Innovative Approaches to Stability of Embankment - A Role of Chemical Stabilization in Erosion Mitigation

Student Name:	Student ID:
Kemia Mahfuz Auty	190051104
Rafi Uz Zaman	190051250
Nurain Naz Kamal	190051123

A THESIS SUBMITTED FOR THE DEGREE OF BACHELOR OF SCIENCE IN CIVIL ENGINEERING

DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

ISLAMIC UNIVERSITY OF TECHNOLOGY (IUT)

2024

Approval

The paper titled "Innovative Approaches to the Stability of Embankment - A Role of Chemical Stabilization in Erosion Mitigation" submitted by Kemia Mahfuz Auty, Rafi Uz Zaman, and Nurain Naz Kamal has been accepted as a partial fulfillment of the requirements for the degree of Bachelor of Science in Civil Engineering.

Supervisor

Prof. Dr. Hossain Md. Shahin
Professor
Department of Civil and Environmental Engineering
Islamic University of Technology (IUT)
Board Bazar, Gazipur, Bangladesh.

Declaration

It is hereby declared that this thesis/project report, in whole or in part, has not been submitted elsewhere for the award of any Degree or Diploma.

Kemia Mahfuz Auty
Student ID: 190051104

Rafi Uz Zaman
Student ID: 190051250

Nurain Naz Kamal
Student ID: 190051123

Supervisor

Prof. Dr. Hossain Md. Shahin
Professor
Department of Civil and Environmental Engineering
Islamic University of Technology (IUT)
Board Bazar, Gazipur, Bangladesh.

ABSTRACT

This study explores new ways to make embankments stronger using chemicals to prevent erosion. The research tests how well chemicals like SB-95 and TX-95 can stabilize sandy soil commonly found there.

First, the soil was tested to understand its qualities like how fine or coarse it is, how much water it can hold, and how compact it is. Then, SB-95 and TX-95 were mixed with the soil in different amounts. Blocks of this mixture were made and left to harden for 3, 7, 14, and 28 days. These blocks were tested to see how strong they became over time.

To simulate real conditions, a small embankment was built inside a clear box. This embankment used the stabilized soil blocks. Tests were done to measure how strong the embankment was using different amounts of SB-95 and TX-95.

Another test involved making a slope with treated sand (mixed with 10% SB-95) in a box. After drying, water was added, and sensors measured how wet the sand became at different depths. This showed how well SB-95 could stop water from getting into the soil and causing erosion.

The stabilized soil outperformed the untreated soil in terms of erosion resistance, according to the submerged embankment test. The stabilized soil's rate of moisture infiltration doesn’t change. According to SEM pictures, the physicochemical reactions between the soil stabilizer and soil particles form bonds that increase the permeability, decrease erosion resistance, and strengthen sandy soil. The fact that thin film fragments were seen outside of the soil particles suggests that the sand particles were successfully coated and developed resistance to erosion. During the testing time, we saw the effect of temperature; at higher temperatures, we also noticed a significantly higher rate of strength gain.

Tests on Gazipur's soil confirmed it is mostly sandy with some silt. This helped understand if SB-95 and TX-95 could work well there to prevent erosion. Results showed that using 10% SB-95 made the soil blocks much stronger, which could help prevent erosion in Gazipur.

In conclusion, SB-95 and TX-95 are effective in keeping soil stable and preventing erosion in different weather and soil conditions. This research shows how these chemicals can be used to build strong and sustainable infrastructure in places like Gazipur where erosion is a big problem.

Acknowledgment

In the name of Allah, the Most Gracious, the Most Merciful, I would like to express my deepest gratitude to my supervisor, Dr. Hossain Md. Shahin, for his invaluable guidance, support, and encouragement throughout this research. His wisdom and patience have been a source of inspiration, and I am immensely thankful for his mentorship.

I am also profoundly grateful to the Department of Civil and Environmental Engineering at the Islamic University of Technology for providing the necessary resources and facilities to conduct this research. The support from the department has been instrumental in the completion of this study. Special thanks go to my teammates and lab assistants for their continuous support, collaboration, and motivation. Their hard work and dedication have been crucial in overcoming the challenges faced during this research.

