A Project report

on

PERFORMANCE ENHANCEMENT OF RED SOIL FOR GEOTECHNICAL APPLICATIONS USING COPPER SLAG AND CEMENT

Submitted in partial fulfilment of the requirements for the award of the degree of

MASTER OF TECHNOLOGY

in

CIVIL ENGINEERING

(With specialization in Geotechnical Engineering)

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CANDIDATE DECLARATION

I hereby declare that the work presented in this report entitled **“PERFORMANCE ENHANCEMENT OF RED SOIL FOR GEOTECHNICAL APPLICATIONS USING COPPER SLAG AND CEMENT”**, in the partial fulfilment of the requirement for the award of the degree of Master of Technology in Civil Engineering with specialization in Geotechnical Engineering submitted in the Department of Civil Engineering, Assam Engineering College, Jalukbari, Guwahati-13 under Assam Science and Technology University, is a work carried out in the said college under the supervision of Dr. Abinash Mahanta, Associate Professor, Department of Civil Engineering, Assam Engineering College, Jalukbari, Guwahati- 13, Assam. Whatever I have presented in this report has not been submitted by me for the award of any other degree or diploma.

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CERTIFICATE OF SUPERVISION

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ABSTRACT

Roads built on weak clay soils with high plasticity can be influenced by the behaviour of these clay soils. Such weak sub-grade clay soils undergo changes in volume due to fluctuations in moisture content, which can trigger cracking, settlement, heaving, and damage to the road pavement, resulting in the degradation of the pavement. To mitigate the swelling of clay soil and enhance soil strength and performance, it is necessary to stabilize these weak sub-grade clay soils. The primary objectives of this research were to investigate the impact of copper slag (CS), both alone and in combination with Cement, on the engineering properties (compaction and unconfined compressive strength) of the composite. To achieve these objectives, a series of extensive laboratory tests were performed on various mixtures (ranging from 5 % to 15 % of CS and 3 % to 9% of Cement by dry weight of the weak subgrade clay soil and also the unconfined compressive strength (UCS) and swelling potential were assessed after longer curing periods.

In general, the study showed that the engineering properties (Compaction, unconfined compressive strength) improved with CS addition and with curing period. The addition of copper slag and Cement to the soil resulted in an enhancement of about 50 % increase in strength of the composite soil reported in the study. For the compaction test, the maximum dry density (MDD) increases while the optimum moisture content (OMC) decreases with increment in CS and Cement content.

The main alterations in the Compaction and the unconfined compressive strength are due to the development of new cementitious materials. The analytical work verified two main reactions when Cement and CS were added to the weak subgrade clay soil, the hydration of CS activated by Cement yield calcium aluminium silicate hydrate paste and hydrotalcite type of phase and the clay soil-Cement reaction yield calcium silicate hydrate, calcium alumina hydrate and calcium alumino silicate hydrate.

The recommendations for further investigations include a study on different curing period with different combination of CS and Cement.

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CHAPTER 1
INTRODUCTION

1.1 General Introduction

The development of any nation relies heavily on a robust and well-integrated road infrastructure system, which serves as the foundation for other infrastructural advancements. The construction and upkeep of highways around the world currently necessitate the utilization of millions of tons of natural aggregates. This need is particularly evident where extensive road networks must be built to promote economic development, including sectors like commerce, agriculture, and industry. Road infrastructures are established over subgrade soils that come with various uncertainties, such as settlement, expansion, and variations in the groundwater table. It is crucial to examine the soil conditions prior to designing the pavement, as both pavement and traffic loads are transferred to the underlying subgrade soils (Bari, 1995; Kok and Khairul, 2001).

Around the world, numerous nations have witnessed a swift rise in civil engineering construction initiatives and the construction sector's engagement in the use of natural aggregates for infrastructure development. The surge in civil engineering construction projects poses a challenge to the availability of suitable naturally sourced aggregates for infrastructure development. Naturally occurring aggregates are being depleted rapidly, while the waste generated by mining industries is significantly increasing (Al-Jabri et al., 2009).

High-quality sub-grade soils are significantly more beneficial for building long-lasting roads. The pavement design team might face challenges with inadequate and weak sub-grade soil. To address this issue in highway construction, various methods can be employed; however, this study focuses on just three.

The first approach involves sourcing appropriate materials from convenient location and replacing the on-site materials with these imported materials. The second approach focuses on enhancing the in-situ geotechnical characteristics of the soil using the standard proctor compaction method and designing modifications accordingly. The third approach aims to improve the properties of the existing sub-grade soil by incorporating or blending additional materials, a process referred to as "soil stabilization" (Ingles and Metcalf, 1972; Little, 1995, 1996 and Puppala et al., 2003).

Biswas and Davenport (2002) describe slag as a glass-like by-product that results from the separation of a desired metal from its raw ore during the smelting process. It can be obtained from ore through either hydrometallurgy or pyrometallurgy. Historically, metallurgical industries have viewed slag as a waste product (Gorai et al., 2002). The European Commission (2012) states that waste from extractive industries must be properly managed to ensure the long-term stability of disposal facilities and to mitigate any potential water and soil contamination from acid or alkaline drainage and the leaching of heavy metals. Current management strategies include the production of value-added products, the recycling and recovery of metals, and the disposal of slag in dumps, stockpiles, or tailing dams.

Failures of copper tailings dams have been associated with significant environmental consequences in the last ten years. Grimalt et al. (1999) documented the 1998 failure of the Aznalcoller tailings pond in Spain, where roughly 2 million cubic meters of mud containing heavy metals were dispersed over an area of 4,286 hectares, affecting both land and surface water. Lungu (2008) pointed out that in 2000, the Nchanga Copper Processing Plant in Zambia experienced a tailings discharge that introduced high levels of heavy metals into nearby surface water, contaminating the local water supply. Likewise, Mutombo et al. (2011) reported pollution of the Katamanda River in Lubumbashi, Democratic Republic of Congo. They found that a nearby heap of slag tailings from the Electronic Foundry Panda Copper Plant (FEP) in Lubumbashi released trace metallic elements, including Co, Cd, Pb, Zn, and Cu, into the Katamanda River. Consequently, it is essential to properly manage copper tailings and copper slag, considering them as viable and environmentally sustainable materials for construction.

Copper slag, has gained prominence in India due to its potential applications in construction and industrial sectors. The country produces approximately 60,000 metric tons of copper slag per month, primarily from states like Madhya Pradesh, Rajasthan, and Jharkhand (B. Jayashree et al,2016).

Cement stabilization is a widely adopted technique to enhance the engineering properties of soils, particularly in infrastructure projects. This method involves mixing cement with soil to improve its strength and durability, making it suitable for construction purposes (Habeeb Solihu). The addition of cement to soil leads to a reduction in plasticity, which is beneficial for construction applications (Neha upadhyay). The effectiveness of cement stabilization depends on factors such as cement dosage, curing methods, and environmental conditions (Suvendu Kumar Das, Dr. S. S. Das).

However, the optimal percentage of cement content varies depending on the soil type, and further research is needed to determine the appropriate amounts for different regions and soil characteristics (Habeeb Solihu).

1.2 Justification

Previous research aimed at assessing the feasibility of using copper slag in the construction sector has identified various applications for copper slag (Collins and Ciesielski, 1994; Zong, 2003; Caliskan and Behnood, 2004; Al-Jabri, 2006):

- Material for pavement or highway aggregate
- Alternative to Portland cement (as a binder)
- Utilized as an abrasive tool
- Replacement for fine and coarse aggregates in concrete, among others.

A considerable amount of research on copper slag utilization has primarily focused on enhancing the strength of concrete, while limited investigations have explored the use of copper slag in strengthening weak subgrade clay soils for road construction (Collins and Ciesielski, 1994; Zong, 2003; Caliskan and Behnood, 2004; Behnood, 2005; Al-Jabri, 2006; Wu et al., 2010). Nevertheless, there is scant research on employing copper slag as an admixture/stabilizer or binder to enhance weak clay subgrade materials. This study was conducted to furnish information regarding the potential of copper slag as an admixture/binder for the strength enhancement of clay subgrade materials and to evaluate its appropriateness as a subgrade material for roadway construction.

The Sterlite copper smelting plant in Thoothukudi has indiscriminately dumped 5,37,765 tonnes of copper slag in various places including the banks of Uppar river, even though various research papers published by highly reputed international journals have confirmed that there is a huge adverse environmental impact due to the dumping of slag in the open, the State government has told the Madras High Court.

The motivation of this research is grounded in the environmental issues and the financial implications of disposing of copper slag waste in recent decades, alongside the scarcity of natural, high-quality subgrade materials for road construction. Utilizing this material is believed to offer both environmental and economic advantages.

1.3 Aim

The main aim of this research was to study the stabilization of weak subgrade clay soils utilizing copper slag and Cement.

1.4 Scope

The purpose of this research was to investigate the stabilization of weak clay subgrade soils using copper slag (CS), and Cement with and to enhance the engineering characteristics of weak clay subgrade soils. To fulfil the aims of this study, the following scope was established:

I. Characteristics investigated include particle size distribution, specific gravity, liquid and plastic limits, optimum moisture content, maximum dry density

II. To study the effect of copper slag on the engineering behaviour of the weak subgrade clay soil

III. To study the effect of Cement on the engineering behaviour of the weak subgrade clay soil

IV. Study the effect of combination of Cooper slag and Cement with different percentages.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

In this chapter, a literature review is carried out on clay soil mineralogy, the structure of the clay mineral in particular montmorillonite and kaolinite, production and composition of copper slag (CS), properties of copper slag (CS) and copper slag (CS) stabilization. The effect of copper slag (CS) on the engineering properties of the soil and the clay-cement reactions. Particular consideration is given to Cement stabilization, including the general soil-cement reaction, volume stability, plasticity, strength and the compaction characteristics.

Balasingam Muhunthan et al (2008) – This study's first section provides a thorough examination of how different additives are used in soil development programs. The effects of cement treatment on the geotechnical properties of soils from the Palouse, Everett, and Aberdeen regions of Washington are then analysed in detail. It was discovered that the use of cement enhanced the soils' workability, compaction qualities, and pace of drying. Significant increases in unconfined compressive strength and elastic modulus are obtained by treating these soils with cement. Undrained triaxial test results showed that different forms of failure behaviour were observed despite the fact that cement treatment greatly enhanced shear strength. Cement treatment of 5%, 10%, or no cement resulted in ductile, planar, or cracking failure modes, in that order. Pore pressures swiftly rose to confining pressures in soils treated with 10% cement, leaving zero effective confining pressure at failure. The specimens split vertically as a result. Consequently, large cement percentages should only be used in field applications under the closest supervision, even though cement treatment may boost strength.

2.2 The Composition of Soil and Clay Minerals

2.2.1 Soil Composition

According to Peck and Terzaghi (1948) ‘soil’ is a natural aggregate of mineral grains that can be classified by gentle means of agitation in water”. Soil is regarded in general as any loose material at the earth’s crust.

2.2.2 Clay Minerals

Any fine-grained, natural earth material which when mixed with water develops plasticity is called clay. The fundamental characteristic of clay soil is plasticity. Clay comprises of alumina, water and silica with little amount of alkali and iron. Clay that does not have plasticity when mixed with water is called flinty clay (Grim, 1953). Civil engineers define the maximum clay particle size as 2 μm.

Clay minerals play an essential role in industry product and building construction (Van Olphen, 1977; Mateos, 1964). In addition, clays are of particular concern to geotechnical engineers, highway engineers and civil engineers globally in construction projects. The presence of clay minerals in the soil is essential as it controls the soil properties such as volume stability, plasticity and reactivity. Non-clay minerals may also be present in the soil and these can be identified by X-ray diffraction analysis, where different non-clay minerals are separated from the clay minerals on the X-ray diffraction diagram.

2.2.3 General Clay Minerals Structure

According to Grim (1968), the atomic lattice of the majority of clay minerals consists of a tetrahedral silica unit and an octahedral aluminium unit or an octahedral magnesium unit. The tetrahedral silica unit comprises of silicon atom at equal distance of four oxygen atoms or hydroxyl ions that are needed to balance the electrical charge of the structure. The tetrahedral silicate groups are usually placed to form a hexagonal network that is repeated to create a sheet with distinctive composition of $Si_4O_6(OH)_4$ (Figure 2.1). The tetrahedral units are positioned in such a manner that all the points above are in alignment with the plane of their bases (Brown, 1984).

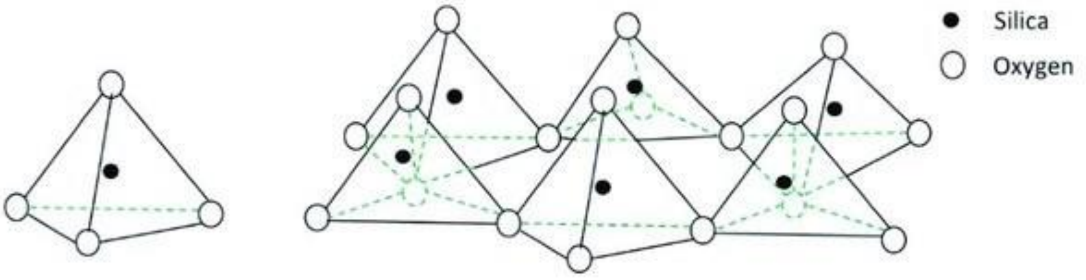


Figure 2.1 Sketch showing (a) single silica tetrahedron unit and (b) the sheet structure of the tetrahedra piled in hexagonal network after Grim (1962)

The octahedral crystal unit structure centre is occupied with aluminium, magnesium or iron atom which is surrounded by six hydroxyls (Figure 2.2). When aluminium is present, two thirds of the potential cations positions are filled up to balance the structure electro-charge forming gibbsite with a chemical formula Al2(OH)6. The presence of magnesium only indicates that all potential positions are occupied resulting in the clay mineral brucite with a formula Mg3(OH)6 (Grim, 1968).

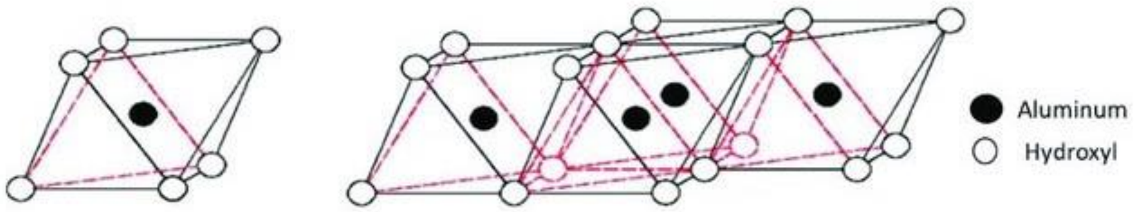


Figure 2.2 Sketch showing (a) single octahedron unit and (b) sheet structure of octahedral unit (Grim,1962)

Majority of the clay minerals consist of two main structural layers piled in various sorts. The order of arrangement of the layers influences the clay mineral chemical and physical characteristics greatly. There are clay minerals that are fibrous with different structural units from the above mentioned one (Grim, 1953; Van Olphen, 1977). The structural unit consists of silica tetrahedron placed in double chain order (Figure 2.3). The structure looks similar to that of silica tetrahedrons sheet, with one plane in a continuous direction while the other is subjected to the width which is about 11.5 Å.

