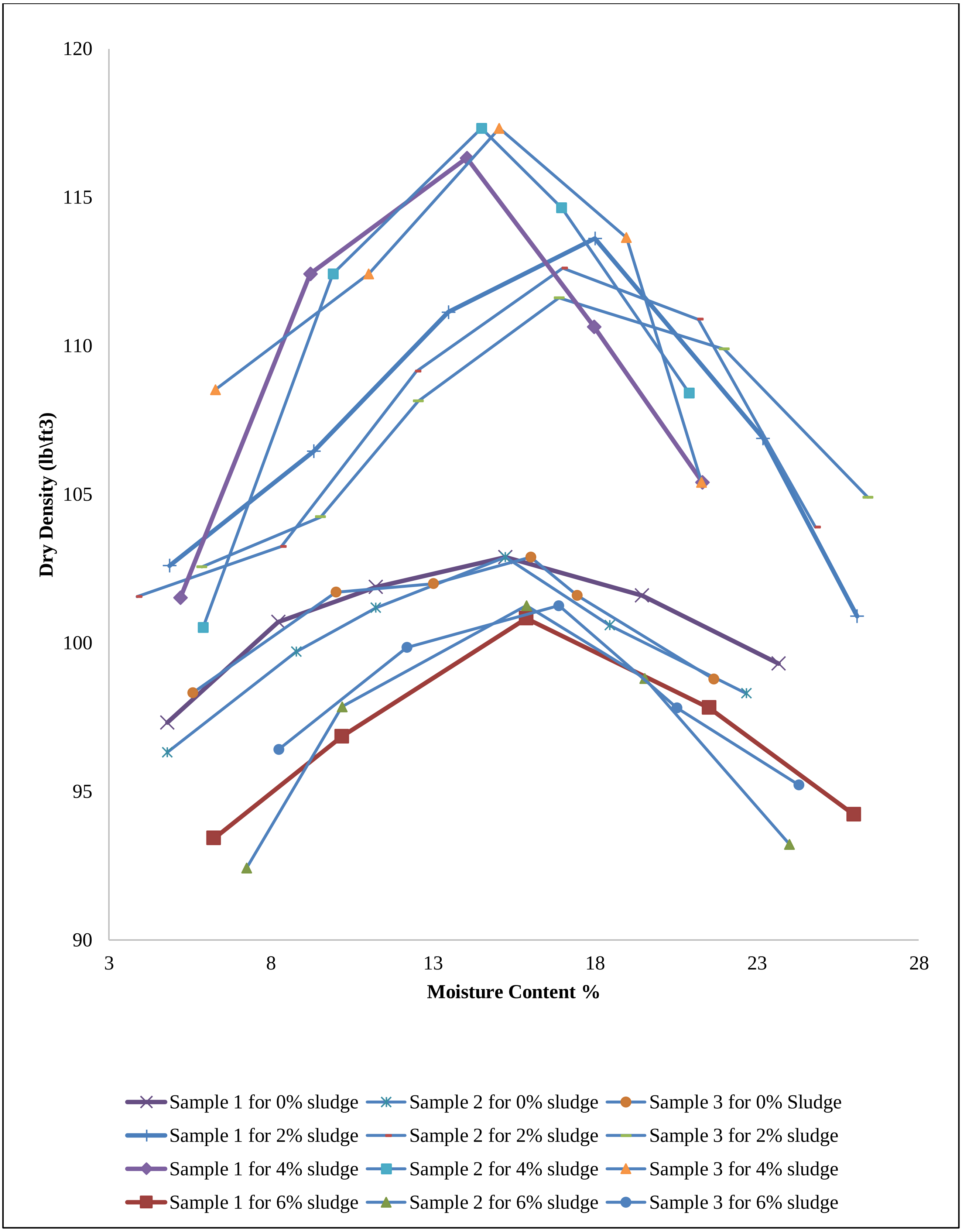


Figure 11 Modified proctor test curves with sludge

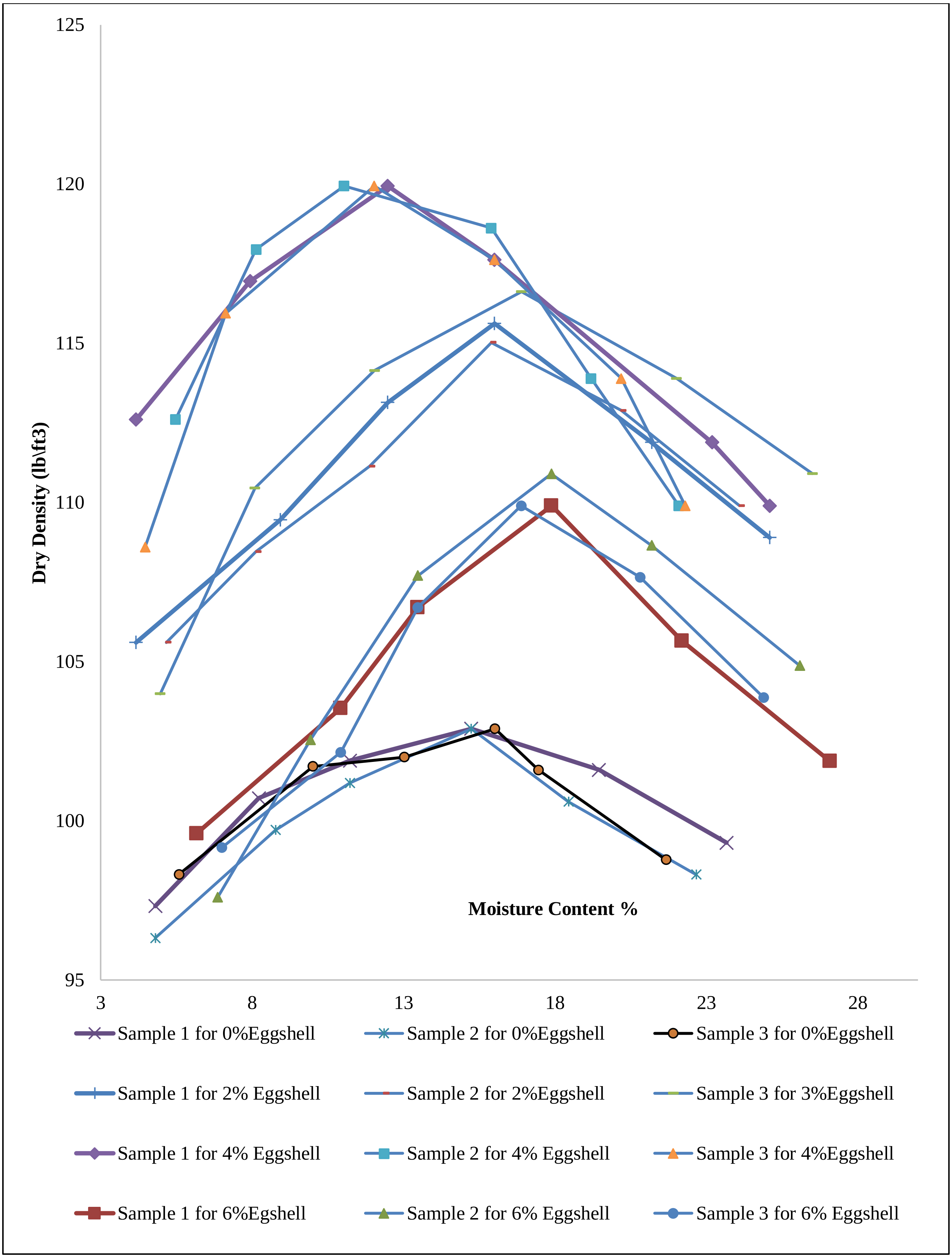


Figure 12 Modified proctor test curves with eggshell powder.