Lastly, I extend my heartfelt appreciation to my family for their unwavering support and understanding throughout this study. Their prayers and encouragement have been my strength, and I am deeply thankful for their presence in my life. May Allah reward all those who have contributed to this work and grant them success in all their endeavors.

Keywords

Chemical soil stabilization, erosion control, sandy soil, embankment protection, shear strength, compressive strength, SB-95, TX-95, K-31, Unconfined Compressive Strength (UCS), Scanning Electron Microscopy (SEM), sustainable construction.

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NOTATIONS

- **UCS:** Unconfined Compressive Strength - Measures soil strength under axial loading.
- **SEM**: Scanning Electron Microscopy - Examines material surface and microstructure.
- **SB-95**: Sodium silicate-based stabilizer for soil stabilization.
- **TX-95**: Polymer-based stabilizer to improve soil properties.
- **°C:** Degrees Celsius - Unit of temperature.
- **mm:** Millimeter - Unit of length.
- **m:** Meter - Unit of length.
- **g:** Gram - Unit of mass.
- **kN:** Kilonewton - Unit of force.
- **µm:** Micrometer - Unit of length.
- **%:** Percentage - Denotes proportion out of 100.
- **ρ:** Density of soil - Symbol used in equations.
- **θ:** Angle of internal friction - Measures soil shear strength.
- **σ:** Stress - Measure of force per unit area.
- **ε:** Strain - Measure of deformation under stress.
- **PAM:** Polyacrylamide - Synthetic polymer for soil stabilization.
- **PVAc:** Polyvinyl acetate - Synthetic polymer known for adhesion.
- **PVA:** Polyvinyl alcohol - Water-soluble synthetic polymer.
- **Geopolymer:** Inorganic aluminosilicate material formed chemically.
- **Biopolymers:** Natural polysaccharides and lignins for eco-friendly soil stabilization.
- **Geotextiles:** Synthetic materials for soil reinforcement and erosion control.
- N**-A-S-H**: Sodium aluminosilicate hydrate.
- (**N, C)-A-S-H**: Sodium-calcium aluminosilicate hydrate.
- **MPa:** Megapascal - Unit of pressure.
- **SP:** Sandy soil.
- **GM-GC:** Gravelly sand and gravelly clay.
- **CH:** Clayey soil.
- **MH:** Marl humus.
- **CI:** Commercial isolates.
- **OMC:** Optimum moisture content.
- **ML:** Marine clay.
- **SM:** Silty sand.
- **SS 299:** Styrene-acrylic copolymer.
- **CL:** Clay soil.

Chapter One

INTRODUCTION

1.1 General

Bangladesh is positioned in the expansive Ganges Delta, characterized by its exceedingly flat and low-lying terrain. This geography makes the country particularly vulnerable to regular flooding. Coastal inundations combined with the frequent overflow of its riverbanks have a profound impact on both the landscape and the Bangladeshi population. Notably, 75% of Bangladesh's land lies below 10 meters above sea level, and 80% is comprised of flood plains, as reported by Wikipedia. These conditions underscore Bangladesh's significant susceptibility to extensive damage, even amid ongoing development efforts.

13,000 km of embankments have been built since 1960 to protect against flooding, saltwater intrusion, and destruction (Islam, 2000). An embankment is a ridge created using rock or dirt to divert floodwaters or to build a road, railroad, or canal. The types of embankments and the conditions under which they operate are diverse. One of the many types of embankments on the floodplains is the flood control embankment, which is intended to reduce or eliminate floods. The establishment of a routine maintenance system was impeded by institutional deficiencies and the absence of a suitable erosion control system. Major repairs have been the only kind of maintenance performed when embankments were in danger of failing altogether or causing significant losses. As a result, soil was eroded by other buildings, terraces, slopes, and water bodies (more than 2,700 million m3/year), interrupting the transportation network, lowering productivity, and worsening the environment.