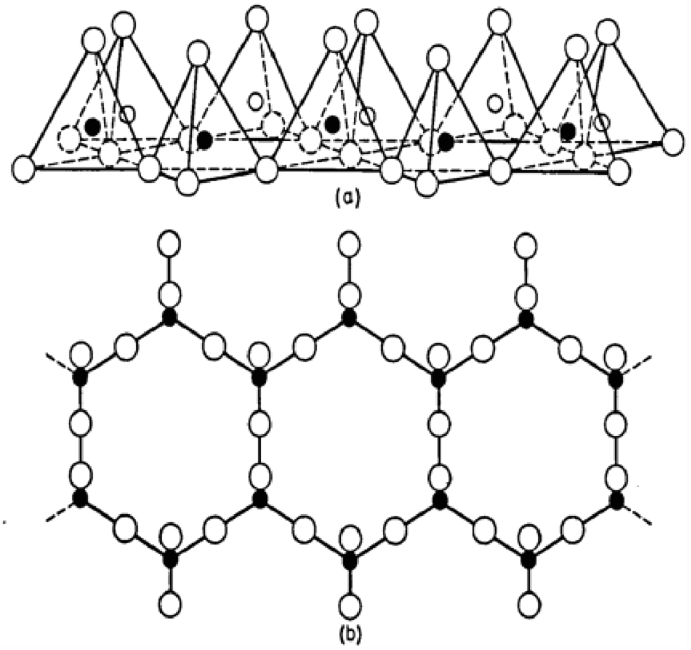


Figure 2.3 Sketches of double chains silica tetrahedra as in the amphibole structure types of clay minerals (a) in perspective (b) projected on the plane of the bases of tetrahedrons (Grim, 1962)

According to Grim (1962) montmorillonite, kaolinite and illite are the most common clay minerals in engineering practices during construction.

2.2.4 MONTMORILLONITE

The weathering of volcanic ash under deplorable drainage condition results in the formation of montmorillonite. Montmorillonite holds a higher liquid limit and higher activity than kaolinite and illite. The shrinkage and swelling potential of montmorillonite are several times higher than its volumetric dryness. The basic structural unit of montmorillonite is a gibbsite sheet $Al_2(OH)_6$ between two sheets of silicate. This mineral structure is three-layers sheet units arranged one above another (Yong and Warkentin, 1966).

Relatively weak hydrogen bonds exist between successive crystal units. The bond strength lies upon exchangeable cations involved. Other cations and water molecules can go in between the sheets, making them to be separated and cause expansion of the particles and split the mineral up into unit layers. Montmorillonite has a small particle size with a specific surface area of 800 g/m2 considering area of the surface charge and it displays high plasticity, swelling, cohesion and shrinkage characteristics based upon exchangeable cation involved.

Grim (1968) showed the chemical formula for montmorillonite as $(OH)_2\ Si_8Al_4O_{20}.nH_2O$ with approximate composition of 5 % of H_2O, 28.3 % of Al_2O_3 and 66.7 % of SiO_2. Aluminium can partially substitute silicon in the tetrahedral sheet and aluminium can be substituted by magnesium. This process of substitution is called isomorphous substitution which is the prime factor of influences in cation exchange capacity. Soils with large magnitude of montmorillonite are unsuitable sub-grade material due to the propensity of large quantity of water adsorption and large volume changes during wet and dry conditions (Mitchell, 1976).

2.2.5 KAOLINITE

The kaolinite structure consists of a single silicate tetrahedral sheet and single alumina octahedral sheet. Kaolinite minerals consist of piled layers with hydrogen bonding between hydroxyls of alumina sheet and oxygen of the silicate sheet (Grim, 1968). Due to the strong hydrogen bonding, the typical kaolinite crystal comprises of approximately 100 layers of kaolinite mineral piled unitedly and it is very hard to disunite. Kaolinite clay mineral has the largest crystals and smallest specific area of 10-20 g/m2 which is due to the strong hydrogen bonding, water molecules and ions between layers which make it hard to break through the layers. The lattice of kaolinite is regarded as non-expansive based on the surface area at which water molecules is attractable to; is limited to the external surface. Kaolinite has a very low plasticity than other clay mineral types.

Kaolinite clay mineral has a lattice ratio of 1 silica :1 alumina sheet. The structural formula of this mineral is $Si_4Al_4O_{10}\ (OH)_8$ with the approximation of the composition of 13.96 % of H_2O, 39.50 % of Al_2O_3 and 46.54 % of Si_2. The interlayer basal unit spacing is 7.2 Å and the number of isomorphous substitutions is less and the flawlessness of the crystal is greater than other clay minerals (Ross and Kerr, 1931; Grim 1962).

2.2.6 ILLITE

Illite has a structure similar to that of montmorillonite. What make them different are their individual layers which are joined together by potassium ions. The system is especially stable because the potassium ions precisely fit within the hexagonal space formed by oxygen ions on the silicate sheets surface. The surface activity and specific surface are lesser than those of montmorillonite. It has an intermediate activity between montmorillonite and kaolinite (Grim, 1962).

2.3 Adsorption of Water at Clay Surface

According to Gillot (1987); Yong and Warkentin (1975) clay particles in soils are surrounded by layers of water molecules adsorbed on to the clay particle always during wet conditions which keeps the soil hydrated. These water molecules are regarded as a part of the surface of clay due to the consideration of the behaviour of clay soils. Clay soil properties including strength, plasticity, compaction and water movement in soil are all affected by the water layer.

Bell (1983) indicates that due to the changes in moisture content resulting in swelling and shrinkage, clay soils undergo volume changes. Clay soil ability to absorb water contributes to swelling while when it is dry it shrinks. According to Gillot (1987) clay soil properties including cation exchange capacity, organic matter content, degree of consolidation and specific surface area are influenced by cementitious agents' presence. The minerals are bonded together by cementitious agents that result in the suppression of the swelling of the clay soil by surface area open to moisture reduction, and by enhancing the materials strength which places an internal expansion constraint.

2.4 Plasticity and Activity of Clay

Atterberg (1911) proposed that soil plasticity properties should be indicated in terms of liquid limit (LL), plastic limit (PL) and plasticity index (PI). Allen (1942) defined plastic limit as the lowest moisture content expressed as a percentage by weight of oven dried soil at which the soil can be rolled into threads 3mm in diameter without breaking into pieces. Liquid limit is the moisture content expressed as a percentage by weight of the oven dried soil at which the soil will just begin to flow when jarred somewhat. Plasticity index is defined as the difference between the liquid limit and plastic limit. It is the range in which the moisture content of the soil is plastic. According to Yong and Warkentin (1966); Terzaghi (1925) water content below which the physical properties of the soil no longer correspond to those of free water is considered as the lowest water content at which the cohesion between particles or groups of particles is sufficient to allow movement but higher to allow particles to maintain the molded position.

Grim (1962) refers to the activity of the soil as the ratio of the plasticity index to the clay size fraction (percentage by weight of the particles finer than 2µm). Activity has been considered a very useful value in indicating plasticity index of the clay fraction of the soil. Activity indicates the ability of clay soils to react with chemical agents' present in the soil. The activity of kaolinite varies from 0.01 to 0.41 and that of montmorillonite varies from 0.5 to 7 all depending on the proportion of clay.

2.5 Ion Exchange

The substitution of one ion on the clay lattice surface by another ion is called ion exchange. Clay soils physical properties depend on exchangeable ion and the exchange of ions are of great importance where clay is being used. The types of exchangeable cation available in the clay make the plastic properties of clay enormously different.

According to Grim (1962, 1968) clay soil surface is generally negatively charged. This leads to the attraction of cation to the surface of the particle. He indicated that the most important sources of negative charge on the clay are as follows:

a. Replacement with the lattice structure of trivalent aluminium Al^{3+} for quadrivalent silicon Si^{4+} in the tetrahedral sheet and lower valence ions Mg^{2+} for trivalent aluminium Al^{3+} in the Octahedral sheet leads to unbalanced charge within the clay structure of some minerals of the clay. The imbalanced charges might be balanced either by other lattices (OH^-) for O^{2-} adsorption of positive cations.
b. b. Due to broken bonds around the edges of the silicate-alumina unit leaving unbalanced charges which are balanced by adsorbed cations. The exchange capacity increases as the particle size decreases based on the number of broken bonds per unit mass.

Yong and Warkentin (1975) referred to exchangeable cation as the positively charged ion from salts in the pore water that is attached to the clay particles surface to balance the surplus negative charge. The occurrence of cation exchange is because one cation is substituted by similar valence. For instance, when clay with sodium as the exchangeable cation is washed with calcium chloride solution, each one of the calcium ions will substitute two sodium ions and this leads to the expulsion of sodium from the solution (see Eqn 2.1).

$$2Na\ Clay + CaCl_2 \longrightarrow Ca\ Clay + 2NaCl \qquad [Eqn.\ 2.1]$$

The cations are arranged in series on the basis of their substituting power. In general, the substitution order of adsorbing cation is: $Li^+ < Na^+ < H^+ < K^+ < NH << Mg^{2+} < Ca^{2+} << Al^{3+.}$

Any cation at equal concentration will tend to substitute those to its left in the series (Grim, 1968).

Exchangeable cation is defined as the cation exchange capacity which is expressed in milliequivalent of cations per 100 gram of dry clay soil (meq3/100g). The definition of milliequivalent is possibly one milligram of hydrogen ions (H+) or number of other cations which will substitute it on the surface of the clay mineral. The measurement of cation exchange capacity is at pH 7 and when the pH is less than 5, the cation exchange capacity is at a constant (Grim, 1962). Table 1.1 shows the cation exchange capacity for the three most common clay minerals.

Table 2.1: Values of Cation exchange capacities by (Wu, 1976)

Clay Mineral	**Exchange Capacity (meq^3/100g)**
Montmorillonite	80 – 150
Illite	10 – 40
Kaolinite	3 – 15

It is observed from Table 2.1 that the clay mineral with largest net negative charge is montmorillonite due to its large specific surface area. The cation exchange capacity of montmorillonite is tremendously high in comparison to illite and kaolinite.

2.6 Soil Stabilization

Several authors have described the properties of soil altered by the addition of other materials (Grim, 1968; Ingles and Metcalf, 1972; Arabi and Wild, 1989 and Higgins et al., 1998). These properties include strength, volume change and plasticity. Some chemical agents utilized include cement, fly ash, sodium chloride, alkali-activated blast furnace, lime etc. with their modification abilities greatly dependent on the magnitude of the clay minerals, type of stabilizer and percentage, moisture content, percentage of clay fraction, temperature, organic matter content in the soil, and curing time and conditions (Mitchell and Hooper, 1961).

According to Mitchell and Hooper (1961) soil stabilization is used to amend deficient soil mechanical properties in civil engineering infrastructure construction projects such as highways pavement, sub-grades, sub-bases, shallow foundation and runways. Hence, the stabilization types selected in any construction project depends on the nature of the project and the properties of the soil (Abdi, 1992).

2.6.1 Copper Slag Production

Copper slag is produced by hydro-metallurgical or pyrometallurgical production of copper from copper ores and it contains material like iron, alumina, calcium oxide, silica etc. (Gorai et al, 2002). The hydro-metallurgical method is considered as flotation method of recovering copper from secondary copper slag or by-product that still has about 0.8 % Cu and other valuable minerals in the slag content produced by pyrometallurgical method. The pyrometallurgical method of production is the only method applicable to ores containing copper-iron-sulphide minerals namely chalcopyrite and chalcobornite which are the most plethoric. The properties of copper slag comprise of the mineralogical and chemical compositions, physical and mechanical properties.

Copper slags are generally suitable for recycling, reuse and use as alternative materials in roads construction and other geotechnical applications. Copper slag can serve as an effective stabilizing agent for the improvement of weak subgrade clay soil, highway construction, embankment fill, sub-base and sub-grade. Copper slag has high angularity and friction angle up to 52 ° of aggregate which contribute to stability and load bearing capacity. It can be used as an alternative aggregate in bituminous mix and other construction aggregates (Collins and Ciesielski, 1994; Zong, 2003 and Caliskan and Behnood, 2004 and Al-Jabri, 2006).

BS 6699 (1986) suggests that whenever chemical stabilization is to be done, the chemical modulus should be calculated in order to ensure an acceptability level of reactivity of the chemical to be used (Eqn 2.1).

$$\frac{CaO + MgO + Al2O3}{SiO2} > 1 \qquad [Eqn.2.1]$$

DIN 1164 also suggests that the chemical modulus should be calculated as shown in Eqn. 2.7 a and b. The chemical modulus should be more than one and the lime/silica ratio (CaO/SiO2) should be less than 1.4.

$$\frac{CaO + MgO + \frac{1}{3}Al2O3}{SiO2 + \frac{2}{3}Al2O3} > 1.0 \qquad [Eqn.2.2a]$$

$$1.4 < \frac{CaO + MgO + 0.56Al2O3}{SiO2} < 2.2 \qquad [Eqn.2.2b]$$

2.6.2 Mineralogical Composition of Copper Slag

Kiyak et al. (1999) through microscopic studies indicated that most copper slags are well crystallized. Moreover, iron oxides and other oxides such as silica, alumina, lime and magnesia constitute 95 % or more of the oxides. They indicated that X-ray diffraction pattern or shape shows $2FeOSiO_2$, Fe_3O_4 and Ca (Mg, Fe) $(SiO_2)_3$ as the principal phases present in copper slag.

According to Najimi et al. (2011) the mineralogical compounds found in copper slag are magnetite (Fe_3O_4), anorthite ($CaAl_2Si_2O_8$), quartz (SiO_2) pyroxene ($CaZnSi_2O_6$) and fayalite (Fe2SiO4) similar to the principal compound of copper slag used in previous study such as magnetite, fayalite and quartz (Tixier et al., 1997; Arino and Mobasher, 1999; Moura et al., 1999 and Sanchez de Rojas et al., 2008 and Alp et al., 2008).

2.6.3 Chemical Property of Copper Slag

The chemical properties and composition of copper slag from different regions around the world are presented in Table 2.2. The properties vary based on the type of processing methods used in the extraction of copper and other minerals.

