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PERFORMANCE ASSESSMENT OF CEMENT STABILIZED SUBGRADE FOR ROAD INFRASTRUCTURE ON EXPANSIVE SOILS

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ABSTRACT

The performance and serviceability of pavements are highly dependent on the engineering characteristics of the underlying subgrade soil. Weak or problematic soils, if left untreated, often lead to premature failures such as rutting, cracking, and differential settlement in highway pavements. In India, expansive and low-strength soils are commonly encountered, necessitating soil improvement techniques for safe and economical road construction. Soil stabilization, particularly with cement, has emerged as one of the most effective methods for improving soil strength, reducing plasticity, and enhancing durability. The present study focuses on the experimental evaluation of cement-stabilized soil intended for highway subgrade applications.The natural soil used in this study was classified as clay of low to intermediate plasticity (CL/CI) in accordance with IS 1498:1970, with a liquid limit of 35.22%, plastic limit of 20.61%, and plasticity index of 14.61%. The soil exhibited a free swelling index of 26.88%, indicating moderate swelling behavior, and a California Bearing Ratio (CBR) value of only 5.08%, which falls below the minimum requirement of 8% specified by IRC:37–2018 for subgrade soils. These results confirmed the necessity of stabilization before its application in highway construction.Cement was selected as the stabilizing agent due to its availability, effectiveness, and proven performance in enhancing soil behavior. Cement contents of 0.5%, 1%, 2%, and 4% by dry weight of soil were blended with the natural soil, and a series of laboratory tests were conducted in accordance with relevant IS code. The experimental results indicated that cement stabilization produced marked improvements in the geotechnical properties of the soil. The maximum dry density (MDD) increased from 1.874 g/cc in the untreated state to 1.906 g/cc at 4% cement, while the optimum moisture content (OMC) decreased from 12.16% to 11.55%. The most noteworthy improvement was observed in the load-bearing capacity of the soil, as reflected by the CBR values. Even at a low cement content of 0.5%, the CBR increased to 18.30%, surpassing the IRC requirement, and further rose to 29.70% at 4% cement content. These findings confirm that cement-treated soils provide significantly higher strength and stability compared to untreated soils, making them suitable for use as subgrade material in flexible pavement construction.

Based on the experimental outcomes, it can be concluded that cement stabilization is an effective and practical method for enhancing the engineering properties of clayey soils. An optimum cement content in the range of 2–4% is recommended, as it provides a balance between technical performance and economic feasibility.

Keywords: Soil Stabilization, Cement, Highway Subgrade, CBR, Plasticity Index, Free Swell Index, Compaction.

1. INTRODUCTION

Soil stability refers to the ability of soil to maintain its mechanical properties—such as shear strength, compressibility, and permeability under applied loads and varying environmental conditions. In geotechnical engineering, this concept is critical because soil acts as the primary load-bearing medium in most civil structures. For highways, where loads from traffic are dynamic and repetitive, the subgrade soil must possess sufficient strength and stiffness to avoid failure.

From a mechanistic perspective, a stable subgrade ensures uniform stress distribution, prevents rutting, cracking, and differential settlements, and provides a strong base for the pavement layers. Failure to stabilize problematic soils—such as those with high plasticity or poor drainage—can result in premature structural failure, increased maintenance costs, and compromised safety.

Key Geotechnical Parameters Affecting Stability

- California Bearing Ratio (CBR) – an indicator of subgrade strength.
- Unconfined Compressive Strength (UCS) – reflects soil shear strength.
- Plasticity Index (PI) and Liquid Limit (LL) – govern deformation characteristics.

- Swelling Index/Free Swell – indicates potential for volumetric change.

1.1 Relevance to Highway Subgrades

In highway engineering, the subgrade forms the lowermost layer of the pavement system. Its primary role is to provide foundational support to the upper pavement layers. When soil exhibits poor load-bearing properties (e.g., low CBR, high water content, or expansive behavior), it leads to pavement distress. The Indian Road Congress (IRC:SP:89-2018) outlines that soils with low plasticity and low swelling potential can be used for subgrades after mechanical or chemical stabilization.

Poor subgrade conditions can lead to:

- Shear failure and rutting.
- Excessive settlements.
- Pavement heaving due to swelling clays.
- Cracking from freeze-thaw or wet-dry cycles.

These issues necessitate soil improvement techniques such as cement stabilization, lime treatment, or mechanical compaction to enhance stability.

1.2 Supporting Research and Empirical Evidence

Several studies have emphasized the importance of subgrade stability in prolonging pavement life and reducing failures:

- Solihu (2020) argued that cement treatment not only improves strength but also reduces plasticity and volumetric changes, making it particularly effective for road subgrades.

PDF Link

1.3 Stabilization as a Mitigation Strategy

To ensure soil stability, especially in weak subgrades, stabilization methods are employed:

- Mechanical stabilization: Compaction or blending with granular materials.
- Chemical stabilization: Use of cement, lime, fly ash, or polymers.
- Geosynthetic reinforcement: Geotextiles or geogrids to improve load dispersion.

Cement stabilization is among the most commonly used methods, especially for CL and CI soils (as per IS 1498:1970). It leads to:

- Increased UCS and CBR
- Reduced PI and LL

1.4 Challenges with Clay of Low to Medium Plasticity in Highway Subgrade Construction

Clay soils classified as CL (low plasticity) and CI (intermediate plasticity) under the Unified Soil Classification System (USCS) and IS 1498:1970, are common in many regions and often used in highway subgrades. While they are more stable than highly plastic (CH) or expansive clays, they still pose notable engineering challenges in pavement construction, especially in terms of strength, durability, and moisture sensitivity.

1.4.1 Moisture Susceptibility

Even low to medium plasticity clays are highly sensitive to moisture variations**.** Upon wetting, their shear strength decreases drastically, leading to a loss of bearing capacity. Seasonal wetting and drying can result in volume changes, although less severe than in highly plastic clays.

- "CL and CI soils tend to become soft and lose structural integrity when water infiltrates, causing differential settlement and loss of strength."

— Solihu (2020) PDF

- "Moisture variation leads to subgrade failures, rutting and long-term deterioration even in medium plasticity soils."

— Adeyemi & Oloruntola (2014) PDF

1.4.2 Moderate Swelling and Shrinkage

Though not as aggressive as CH clays, CL/CI soils still undergo minor to moderate volume changes**,** which can result in pavement cracks**,** especially if untreated or poorly compacted. This is more critical in areas with seasonal rainfall or irrigation leaks**.**

- "Volume instability in intermediate plastic clays can be sufficient to induce tensile stresses in pavement layers."

— Zheng et al. (2009) PDF

1.4.3 Low Bearing Capacity

CL and CI clays generally have low California Bearing Ratio (CBR) values, often below the minimum required for subgrade standards (IRC recommends a minimum soaked CBR of 8% for flexible pavements). This necessitates either replacement or stabilization to avoid rutting and deformation under traffic loading.