Erosion of soil is the physical loss of topsoil which is caused by a variety of factors, such as wind, gravity, water passing over and through the soil profile, and raindrops dropping. Accelerated erosion and geological erosion are two different kinds of removal of soil. Every piece of land experiences the natural process of soil erosion. Water and wind are the main causes of soil erosion, each of which removes a sizable portion of soil annually. Other severe characteristics of soil degradation, such as salinization, low organic matter, loss of soil structure, poor internal drainage, compaction of the soil, and acidity problems in the erosion, could accelerate the process.

The most common type of degradation, accounting for 25% of Bangladesh's agricultural land, is water erosion. Numerous types of soil erosion, including landslides, riverbank erosion, sheet, gully, and rill erosion, as well as coastal erosion, are happening throughout Bangladesh. Approximately 1.7 million hectares of the country's hilly regions have seen accelerated soil erosion. A study conducted at the Bangladesh Agricultural Research Institute (BARI) Ramgati Station revealed a total yearly soil loss of 2.0 to 4.7 tons/ha.

Shifting agriculture is projected to cause 4.2 tons/ha/year and 7-120 tons/ha/year on 30–40% and 40–80% of slopes, respectively, of soil loss. Significant amounts of plant nutrients are also removed from the top layer, in addition to soil loss, leading to enormous soil decline. Furthermore, deforestation is causing the nation to lose forest land at a pace of roughly 3% per year. At roughly 102 tons/ha/yr, the deforested land is also growing more vulnerable to severe water erosion. In Bangladesh, during the rainy season, strong river currents are the primary cause of bank erosion.

Riverbank erosion threatens over 1.7 million hectares of floodplain regions. During the dry months of the year, wind erosion also affects some parts of Bangladesh, especially in the Rajshahi and Dinajpur regions. Somewhere downstream are the soils that have been eroded from the hills. Agricultural land burial by sand washes is a typical occurrence in locations close to running rivers and hill streams. Runoff water brings course materials down, which negatively affects the Chittagong hill tracts and the entire piedmont alluvium in the north and east (http://www.banglapedia.org/HT/S_0459.HTM)

Normally, flooding happens between June and September, when the monsoon season arrives. The relief rainfall brought on by the Himalayas augments the monsoon's convectional rainfall. Another major annual flood and contribution is meltwater from the Himalayas.

Erosion control is required for hill slopes, coastal embankments, road embankments, and river banks in order to prevent this calamity. Technically sound, economically viable, people-centered, sustainable, and environmentally benign solutions are therefore required.

1.2 Background of the Study

In Bangladesh, erosion of riverbanks and embankment failure are frequent issues. Devastating floods, an abundance of rain, and tidal surges quicken the breakdown process, causing massive damage to infrastructure and crops every year (Islam, 2000). Conventional methods for embankment protection often prove costly and can be inefficient due to suboptimal design and construction deficiencies, which compromise their effectiveness throughout their intended lifespan. Chemical soil stabilization is vital in modern construction and infrastructure development as it enhances the load-bearing capacity, strength, and durability of soils, making them suitable for supporting heavy structures and roads. By altering soil properties, chemical stabilizers create hydrophobic surfaces that resist water infiltration, crucial for preventing erosion and structural failure. This method is versatile, working with various soil types and enabling cost-effective, sustainable construction practices. It reduces maintenance costs and environmental impacts compared to traditional methods, and new advancements in chemical stabilization offer innovative, efficient solutions. Overall, chemical stabilization allows for safe and durable infrastructure, even in challenging soil conditions (Wikipedia). Nawankwo (2001) introduces polyacrylamide as a soil erosion control solution for soil stabilization. The Wisconsin Department of Transportation (WisDOT) has seen rising costs for erosion control, traditionally using expensive erosion mats on construction projects. This report evaluates the use of polyacrylamide (PAM), a soil stabilizer, as a more cost-effective alternative. PAM acts as a flocculant, bonding soil particles to enhance resistance to erosion and improve water infiltration, promoting seed germination and reducing runoff. Comparatively, PAM is not only effective and easy to apply but also cheaper, weather-resistant, and environmentally safe, making it a superior choice over traditional erosion mats for controlling soil erosion on WisDOT project