4.6. CALIFORNIA BEARING RATIO TEST

The California bearing ratio (CBR) test was performed on soil for three different number of blows i.e., 10, 30, and 56. CBR percentage increased with an increase in the modifier percentage until the modifier percentage reached 4%. After 4% at 6% the CBR again started to decline. For 10 number of blows the CBR percentage increased from 5.23% to 7.98% whereas, at 6% again CBR decline to 5.61%. For 30 number of blows the CBR calculated when no modifier was added was 6.75% and it increased to 11.04% on addition of 4% of sludge. When the sludge percentage was increased to 6% the CBR dropped to 9.12%. The maximum CBR was observed for 56 number of blows when CBR increased from 8.69% to 14.79% for 4% addition of sludge to the soil. Whereas CBR again decreased to 10.23% when sludge percentage was raised to 6%.

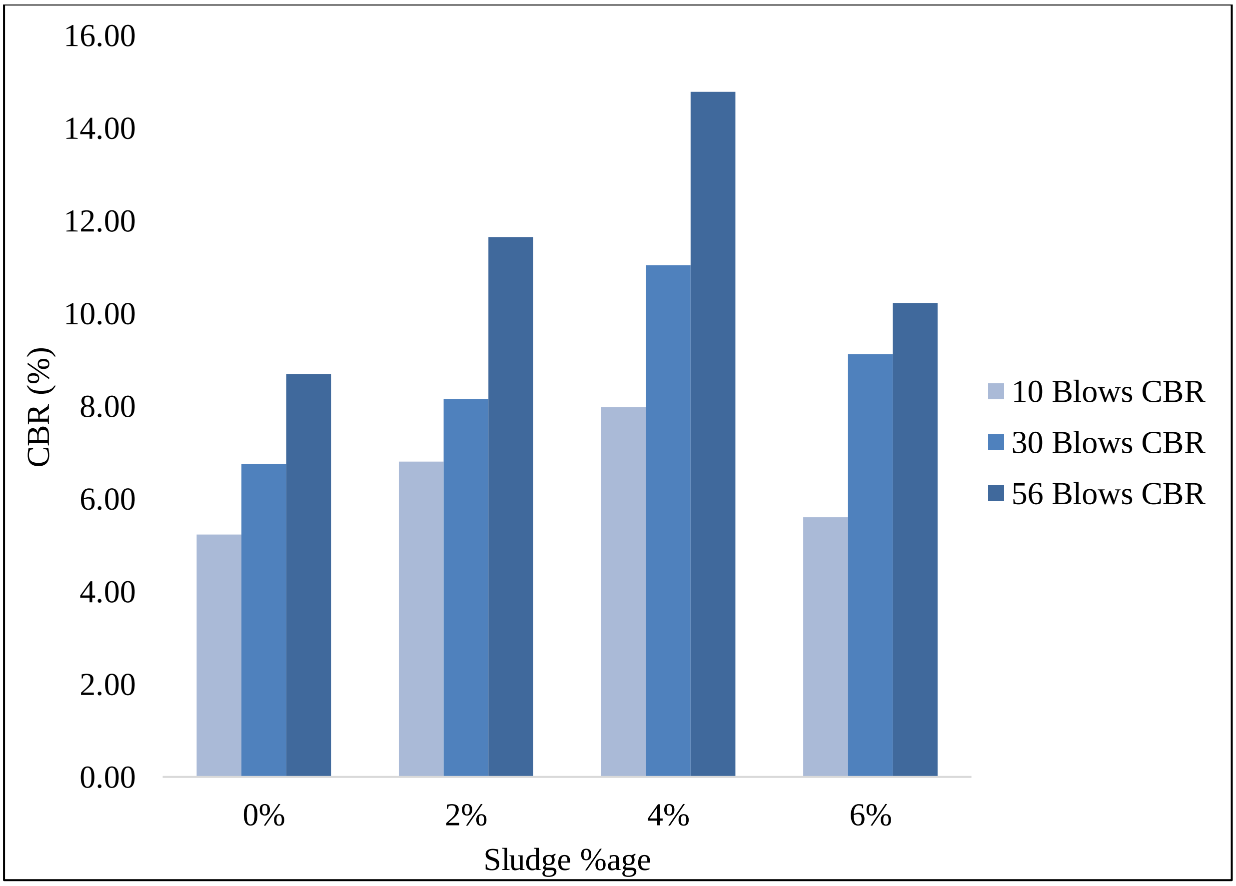


Figure 13 CBR graph with sludge

In case of eggshells again similar trend was observed as 4% was maximum addition of eggshell powder to soil after which the CBR declined. For 10 number of blows the CBR percentage increased from 5.23% to 7.92% whereas, at 6% again CBR decline to 5.83%. For 30 number of blows the CBR calculated when no modifier was added was 6.75% and it increased to 12.89% on addition of 4% of sludge. When the sludge percentage was increased to 6% the CBR dropped to 8.41%. The maximum CBR was observed for 56 number of blows when CBR increased from 8.69% to 16.11% for 4% addition of sludge to the soil. Whereas CBR again decreased to 10.77% when sludge percentage was raised to 6%. Eggshell powder improved CBR more than sludge as the maximum CBR% for sludge was 14.79% and for eggshell was 16.11%.