- "Typical CBR values for CL soils range from 2–6% under soaked conditions, insufficient for direct use without stabilization."

— Hopkins et al. (1995) CORE PDF

1.4.4 Susceptibility to Compaction Deficiencies

CL and CI soils often require precise moisture control during compaction. Over-compaction or working the soil outside its Optimum Moisture Content (OMC) window can lead to poor strength development and air void entrapment, which affects performance under repeated loads.

- "Achieving uniform compaction in medium plastic clays is challenging, and field moisture variations can drastically impact in-situ strength."

— Daud et al. (2019) IOP PDF

1.4.5 Permeability and Drainage Issues

CL and CI clays have low permeability, which can lead to water retention and pore pressure buildup under the pavement. This makes them more susceptible to pumping, weakening, and erosion under cyclic loading—especially under water-logged conditions.

- "Medium plasticity clays trap moisture, weakening the base and accelerating pavement fatigue under repetitive axle loads."

— Archibong et al. (2020) ResearchGate

1.4.6 Environmental Sensitivity and Degradation

Even moderate clays show strength reduction after freeze-thaw or wet-dry cycles, particularly when used in unbound condition. This limits their long-term durability unless chemically stabilized.

- "CL soils showed strength losses exceeding 25% after three wet-dry cycles, indicating need for durability enhancement measures."

— Solihu (2020) PDF.

Table 1.1: Summary of Cited Challenges

Challenge	Implication	Source
Moisture sensitivity	Weakening, softening, loss of CBR	Solihu (2020), Adeyemi (2014)
Volume instability	Minor swelling/shrinkage → cracks	Zheng et al. (2009)
Low bearing capacity	CBR < 8% → unsuitable without treatment	Hopkins et al. (1995)
Compaction challenges	Difficult to maintain target density in field	Daud et al. (2019)
Poor drainage	Water retention → pumping, structural degradation	Archibong et al. (2020)
Durability under cyclic conditions	Loses strength after wet-dry, freeze-thaw cycles	Solihu (2020)

1.5 Introduction to Soil Stabilization Methods

Soil stabilization refers to the process of improving the engineering properties of soil—such as shear strength, bearing capacity, and volume stability—to make it suitable for construction. This is particularly crucial for subgrades in highways, where weak or problematic soils are common.

Broadly, soil stabilization is categorized into two major types:

1.5.1 Mechanical Stabilization

This involves physical alteration of the soil structure to enhance its properties. It includes:

- Compaction to increase density and reduce voids
- Blending with granular materials (sand, gravel) to improve gradation
- Reinforcement using geosynthetics (geotextiles, geogrids)

1.5.2 Chemical Stabilization

Articles to form calcium silicate hydrates (C–S–H), leading to:

- Significant improvement in Unconfined Compressive Strength (UCS)

Reduced Plasticity Index (PI) and this method involves adding chemical agents to modify the soil's physical and chemical characteristics. Common stabilizers include:

- Lime – Effective for high plasticity clay (CH)
- Cement – Widely used for clayey and silty soils (CL, CI)
- Fly Ash, GGBS, Bitumen, Polymers – For cost-effective or specialized needs

Chemical reactions (e.g., pozzolanic or hydration) result in reduced plasticity, increased strength, and improved durability.

1.5.3 Cement Stabilization: Focus Area

Cement stabilization involves mixing Ordinary Portland Cement (OPC) with soil in calculated proportions (typically 2%–10%) to form a soil-cement mixture. Upon hydration, cement reacts with water and soil particles to form calcium silicate hydrates (C–S–H), leading to:

- Significant improvement in Unconfined Compressive Strength (UCS)
- Reduced Plasticity Index (PI) and swelling potential.
- Better resistance to moisture and durability under load.

1.6 Problem Statement

In India and many developing countries, infrastructure development often encounters subgrade soils with inadequate engineering properties, particularly in rural and semi-urban areas. Clayey soils of low to medium plasticity (CL and CI) are widespread, and while less problematic than highly expansive clays, they still present significant challenges, such as low bearing capacity, moderate swelling and shrinkage, moisture sensitivity, and poor durability under cyclic loading conditions. These deficiencies make such soils unsuitable for direct use in highway subgrades, leading to premature pavement failures, including rutting, cracking, and differential settlement. Traditional replacement or soil improvement methods can be time-consuming, costly, and resource-intensive.Cement stabilization has been recognized as a reliable technique to address these limitations by enhancing the strength, stiffness, and moisture resistance of weak soils. However, the optimum cement content, curing requirements, and resulting environmental conditions, and field practices.

1.7 Objectives of the Study

a. To determine the effect of varying cement content on strength properties.
b. To evaluate CBR and UCS of stabilized soil.
c. To analyze durability through wet-dry or freeze-thaw cycles.
d. To recommend optimum cement content for stabilization.

1.8 Scope of the study

This study focuses on the experimental evaluation of soil stabilization using Ordinary Portland Cement (OPC) for improving the engineering properties of clayey soils classified as CL and CI (i.e., low to medium plasticity) commonly found in subgrade applications.

The scope of the study is structured as follows:

1.8.1 Soil Characterization

- Soil samples were collected from a local site with subgrade relevance.
- Laboratory tests were conducted to determine the Atterberg limits (LL, PL, PI), Free Swelling Index (FSI), Moisture-Density Relationship (MDD & OMC), and classification as per IS 1498:1970.

1.8.2 Stabilization Process

- Ordinary Portland Cement (OPC 43 grade) was used as the stabilizing agent.

- Cement was added in varying proportions (e.g., 2%, 4%, 6%, 8%, and 10% by dry weight of soil) to study its effect.

1.8.3 Laboratory Testing

- **Tests conducted include:**
  - Unconfined Compressive Strength (UCS) as per IS 2720 (Part 10):1991
  - California Bearing Ratio (CBR) as per IS 2720 (Part 16):1987
  - Plasticity Index (PI) and Free Swelling Index (FSI) to assess volume change behavior
  - Compaction characteristics (OMC & MDD) using Proctor tests (IS 2720 Part 7/8)

1.8.4 Curing Regime

- Samples were cured for 4 (96 Hours) days to evaluate strength development over time.

1.8.5 Analysis

- The results were analyzed to determine:
  - Optimum cement content for effective stabilization
  - Improvement trends in strength, plasticity, and compaction
  - Suitability of stabilized soil for highway subgrade layers as per IRC:SP:89-2018 and MORTH guidelines.