Liu (2011) observed that clayey slopes are prone to erosion due to their inherent weakness in strength, water stability, and erosion resistance. This study introduces a new organic polymer soil stabilizer, STW, designed to enhance these properties in clay slope topsoil. Laboratory tests demonstrated that STW significantly boosts unconfined compressive strength, shear strength, water stability, and erosion resistance, especially within the first 24 hours of application, with further improvements over 48 hours as STW concentrations increase. SEM analysis revealed that STW stabilizes clay by altering its microstructure. Field tests confirmed that STW effectively reduces soil erosion, improves vegetation protection, and enhances overall slope stability, making it a promising technique for topsoil protection on clay slopes.

Liu (2019) addressed that sandy slopes are highly prone to erosion due to weak internal cohesion. To address this, water-based polyurethane (PU) soil stabilizer has been introduced as an ecological solution to reinforce sandy topsoil and control erosion. This study evaluates the effectiveness of PU treatment through various laboratory tests on specimens with different PU concentrations. Results show that PU significantly enhances the shear strength, unconfined compressive strength, tensile strength, and cohesion of natural sand, although it has minimal effect on the internal friction angle. PU also improves water stability and reduces permeability, fostering better soil moisture retention. Additionally, PU creates a network structure that boosts erosion resistance and supports vegetation growth. The combination of vegetation and PU treatment offers robust erosion protection, making PU a viable, environmentally friendly option for stabilizing sandy slopes. Zezin (2015) The article explores the design, development, and application of innovative binders for various dispersed systems such as soil, sand, and waste rock. These binders are created through the interaction of oppositely charged polyelectrolytes, which can be either chemically stable or biodegradable. The study delves into the fundamental aspects of these interpolyelectrolyte reactions and the unique properties of the resulting interpolyelectrolyte complexes (IPCs), positioning them as versatile binders. Laboratory and field trials, including large-scale tests in the Chernobyl accident zone, demonstrated IPCs' effectiveness in controlling water and wind erosion and preventing the spread of radioactive particles. The article also highlights eco-friendly IPC formulations using commercially available polymers and discusses potential improvements and broader applications for these binders.

Typically, earthen embankments are constructed with a 2:1 slope ratio, meaning 2 units horizontal to 1 unit vertical. However, over time, erosion and soil particle displacement from the embankment surface cause the slope to steepen. This increasing steepness makes the embankment more susceptible to damage from rainfall, flooding, and tidal surges. To ensure the long-term stability of these structures, it is crucial to mitigate rain-induced erosion and protect the surface against shallow-depth erosion.

1.3 OBJECTIVE OF THE RESEARCH

Based on the above-mentioned background the main objective of this research was proposed to investigate the optimum quantity of stabilizers and the effect of the stabilizers on erosion control and slope protection for sandy soil. The objective of the present study is as follow:

1. Enhance Mechanical Properties of Sand:
- Strengthen the shear strength, compressive strength, and overall cohesion of sandy soils to improve their structural integrity and stability.

2. Increase Erosion Resistance:
- Develop methods to make sand resistant to erosion caused by water, wind, and mechanical stress, thereby preventing soil loss and surface degradation.

3. Optimize Chemical Stabilizer Use:
- Identify and utilize effective chemical stabilizers that can significantly improve the erosion resistance and mechanical properties of sand, making it durable and robust.

4. Promote Environmental Sustainability:
- Focus on using eco-friendly and efficient chemical stabilizers that not only reinforce the sand but also minimize adverse environmental impacts.

5. Evaluate Long-Term Stability:
- Assess the long-term performance and durability of the chemically stabilized sand under various environmental conditions to ensure lasting protection and stability.

6. Facilitate Practical Application:
- Develop practical guidelines and methodologies for applying chemical stabilizers to sandy slopes and embankments to improve their erosion resistance and mechanical strength in real-world scenarios.