Table 2.2: Typical chemical property and the composition of copper slag

No	**Origin of copper slag**	**Al2O3**	**SiO2 (%)**	**CaO (%)**	**Fe2O3**	**Cu (%)**	**S (%)**	**MgO (%)**	**K2O (%)**	**Na2O (%)**
1	National Iranian Copper, Iran	3.78	40.7	5.24	44.78	0	1.06	1.16	0	0
2	Kure Copper Slag, Turkey	6.8	26.1	0.7	47.8	0.82	1.5	1	0	0
3	Copper Queen, Prince, USA	14.7	27.16	17.42	34.62	1.64	0.33	3.51	0	0
4	Etibank Ergani Copper Plant, Turkey	2.4	31.95	3.95	39.65	1.01	0	2.82	0	0
5	Tsumeb, Namibia	2.82 - 18.5	9.83 - 35.5	2.29 - 17.44	8.42 - 64.22	0.49 - 12.13	0	0.69 - 5.10	0.10 - 0.93	0.25 - 1.87
6	Copperbelt Province, Zambia	3.9 - 12.60	15.53 - 60.18	3.18 - 21.87	0.68 - 18.79	< 2	0	0.64 - 6.45	1.13 - 4.83	0.03 - 0.30
7	Okiep copper district, South Africa	3.50 - 12.16	43.76 - 66.52	1.57 - 4.22	12.76 - 29.87	0.015 - 0.53	0	1.89 - 10.28	0.32 - 0.82	0.19 - 1.54
8	Sterlite Industries India Limited (SIIL), Tuticorin, Tamil Nadu, India	0.22	25.84	0.15	68.29	0	0.25	0	0.23	0.58

1. Marghussan et al., (1999) 2. Yocel et al., (1999) 3. Mobasher et al., (1996) 4. Kiyak et al., (1999), 5. Etter et al., (2009); 6. Vítková et al., (2010) 7. Rozendaal and Horn, (2013) and 8. Brindha et al (2010)

2.6.4 Physical and Mechanical Properties of Copper Slag

Copper slag (air cooled and granulated) has many favourable physical and mechanical properties that make it suitable as construction material. Due to the high internal friction angle of copper slag, it has excellent soundness characteristics, good abrasion resistance, good skid resistance and good stability. The air-cooled copper slag aggregates are black in colour and typically have a glassy appearance while granulated copper aggregates are similar to the air-cooled type but more vesicular. Copper slag can be processed into fine or coarse aggregate and screened to produce aggregates which satisfy the gradation requirements. The unit weight of air-cooled copper slag is 2800 kg/m3 to 3800 kg/m3 while granulated copper slag has a low unit weight than air-cooled slag ranging from 1000 kg/m3 to 1500 kg/m3. The unit weight of copper slag is comparably higher than that of conventional aggregate. Water absorption capacity of air-cooled slag is typically very low about (0.13 %), while granulated copper slag has higher water absorption (Scullion et al., 2008). Granulated copper slag is more porous, has low specific gravity and is made up of regular shape, angular particles, mostly between 0.075 mm and 4.75 mm in size which is similar to conventional fine aggregate for concrete particle size range (Hughes and Haliburton, 1973; Emery, 1986). Table 2.8 shows the typical physical and mechanical properties of copper slag.

Table 2.3 Typical physical and mechanical properties of copper slag

Properties	**Appearance and unit**
Physical state at 20 °C and 101.3 kPa	Solid
Colour	Black glassy
Melting Point	1027 ° C - 1341 ° C
Unit Weight	2800 kg/m3 - 3800 kg/m3
Buck Density Conductivity	2300 kg/m3 - 2600 kg/m3
Angle of internal friction	40 ° C -50 ° C
Specific gravity	2.8 - 3.8
Hardness	6 - 7 mol
Moisture Content	< 5 %
Abrasion loss	24.1 %
Sodium sulphate soundness loss	0.90 %
Water absorption	0.13 %

After Hughes and Haliburton, (1973), Feasby, (1975), Emery, (1986), EU No. 453 Commission Regulation, (2010) and Das et al., (1993)

2.7 Cement

2.7.1 Introduction

Cement stands as an elemental force in the realm of construction, anchoring the structures that shape our urban landscapes and define the contours of our modern living spaces. This ubiquitous binding material plays a pivotal role in the evolution of architecture and engineering, serving as the bedrock upon which our built environment rests. Cement, in its contemporary form, is a finely ground powder composed primarily of limestone, clay, silica, and iron ore. The manufacturing process involves heating these raw materials to high temperatures in a kiln, resulting in a clinker that is subsequently ground into the fine powder we recognize as cement. This transformation releases calcium silicates and aluminates, the compounds responsible for cement's remarkable binding properties.

2.7.2 Types of cement

There are several types of cement, each designed to meet specific construction needs and requirements. Here are some common types of cement:

2.7.2.1 Ordinary Portland cement (OPC):

OPC is the most widely used type of cement and is suitable for general construction purposes. It's a hydraulic cement that hardens over time through a chemical reaction with water. OPC is manufactured by heating limestone and clay or other materials in a kiln at a high temperature. The resulting clinker is then ground into a fine powder, which is the cement.

2.7.2.2 Portland pozzolana cement (PPC):

Portland Pozzolana Cement (PPC) is a type of hydraulic cement that is produced by combining Portland cement clinker with pozzolanic materials. The pozzolanic materials, such as fly ash, volcanic ash, or silica fume, are added to enhance the properties of the cement. The term "Pozzolana" comes from the name of a volcanic ash found near the city of Pozzuoli in Italy, which was historically used as a pozzolanic material. The addition of pozzolanic materials to Portland cement improves certain characteristics of the cement, such as durability, workability, and long-term strength.

2.7.2.3 Rapid hardening cement (RHC):

Rapid Hardening Cement (RHC), also known as High Early Strength Cement, is a type of Portland cement that is designed to develop higher strength at an early age compared to Ordinary Portland Cement (OPC). This property makes it particularly useful in situations where quick setting and early strength gain are crucial, such as in cold weather concreting or when a rapid construction pace is required. The manufacturing process of rapid hardening cement is similar to that of OPC, but the clinkering temperature is higher, resulting in a finer grind of the cement clinker.

2.7.2.4 Low heat cement (LHC):

Low Heat Cement (LHC) is a type of Portland cement designed to generate less heat during the hydration process compared to Ordinary Portland Cement (OPC). The reduced heat of hydration is beneficial in certain construction scenarios where the risk of thermal cracking or damage from the heat generated during cement hydration needs to be minimized. The manufacturing process of low heat cement is similar to that of OPC, but specific adjustments are made to the composition to control the heat released during the hydration reactions.

2.7.3 Properties of a good quality cement

- The chemical composition of cement, including the amount of calcium, silica, alumina, iron oxide, and other components, must comply with established standards.
- Good quality cement should have a fine and uniform particle size distribution.
- Cement should have a well-defined setting time, indicating the time it takes for the cement paste to change from a plastic state to a solid state.
- Cement should have well-defined initial and final setting times.
- The colour of cement is typically Gray. Significant variations in colour may indicate impurities or inconsistent manufacturing processes.

2.7.4 Use of cement in soil stabilization

Cement is often used in soil stabilization to improve the engineering properties of soil, making it more suitable for construction and infrastructure projects. Soil stabilization with cement involves the addition of cementitious materials to the soil to enhance its strength, durability, and load-bearing capacity. This process is commonly employed in the construction of roads, embankments, foundations, and other structures.

Cement reacts with the soil particles, forming cementitious bonds that increase the overall strength of the soil. Stabilizing soil with cement reduces its plasticity and susceptibility to changes in moisture content. Soil stabilization with cement enhances the load-bearing capacity of the soil, making it suitable for supporting heavy structures and traffic loads. Soil stabilization with cement allows for quicker construction by reducing the time required for soil consolidation and curing.

The stabilized soil gains durability and resistance to environmental factors, ensuring the long-term stability of constructed structures. Soil stabilization with cement can be a cost-effective alternative to other foundation or soil improvement methods.

2.7.5 Precautions while handling cement

- Workers should use waterproof and alkali-resistant gloves to protect their hands from cement's caustic properties.
- Safety goggles or a face shield should be used to protect the eyes from cement dust and splashes.
- A dust mask or respirator should be used if cement dust is present, especially in enclosed or poorly ventilated areas.
- Proper ventilation should be ensured in areas where cement is being mixed or used to avoid inhaling dust.

2.7.6 Action of cement in soil

When cement is mixed with soil, important processes occur that change the physical characteristics of the soil and make it more suitable for building and stabilization. These reactions are called cementation and hydration. Here’s a brief note on these reactions –

2.7.7 Hydration Reaction

When cement is mixed with soil and water, the hydration process begins. The primary compounds in cement, such as tricalcium silicate (C_3S) and dicalcium silicate (C_2S), react with water to form calcium silicate hydrate (C-S-H) and calcium hydroxide ($Ca(OH)_2$).

- **$C_3S + \text{Water} \rightarrow \text{C-S-H} + Ca(OH)_2$**

- **C_2S + Water → C-S-H + $Ca(OH)_2$**

The hydration reaction is exothermic, releasing heat, which can further accelerate the reaction process.

2.7.8 Cementation Reaction

The main binding component that adds to the cement-soil mixture's strength and durability is the C-S-H gel that is created during hydration. This gel binds soil particles together by filling up the spaces between them. Particularly in clayey soils, the $Ca(OH)_2$ created during hydration elevates the pH of the soil, creating an alkaline environment that encourages additional interactions with soil minerals.

In the presence of certain soil types, particularly those containing silica and alumina, the $Ca(OH)_2$ reacts with these components to form additional cementitious compounds.

- SiO_2 (from soil) + $Ca(OH)_2$ → C-S-H
- Al_2O_3 (from soil) + $Ca(OH)_2$ → Calcium Aluminate Hydrate

These cementitious compounds grow and mature over time, greatly enhancing the compressive and shear strengths of the soil. The soil can get even stronger over time as a result of the prolonged hydration and pozzolanic reactions.

2.8 Slag Activation

Slag can be activated in many different ways but the most common is by chemical activation. In chemical activation, an activator or an alkali medium is needed. Many activators have been proposed to activate slags. The most commonly used activators are ordinary Portland cement, calcium sulphate, sodium hydroxide, sodium sulphate, calcium hydroxide and sodium carbonate (Gjorv, 1989). Wu et al. (1990) proposed that sodium sulphate, potassium aluminum sulphate and sodium hydroxide can be used as activator and can assist in breaking the Al-O and Si-O bonds. According to Wild and Tasong (1999) when lime was employed as an activator in a study to influence slag in the sulphate resistance of lime-stabilized kaolinite, they noticed an optimum slag/lime ratio of 1:5 to activate the slag and to prevent it from attack by the excess sulphate solution. They also observed that the lime activated slag hydration reaction is faster than that of pozzolanic reaction of lime-clay. The principal reaction products of slag activated by lime are calcium aluminate silica hydrate (C-A-S-H) gel and hydrotalcite type phases made up of magnesium due to the high alumina and silica content.

The most commonly used activator is Portland cement. The reaction of slag with Portland cement and water is a complex process. Water hydration of Portland cement produces mainly calcium hydroxide $Ca(OH)_2$ and calcium silica hydrate (C-S-H) gel. In the hydration of blended Portland cement minor quantities of alkalis are released while slag is mainly activated by the hydration product $Ca(OH)_2$ (Hakkinen, 1993). Therefore, lime in the form of $Ca(OH)_2$ may be added as an additive or released from Portland cement hydration due to the high aluminium, iron and silica content in slag which produces slightly different hydrates from Portland cement (Higgins et al., 1998). The principal reaction products of slag hydration are calcium aluminate hydrate, calcium silicate hydrate and small quantities of calcium hydroxide.

2.8.1 Hydration Products and Mechanism of Slag Cement Mixture

Wild et al. (1999) and Tasong et al. (1999) indicate that slag hydration products utilizing alkali are mainly calcium silicate hydrate and hydrotalcite type phase containing magnesium. Song et al. (2000) indicated the formation of the hydrotalcite type phase in higher pH paste along with calcium silicate hydrate and also indicated that the pH of the mixing solution may affect the nature of the calcium silicate hydrate and its Ca/Si ratio. Similarly, the solubility of Si increases with higher pH solution while that of Ca decreases with a higher pH solution which is a result of C-S-H with a lower Ca/Si ratio. The hydration process when water is added to slag-cement mixture can be summarized as follows:

- Water begins to combine with Portland cement and calcium silicate hydrate begins to form.
- The other reactions products of Portland cement are calcium hydroxide and later sodium and potassium hydroxides.
- These alkalis activate the slag which reacts with the water to produce hydrate similar to those produced by Portland cement hydration.
- The excess silicates and aluminates from the slag hydration combine with the calcium hydroxide in a pozzolanic reaction.

Hydrotalcite is a mineral that can be easily crushed into a white powder similar to talc. It is also a hydroxyl carbonate of magnesium and aluminium and occur in nature in foliated and contorted plates or fibrous masses. The hydrotalcite type of hydroxyl compounds observed during slag cement hydration reaction have the compositions of the type in Eqn. 2.9;

$[R_{1-k}{}^{2+}R_k{}^{3+}(OH)_2]^{+k} + k\ .R_{k/r}{}^{r}\ .JH_2O$ [Eqn. 2.9]

Many of these minerals and synthetic compounds have the composition of this type with R2+ = $Mg^{2\ +}$, the divalent cation at the octahedral site within hydroxyl layers, $R^{3+} = Al^{3+}$ or Fe^{3+}, the trivalent cation at the octahedral site within hydroxyl layers, Rr =OH^{-}, SO^{4}, is an exchangeable interlayer anion, J = 1; k lies mainly in the range of 0.20 – 0.33 and is equal to the ratio of $R^{3+}/\ (R^{2+}\ +\ R^{3+})$. Among natural minerals, hydrotalcite is typical with the approximate formula $Mg_6Al_2\ (OH)_{16}\ CO_3\ .4H_2O$ which corresponds with k = 0.25 in the general formula. The brucite-like hydroxide layers of this material structure consist of positively charged k per formula unit balance by equal negatively charged interlayer anions. The layer spacing depends on the nature of the interlayer anions and the state of hydration and to a lesser extent on the magnitude of the electrostatic attraction between layers and interlayers (Brindley and Kikkawa, 1979; Mascolo and Marino, 1980; Miyata, 1983; Mills et al., 2012).

2.8.2 Effect of Copper Slag on the Engineering Behaviour of Clay Soil

The activation of slag by lime affects many engineering properties of soil. The effects of slag activated by lime on the plastic limit (PL), liquid limit (LL), plasticity index (PI), maximum dry density (MDD), volume stability and swelling potential, optimum moisture content (OMC) and the UCS are discussed below.

2.8.2.1 Effect of Slag on the Consistency Characteristics

The addition of slag to clay soil changes the consistency characteristics of the clay soil. According to Akinmusuru (1991) the consistency, strength and compaction characteristics of lateritic soil effects are depending on the slag content that varied from 0 % to 15 % by dry weight of soil. He observed a reduction in both the plastic and liquid limits and an increase in the plasticity index with increasing proportion of added slag.

Wild et al. (1996) noticed that small additions of lime to kaolinite clay produce an easily noticeable rise in the plastic limit while the liquid limit might decrease or increase in a way that there is a rise in plasticity index with an increasing percentage of lime.

2.8.2.2 Effect of Slag on the Compaction Characteristics of Soil

Akinmusuru (1991) indicated that the addition of slag up to 10 % to soil raised the maximum dry density and above which the maximum dry density will decrease. This could have been due to the rise in fine powder in the mixture which contributes to the reduction in the proportion of the coarse material making it not easy to achieve better compaction.

2.8.2.3 Effect of Slag on the strength of Soil

The primary advantages of lime/slag usage are relative to the use of lime alone at which the rate of strength development is slow and prolongs the construction time to completion and increase the long-term strength that improves the performance of the structure.