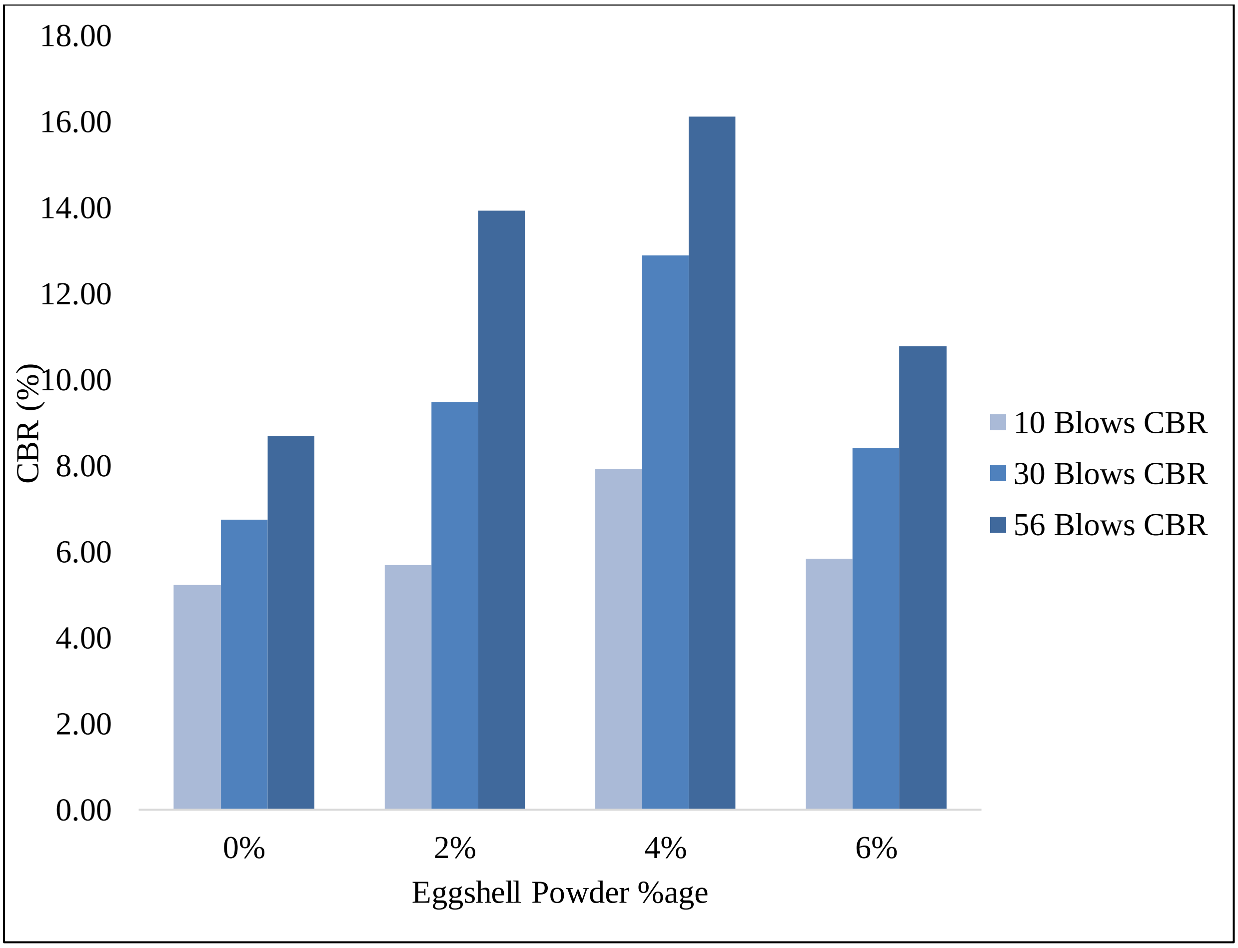


Figure 14 CBR graph chart with eggshell powder

4.7. UNCONFINED COMPRESSIVE STRENGTH TEST

Unconfined compressive strength was recorded at intervals of 0, 3 and 7 days. Maximum compressive strength obtained was on 7th day when 4% of sludge was added to soil. At 6% addition of sludge the compressive strength started to decrease again. At 0days of curing the unconfined compressive strength increased from 17.82psi to 30.47psi when sludge percentage was increased from 0 to 4%. UCS decreased at 6% addition of sludge to 21.69psi. After 3days of curing, when the sample was tested, the unconfined compressive strength increased from 60.49psi to 127.57psi when sludge percentage was increased from 0 to 4%. After 7days of curing, when the soil sample were tested UCS at 0% sludge was 74.91 psi which increased to 167.91 at 4% addition of sludge. The UCS decreased upon 6% sludge addition to soil and was calculated 103.07psi.

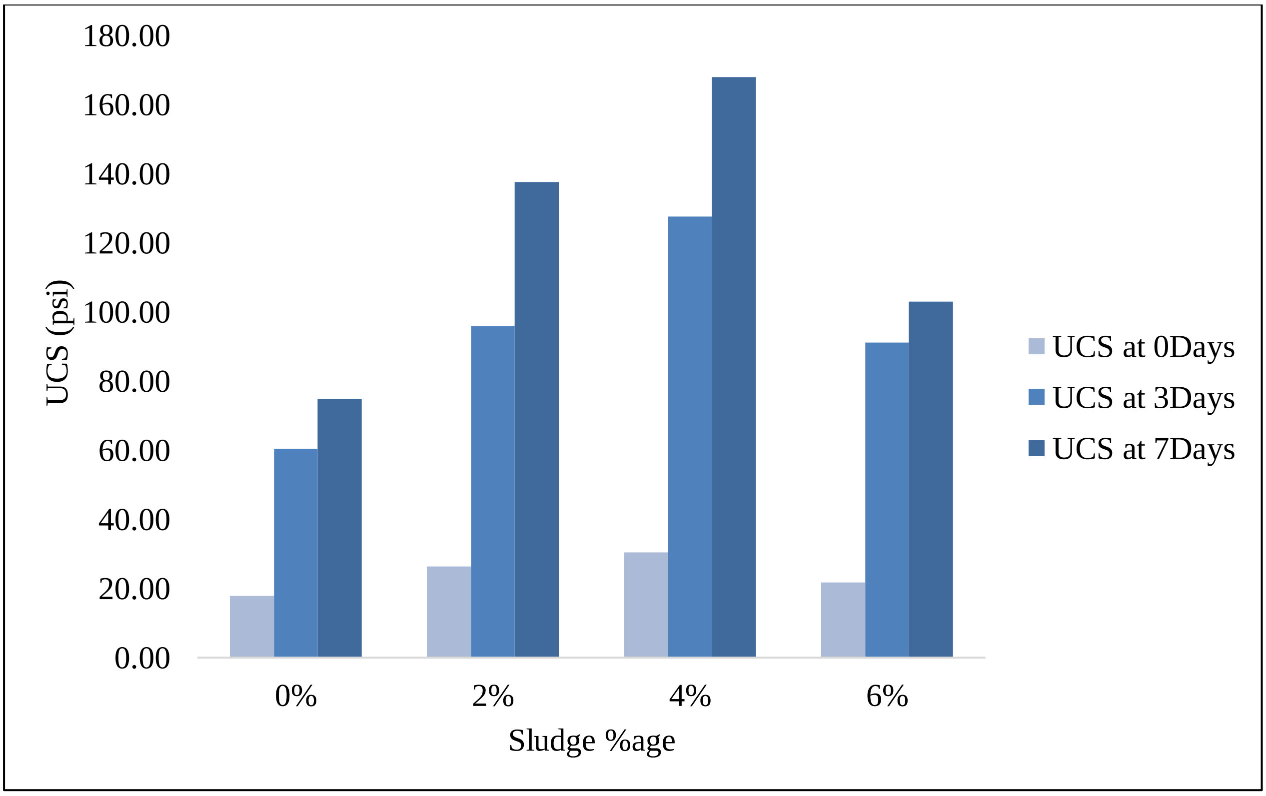


Figure 15 UCS graph with sludge addition

Unconfined compressive strength was recorded at intervals of 0, 3 and 7 days. Maximum compressive strength obtained was on 7th day when 4% of eggshell powder was added to soil. At 6% addition of eggshell powder the compressive strength started to decrease again. At 0days of curing the unconfined compressive strength increased from 17.81psi to 46.83psi when eggshell powder percentage was increased from 0 to 4%. UCS decreased at 6% addition of eggshell powder to 21.87psi. After 3days of curing, when the sample was tested, the unconfined compressive strength increased from 60.48psi to 131.42psi when eggshell powder percentage was increased from 0 to 4%. After 7days of curing, when the soil sample were tested UCS at 0% eggshell powder was 74.91 psi which increased to 141.61 at 4% addition of eggshell powder. The UCS decreased upon 6% eggshell powder addition to soil and was calculated 126.60psi.