2. REVIEW OF LITERATURE

The performance and longevity of any pavement structure are fundamentally contingent upon the strength and stability of its foundational layer: the subgrade. In many regions, naturally occurring soils are weak, expansive, or otherwise unsuitable to support the stresses imposed by traffic loading and environmental changes. These problematic soils, characterized by low bearing capacity, high plasticity, and susceptibility to moisture, can lead to pavement distresses such as rutting, cracking, and excessive settlement, resulting in increased maintenance costs and reduced service life.To mitigate these challenges, soil stabilization has emerged as a critical geotechnical engineering practice. Among various stabilization techniques, the use of ordinary Portland cement (OPC) as a primary binding agent has been widely adopted due to its effectiveness in significantly enhancing the strength, durability, and stiffness of subgrade soils through hydration and pozzolanic reactions. However, conventional cement stabilization is not without its limitations, including inherent brittleness, environmental concerns related to the high carbon footprint of cement production, and economic inefficiencies when high cement contents are required.

Aneke and Mostafa 2024 investigated that fine ground waste glass powder can effectively replace up to 20% of cement in soil stabilization mixes. The glass, rich in silica, undergoes a pozzolanic reaction with the calcium hydroxide produced by cement hydration, forming additional cementitious compounds (C-S-H gel). This leads to significant improvements in Unconfined Compressive Strength (UCS) and California Bearing Ratio (CBR) while reducing the harmful expansion caused by alkali-silica reactivity. The research promotes an eco-friendly solution by diverting waste glass from landfills and reducing the carbon footprint associated with cement production.

Deng et al. 2023 have done the research which demonstrates that blending a small percentage of silica fume (a nano-sized byproduct from the silicon industry) with cement is highly effective in stabilizing weak, high-water-content marine clay. Silica fume fills the microscopic pores between soil particles and reacts powerfully with cement, creating a much denser and less permeable matrix. This results in dramatically higher UCS values and superior resistance to water infiltration and long-term leaching, making it an excellent solution for subgrade in coastal and offshore projects.

2.1 General Studies on Cement-Stabilized Subgrade

Amu and Adewumi 2018 provided findings from numerous studies on cement stabilization. It covers the fundamental mechanisms of stabilization (hydration and pozzolanic reactions), the key factors affecting performance (soil type, cement content, moisture, compaction, and curing), and the resulting improvements in engineering properties like strength, stiffness, and durability. It serves as an excellent foundational text for understanding the principles and state-of-the-art up to its publication.

Georgees et al. 2017 experimentally investigated the quantitative improvement in strength (via Unconfined Compressive Strength - UCS tests) and reduction in compressibility (via consolidation tests) for different soil types treated with varying percentages of cement. It provides practical relationships between cement dosage and the resulting mechanical properties, aiding in design decisions for mitigating settlement and bearing capacity failure.

Okyay and Dias 2018 explored the synergistic effect of using lime and cement together. Lime is particularly effective at first modifying clayey soils (reducing plasticity and improving workability), while cement provides strong, durable hardening. The blend can be more effective and sometimes more economical than using either stabilizer alone for certain soil types.

Georgees et al. (2020) have done the research that directly links stabilization to pavement design by measuring the California Bearing Ratio (CBR), a key input for flexible pavement thickness design. It also specifically quantifies the reduction in swell potential for expansive soils treated with cement, a critical concern for pavement performance.

Harichane et al. 2018 investigated the performance under repeated loading, simulating traffic. It likely measures the Resilient Modulus (Mr) and permanent deformation (rutting) of stabilized soils, providing crucial data for mechanistic-empirical pavement design methods and assessing long-term performance under stress.

James and Pandian 2020 presented a real-world case study where cement stabilization was used in a highway project. It compares field results (e.g., in-situ density, stiffness measurements using tools like the DCP or FWD) with laboratory predictions, discussing practical challenges, quality control measures, and overall performance validation.

Rahman et al. 2017 has done the study that makes an economic argument for stabilization. It compares the initial cost of adding cement to a subgrade against the lifecycle cost savings from constructing a thinner pavement section, reduced maintenance needs, and improved service life, proving its economic viability for low-volume road projects.

3. EXPERIMENTAL PROGRAM

The efficacy of stabilizing subgrade soils through the blending of cement with supplementary materials is fundamentally determined through rigorous empirical investigation. This chapter provides a comprehensive description of the systematic experimental program designed and executed to achieve the research objectives of this study. It details the complete framework of the investigation, encompassing the materials utilized, the methodology employed for sample preparation, the testing procedures adopted to evaluate engineering properties, and the experimental variables considered. The primary aim of this program was to quantitatively assess the influence of different cement-based blends on the strength, durability, and microstructural characteristics of the stabilized soil. By meticulously outlining the experimental design, this chapter ensures the transparency, reproducibility, and scientific validity of the results presented and discussed in the subsequent chapters. Furthermore, it establishes a clear link between the theoretical background presented in the literature review and the empirical data generated through this structured laboratory investigation.

3.1 Materials for Experimental Program

3.1.1. Soil Sample

- Locally available clayey soil classified as CL/CI (low to medium plasticity) as per IS 1498:1970.
- Collected from a designated borrow pit/subgrade site at a depth of ~1.0 m below ground surface to avoid organic matter contamination. Approx 25 no sample from different pit has been taken.
- Preliminary tests:
  - Liquid Limit (LL), Plastic Limit (PL), and Plasticity Index (PI) as per IS 2720 (Part 5):1985
  - Free Swelling Index (FSI) as per IS 2720 (Part 40):1977
  - Specific Gravity as per IS 2720 (Part 3/Sec 1):1980

3.1.2 Stabilizing Agent – Cement

- Ordinary Portland Cement (OPC), 43 Grade conforming to IS 8112:2013.
- Used in varying proportions (e.g., 2%, 4%, 6%, 8%, 10% by dry weight of soil).
- Stored in airtight bags to prevent moisture absorption before use.

3.1.3 Water

- Potable water, free from organic matter, oils, and salts.
- Conforming to the requirements of IS 456:2000 (clause 5.4.2) for mixing and curing.

3.2 Molds and Accessories

3.2.1 Cylindrical and CBR molds as per IS specifications:

Collar and base plates for compaction.

3.3 Testing Equipment

3.3.1 Proctor compaction apparatus (Light/Heavy) as per IS 2720 (Part 7/8).

3.3.2 CBR testing machine with proving ring and dial gauge.

3.3.3 UCS testing machine with compression frame.

3.3.4 **Liquid Limit Device** (Casagrande's apparatus) and **Plastic Limit equipment**.

3.3.5 **Oven** for drying soil samples at 105–110 °C.

3.3.6 **Balance** with 0.01 g accuracy.

3.3.7 **Curing tank/room** for maintaining constant humidity during curing period.