Wild et al. (1999) indicated that slag decreased the strength of kaolinite clay in the presence of sulphate as the ratio of slag/lime was raised. The outcome from slag activated by lime reaction is more rapid than kaolinite-lime reaction.

Akinmusuru (1991) noticed an increase in cohesion with an increasing slag content up to 10 % after which there is decrease in the internal friction angle with increase in percentage of slag content. He noted an increase in the CBR with an increase in slag percentage up to 10 % slag content and a reduction in value thereafter.

2.9 Curing Condition

The curing conditions comprising time, temperature and relative humidity are of great significance in influencing the strength increase and the final strength of the soil mixtures. According to Laguros et al. (1956) the pozzolanic reaction rate increases with increase in the temperature. Bell (1988 a, b) indicate that higher curing temperatures speed up the reaction and result in an early higher strength to be achieved. Many authors have confirmed this including Marks and Halliburton (1972) and Al-Rawi and Awad (1981); Wild et al. (1989). It was established by Mateos (1964) that clay soil specimens cured at 35°C produced twice the strength of those that were cured at 25°C. Thompson (1970) indicated that no pozzolanic reaction can occur below 4°C because it is low temperature that retard the strength of development

CHAPTER 3
MATERIALS AND METHODS

3.1 Introduction

In this chapter, a description of the materials used and the primary testing methods applied in the study are presented. Two types of materials namely natural soil from boreholes and stabilizers comprising of copper slag and Cement were used.

The testing procedure is subdivided in three parts namely; characterization tests, engineering tests and analytical methods. The characterization tests include specific gravity, Atterberg limits and gain size distribution tests. The engineering tests comprise of compaction and unconfined compressive strength tests. X-ray diffraction (XRD) analyses were used to provide some indications of the characteristics of the primary materials and the reaction products.

3.2 Materials

3.2.1 Red Soil

Soils used for this research were obtained from nearby hills around the Assam Engineering college. The sample was selected from random site as per shown in the map (Figure 3.1).

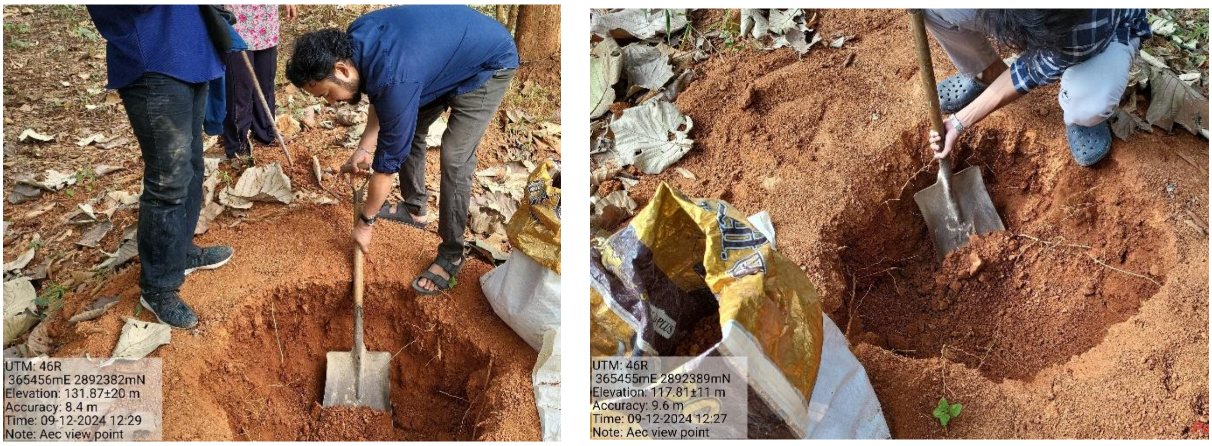


Fig 3.1: Sample Collection

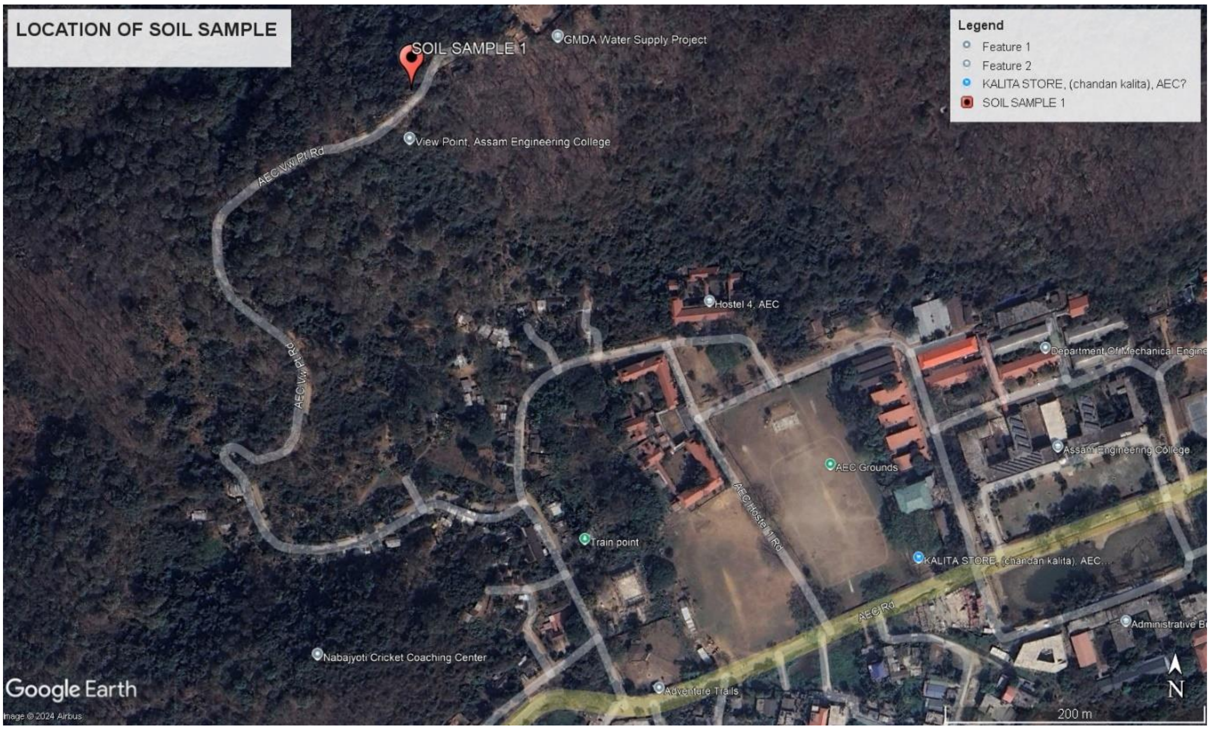


Fig 3.2: Location of soil sample (Near Assam Engineering College View Point)

(Source: Google Earth Pro)

3.3 Stabilizers

3.3.1 Copper Slag

Copper slag used for this study was obtained from KEDIA MINERALS located in KEDIA CHAMBERS, F-109, Venketeshwar Tower, Near Cine Star, Central Spine, Vidhyadhar Nagar, Jaipur, Rajasthan. The physical properties and chemical composition of this material are presented in Chapter 4.

3.3.2 Cement

Cement used in this study was obtained from local market. Dalmia cement was chosen for the test mixture.

3.4 Testing Methods

3.4.1 Specific Gravity Measurement

Specific gravity measurements are made in accordance with IS-2720 (Part 3/ Section 1)-1980: Technique for soil testing. Section Eight Section 1: Specific Gravity Determination soil with fine grains. The mass density of soil at standard temperature of 27℃ is equal to that of distilled water, which is known as the specific gravity of soil particles. It is the mass of a particular volume of soil divided by the mass of a corresponding volume of water. The letter G stands for it. A digital balance, vacuum desiccator, oven, and density container with a 50 ml capacity are among the equipment needed to conduct this test. The following steps are part of the procedure:

- Firstly, the density bottle was cleaned and dried properly before conducting the test.
- The density bottle along with the stopper been weighed and demoted as M1.
- 5-10g of soil sample was taken in the density bottle and weigh the bottle along with the stopper as M2.
- Now add distilled water to the soil in the density bottle upto the soil level and shake gently to mix soil and water.
- Now the stopper of density bottle was removed and placed in the vacuum desiccator and connect the vacuum pump.
- Take out the bottle after attaining constant temperature and dry the outer surface using cloth and weighed the bottle as a total of mass of bottle, soil and water as M3.
- In the last step, bottle was emptied and filled solely with distilled water along with stopper and weighed as M4.

The specific gravity is determined by the following equation,

$$G = \frac{(M2-M1)}{(M4-M1)-(M3-M2)}$$

Fig 3.3: Density Bottle with soil sample

3.4.2 Proctor test

In accordance with IS: 2720 (Part 7) 1980, the standard Proctor's compaction test was conducted in the lab, and the optimal moisture contest corresponding to the maximum dry density was determined.

The following steps make up the Proctor Compaction Test process:

a) About 3 kg of soil was obtained.
b) Then the soil was passed through the No. 4 sieve.
c) The mass of soil and the mould (W_m) without the collar are weighed.
d) The soil was placed in the mixer and gradually more water was added to it to reach the desired moisture content (w).
e) The collar was then coated with lubricant.
f) The soil was taken out of the mixture and added to the mole in three layers in the following phase. The compaction procedure necessitates 25 blows for per layer. After then, the droplets were applied steadily by hand or mechanically. The dirt then fills the mole and reaches, but does not penetrate, the collar by more than 1 cm.
g) As the collar was being carefully lifted from the dirt, it was trimmed with a straight edge that had been sharpened so that it extended above the mould.
h) Then the weight of the mould and soil (W) was noted.

i) In a subsequent stage, a metallic extruder is used to extrude the soil from the mold in a manner that aligns the extruder with the mould.
j) The water content of the sample was then measured at the top, middle and bottom.
k) The soil was then placed again and water was added to it to achieve a higher water content.

3.4.3 Atterberg Limits

3.4.3.1 Liquid limit test

In compliance with IS specification IS:2720 (Part 5)-1985, this test was carried out. The water content that corresponds to the arbitrary boundary between the plastic and liquid limits is known as the liquid limit (WL). The lowest water content at which soil retains its liquid condition yet has a minimal shearing power to resist flowing is known as the liquid limit. Plotting a graph between cone penetration (x) and water content (y) will reveal the soil's liquid limit. The 20 liquid limit is then determined by taking the water content that corresponds to a cone penetration of 20 mm. The graphs' set of values indicates that the penetration should range from 14 to 28 mm. This experiment was conducted using a 425µ passing IS sieve.

3.4.3.2 Plastic limit test

In compliance with IS specification IS:2720 (Part 5)-1985, this test was carried out. The ability of soil to undergo fast deformation without rupture, elastic rebound, or volume change is known as plasticity. The water content that separates the plastic from the semi-solid soil consistency states is known as the plastic limit (WP). It is the lowest water content at which, when rolled into a thread about 3 mm in diameter, the soil will just start to collapse. This experiment uses a 425µ sieve for passage. IP = WL-WP is the plasticity index.

3.4.4 Specimen Preparation for Unconfined Compressive Strength Test

As per **IS: 2720 (part10)-1991**, soil specimens with a diameter (d) of 38 mm and a length (l) to diameter ratio of 2 are subjected to unconfined compression tests. The optimum moisture contents were used in this study to obtain the maximum dry density for each individual mixture.

Fig 3.4: Unconfined Compressive Strength Test Setup

CHAPTER 4
ENGINEERING PROPERTIES TESTS RESULTS

4.1 Introduction

The effects of CS with and without Cement on some engineering properties that include compaction and unconfined compressive strength (UCS) of the soil are presented.

4.2 Chemical and Engineering Properties of the Soil, Cement and Copper Slag

Figure 4.1 presents samples of the natural soil, copper slag and hydrated lime. Results of the particle size distribution analysis of the natural soil, copper slag are presented in the grading curves shown in Figure 4.2 and Figure 4.3. Table 4.1 presents the physical, mineralogical and engineering properties of the natural soil, copper slag and hydrated lime while Table 4.2 presents the chemical oxides and their proportions in the natural soil, copper slag and hydrated lime.