7. Support Vegetation Growth:
- Investigate the potential for stabilized sand to retain moisture and support vegetation, which can further enhance erosion control and ecological stability.

8. Conduct Comparative Analysis:
- Compare the effectiveness of different chemical stabilizers in enhancing the mechanical properties and erosion resistance of sand to identify the most suitable options for various applications.

9. Integrate Field and Laboratory Data:
- Utilize both laboratory tests and field trials to validate the effectiveness of chemical stabilizers in improving the mechanical properties of sand and ensuring erosion-proof characteristics.

Based on the objectives and the use of chemical stabilizers for improving the mechanical properties of sand to make it erosion-proof, the expected outcomes from your research could be summarized as follows:

Expected Outcomes of the Research

1. Establishment of Correlation:

- Determine a correlation between the mechanical properties (such as shear strength, compressive strength) of chemically stabilized sand, assessed through laboratory tests, and their performance in real-world conditions (in-situ). This correlation will provide insights into the stability and effectiveness of the stabilized sand in preventing erosion.

2. Optimization of Stabilizer Effects:

- Clarify how different chemical stabilizers affect the mechanical properties of sand, particularly focusing on improvements in erosion resistance and overall stability. Evaluate factors such as stabilizer concentration and application methods to optimize their effectiveness.

3. Long-term Stability Assessment:

- Evaluate the long-term stability of chemically stabilized sand against erosion caused by rainfall, wind, and other environmental factors. Assess how the stabilized sand maintains its structural integrity over time and its ability to resist erosion under varying conditions.

4. Environmental Impact Analysis:

- Conduct an environmental impact assessment of the chemical stabilizers used, ensuring that they are environmentally friendly and sustainable. Compare the erosion control efficacy and ecological footprint of different stabilizer formulations.

These outcomes will collectively demonstrate the efficacy, practicality, and environmental benefits of using chemical stabilizers to improve the erosion resistance and mechanical properties of sand in various engineering and environmental applications.

1.4 RESEARCH METHODOLOGY

The whole research was conducted according to the following steps:

1. Soil Characterization and Stabilizer Preparation:

- Initially, the research focused on identifying the soil type, specifically sandy soil sourced from a riverbank. Detailed properties of the collected sand were determined, including grain size distribution, moisture content, and initial strength characteristics. Commercially available chemical stabilizers, namely SB-95, TX-95, and K-31, were selected for use in the study. These stabilizers were mixed in different ratios to prepare samples for subsequent testing. The mixing process followed precise protocols to ensure uniform distribution and consistency.

2. Unconfined Compressive Strength (UCS) Testing:

- ASTM D2166/D2166M-16 standard procedures were adhered to for conducting UCS tests on the prepared samples. Testing intervals were set at 3, 7, 14, and 28 days to evaluate the temporal evolution of compressive strength under laboratory conditions. This allowed for the assessment of how the stabilizers influenced the mechanical properties of the sandy soil over time, providing crucial data for stability analysis and comparison.

3. Moisture Monitoring System Setup:

- A sophisticated moisture monitoring system was established using advanced sensors to measure moisture levels within the embankment. This system featured a "Soil Moisture Hygrometer Detection Humidity Sensor Module" and a "DHT-11 Digital Relative Humidity and Temperature Sensor Module," integrated with an Arduino Uno microcontroller. These sensors enabled precise monitoring of moisture content at different depths within the embankment before and after immersion in water, ensuring comprehensive data collection for analysis.

4. Erosion Testing Setup:

- To simulate real-world conditions, an acrylic box with dimensions of 120cm × 75cm × 45cm was constructed for erosion testing. The embankment within the box consisted of two distinct layers: the top layer treated with stabilizers (specifically 10% SB-95 and 1.3 gm/kg of TX-95) and an untreated base layer, each 13cm in height. After curing for 28 days, moisture content measurements were taken using the established sensor system at depths of 1.5 inches, 4 inches, and within the base soil.

5. Submerged Embankment Testing:

- Following the curing period, the embankment was submerged in 300 liters of water for a duration of 24 hours. Post-submersion, the moisture sensor system was again utilized to record moisture data at specified depths within the embankment. This phase of testing aimed to assess the water resistance and moisture retention capabilities of the stabilized sandy soil compared to the untreated base soil.