3.3.8 **Miscellaneous Materials**

- Spatulas, trays, trowels, and measuring cylinders.
- Polythene sheets/bags for storing soil-cement mix samples before compaction.
- Desiccators for preventing moisture loss during testing prep

3.4 Experimental Methodology

The experimental program was designed to evaluate the effect of cement stabilization on the engineering properties of low to medium-plasticity clay (CL/CI) soils. The methodology adopted is outlined in the following steps:

3.4.1 Soil Collection and Preparation

- Disturbed soil samples were collected from a borrow pit at ~1.0 m depth to avoid organic and topsoil contamination.
- The soil was air-dried, pulverized, and sieved through a 4.75 mm IS sieve as per IS 2720 (Part 1):1983.
- The processed soil was stored in airtight containers to maintain uniform moisture condition prior to testing.

3.4.2 Index Properties Determination

The natural soil was characterized for basic engineering properties to establish its classification:

- Specific Gravity **–** IS 2720 (Part 3/Sec 1):1980.
- Grain Size Distribution – IS 2720 (Part 4):1985.
- Liquid Limit & Plastic Limit – IS 2720 (Part 5):1985.
- Plasticity Index (PI) – Derived from LL & PL.
- Free Swelling Index (FSI) – IS 2720 (Part 40):1977.
- Compaction Characteristics (OMC & MDD) – IS 2720 (Part 7/8):1980.

3.5 Selection of Stabilizer

- Ordinary Portland Cement (OPC 43 Grade**)** was selected as the stabilizing agent.
- Cement was added in proportions of 0.5%, 1%,2%, 4%, 6%, 8%, and 10% by dry weight of soil**.**

3.6 Mixing Procedure

- The required weight of soil was thoroughly mixed with the designated cement percentage.
- The optimum moisture content (OMC) obtained from the Proctor test was added gradually.
- Mixing was done manually until a uniform color and consistency were achieved.
- Care was taken to minimize time delay between mixing and compaction**,** as cement hydration begins immediately.

3.7 Compaction of Samples

- Compaction was carried out in molds using Standard Proctor test procedure as per IS 2720 (Part 7):1980.
- Samples for CBR and UCS tests were prepared at OMC and MDD conditions**.**
- CBR Molds**:** 150 mm dia × 175 mm height (as per IS 2720 Part 16:1987).
- UCS Specimens: Cylindrical molds, 38 mm dia × 76 mm height (as per IS 2720 Part 10:1991).
- Compacted specimens were carefully extracted from molds and sealed in polythene bags to avoid moisture loss.
- Specimens were cured in a curing tank/controlled humidity room for 4 days (96 HRS)
- Curing followed IS 4332 (Part 4):1968 for stabilized soils.

3.9 Testing of Stabilized Soil

After curing, the following tests were conducted:

3.9.1 Unconfined Compressive Strength (UCS)

- Conducted as per IS 2720 (Part 10):1991.
- Compressive strength values were recorded at different curing periods to evaluate strength gain.

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3.9.2 California Bearing Ratio (CBR)

- Performed on soaked and unsoaked samples as per IS 2720 (Part 16):1987.
- Load-penetration curves were obtained to determine the CBR value at 2.5 mm and 5.0 mm penetrations.

3.9.3 Plasticity and Swelling Characteristics

- Atterberg limits (LL, PL, PI) were re-determined for stabilized soil.
- Free Swelling Index (FSI) was measured as per IS 2720 (Part 40):1977.

3.9.4 Compaction Characteristics

- OMC and MDD were re-evaluated for stabilized soil mixes to observe changes in compaction behavior.

3.10 Data Analysis

- Results were tabulated and compared for different cement percentages.
- Improvement trends in strength, plasticity reduction, swelling behavior, and bearing capacity were analyzed.
- The optimum cement content was determined based on maximum strength gain and compliance with IRC:SP:89-2018 for subgrade requirements.

3.11 Standards and Guidelines Followed

- IS 1498:1970 – Classification of soils
- IS 2720 series – Methods of soil testing
- IS 4332 (Part 4):1968 – Methods for testing stabilized soils
- IRC:SP:89-2018 – Guidelines for soil and granular material stabilization for roads
- MORTH Specifications (2020) – Road and Bridge works

4. RESULTS AND DISCUSSION

A total of 36 samples have been taken from different areas within a radius of 10 km, and all the parameters like proctor, Atterberg limit, GSA, FSI and CBR etc. have been tested in the in-house lab, and summery of the results have been tabulated below.

Table 4.1: Experimental Results

	Summary Sheet of Borrow Area Test Result										
Sl. No.	Borrow Area No.	Proctor		Atterberg Limit			GSA			FSI	CBR
		MDD	OMC	LL	PL	PI	Gravel	Sand	Silt & Clay		
1	Pit-01	1.874	12.16	35.22	21.21	14.61	0.51	21.20	78.19	26.88	5.08
	Pit-01 cement 0.5%	1.887	11.90	33.97	24.87	9.10	0.75	24.64	74.61	19.00	18.30
2	Pit-02	1.874	11.71	35.13	23.28	11.85	0.91	22.20	76.92	25.55	5.05
	Pit-02 cement 0.5%	1.894	12.50	33.95	25.00	8.95	0.74	23.24	76.03	20.50	17.69
3	Pit-03	1.874	11.62	35.17	23.86	11.31	0.66	21.95	77.38	25.25	5.11
	Pit-03 cement 0.5%	1.899	12.82	-	-	-	-	-	-	-	18.44
4	Pit-04	1.873	12.05	35.36	24.02	11.34	0.64	21.70	77.70	26.25	7.29
	Pit-04 cement 0.5%	1.903	12.45	33.09	24.05	9.04	0.70	23.89	75.41	22.19	17.76
5	Pit-05	1.886	13.17	27.37	-	-	0.00	44.64	55.21	0.00	
	Pit-05	1.901	14.24	-	-	-	-	-	-	-	18.90