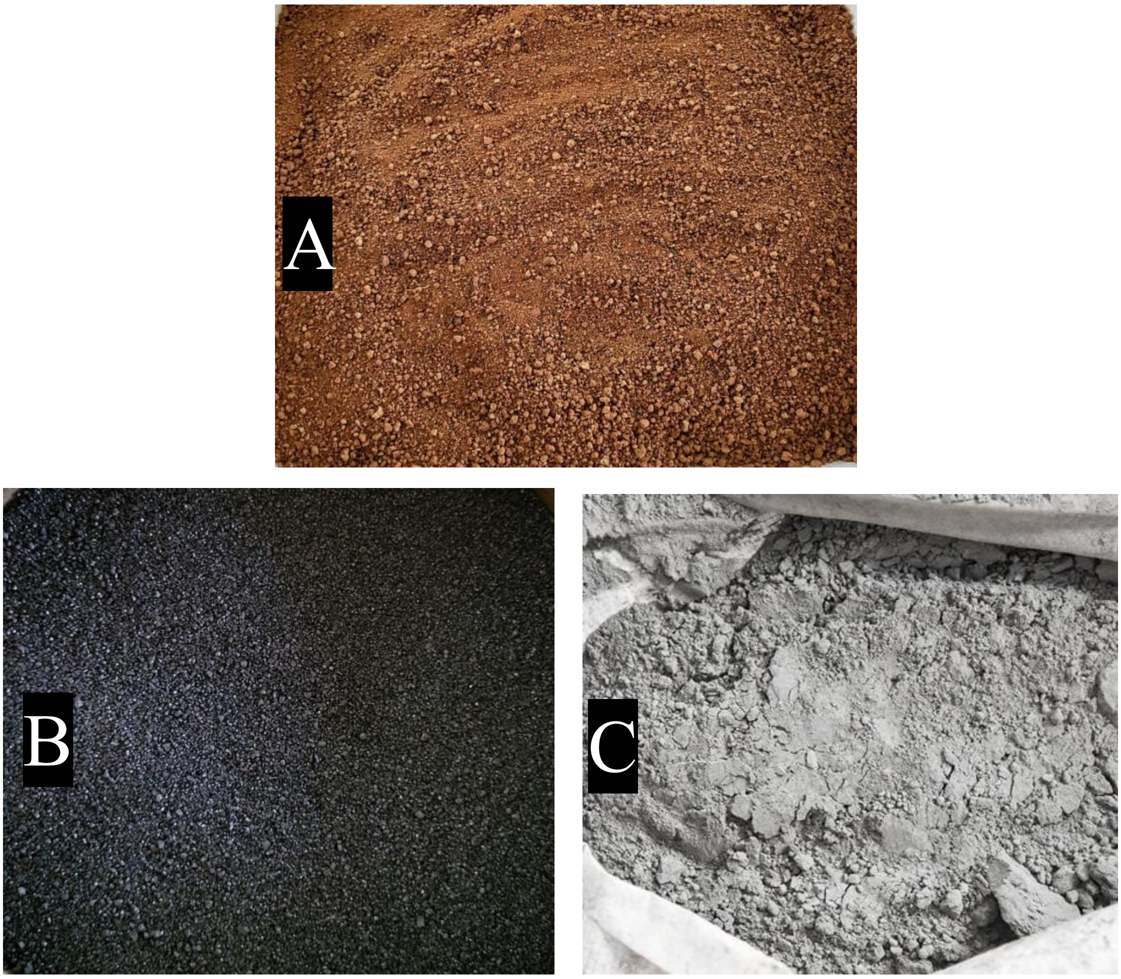


Fig 4.1: A) Natural soil, B) Copper slag and, C) Cement

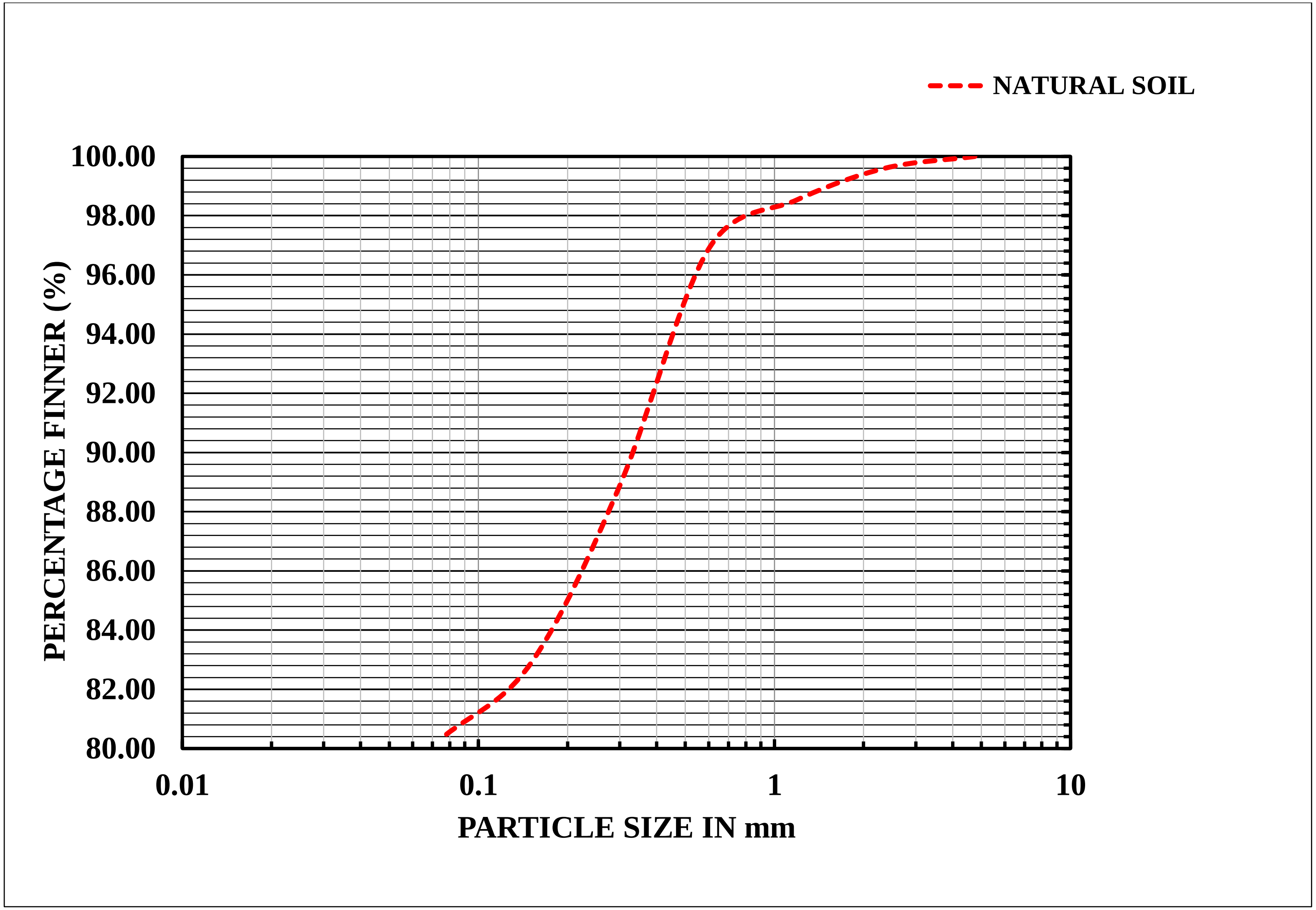


Fig. 4.2: Gradation curve for Natural Soil sample

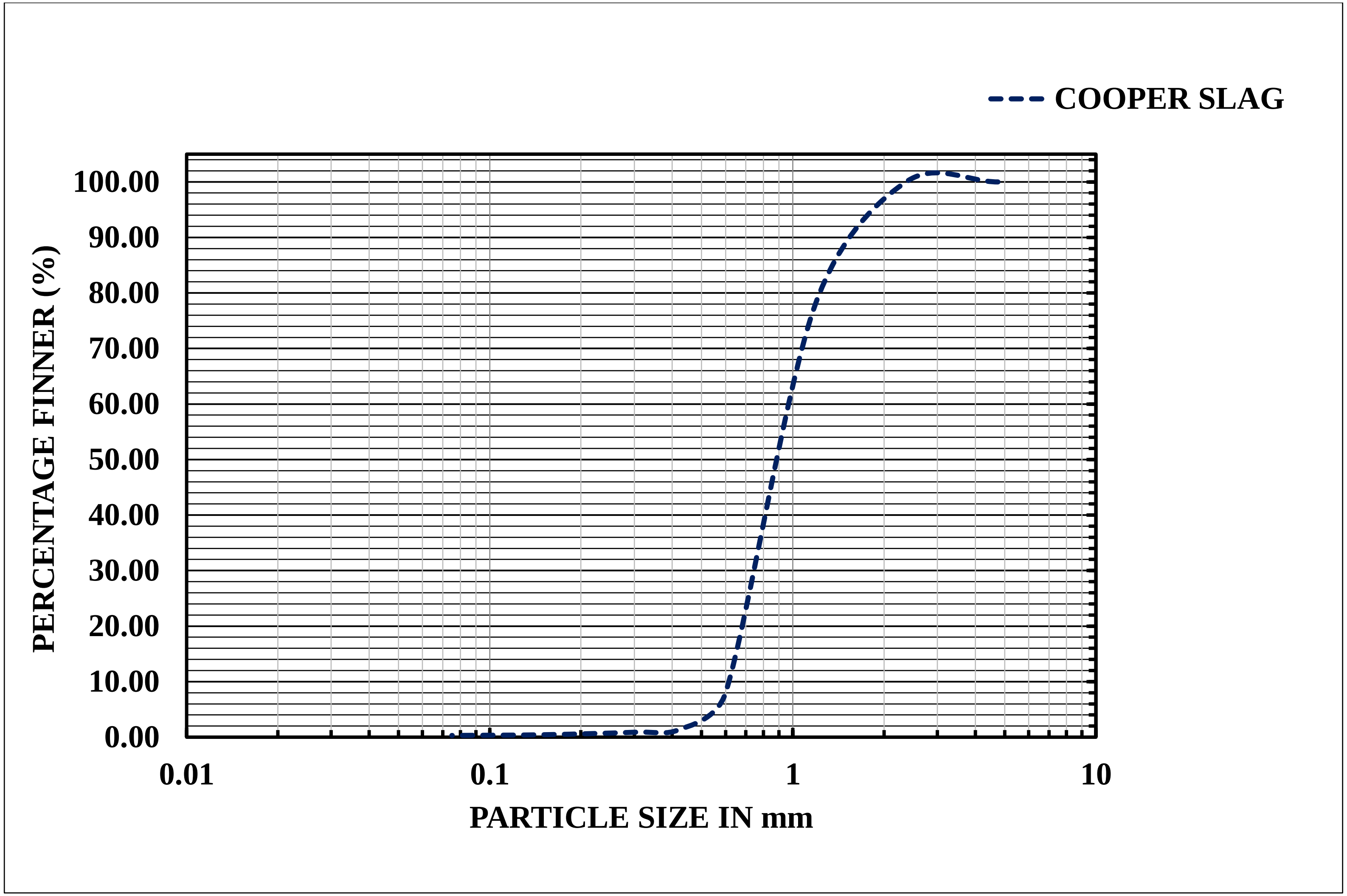


Fig. 4.3: Gradation curve for Cooper Slag

Table 4.1: Physical, mineralogical and engineering properties of the natural soil, copper slag and Cement

Physical Property	**Natural Soil**	**Cooper Slag**	**Cement**
Gravel	10 %	5 %	
Sand (2 mm – 0.075 mm)	20 %	94 %	
Silt + Clay (< 0.075 mm)	70%	1 %	
Specific Gravity	2.58	3.8	3.1
Liquid Limit	60 %		
Plastic Limit	33.24 %		
Plasticity Index	26.76 %		
Maximum Dry Density (Gm/cm3)	1.55		
Optimum Moisture Content (%)	25.25	< 5	
Casagrande			
Textural	Clay		
Appearance:	Reddish brown colour	Black glassy, vesicular when granulated	Dry powder
Unit Weight		2162.49 Kg/m^3	1,440 kg/m^3
Water Absorption		0.01 %	
Bulk Density		1842.12 Kg/m^3	1,300 kg/m^3
Conductivity		500 µs/cm	
Hardness		7 mol	
Abrasion loss		23.60 %	
Sodium sulphate Soundness loss		0.85 %	
Angle of internal friction		46^o	
Specific surface area			
Melting point/decomposition temperature		1259 ^{o}C	

Table 4.2: Chemical oxides and the percentage present in natural soil, copper slag and Cement

Chemical Oxides	Natural Soil (%)	Copper Slag (%)	Cement (%)
Fe_2O_3		53-60	3-6
SiO_2		32-37	20-35
Al_2O_3		3-6	5-10
CaO		1-3	50-60
MgO		1-2	< 5
Zn		<1.0 %	
SO_3			2-3

4.3 Compaction Characteristics of the Soil, Copper Slag and Cement as Activator

4.3.1 Moisture Content and Dry Density Relationship

Moisture content - dry density relationship was established through the proctor compaction test. The test was conducted on the soil with varying quantities of added copper slag (CS) and also mixtures of soil with 5 %, 10 % and 15 % total binder content (CS) by weight of dry soil. Furthermore, the test was performed on soil in which CS was replaced by Cement with total binder content of 3 %, 6 % and 9 %. Compaction curves for these samples are presented in Figures 4.4, 4.5 and 4.6. From the compaction test, the natural soil dry density increases to a maximum value of 1.55 gm/cm^3 called the maximum dry density (MDD). The moisture content corresponding to the maximum dry density termed as the optimum moisture content (OMC) was determined to be 25.25 %. In Figure 4.3, 5 % addition of binder content to the natural soil resulted in an increase in the MDD to 1.59 gm/cm^3 and a decrease in the OMC to 24.2 %. The combination of CS with Cement at 3%, 6% and 9% cement content result in increase in the MDD to 1.63 gm/cm^3, 1.64 gm/cm^3 and 1.66 gm/cm^3 respectively and the corresponding OMCs decreased to 24 %, 23.5 % and 23 %.

Again 10 % addition of binder content to the natural soil resulted in an increase in the MDD to 1.60 Gm/cm3and a decrease in the OMC to 23.8 %. The combination of CS with Cement at 3%, 6% and 9% cement content result in increase in the MDD to 1.61 gm/cm^3, 1.625 gm/cm^3 and 1.65 gm/cm^3 respectively and the corresponding OMCs decreased to 23.2 %, 23 % and 22.45 %.

Further, 15 % addition of binder content to the natural soil resulted in an increase in the MDD to 1.69 gm/cm^3 and a decrease in the OMC to 22.58 %. The combination of CS with Cement at 3%, 6% and 9% cement content result in decrease, increase and again decrease in the MDD to 1.67 gm/cm^3, 1.68 gm/cm^3 and 1.65 gm/cm^3 respectively and the corresponding OMCs decreases to 21 %, 21.8 % and 20.5 %.

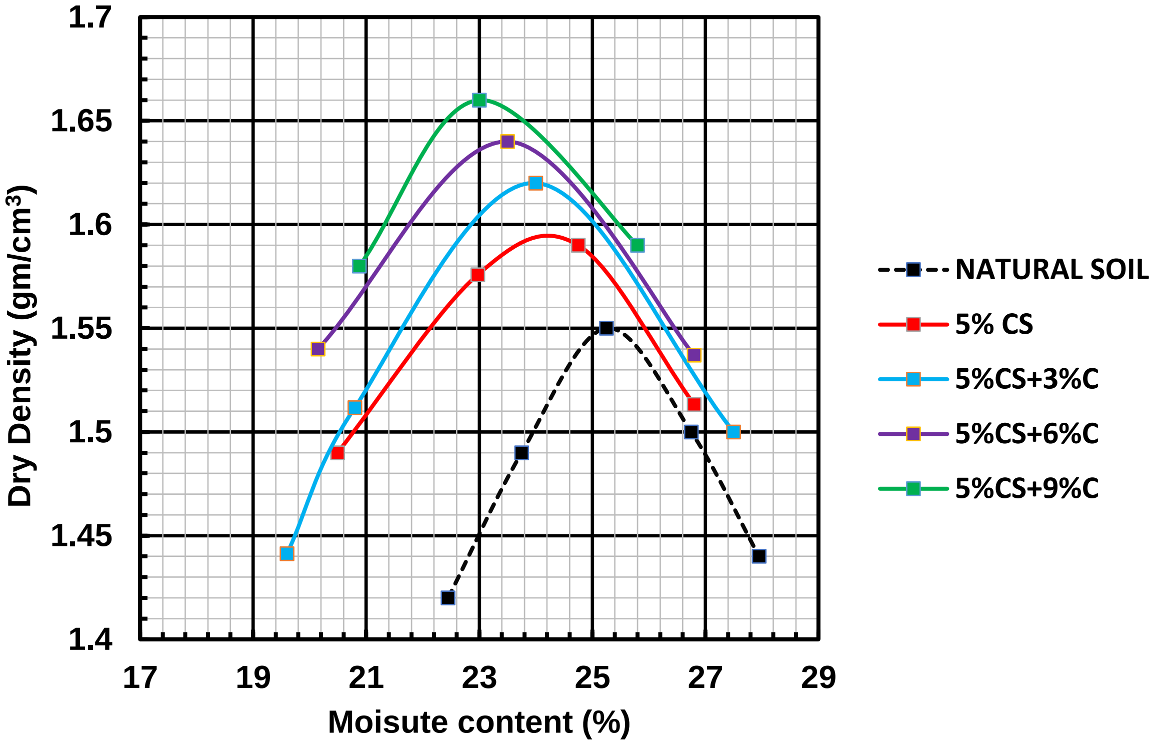


Fig 4.4: Compaction curves for the natural soil, natural soil + 5 % CS and Natural Soil+ 5 % CS with 3 %, 6 % and 9 % Cement mixture