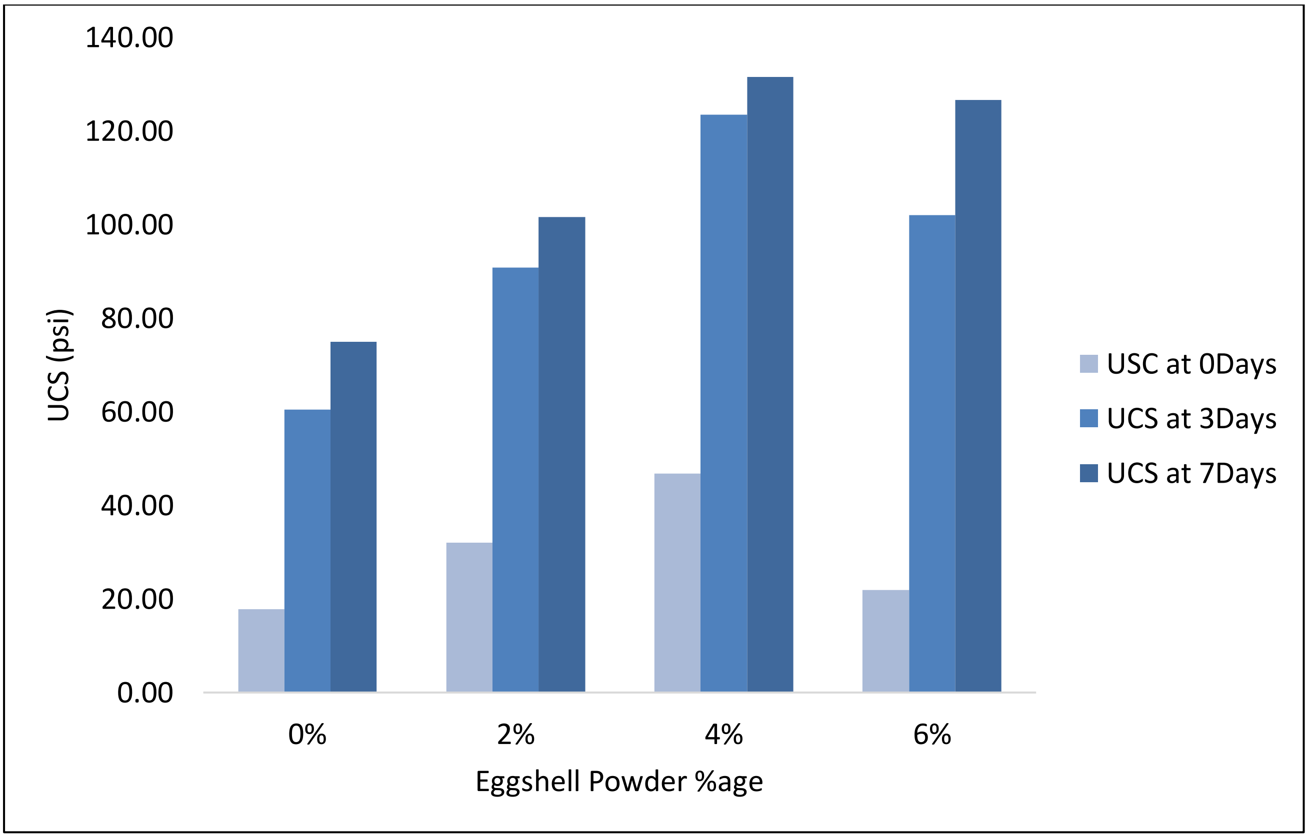


Figure 16 UCS graph with eggshell powder addition

4.8. ARTIFICIAL NEURAL NETWORK

The data was analyzed using 3 variable outputs, the complex mechanism of artificial neural network was used to calculate the weight of each node and the prediction models as well as the variable importance analysis is described in this section.

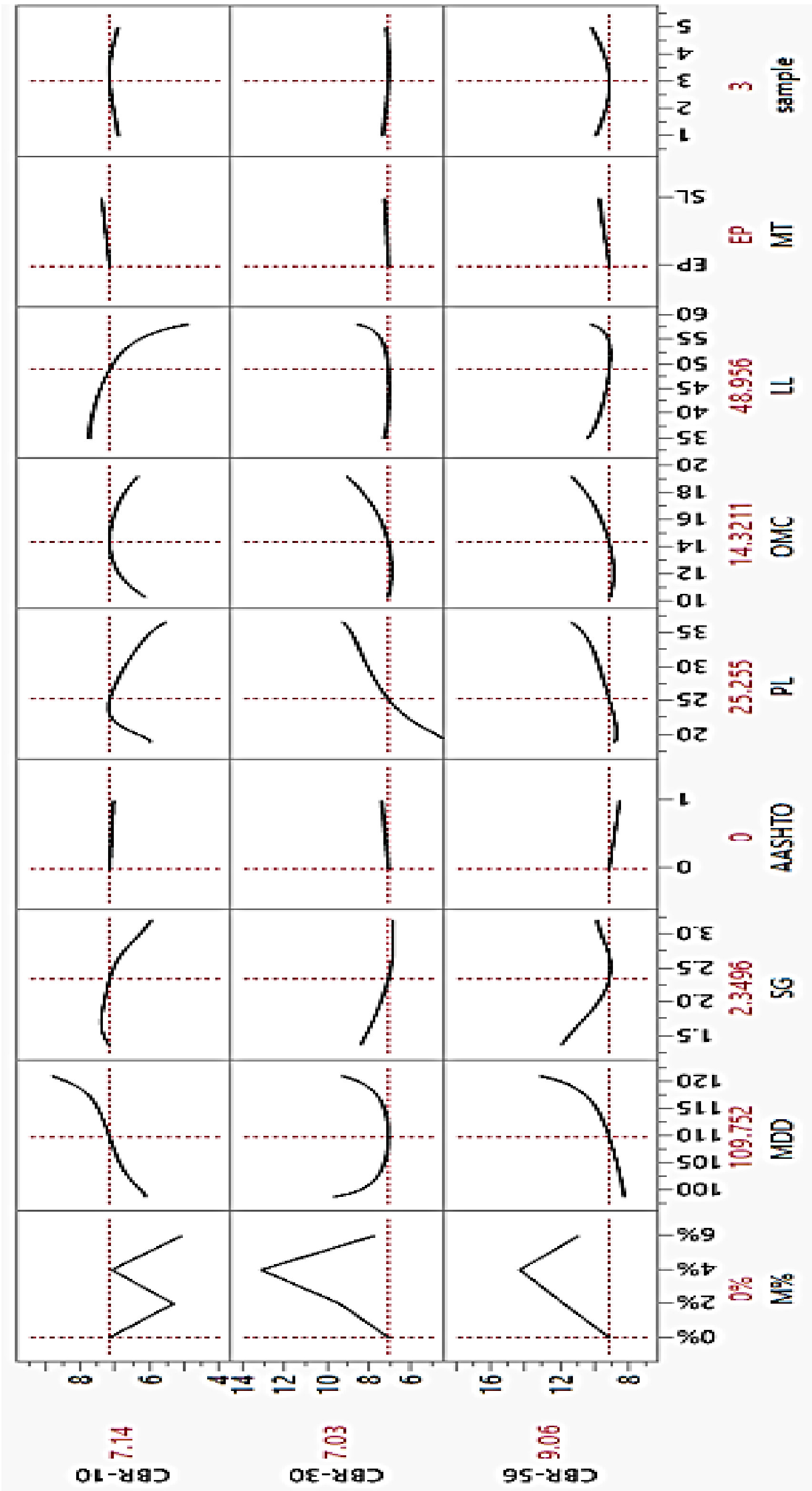


Figure 17 Prediction profiler

The above prediction profiler demonstrates all of the three outputs added to the model collectively with the parameters that may be affecting the CBR of soil with varying numbers of blows. M%, The modifier percentage added to the soil either in the terms of sludge or eggshell powder showed that the CBR eventually increased for 30 and 56 blows but and an irregular behavior was observed with CBR at 10 blows. the maximum dry density of the soil eventually increased as the number of blows increased for the CBR for instance the maximum dry density curve seemed to be increasing more simultaneously when 56 blows CBR was performed. similarly, in case of specific gravity the model predicted an inverse relation as the CBR decreased with increase in SG. the plastic limit and the liquid limit of the soil according to the model were shown directly related to CBR irrespective of the number of blows being applied to the soil. The two modifier types used actual powder and the sludge it was seen that there was a very minute difference but the CBR was slightly greater for sludge as compared to eggshell powder. The optimum moisture content of the soil also increased as the number of blows for the CBR increased.