6. Scanning Electron Microscopy (SEM) Analysis:

- SEM analysis was conducted to examine microstructural changes in the sandy soil before and after stabilization with chemical binders. This microscopic evaluation provided insights into how the stabilizers interacted with soil particles, potentially altering pore structures and enhancing cohesion. SEM images were analyzed to correlate structural changes with observed improvements in mechanical and erosion resistance properties.

7. Data Analysis and Interpretation:

- Comprehensive analysis of UCS data, moisture sensor readings, and SEM images was carried out to fulfill the research objectives. The UCS results were evaluated to determine the effectiveness of different stabilizer formulations in enhancing compressive strength and shear resistance over the curing period. Moisture content data before and after immersion provided insights into the stability and water resistance of the embankment layers. SEM findings were crucial in understanding the mechanisms behind the stabilizers' performance and their impact on soil microstructure.

By meticulously following these experimental steps and integrating advanced monitoring and analytical techniques, the research aimed to advance understanding and application of chemical stabilizers for enhancing the mechanical properties and erosion resistance of sandy soils. The findings contribute to sustainable soil management practices and offer practical insights for engineering applications in erosion-prone environments.

1.5 THE THESIS LAYOUT

To facilitate a clear and structured understanding of the research process and the progression towards achieving the stated objectives, the entire work has been organized into several chapters. Each chapter is briefly outlined below, reflecting the chronological development and comprehensive exploration of the study:

Chapter Overview

1. Introduction:
    - This chapter sets the stage by outlining the scope, significance, and objectives of the research. It provides a background on the challenges of sandy soil erosion and the potential of chemical stabilizers to enhance soil properties. The rationale behind selecting specific stabilizers (SB-95, TX-95, and K-31) and their expected impact on sand stabilization is also discussed.
2. Literature Review:
    - A thorough review of existing literature is presented, covering previous studies on soil stabilization techniques, especially chemical methods. It includes an examination of traditional and contemporary approaches to improving the

mechanical properties of sandy soils and protecting them against erosion. The chapter highlights gaps in the current knowledge and sets the context for the research.

3. Experimental work & Data collection:
    - A comprehensive account of the experimental work conducted is provided. This includes step-by-step descriptions of the UCS tests performed at various intervals, the setup of the moisture monitoring system, and the construction and testing of the embankment in the acrylic box. Detailed observations and data collection methods are documented to ensure transparency and reproducibility of the results.
4. Results & Discussion:
    - This chapter presents the findings from the various tests conducted. UCS results are analyzed to evaluate the impact of chemical stabilizers on the strength of the sand over time. Moisture content data from the embankment tests before and after submersion are discussed, highlighting the performance of stabilized versus untreated soil. SEM images are interpreted to understand the microstructural changes induced by the stabilizers. Comparative analyses are conducted to assess the overall effectiveness of each stabilizer.

Chapter Two

LITERATURE REVIEW

2.1 General

In Bangladesh, embankment failure and river bank erosion have historically been significant problems. These issues will only get worse in the future as the country's population continues to rise and its land resources are used more intensively—often to the point of ruination. More soil erosion results in increased land loss, decreased soil fertility, increased rainfall, decreased groundwater recharge, increased sediment flows in rivers, higher levels of pollutants in depleting water supplies, lower-quality drinking water, more flooding, lessened economic benefits, and more hardships for both rural and urban populations.

Devastating floods, copious amounts of rainfall, cyclonic storms, and tidal surges quicken the process, causing enormous annual damage to infrastructure and crops. The initial line of defense against flood and cyclonic storm surge should be protected by embankments, riverbanks, and other hydraulic infrastructure in order to reduce the amount of damage. The nation features 24,000 km of rivers on an alluvial plain that is quickly eroded by rainfall, river currents, wave action, etc., over 4,000 km of coastal embankments, and around 13,000 km of flood and river embankments (BWDB, 1998). Once more, the nation has 13,247.79 km of zilla roads, 4221.52 km of regional highways, and 3,478.42 km of national highways that are all susceptible to various types of erosion.