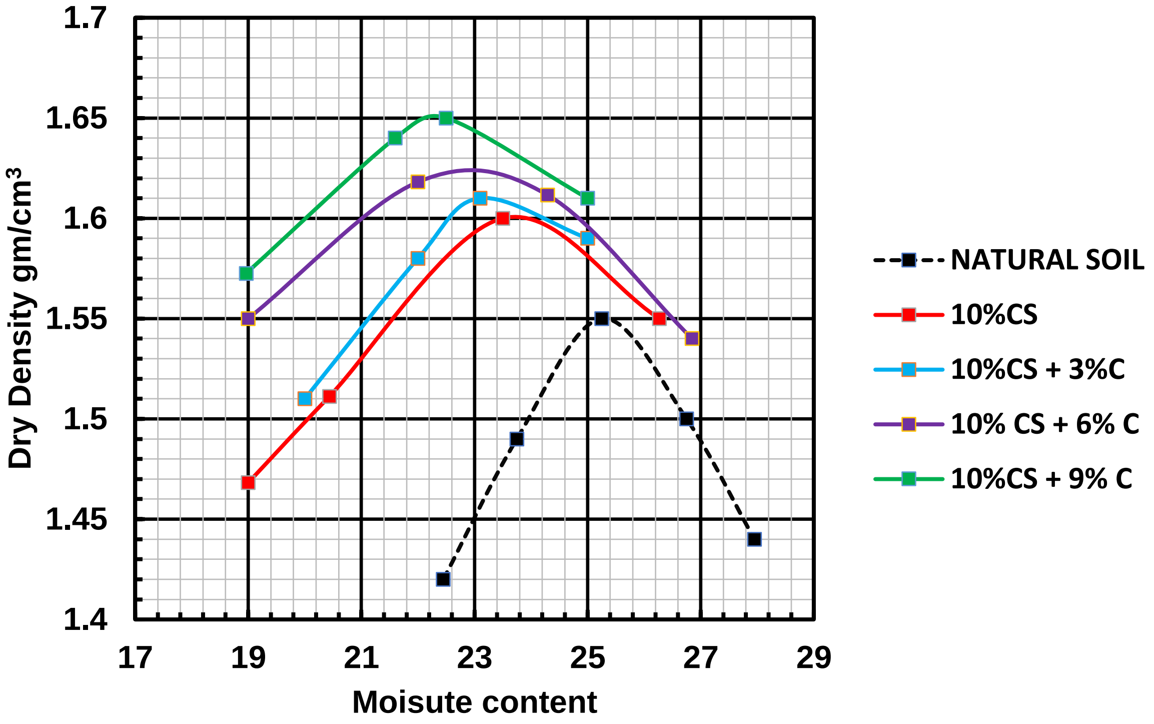


Fig 4.5: Compaction curves for the natural soil, natural soil + 10 % CS and Natural Soil+10 % CS with 3 %, 6 % and 9 % Cement mixture

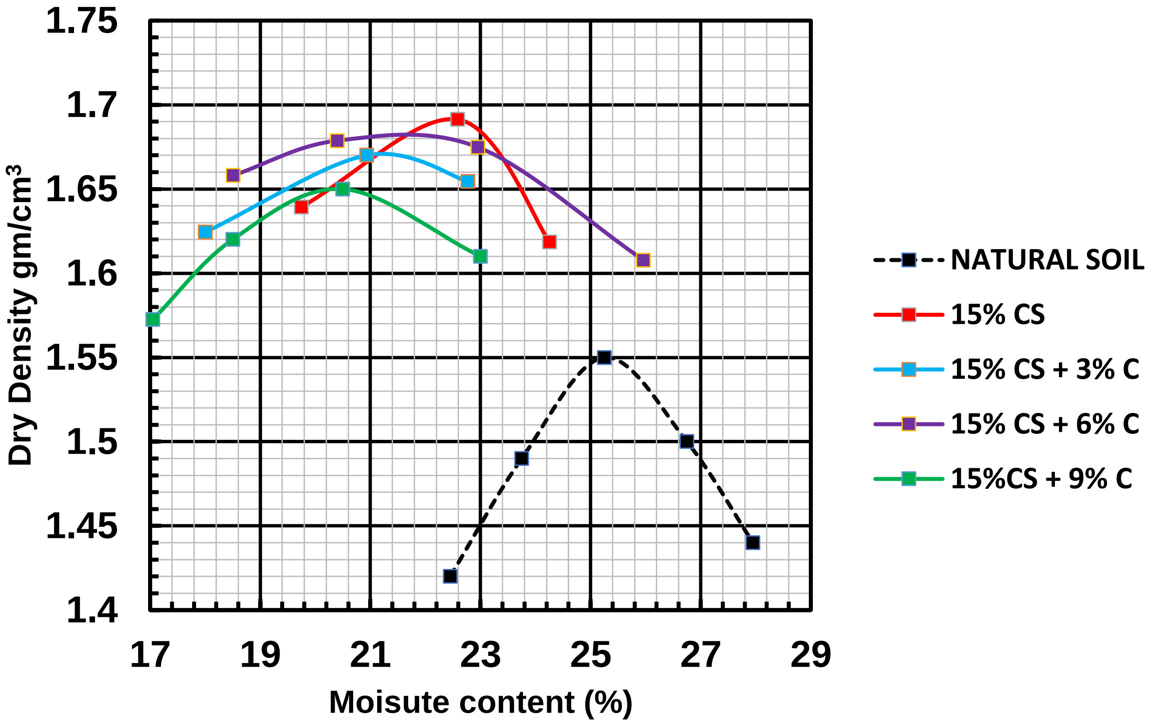


Fig 4.6: Compaction curves for the natural soil, natural soil + 15 % CS and Natural Soil+15 % CS with 3 %, 6 % and 9 % Cement mixture

4.3.2 Effect of Copper Slag on Compaction Characteristics of Natural Soil

Results of the effect of copper slag percentage on the optimum moisture content and the maximum dry density of the soil and composite soil are presented in Figure 4.6. As the CS percentages increase from 5 % to 15 % by 5 % incremental value, the optimum moisture content decreased from 25.25 % to 20.5 % while the maximum dry density increased from 1.55 gm/cm^3 to 1.69 gm/cm^3.

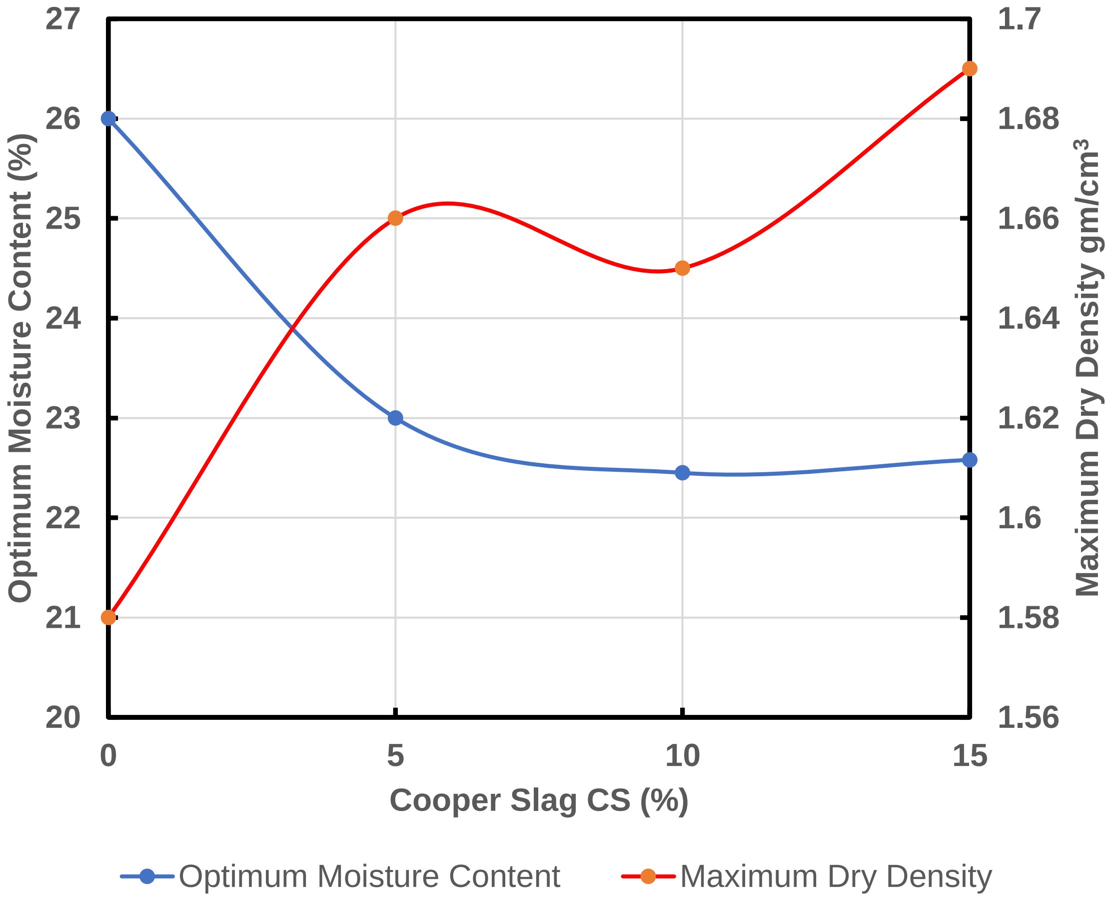


Fig 4.7: Effect of CS on the MDD and OMC of the soil against binder content

4.3.3 Effect of Copper Slag and Cement on Compaction Characteristics of Natural Soil

Results of the effect of CS with Cement on the maximum dry density of the soil and composite soil have been shown in Figures 4.3, 4.4 and 4.5. Figure 4.7 presents the effect of the proportion of total binder content on the MDD of the soil. It is observed from the figure that the maximum dry density increases with an increase in CS and Cement with constant total binder content.

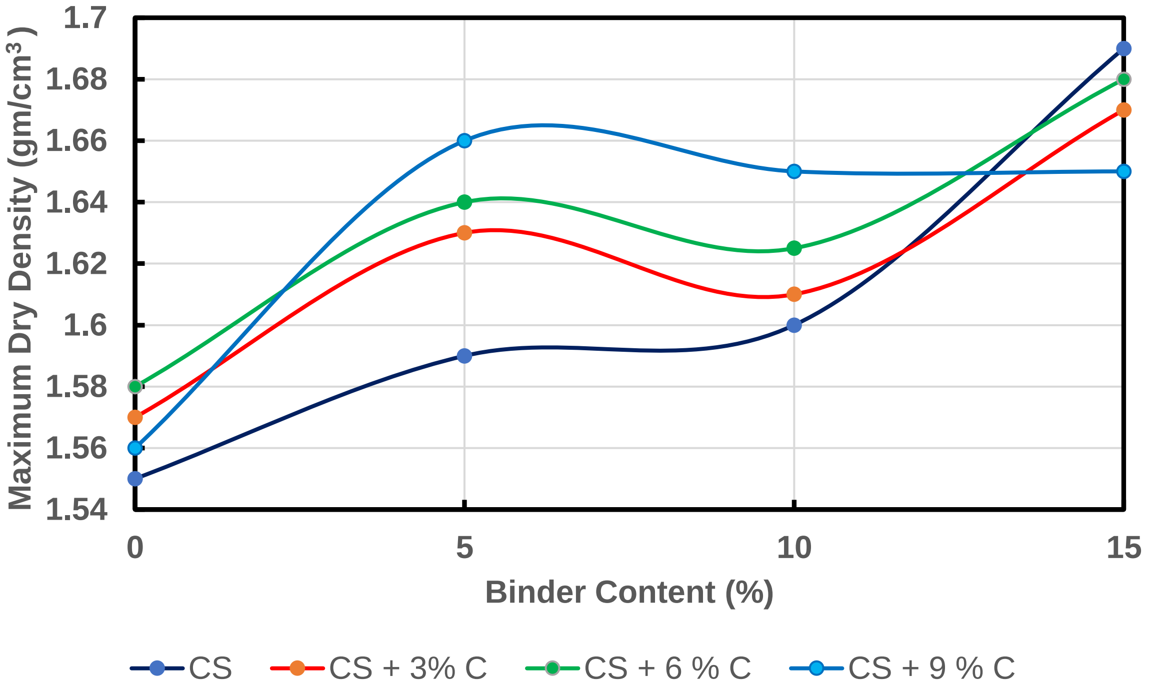


Fig 4.8: Effect of the proportion of total binder content on the MDD of the soil

Figure 4.8 also presents the effect of the proportion of total binder content on the OMC of the soil. The OMC is observed to decreases with an increase in CS and Cement with constant total binder content.

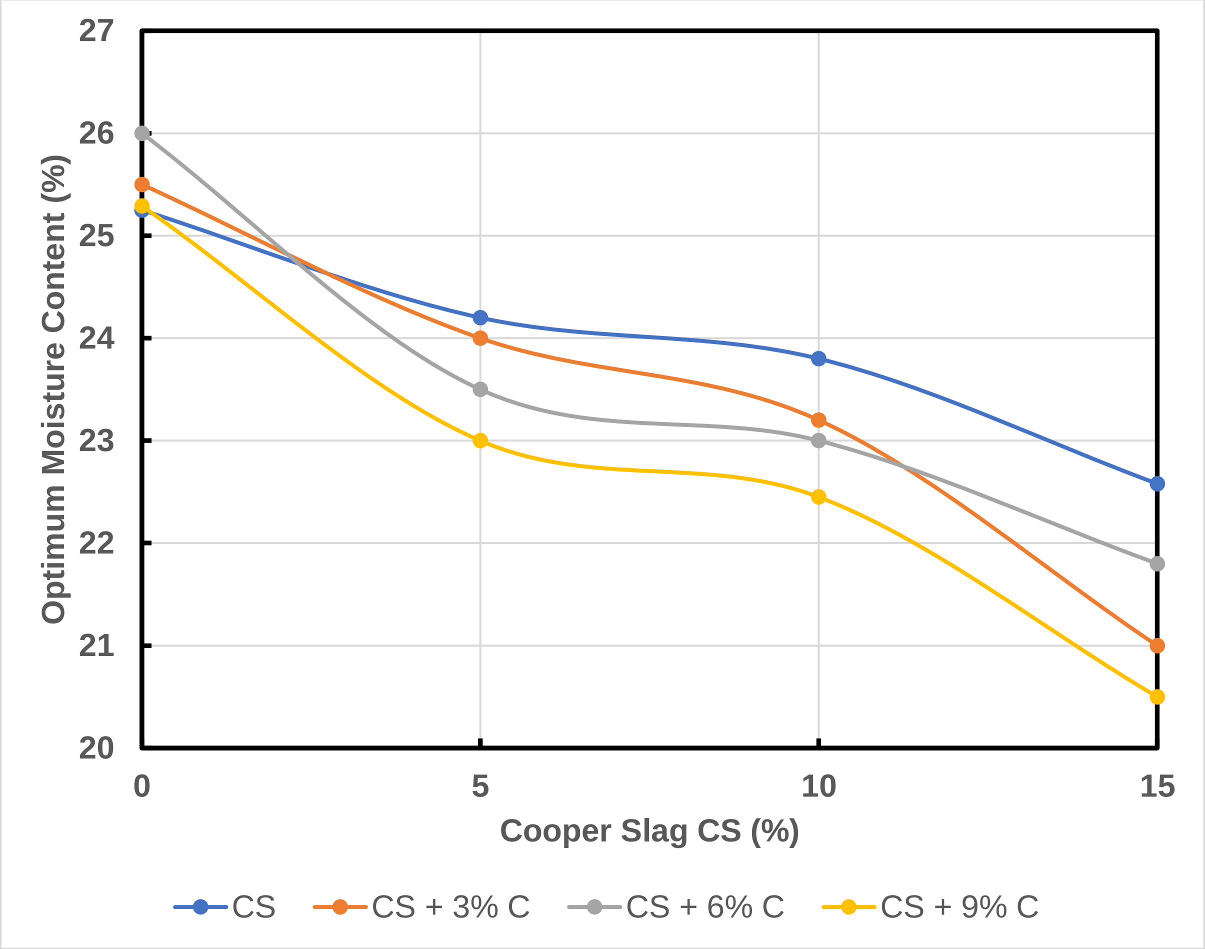


Figure 4.9: Effect of the proportion of total binder content on the OMC of the soil

4.4 Compaction Characteristics of the Soil and Cement

4.4.1 Moisture Content and Dry Density Relationship

The test was performed on soil in which CS was replaced by Cement with total binder content of 3 %, 6 % and 9 % Cement by dry weight. Compaction curves for these samples are presented in Figures 4.3, 4.4 and 4.5. From the compaction test, the natural soil dry density increases to a maximum value of 1.55 Gm/cm3called the maximum dry density (MDD). The moisture content corresponding to the maximum dry density termed as the optimum moisture content (OMC) was determined to be 25.25 %. In Figure 4.3, 3 % addition of binder content to the natural soil resulted in an increase in the MDD to 1.57 Gm/cm3and also an increase in the OMC to 25.5 %. Further, 6% cement content initially result in increase in the MDD to 1.58 Gm/cm3, but with 9% cement content decreases the MDD to 1.56 Gm/cm3and the corresponding OMCs increase to 26 %, and decrease to 25.29%.