	cement 0.5%										
6	Pit-06	1.900	12.85	-	-	-	-	-	-	-	17.72
	Pit-06 cement 0.5%	1.879	11.91	35.25	23.71	11.55	0.82	22.77	76.41	25.63	7.49
7	Pit-07	1.881	12.11	35.18	23.53	11.65	1.50	23.26	75.18	26.67	
	Pit-07 cement 0.5%	1.901	13.99	-	-	-	-	-	-	-	18.29
8	Pit-08	1.883	12.35	34.69	22.64	12.05	1.55	24.26	74.20	26.88	
	Pit-08 cement 0.5%	1.905	14.20	-	-	-	-	-	-	-	18.57
9	Pit-09	1.843	13.03	35.26	23.72	11.54	0.93	22.01	77.06	27.98	4.76
	Pit-09 cement 0.5%	1.882	13.88	-	-	-	-	-	-	-	17.95
10	Pit-10	1.859	12.78	35.73	23.75	11.90	0.97	21.21	77.82	27.78	5.11
	Pit-10 cement 0.5%	1.888	13.28	-	-	-	-	-	-	-	17.64
11	Pit-11	1.868	12.26	35.18	23.67	11.51	1.22	23.47	75.40	25.88	5.52
	Pit-11 cement 0.5%	1.892	13.13	-	-	-	-	-	-	-	17.99
12	Pit-12	1.861	12.21	35.46	23.89	11.58	1.12	22.00	76.94	27.22	5.62
	Pit-12 cement 0.5%	1.888	12.97	-	-	-	-	-	-	-	17.77
13	Pit-13	1.841	12.21	35.78	24.07	11.71	1.42	23.76	74.82	25.90	5.26
	Pit-13 cement 0.5%	1.893	13.06	-	-	-	-	-	-	-	17.74
14	Pit-14	1.845	12.58	35.78	23.85	11.92	1.73	24.01	74.27	27.50	
	Pit-14 cement 0.5%	1.886	11.95	-	-	-	-	-	-	-	17.16
15	Pit-15	1.860	12.17	35.31	23.60	11.71	1.46	23.39	75.14	26.50	5.06
	Pit-15 cement 0.5%	1.897	13.08	-	-	-	-	-	-	-	17.76
16	Pit-16	1.862	12.29	35.37	23.72	11.65	1.43	23.50	75.07	27.00	
	Pit-16 cement 0.5%	1.900	13.15	-	-	-	-	-	-	-	17.77

17	Pit-17	1.842	12.42	36.03	24.07	11.97	1.47	23.29	75.24	28.50	5.19
	Pit-17 cement 0.5%	1.884	13.20	-	-	-	-	-	-	-	18.33
18	Pit-18	1.858	12.18	35.58	23.65	11.93	1.47	23.40	75.12	26.92	5.16
	Pit-18 cement 0.5%	1.894	13.27	-	-	-	-	-	-	-	18.05
19	Pit-19	1.852	12.17	35.76	24.03	11.67	1.50	23.20	75.31	29.38	7.62
	Pit-19 cement 0.5%	1.885	13.60	-	-	-	-	-	-	-	17.10
20	Pit-20	1.871	11.96	35.57	23.76	11.81	1.94	22.32	75.74	22.73	6.92
	Pit-20 cement 0.5%	1.893	13.06	-	-	-	-	-	-	-	18.32
21	Pit-21	1.852	12.58	35.46	23.49	11.97	1.11	22.85	76.04	24.69	6.97
	Pit-21 cement 0.5%	1.891	13.35	-	-	-	-	-	-	-	18.15
22	Pit-22	1.869	11.96	35.21	24.08	11.12	0.73	23.14	76.11	26.31	5.81
	Pit-22 cement 0.5%	1.900	12.88	-	-	-	-	-	-	-	18.34
23	Pit-23	1.867	11.92	34.90	24.02	10.88	0.94	23.81	75.25	25.59	5.66
	Pit-23 cement 0.5%	1.899	13.00	-	-	-	-	-	-	-	18.28
24	Pit-24	1.867	11.94	35.11	24.06	11.05	1.18	22.86	76.02	26.67	
	Pit-24 cement 0.5%	1.896	13.08	-	-	-	-	-	-	-	18.28
25	Pit-25	1.868	11.96	35.27	24.12	11.16	0.94	22.49	76.56	27.74	5.66
	Pit-25 cement 0.5%	1.897	12.88	-	-	-	-	-	-	-	18.42
26	Pit-26	1.862	11.97	34.95	24.02	10.93	0.48	21.09	78.43	29	5.05
	Pit-26 cement 0.5%	1.892	13.08	-	-	-	-	-	-	-	18.44
27	Pit-27	1.867	11.78	35.25	24.11	11.13	1.11	23.12	75.77	26.9	6.06
	Pit-27 cement 0.5%	1.901	13.08	-	-	-	-	-	-	-	18.18
28	Pit-28	1.868	11.75	35.07	24.07	11.00	0.91	22.88	76.21	27.17	5.54
	Pit-28	1.901	13.08	-	-	-	-	-	-	-	18.86

	cement 0.5%										
29	Pit-29	1.867	11.76	35.00	24.02	10.99	0.99	23.01	76.00	27.13	5.54
	Pit-29 cement 0.5%	1.899	12.99	-	-	-	-	-	-	-	18.51
30	Pit-30	1.872	11.77	34.65	23.78	10.87	1.02	22.59	76.39	25.63	5.74
	Pit-30 cement 0.5%	1.901	12.96	-	-	-	-	-	-	-	18.41
31	Pit-31	1.868	11.82	35.21	24.11	11.1	0.93	22.3	76.77	27.14	5.44
	Pit-31 cement 0.5%	1.890	13.00	-	-	-	-	-	-	-	17.90
32	Pit-32	1.871	11.83	34.99	24.04	10.95	0.82	22.71	76.47	26.47	6
	Pit-32 cement 0.5%	1.902	13.05	-	-	-	-	-	-	-	18.37
33	Pit-33	1.862	11.78	35.25	24.12	11.12	0.9	23.12	75.99	26.54	5.74
	Pit-33 cement 0.5%	1.892	13.03	-	-	-	-	-	-	-	18.16
34	Pit-34	1.875	11.96	35.11	24.08	11.03	0.92	22.83	76.25	25.18	5.84
	Pit-34 cement 0.5%	1.901	13.02	-	-	-	-	-	-	-	18.41
35	Pit-35	1.873	11.86	35.34	24.31	11.04	0.88	22.89	76.23	26.25	5.54
	Pit-35 cement 0.5%	1.899	12.94	-	-	-	-	-	-	-	18.23
36	Pit-36	1.872	11.62	35.23	24.1	11.26	0.94	23.01	75.92	26.11	5.87
	Pit-36 cement 0.5%	1.898	12.97	-	-	-	-	-	-	-	18.63

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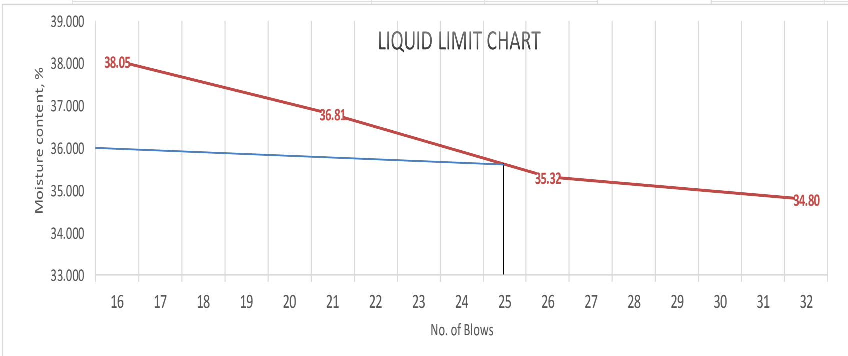
4.1 Index Properties Of Natural Soil:

DETERMINATION OF LIQUID LIMIT & PLASTIC LIMIT TEST

(As per IS : 2720 Part - 5)

Chainage / Location	: 120+750 L/S	Date of Sampling	
Source of Material	: 15B	Date of Testing	
Sample No.	: 05	Sampled & Tested by	
Type of Material	: Soil	Material passing on	425mic.