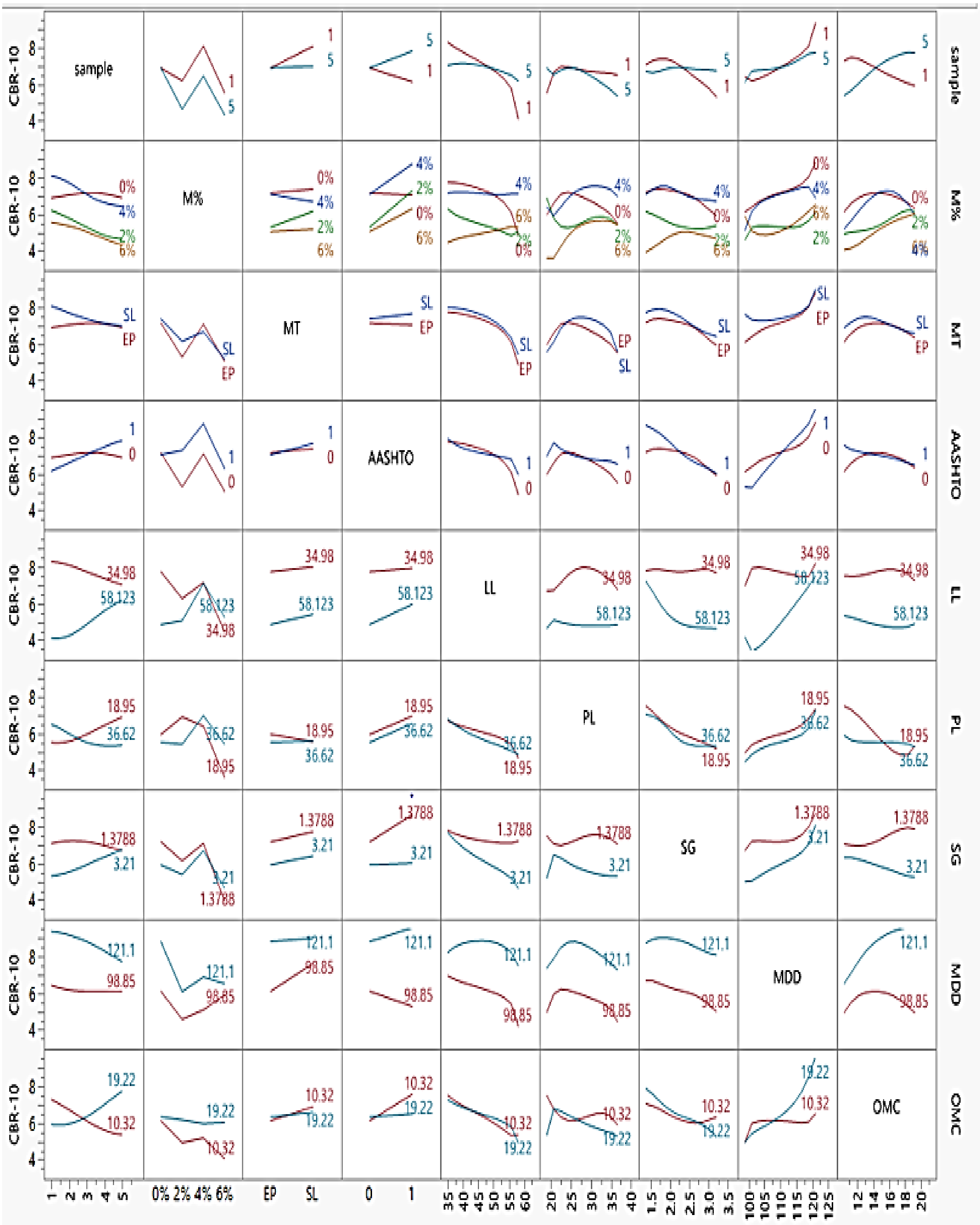


Figure 18 Interaction profile for CBR 10

The interaction profiles were plotted against the CBR and different variables. The above graph shows the interaction of variables i.e., Samples, modifier percentage, modifier type, soil type according to AASHTO, liquid limit, plastic limit, specific gravity, maximum dry density, and optimum moisture content. The first row from the top shows combined interaction of CBR 10, and sample numbers to other parameters. The second row from the top shows the interaction profile of CBR 10 and modifier percentage in relevance to the other parameters as well. Similarly, the third row demonstrates the interaction of CBR 10 and modifier type to the remaining parameters of the soil. AASHTO and CBR 10 interaction could be seen in the 4^{th} row from above where other variables also affected the relation of soil type to the CBR 10. Liquid limit and plastic limit interaction to CBR 10 is individually shown in row 5 and 6 with respect to other parameters. Followed by liquid limit and plastic limit specific gravity, maximum dry density and optimum moisture content interaction profiles are shown in 7^{th}, 8^{th}, and 9^{th} rows of the above graph chart.