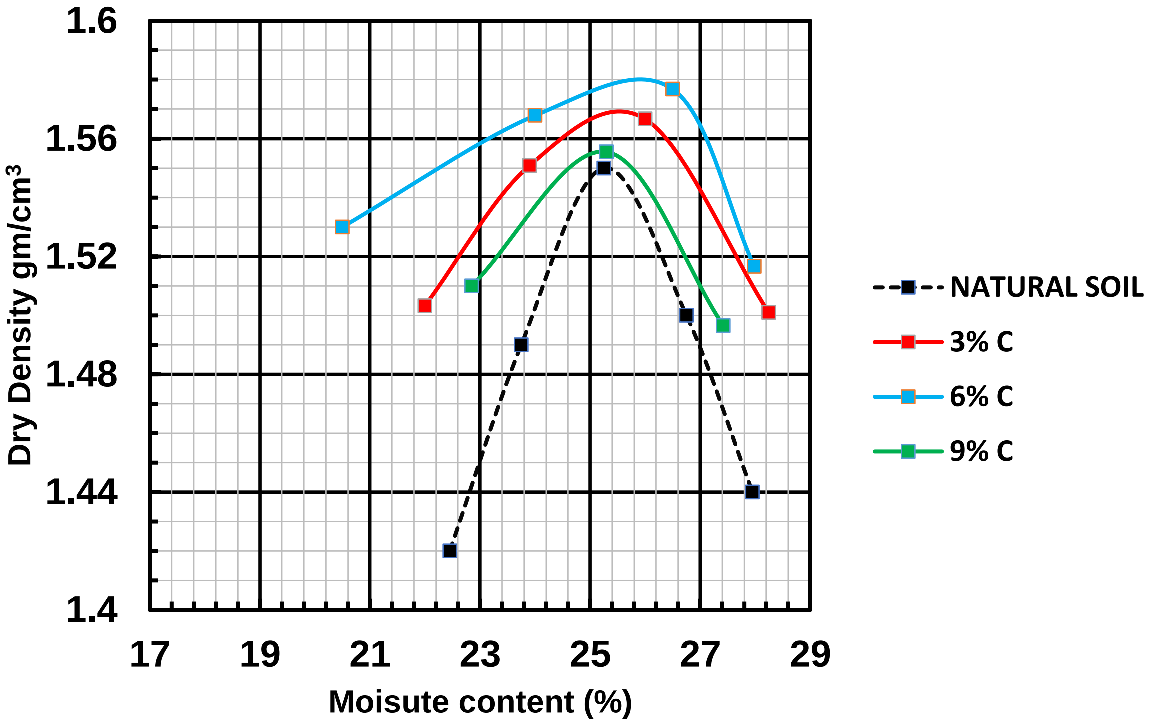


Fig 4.10: Compaction curves for the natural soil and Cement with 3 %, 6 % and 9 % Cement mixture

4.4.2 Effect of Cement on Compaction Characteristics of Natural Soil

Results of the effect of CS with Cement on the maximum dry density of the soil and composite soil have been shown in Figures 4.11and 4.12. Figure 4.11 presents the effect of the proportion of total binder content on the MDD of the soil. It is observed from the figure that the maximum dry density increases with an increase in Cement with constant total binder content. And Figure 4.12 presents the effect of the proportion of total binder content on the OMC of the soil. The OMC also increases with increase in total binder content.

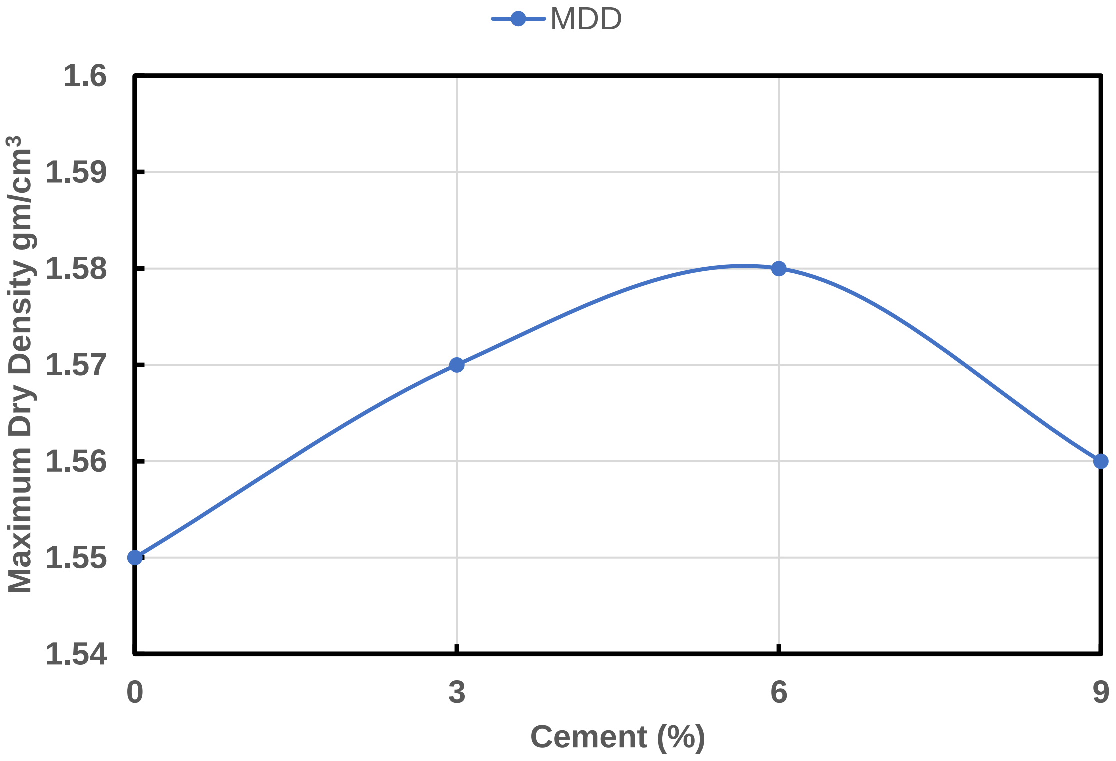


Fig 4.11: Effect of the proportion of total binder content on the MDD of the soil

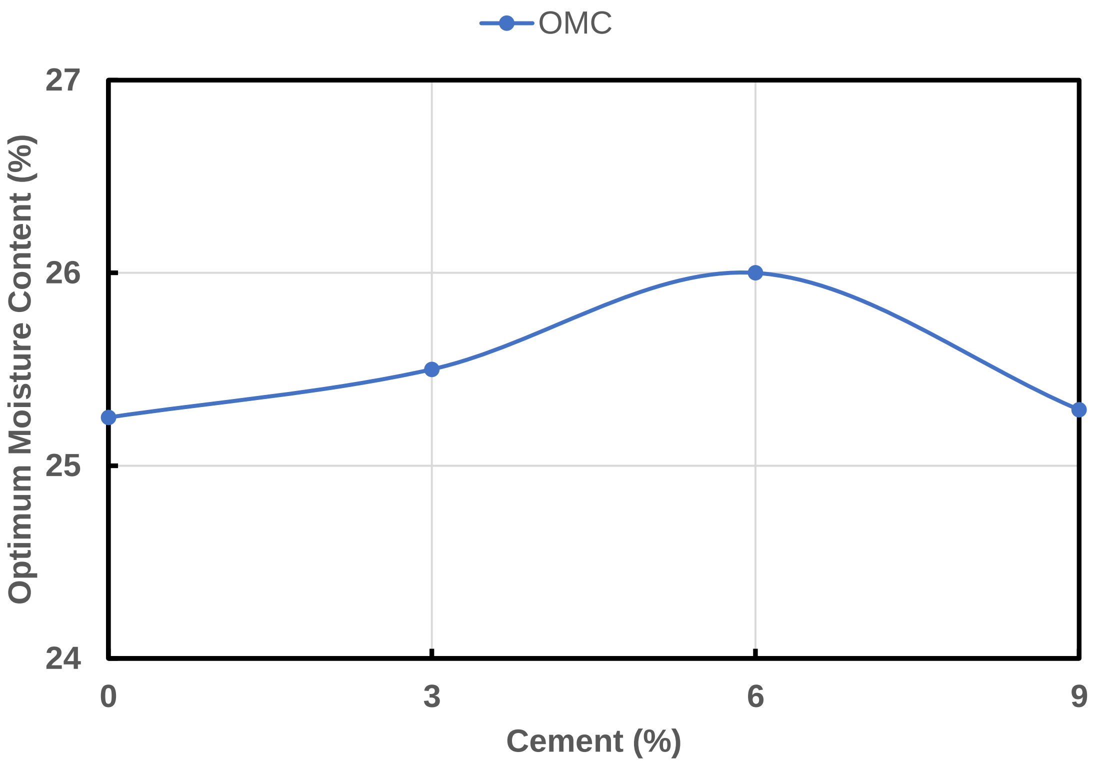


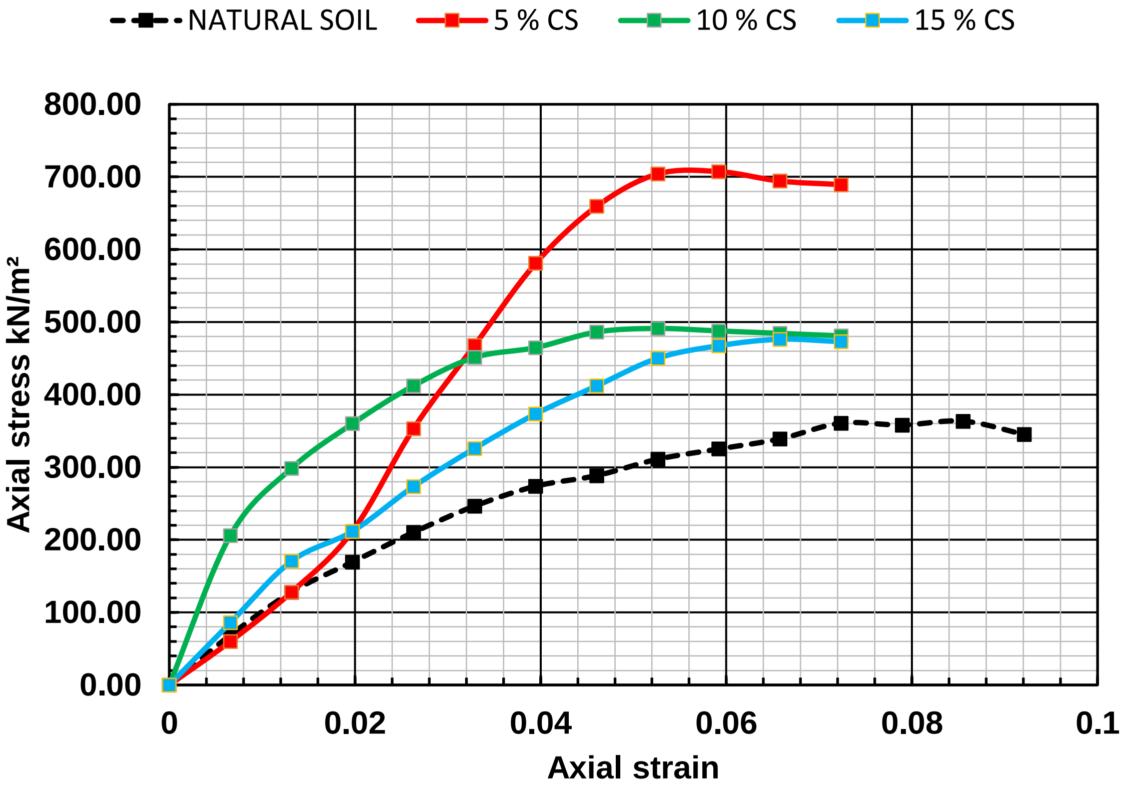
Fig 4.12: Effect of the proportion of total binder content on the OMC of the soil

4.5 Unconfined Compressive Strength of Soil-Copper Slag and Soil-Copper Slag-Cement

As per **IS: 2720 (part10)-1991**, soil specimens with a diameter (d) of 38 mm and a length (l) to diameter ratio of 2 are subjected to unconfined compression tests. The type of soil specimen used for the determination of unconfined compressive strength is dynamically and statically compacted specimens at the same water contents at which CBR test is done.

4.5.1 Effect of the Addition of Copper Slag on the Unconfined Compressive Strength of the Natural Soil

Figures 4.16 present the results of the effect of CS percent on the UCS of the soil. Generally, as the CS content increased, the UCS also increased. But here, at 5 % CS the USC value increases from 363.50 kN/m^2 to 707.26 kN/m^2. But if we increase the CS percentage to 10% and 15%, then the USC value decreases to 491.18 kN/m^2 and 476.28 kN/m^2 respectively.