Sr.No.	Determination Details	Liquid Limit				Plastic Limit	
		1	2	3	4	1	2
1	No of Blows & Penetration in mm	32	26	21	16	-	-
2	Container identification no.	C 25	C 26	C 27	C 28	C 29	C 30
3	Weight of empty container, gm (W1)	29.78	27.71	32.07	36.32	29.43	29.29
4	Weight of wet soil + container, gm (W2)	68.32	67.44	71.02	76.23	38.07	37.41
5	Weight of dry soil + container, gm (W3)	58.37	57.07	60.54	65.23	36.4	35.83
6	Weight of water, gm W4, (W2- W3)	9.95	10.37	10.48	11	1.67	1.58
7	Weight of dry soil, gm W5, (W3-W1)	28.59	29.36	28.47	28.91	6.97	6.54
8	Moisture content, % M.C =(W4/W5)x100	34.80	35.32	36.81	38.05	23.96	24.16



As per MORT&H specifications

Earthwork	LL < 50 %
	PI < 25 %
GSB	LL < 25 %
	PI < 6 %
WMM	LL < 25 %
	PI < 6 %

Liquid Limit (LL) %	36.25	Avg. Plastic Limit (PL) %	24.06	Plastcity Index (PI) % = LL - PL	12.19

Fig 4.1: Determination of liquid limit and plastic limit test of soil

The index properties of the natural soil, i.e liquid limit, Plastic limit, Plasticity index, and free swell index of all 36 samples have been checked, and the average from the summary sheet has been tabulated in Table, and a sample graph as well as test data has also been produced for ready reference.

Table 4.2: Index Properties of Natural Soil

Property	Value	IS Code Reference
Liquid Limit (LL)	35.22 %	IS 2720 (Part 5):1985
Plastic Limit (PL)	20.61 %	IS 2720 (Part 5):1985
Plasticity Index (PI)	14.61 %	IS 2720 (Part 5):1985
Free Swell Index (FSI)	26.88 %	IS 2720 (Part 40):1977
Classification	CL/CI	IS 1498:1970

4.2 Compaction Characteristics with Cement Stabilization

A natural soil sample and a sample prepared by adding 0.5% OPC 43 grade cement by weight of the dry soil have been tested for compaction characteristics. The average from the summary sheet has been tabulated in Table 4 and a sample graph as well as test data have also been produced for ready reference.

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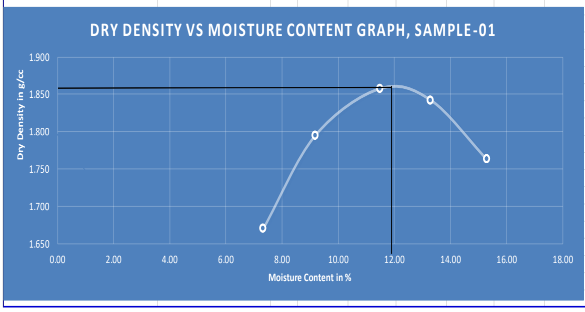
Type of Material	:Soil							
Volume of the mould(V): cc	: 1000							
Description	Formula	Unit	Trial No					
			1	2	3	4	5	6
Mould No			1	1	1	1	1	
Mould Weight	M1	(gm)	4309	4309	4309	4309	4309	
Wt of Wet Soil + Mould	M2	(gm)	6102	6269	6380	6396	6342	
Wt of Wet Soil	M2 - M1	(gm)	1793	1960	2071	2087	2033	
Wet Density	Ym=(M2 - M1) / Vm	(g/cc)	1.793	1.960	2.071	2.087	2.033	
Container No			A 1	A 2	A 3	A 4	A 5	
Wt of Container	W1	(gm)	25.52	28.35	26.27	27.54	27.44	
Wt of Wet soil.+Cont.	W2	(gm)	128.96	130.22	125.11	133.98	131.96	
Wt of OvenDry soil.+Cont.	W3	(gm)	121.90	121.65	114.92	121.49	118.10	
Wt of Water	W2-W3	(gm)	7.06	8.57	10.19	12.49	13.86	
Wt of Oven Dry soil	W3-W1	(gm)	96.38	93.30	88.65	93.95	90.66	
Moisture Content	Mc =(W2-W3)*100/(W3-W1)	(%)	7.33	9.19	11.49	13.29	15.29	
Dry Density	Yd =(100Ym)/(100+Mc)	(g/cc)	1.671	1.795	1.857	1.842	1.763	
MDD (g/cc) :	1.851			OMC:	11.994	%		



Type of Material	:Soil+ 0.6% Cement							
Volume of the mould(V): cc	: 1000							
Description	Formula	Unit	Trial No					
			1	2	3	4	5	6
Mould No			1	1	1	1	1	
Mould Weight	M1	(gm)	4328	4328	4328	4328	4328	
Wt of Wet Soil + Mould	M2	(gm)	6143	6307	6422	6480	6407	
Wt of Wet Soil	M2 - M1	(gm)	1815	1979	2094	2152	2079	
Wet Density	Ym=(M2 - M1) / Vm	(g/cc)	1.815	1.979	2.094	2.152	2.079	
Container No			B 1	B 2	B 3	B 4	B 5	
Wt of Container	W1	(gm)	46.10	43.21	53.93	56.44	46.06	
Wt of Wet soil.+Cont.	W2	(gm)	148.32	144.60	156.64	159.32	149.12	
Wt of OvenDry soil.+Cont.	W3	(gm)	141.28	135.96	146.24	147.24	135.06	
Wt of Water	W2-W3	(gm)	7.04	8.64	10.40	12.08	14.06	
Wt of Oven Dry soil	W3-W1	(gm)	95.18	92.75	92.31	90.80	89.00	
Moisture Content	Mc =(W2-W3)*100/(W3-W1)	(%)	7.40	9.32	11.27	13.30	15.80	
Dry Density	Yd =(100Ym)/(100+Mc)	(g/cc)	1.690	1.810	1.882	1.899	1.795	
MDD (g/cc) :	1.901			OMC:	12.500	%		

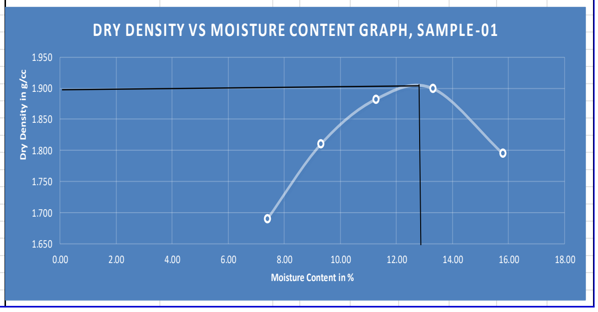


Fig 4.2: Comparison of MDD and OMC with natural soil and Soil with Cement.