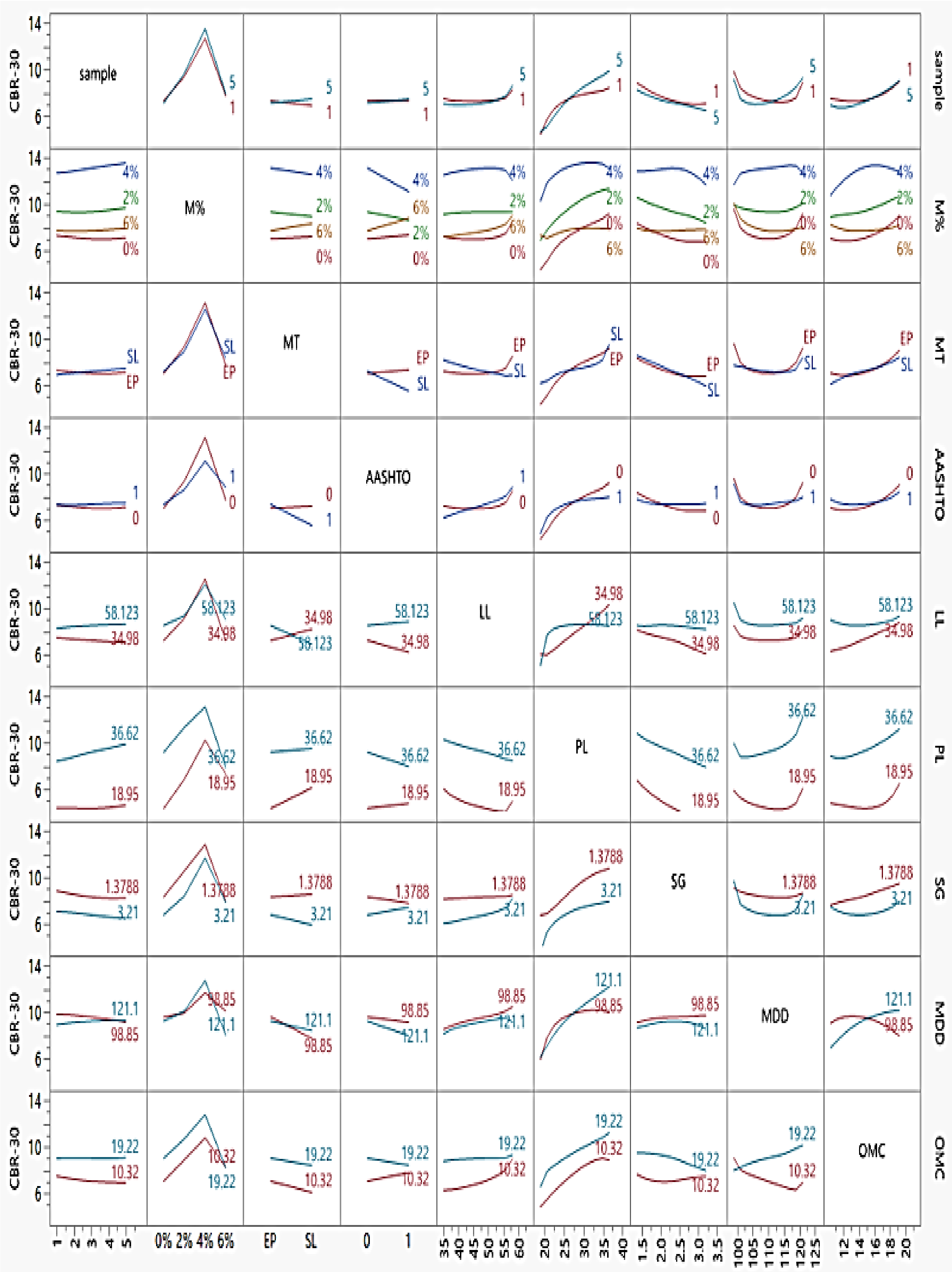


Figure 19 Interaction profile for CBR 30

The above figure shows the interaction of CBR 30 with other parameters. The first row from above shows a very close behavior for 1 to 5 samples as all the samples were prepared almost under the same conditions and same percentage and type of modifier was added. In the second row from top, the first graph shows that CBR 30 eventually increased for different percentage of the modifier whereas the modifier type interaction to modifier percentage and CBR 30 again showed the gradual increase in the CBR. And modifier percentage led to change of soil type from AASHTO A-7-6 to A4 or A5. Gradual increase in liquid limit is predicted as modifier percentage increased and is related to CBR 30 whereas a sharp increase in CBR was observed with increasing plastic limit when the modified percentage was improved. The decline in specific gravity was observed when the MT% increased and the number of blows for CBR were 30. Maximum dry density and optimum moisture content show the similar result as there is gradual increase in their values for increasing modifier percentage and CBR 30. The third row depict effect of modifier type in relevance to the other parameters as it could be seen that the two modifier types used i.e., sludge and eggshell powder both had relatively similar behavior for all the parameters except classification of soil as per AASHTO. Similar trends were observed for liquid limit and plastic limits for CBR 30 and other parameters as with increase in modifier percentage, liquid limit and plastic limit showed a sharp increase in CBR 30 and then a decrease is observed eventually when the modifier increased to 6%. Specific gravity and maximum dry density relation to CBR30 shown in the 7th and 8th rows demonstrated that increase in modifier percentages increased specific gravity and MDD till 4% and showed a decline afterwards. Whereas a declining behavior was seen in specific gravity and MDD for both the modifier types. The eggshell powders and sludge both increased the liquid limit and plastic limit in relevance to specific gravity and maximum dry density as well for CBR30. The CBR 30 when related to specific gravity decreased with the increase in the value of modifier percentage. Similarly with the increase in maximum dry density the

CBR 30 interaction showed decline. The optimum moisture content increased till an increase of 4% of the modifier whereas the optimum moisture content and CBR relationship with modifier type showed that CBR decreased for increasing optimum moisture content. The CBR increased with increase in liquid limit and plastic limit in relevance to optimum moisture content as shown in 5th and 6th graph of the last row. The increasing specific gravity and maximum dry density in relevance to optimum moisture content decreased CBR values as per the model analysis.

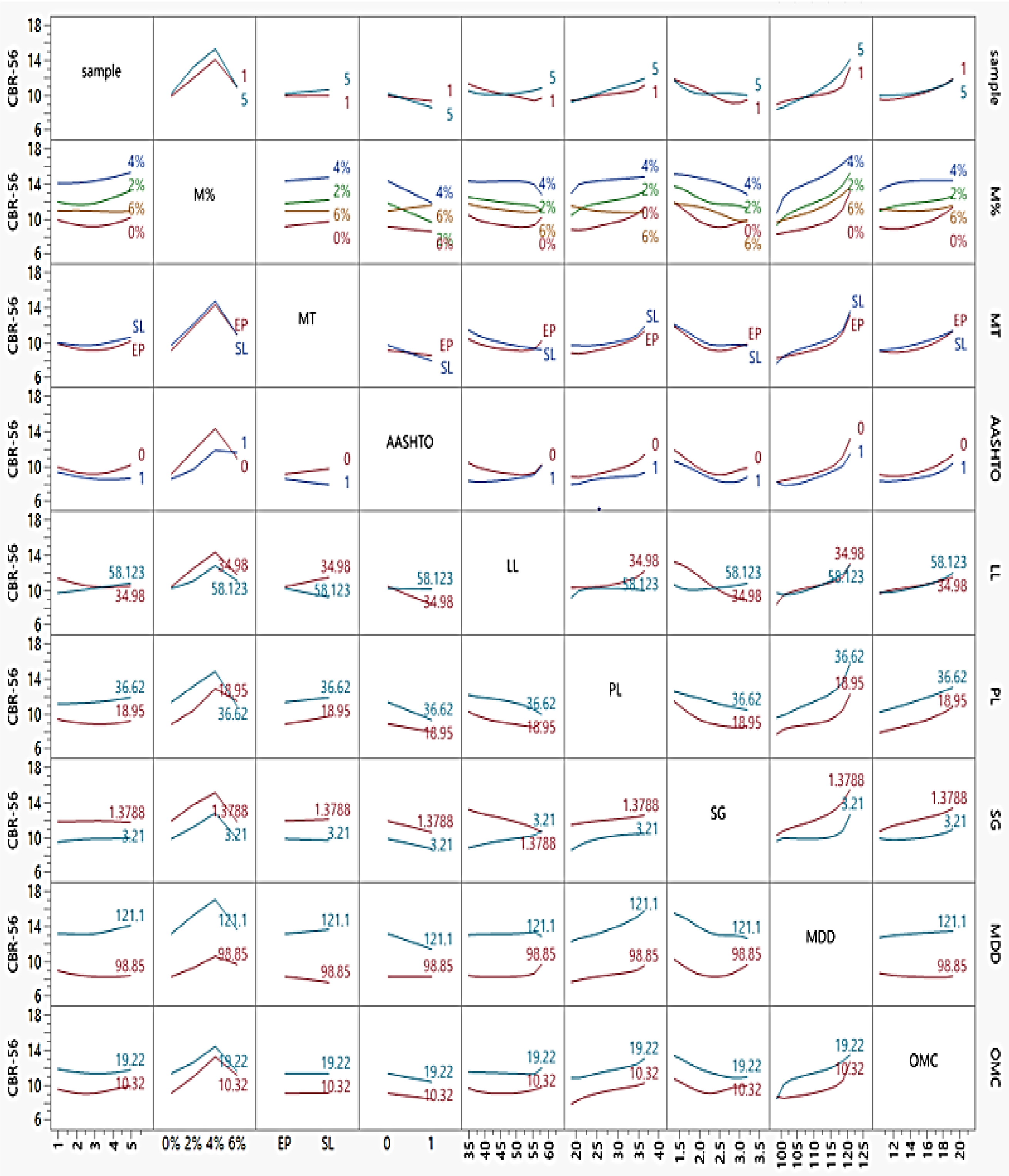
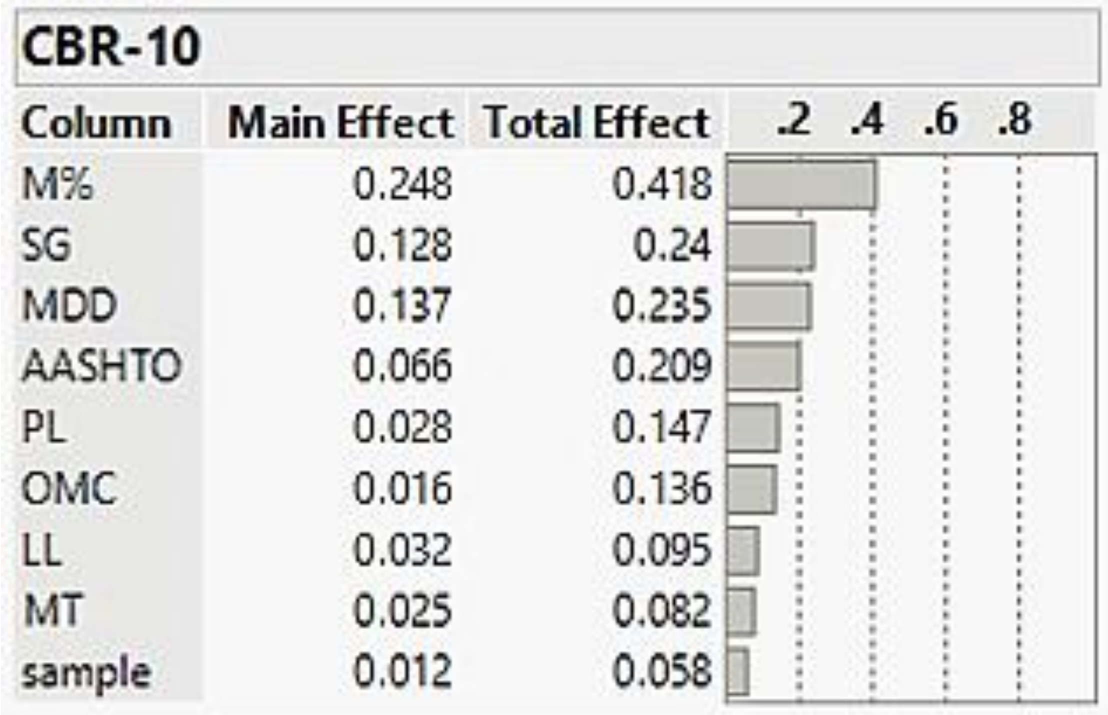