Fig

4.13: Effect of CS percent on the UCS of the soil

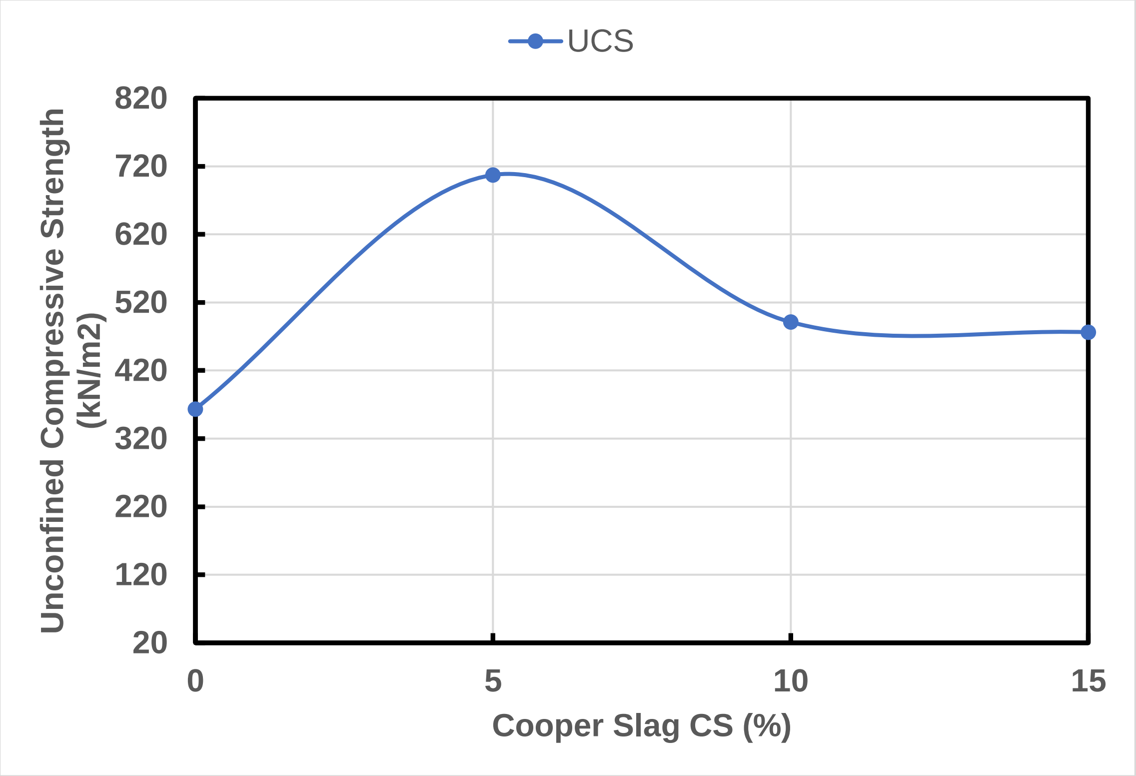


Fig 4.14: Effect of CS percent on the UCS of the soil

4.5.2 Effect of the Addition of Cement on the Unconfined Compressive Strength of the Nat the Natural Soil

Figures 4.16 present the results of the effect of CS percent on the UCS of the soil. Generally, as the Cement content increased, the UCS also increased. But here, at 3 % CS the USC value increases from 363.50 kN/m^2 to 448.88 kN/m^2. And if we increase the Cement percentage to 6% and 9 %, the USC value increases to 634.10 kN/m^2 and 682.88 kN/m^2 respectively.

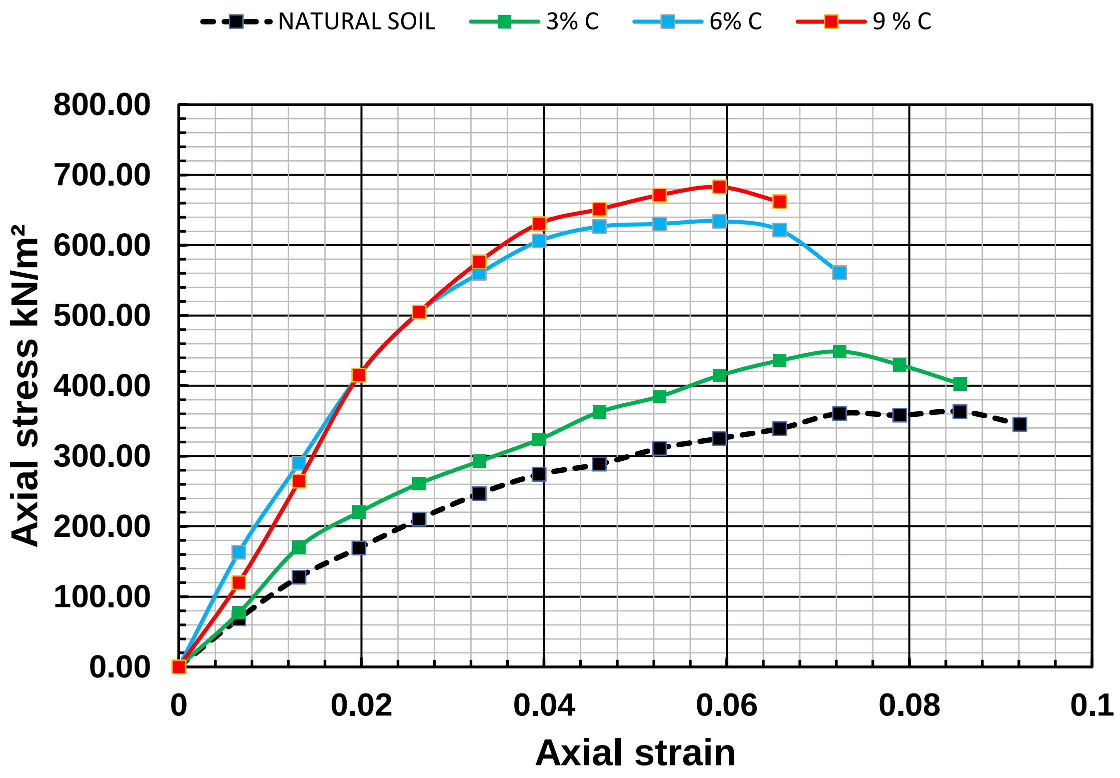


Fig 4.15: Effect of Cement percent on the UCS of the soil

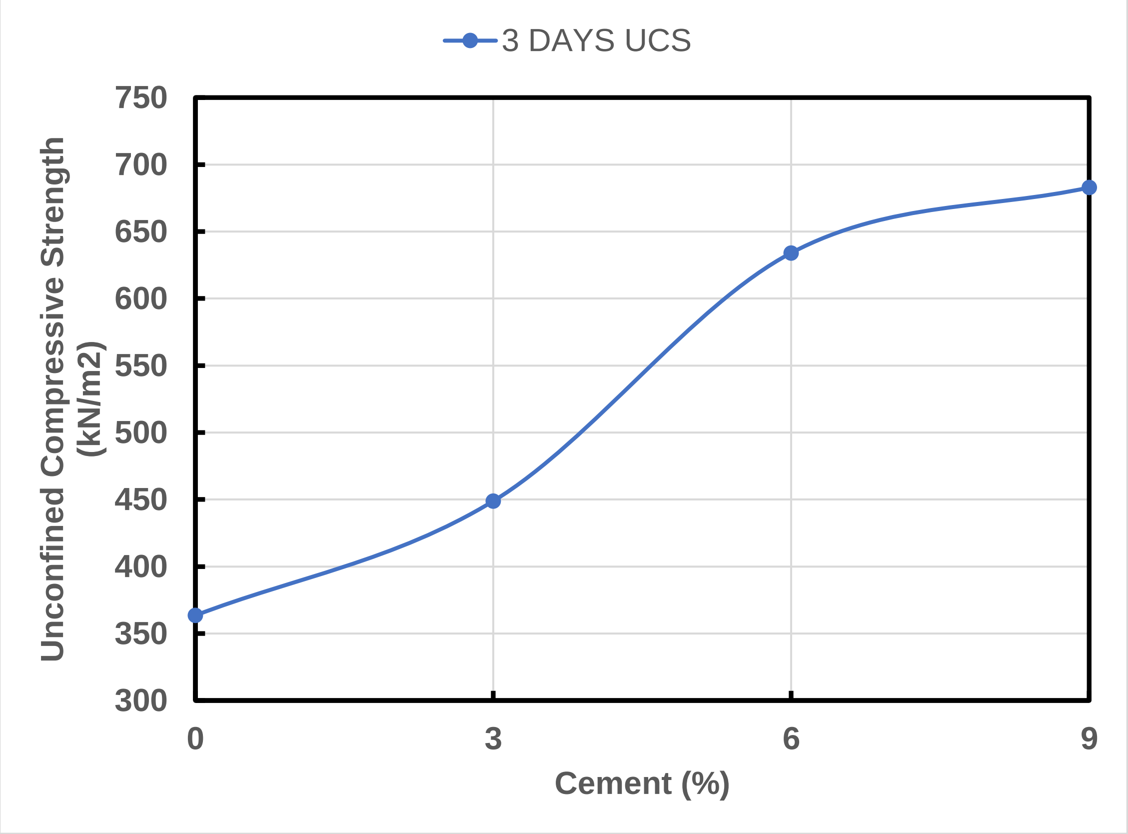


Fig 4.16: Effect of Cement percent on the UCS of the soil

CHAPTER 5
DISCUSSION OF TESTS RESULTS

5.1 Introduction

This chapter discusses the results of the engineering and analytical tests in relation to the composition and changes in properties. The changes in the soil-CS-Cement system are explicated in terms of short-term changes in chemical and physical properties that occur after the addition of CS and Cement (between few hours and three days) during the initial stabilization process and the long-term changes in material properties occurring over a long period of time.

The changes in properties of the soil are mainly physical and chemical changes. The physical changes include change in moisture content, plasticity characteristics, compaction characteristics and particle size distribution. The chemical effects include flocculation, pozzolanic reaction and change in mineralogical composition that affect the strength and volume stability of the soil.

5.2 Chemical and Engineering Properties of the Soil, Cement and Copper Slag

The natural soil, copper slag and hydrated lime chemical oxides have been presented in Table 4.2 in Chapter 4. The physical, mineralogical and engineering properties of the natural soil, copper slag and hydrated lime are presented Table 4.1. The natural soil liquid limit and plasticity index fall on the A-line shown in Figure 4.13 and was classified as silty clay with very high plasticity. The addition of CS and hydrated lime to the natural soil, changed the soil from very high plasticity silty clay to high plasticity silt (Figure 4.13).

It is important to understand the chemical composition and the physical properties of copper slag and Cement before their usage in road construction due to the existence of heavy metal content which may cause both soil and ground water pollutions in the surrounding region. A knowledge of the percentage of the chemical composition of the stabilizers help to know the amount of heavy metal content in the stabilizers and help to not exceed the acceptance level of heavy metal content in the materials.

The investigation on the physical, geochemical and geotechnical characteristics of copper slag and Cement shows that the materials have favourable engineering properties which make them suitable for use as stabilizers or admixtures to improve the strength of weak subgrade soil.

Copper slag contains a high amount of Fe_2O_3 (48.28 %), SiO_2 (24.84 %), CaO (16.89 %), and other chemicals which make it amenable for chemical stabilization (Das et al., 1993). Hydrated lime also contains a high amount of Ca $(OH)_2$ of about 65.09 % and CaO of about 20.91 % and other chemicals which make it suitable for use in chemical stabilization. Therefore, it is the properties of these materials which qualify them to be suitable alternative materials for use as stabilizers or binders in improving subgrade clay materials strength.

5.3 Effect of CS and Cement Addition on Compaction Characteristics of the Soil

5.3.1 Effect of CS Addition on the Compaction Characteristics of the Natural Soil

The effect of CS addition on the compaction characteristics of the composite soil are presented in Section 4.3. 5 % addition of binder content to the natural soil resulted in an increase in the MDD to 1.59 gm/cm^3 and a decrease in the OMC to 24.2 %. The combination of CS with Cement at 3%, 6% and 9% cement content result in increase in the MDD to 1.63 gm/cm^3, 1.64 gm/cm^3 and 1.66 gm/cm^3 respectively and the corresponding OMCs decreased to 24 %, 23.5 % and 23 %.

Again 10 % addition of binder content to the natural soil resulted in an increase in the MDD to 1.60 gm/cm^3 and a decrease in the OMC to 23.8 %. The combination of CS with Cement at 3%, 6% and 9% cement content result in increase in the MDD to 1.61 gm/cm^3, 1.625 gm/cm^3 and 1.65 gm/cm^3 respectively and the corresponding OMCs decreased to 23.2 %, 23 % and 22.45 %.

Table 5.1: **Effect of CS and Cement Addition on Compaction Characteristics of the Soil**

CS (%)	CEMENT (%)	OMC (%)	MDD (gm/cm^3)
0	0	25.25	1.55
0	3	25.5	1.57
0	6	26	1.58
0	9	25.29	1.56
5	0	24.2	1.59
5	3	24	1.63
5	6	23.5	1.64
5	9	23	1.66
10	0	23.8	1.6
10	3	23.2	1.61
10	6	23	1.625
10	9	22.45	1.65
15	0	22.58	1.69
15	3	21	1.67
15	6	21.8	1.68
15	9	20.5	1.65

Therefore, because of the greater specific area that has to be lubricated, the soil-CS mixture is anticipated to require less moisture to attain maximum dry density than the untreated soil. The increase in the maximum dry density corresponding to CS addition is probably associated with the replacement of the soil particles by glassy angular shaped CS particles in a given volume. The voids between the soil particles are partially filled by CS particles to allow them from coming into closer state of packing and filling large volume of voids. In this stage of mixing there is unlikely to be any pozzolanic reaction between CS and the soil particles.

CHAPTER 6
CONCLUSIONS

6.1 Conclusions

The main aim of this work was to study the effect of copper slag without and with hydrated Cement on the geotechnical properties of weak subgrade clay soil. From the tests results and discussions, the following conclusions have been drawn:

1. The natural soil was classified as silty clay. The addition of copper slag and Cement to the natural soil, changed the soil from very high plasticity silty clay to high plasticity silt.
2. 5 % addition of binder content (CS) to the natural soil resulted in an increase in the MDD to 1.59 gm/cm^3 and a decrease in the OMC to 24.2 %. The combination of CS with Cement at 3%, 6% and 9% cement content result in increase in the MDD to 1.63 gm/cm^3, 1.64 gm/cm^3 and 1.66 gm/cm^3 respectively and the corresponding OMCs decreased to 24 %, 23.5 % and 23 %.
3. Again 10 % addition of binder content to the natural soil resulted in an increase in the MDD to 1.60 gm/cm^3 and a decrease in the OMC to 23.8 %. The combination of CS with Cement at 3%, 6% and 9% cement content result in increase in the MDD to 1.61 gm/cm^3, 1.625 gm/cm^3 and 1.65 gm/cm^3 respectively and the corresponding OMCs decreased to 23.2 %, 23 % and 22.45 %.
4. 3 % addition of binder content (Cement) to the natural soil resulted in an increase in the MDD to 1.57 gm/cm^3 and also an increase in the OMC to 25.5 %. Further, 6% cement content initially result in increase in the MDD to 1.58 gm/cm^3, but with 9% cement content decreases the MDD to 1.56 gm/cm^3 and the corresponding OMCs increase to 26 %, and decrease to 25.29%.
5. The maximum increase in the unconfined compressive strength was observed at 5 % copper slag content.

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