Table 4.3: Compaction Characteristics with Cement Stabilization

Cement Content (%)	Maximum Dry Density (g/cc)	Optimum Moisture Content (%)	IS Code Reference
0.0 (Natural Soil)	1.874	11.90	IS 2720 (Part 7):1980
0.5	1.887	11.98	IS 2720 (Part 7):1980
1.0	1.892	12.20	IS 2720 (Part 7):1980
2.0	1.898	12.35	IS 2720 (Part 7):1980
4.0	1.906	12.55	IS 2720 (Part 7):1980

4.4 Plasticity and Swelling Behavior with Cement

Plasticity and sweeling index has been checked and average value has been tabulated below in table 5.

Table 4.4: Plasticity and Swelling Behavior with Cement

Cement Content (%)	Plasticity Index (PI)	Free Swell Index (FSI)	IS Code Reference
0.0 (Natural Soil)	14.61	26.88	IS 2720 (Part 5,40)
0.5	9.10	19.00	IS 2720 (Part 5,40)
1.0	8.20	17.50	IS 2720 (Part 5,40)
2.0	7.60	16.20	IS 2720 (Part 5,40)
4.0	6.80	15.00	IS 2720 (Part 5,40)

4.5 California bearing ratio (CBR) with cement

A natural soil sample and a sample prepared by adding 0.5% OPC 43 grade cement by weight of the dry soil have been tested for California bearing ratio(CBR). The average from the summary sheet has been tabulated in Table 6, and a sample graph as well as test data have also been produced for ready reference.

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COLIFORNIA BERINGN RATIO

(As per IS : 2720 Part - 16)

Package No.	Package No. 02	Lab Job No.	
Sample. No		Date of sampling	
Location of Sampling		Date of testing	
Source of Material	Soil	Tested by	
Kind of Material	Emabankment & Subgrade	Sampled by	
MDD (gm/cc)	1.868 OMC (%) 12.10	Soaking Periad : 96 hrs	

OBSERVATION

Sr No.	Description	Mould No.01		Mould No.02		Mould No.03	
		Before soking	After soking	Before soking	After soking	Before soking	After soking
1	No. of Blows	56	56	56	56	56	56
2	Weigth of Mould, W1 g	7137	7137	7390	7390	7915	7915
3	Weigth of Mould (CC)	2250	2250	2250	2250	2250	2250
4	Volume of Mould + Wet Soil, W2 g	11718	11779	11967	12030	12507	12573
5	Weigth of Wet Soil, (W2-W1) g	4581	4642	4577	4640	4592	4658
6	Bulk Density, Yb = (W2-W1) / Vg/cc	2.036	2.063	2.034	2.062	2.041	2.070
7	Container No.	81	81	82	82	83	83
8	Weigth of container , W3 g	46.10	46.10	43.21	43.21	53.93	53.93
9	Weigth of containe + Wet Soil, W4 g	148.36	143.92	147.14	144.18	156.38	158.62
10	Weigth of Container + Over dry Soil, W5 g	137.39	132.78	135.93	131.87	145.25	145.73
11	Water Content w= (W4-W5)/(W5-W3)x100 %	10.97	11.14	11.21	12.31	11.13	12.89
12	Dry Density, Yb /(1+w/100) g/cc	1.835	1.856	1.829	1.836	1.836	1.834
13	% Compaction, (Yb /MDD)x100	98.219	99.375	97.921	98.297	98.313	98.171

Proving Ring No. | Area of Plunger= 19.625 Cm² | P. Ring factor (PRF)= 4.15 kg/dlvn

PROVING RING DIAL GAUGE READING

Sr. No.	PENETRATIO N mm	Mould No. 01			Mould No. 01			Mould No. 01		
		Dial gauge reading (divison)	Applied load (kg)	% CBR VALUE	Dial gauge reading (divison)	Applied load (kg)	% CBR VALUE	Dial gauge reading (divison)	Applied load (kg)	% CBR VALUE
	0		0			0			0	
1	0.5	4	16.6		4	16.6		5	20.75	
2	1.0	7	29.05		8	33.2		9	37.35	
3	1.5	10	41.5		11	45.65		13	53.95	
4	2.0	13	53.95		14	58.1		15	62.25	
5	2.5	15	62.25	4.54	16	66.4	4.85	18	74.7	5.45
6	4.0	19	78.85		21	87.15		23	95.45	
7	5.0	21	87.15	4.24	23	95.45	4.64	25	103.75	5.05
8	7.5	24	99.6		26	107.9		28	116.2	
9	10.0	26	107.9		27	112.05		30	124.5	
10	12.5	27	112.05		28	116.2		31	128.65	

Corrected CBR per graph

CBR VALUE 2.5 MM	4.54	4.85	5.45
cbr VALUE 5.0 MM	4.24	4.64	5.05
CBR at 97/98% MDD	4.95		

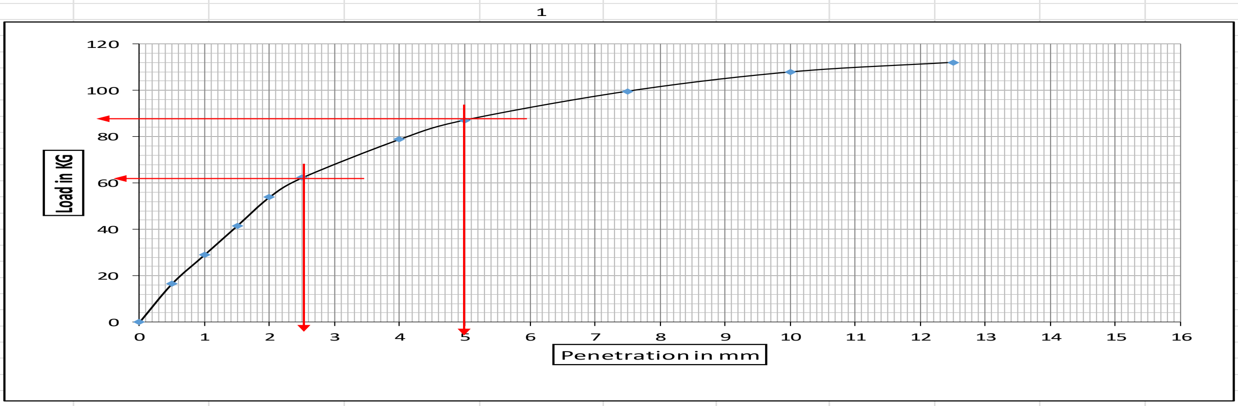

Fig 4.3: CBR test of soil

Table 4.5: California Bearing Ratio (CBR) with Cement

Cement Content (%)	CBR (%)	IS Code Reference
0.0 (Natural Soil)	5.08	IS 2720 (Part 16):1987
0.5	18.30	IS 2720 (Part 16):1987
1.0	22.40	IS 2720 (Part 16):1987
2.0	25.60	IS 2720 (Part 16):1987
4.0	29.70	IS 2720 (Part 16):1987