Figure 20 Interaction profile for CBR 56

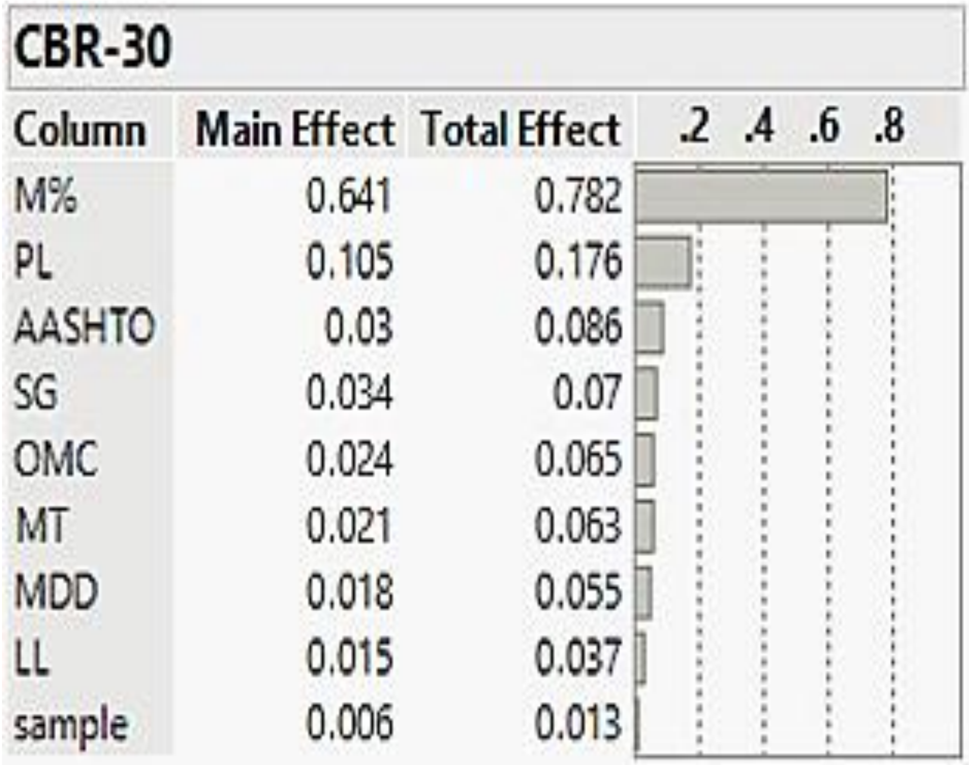
The above prediction profiler graphs are plotted between CBR 56 and other parameters. The first row simply shows very similar behavior because each sample was prepared with same modifier percentage and in similar conditions. In the second row it could be observed that the increase in modifier percentage led to an increase in CBR percentage, the maximum CBR is seen to be observed at 4% addition of the modifier while the minimum CBR is still at 0% addition of any of the modifier. The second graph from left in 2nd row shows that for both modifier types the increase in the modifier percentages increased the CBR. Change in the soil type due to the addition of the modifier either sludge or eggshell powder showed a different behavior of CBR, the soil type changed from clay to silty for 2% and 4% but addition of 6% modifier soil started to shift towards clayey soil. The liquid limit and the plastic limit of the soil slightly increased the CBR with the increase in the modifier percentages whereas the specific gravity led to a decrease in CBR with increasing percentages of modifier. Maximum dry density and optimum moisture content both gradually increased when more modifier was added to soil and similarly the CBR also increased. For the third row the modifier types showed similar results for all the parameters. The liquid limit and plastic limit showed similar trends i.e., CBR increased due to these Atterberg limits until the modifier addition was up to 4% after that gradual decrease in CBR was observed whereas liquid limit and plastic limit were still increasing. The specific gravity and CBR relation remained the same irrespective of the modifier type that was added but when related to liquid limit and plastic limit, increase in these Atterberg limits and specific gravity, the value of CBR slightly decreased. The clearer perspective of interaction profilers can be understood by the variable importance report where independent uniform inputs are represented in the form of bar charts for each CBR as output.



CBR-10			
Column	Main Effect	Total Effect	.2 .4 .6 .8
M%	0.248	0.418	
SG	0.128	0.24	
MDD	0.137	0.235	
AASHTO	0.066	0.209	
PL	0.028	0.147	
OMC	0.016	0.136	
LL	0.032	0.095	
MT	0.025	0.082	
sample	0.012	0.058	