4.6 Discussion on the results

4.6.1. Index Properties of Natural Soil

The natural soil collected from the borrow area exhibited a liquid limit (LL) of 35.22%, plastic limit (PL) of 20.61%, and a plasticity index (PI) of 14.61%. According to the IS 1498:1970 classification system, the soil falls under the category of clayey soils of low to intermediate compressibility (CL/CI). The free swelling index (FSI) of 26.88% further indicates that the soil has low expansiveness, making it moderately suitable for subgrade applications. However, its strength characteristics, reflected in a California Bearing Ratio (CBR) of 5.08%, fall short of the minimum requirement for highways as per IRC:37–2018, which specifies 8% CBR for flexible pavement subgrades.

4.6.2. Compaction Characteristics

The results of the Standard Proctor Compaction test show a consistent increase in Maximum Dry Density (MDD) with the addition of cement, rising from 1.874 g/cc (0% cement) to 1.906 g/cc (4% cement). This improvement may be attributed to the filling of voids and flocculation-agglomeration reactions between soil particles and cement hydrates, leading to denser packing.

The Optimum Moisture Content (OMC) decreased marginally, from 12.16% to 11.55%, with increasing cement. This reduction is due to the reduction in the affinity of clay minerals for water, as cement hydration products bind the soil particles and reduce their surface activity. Similar findings have been reported by Consoli et al. (2011) and Sherwood (1993), who observed that cement treatment reduces water demand while improving soil density.

4.6.3. Plasticity and Swelling Behavior

Cement stabilization markedly reduced the plasticity index (PI) from 14.61% to 6.80% at 4% cement. This is a direct consequence of the cation exchange and pozzolanic reactions, which transform the soil structure from a dispersed to a flocculated form, thereby reducing plasticity. The Free Swell Index (FSI) also decreased from 26.88% (natural soil) to 15.00% (4% cement), highlighting the effectiveness of cement in controlling volume change behavior. This is of particular significance for highway subgrades, as it minimizes the risk of swelling-shrinkage-related distress in pavements.

4.6.4. California Bearing Ratio (CBR)

The CBR value exhibited significant improvement with cement content. From a baseline of 5.08% (untreated soil), the value increased to 29.70% at 4% cement. Notably, even at 0.5% cement, the CBR rose to 18.30%, which exceeds the minimum subgrade requirement per IRC guidelines.The sharp rise in CBR can be explained by the formation of cementitious bonds due to hydration and pozzolanic reactions, which enhance load-bearing capacity. Studies by Little (1995) and Ravi Shankar et al. (2012) support this observation, demonstrating that small dosages of cement significantly enhance the strength of fine-grained soils.These results confirm that cement stabilization is an effective method for improving strength, durability, and deformation resistance of clayey subgrades.

4.6.5. Discussion of Optimum Cement Content

Although higher cement content yields greater improvements, an optimum value is generally considered in practice to balance performance and economy. In this study, a cement content of 2%–4% provided substantial gains in CBR (25.60%–29.70%), while also reducing plasticity and swelling to acceptable limits. Thus, this range may be recommended as the optimum dosage for stabilizing the studied soil in highway applications.

5. CONCLUSION

This research has systematically investigated the efficacy of stabilizing subgrade soils through the blending of cement with various supplementary materials. The preceding chapters have detailed the methodology, experimental results, and a comprehensive discussion on the mechanical performance, durability, and microstructural evolution of the stabilized soils. The objective of this concluding chapter is to synthesize the key findings from this investigation, providing clear and concise answers to the research questions posed at the outset. Furthermore, this chapter will articulate the significant contributions this study makes to the field of geotechnical engineering, particularly in the realm of sustainable ground improvement. It will also acknowledge the limitations encountered during the research process and, based on the insights gained, propose pertinent recommendations for future research directions and practical applications in the field. Ultimately, this chapter serves to encapsulate the value and implications of the work, drawing the study to a definitive close. The following are the conclusions of the work.

1. The laboratory investigations revealed that the natural soil sampled from the borrow area falls under the category of clay of low to intermediate plasticity (CL/CI) as per IS 1498:1970, with a liquid limit of 35.22%, plasticity index of 14.61%, and free swelling index of 26.88%. These characteristics indicate that, in its untreated form, the soil exhibits moderate swelling potential and insufficient strength, as reflected by a CBR value of only 5.08%. Hence, the natural soil cannot be used directly as a reliable subgrade material for highway construction without stabilisation.

2. With the addition of cement, the soil exhibited notable improvements in its compaction behaviour. The maximum dry density (MDD) increased from 1.874 g/cc to 1.906 g/cc, while the optimum moisture content (OMC) increased from 11.55% to 12.16%. This trend demonstrates that cement stabilization enhances soil packing by reducing the

affinity of clay minerals for water and encouraging flocculation-agglomeration. These changes collectively contribute to a denser, more stable soil matrix that is advantageous for highway subgrade layers.

3. The plasticity index (PI), which is an important indicator of soil workability and sensitivity to moisture, decreased significantly with cement addition, from 14.61% for the untreated soil to 6.80% at 4% cement content. This reduction is a result of the chemical interactions between soil particles and cement hydration products, which transform the soil structure and reduce its plastic nature. The lower PI values confirm that cement treatment produces a more stable and less moisture-sensitive material suitable for subgrade purposes..

4. The most significant improvement was observed in the California Bearing Ratio (CBR) values, which increased from 5.08% in the untreated condition to 29.70% at 4% cement content. Even at a very small dosage of 0.5% cement, the CBR rose to 18.30%, thereby surpassing the minimum CBR requirement of 8% prescribed by IRC:37–2018 for subgrade soils. This dramatic improvement underscores the effectiveness of cement in enhancing the load-bearing capacity and structural stability of the soil, making it suitable for high-performance pavement applications.

5. The study further highlights that even low dosages of cement (0.5–1%) are highly effective, producing substantial gains in soil strength and durability. Higher cement contents (2–4%) provide further improvements in strength and stability, though they may be less economical. Thus, the results show that cement stabilization is not only technically effective but can also be tailored for cost-efficiency depending on project requirements.

6. Based on the results of the experimental program, it can be concluded that the optimum cement content lies between 2% and 4%, which strikes a balance between improved strength (CBR values above 25%), reduced plasticity, controlled swelling, and economic feasibility. This dosage ensures that the stabilized soil performs satisfactorily as a highway subgrade material in compliance with IS and IRC standards.

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