Figure 21 Variable importance: Independent uniform outputs for CBR 10

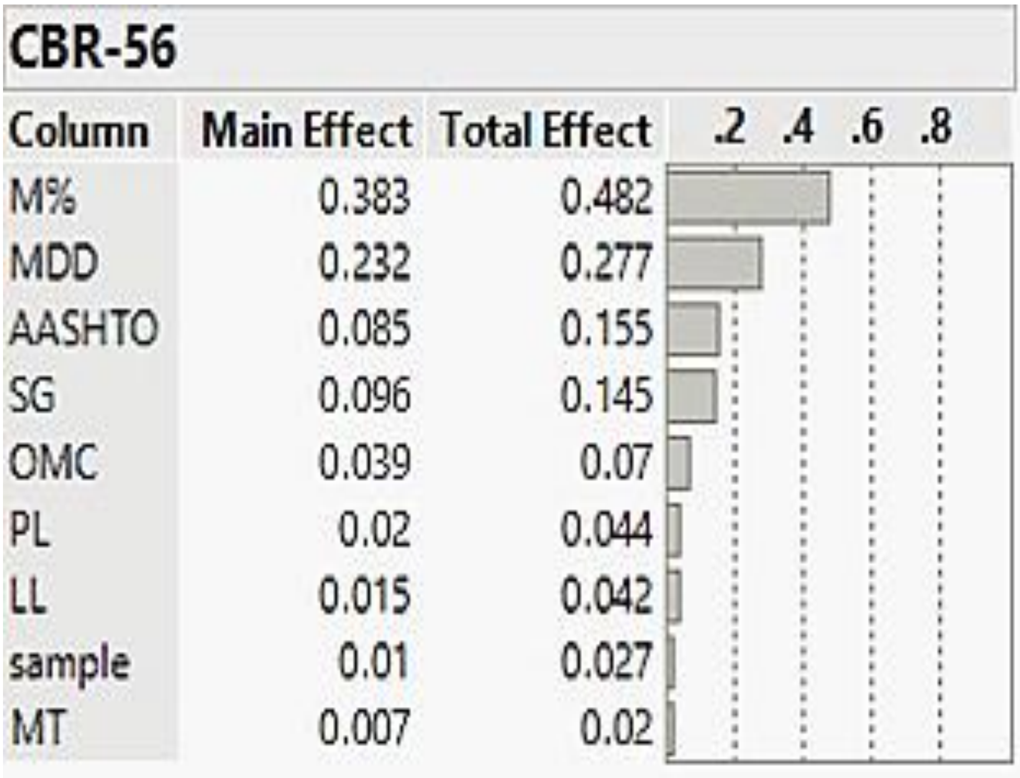
The above figure demonstrates the variable importance for CBR 10. The analysis showed that modifier percentage was the main contributor to the varying CBR percentages in the soil samples. The second most important variable is specific gravity followed by maximum dry density and soil type classified as per AASHTO. As the samples were prepared with same percentages and under similar condition, it was the least important variable with minimum effect whereas modifier type was the 2nd last parameter to have any effect on CBR. Plastic limit and optimum moisture content showed relatively similar importance followed by the liquid limit.



CBR-30		
Column	Main Effect	Total Effect
M%	0.641	0.782
PL	0.105	0.176
AASHTO	0.03	0.086
SG	0.034	0.07
OMC	0.024	0.065
MT	0.021	0.063
MDD	0.018	0.055
LL	0.015	0.037
sample	0.006	0.013

Figure 22 Variable importance: Independent uniform outputs for CBR 30

The number of blows in CBR 30 increased which means compaction was better but still the modifier percentage remained the most important and effective variable followed by plastic limit this time. The soil type according to AASHTO was the third most important variable. Specific gravity, optimum moisture content, and modifier type showed quite similar importance for CBR30. Again, the sample number remained the least important variable whereas the liquid limit was second last important variable.



CBR-56			
Column	Main Effect	Total Effect	.2 .4 .6 .8
M%	0.383	0.482	
MDD	0.232	0.277	
AASHTO	0.085	0.155	
SG	0.096	0.145	
OMC	0.039	0.07	
PL	0.02	0.044	
LL	0.015	0.042	
sample	0.01	0.027	
MT	0.007	0.02	

Figure 23 Variable importance: Independent uniform outputs for CBR 56

The most important parameter for CBR56 was modifier percentage that was added to the soil. CBR56 means 56 number of blows are blown on each of the five layers of soil which gives a better compaction. Increase in compaction directly relates to an increase in dry density of the soil due to which maximum dry density is the second most important variable for CBR56 followed by the type of soil and specific gravity. A very small difference in CBR percentages was observed for both sludge and eggshell powder at CBR 56 due to which modifier type is the least important variable in this case. Other parameters those slightly affected the CBR were OMC, plastic limit, and liquid limit.

5. FINANCIAL AND ENVIRONMENTAL ANALYSIS

5.1. FINANCIAL ANALYSIS OF CEMENT SUBSTITUTION

Cement stabilization is one of the traditional methods of soil stabilization. In this method of stabilization generally a certain amount of cement is added to soil to increase the strength of subgrade. In this research we tested our soil samples with complete replacement of cement. For financial analysis when cement is substituted, let's suppose that we need to stabilize the soil of subgrade of two-lane highway pavement with a width of 12 meter and for just 500m (length) section. The thickness on this upgrade is taken as 0.2 meter. So, for these dimensions the calculated volume of soil is 1200m^3. The density of Nandipur soil Was calculated to be 1649.9 kgm^{-3}.

$$\text{Mass of Soil} = \text{Density} \times \text{Volume} = 1979880 \text{ kg}$$

If 4% cement replacement is required, then.

$$\text{Mass of cement} = 4\% \text{ of } 1979880 = \mathbf{79195.2\ kg}$$

$$1 \text{ cement bag} = 50 \text{ kg}$$

Thus, **1584 bags** of cement will be required. Since one bag of cement at least costs 1100 rupees in Pakistan. So, for 1584 bags of cement the total cost of cement required in the subgrade will be **Rs 1742400.** As we have completely replaced cement for stabilization in our research project so we can save an amount of about 1.7 million rupees for only a small section of road. Therefore, it can be concluded that replacing cement with any Material like sludge and eggshell powder can affect the total cost of the project significantly.

5.2. ENVIRONMENTAL ANALYSIS OF CEMENT SUBSTITUTION

Cement industry according to several researchers is one of the major contributors of CO_2 and many other pollutants in the environment. It is estimated that 0.9 pounds of carbon dioxide are produced for every single pound of cement. As per the calculations done in the previous section of this thesis 79195.2 kilograms of cement will be required for a section of 500m of two-lane highway. So,

$$1kg = 2.204lbs$$

CO_2 produced will be: **157135.97lbs or 32330.094kg**

So, 32330.094kg of CO_2 will be produced for stabilization of such a small section of road. This means replacement of sludge and eggshell powder will be reducing utilization of cement for subgrade stabilization and will be directly reducing the emissions of carbon dioxide in the air. Therefore, utilization of sludge and eggshell powder will be a step towards environmentally friendly and sustainable stabilization.

6. CONCLUSION

This thesis focuses on stabilization of weak soil from Nandipur (Punjab, Pakistan) by using sewage sludge and eggshell powder. These modifiers were added to improve the strength of weak soil with a very low bearing capacity. The addition of 4% of the sludge and eggshell powder changed the soil type from A-7-6 which is a high plastic clayey soil as per AASHTO classification to A-4 which is silty soil and possess relatively better properties. But as soon as the percentage addition of sludge and eggshell powder was increased to 6%, the soil type again started to shift towards clayey properties which was an indication towards weak soil. The addition of Sludge and Eggshell Powder significantly improved the CBR of soil from 8.69% to 14.79% and 16.11% respectively. as well. Moreover, the increase in percentage of modifier up to 4% improved the soil strength thrice the untreated soil. Moreover, the use of artificial neural networks (ANNs) also helped to correlate the relationship between physical properties and strength parameters of soils particularly in correspondence to CBR. The analysis determined the indirect relation of CBR to other parameters of soil which may be helpful in further studies as well to pre-analyze and predict the CBR based on physical properties of soil. The cost and environmental analysis of replacement of cement to soil for a very small section of road was also calculated in this study. It was determined that a significantly huge cost could be saved if cement is replaced by these waste materials and similarly the CO_2 production could be extensively reduced too. The use of these materials can help in promoting circular economy, sustainability, and environmentally friendly stabilization of soil.

7. RECOMMENDATIONS

The following recommendations may be considered for further studies.

- This study has been done on individual addition of sludge and eggshell powders to soil. Further, both the modifiers could be combined in varying ratios and then added to soil to see the combined effect of these.
- As this study has been conducted on high plastic clayey soil of Nandipur, the soil type could be changed in further studies to figure out that either these modifiers will bond with other soil types too or are only limited to this particular soil.

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