To safeguard embankments, riverbanks, and other hydraulic structures, a variety of techniques are employed, including CC blocks, sand bags as revetment or sand-cement mixed bags, gravity walls, RCC walls, and air bags. However, those approaches are pricy, ineffectual, and harmful to the environment.

This chapter delves into the causes of embankment failure and soil erosion in Bangladesh, focusing particularly on the role of soil stabilization methods. It reviews past research related to soil erosion control and the various techniques for soil stabilization, including both traditional and modern approaches. The chapter explores the characteristics and properties of different chemical stabilizers, such as SB-95, TX-95, and K-31, and their effectiveness in enhancing soil strength. Additionally, it examines how these stabilizers contribute to improving the performance and longevity of embankments by increasing soil cohesion and resistance to erosive forces.

2.2 Past Research

Chemical soil stabilizers are utilized for a wide range of applications, including enhancing slope stability, controlling soil erosion, improving agricultural land, mitigating disasters, and treating contaminated water and land. Extensive research, both locally and internationally, has been conducted to understand the propagation and effectiveness of these stabilizers under various conditions. Studies have investigated their performance in enhancing soil properties, adapting to climatic changes, protecting slopes and embankments, and controlling soil erosion. This chapter presents a review of select research papers relevant to the use of chemical stabilizers in soil stabilization, highlighting their mechanisms, benefits, and practical applications in improving soil stability and resilience.

2.2.1 Research conducted in abroad:

Santoni et al. (2001) investigated the effects of various synthetic polymers, including polyvinyl alcohol (PVA) and polyvinyl acetate (PVAc), on the geotechnical properties of sand. The study on PVA grout injection in sandy soils revealed significant enhancements in compressive strength and elastic modulus across varying PVA concentrations and initial dry densities. Specifically, loose sand samples treated with 25% PVA grout achieved compressive strengths of up to 4 MPa, a remarkable 50-fold increase over untreated samples, whereas medium and dense sands reached 3.7 MPa and 3.5 MPa, respectively, representing 40 and 30 times their control values. It was found that lower PVA concentrations (less than 20%) combined with higher dry densities improved compressive strength, but this trend reversed for thicker grouts (20% or more PVA), where increased dry density reduced strength. Furthermore, the elastic modulus of grouted samples peaked at about 200 MPa with 25% PVA, with loose sands showing the most significant increase, up to 8.3 times higher than controls, compared to 3.8 times in medium sand and 2.4 times in dense sand. This effect is attributed to loosen sand's ability to retain more grout, resulting in higher weight and volume increases post-treatment.

Shainberg I. et al (2002) Adding high molecular weight soil polymers (< 20 kg/ha) to the soil surface, either in solution or dry form, is a viable method for preventing soil erosion by reducing particle detachment and resisting hydraulic shear stress. This approach, already implemented on over 1 million hectares, particularly aids in preventing furrow erosion. The application of dissolved PAM (polyacrylamide) has shown effectiveness in mitigating runoff and erosion, though it poses challenges under rain-fed conditions. Initial research suggests that spreading dry PAM, either alone or mixed with gypsum or soil material, holds promise for erosion prevention in rain-fed environments, but further investigation is necessary to determine its economic feasibility and suitability for widespread agricultural and environmental applications.

Al-Khanbashi et al. (2002) A water-borne polymer system was investigated for enhancing the mechanical stability and hydraulic conductivity of loose sand soil. At a polymer concentration of 2%, significant improvements were observed in hydraulic conductivity: mixed materials exhibited 2.1 × 10^(-6) m/s and sprayed specimens showed 7.2 × 10^(-7) m/s. Even at the lowest concentration tested, the polymer transformed loose sand into a solid material. Both preparation methods—mixed and sprayed—showed linear increases in modulus of elasticity and compressive strength with increasing polymer concentration. At 2% polymer concentration, mixed samples achieved approximately 2.7 MPa compressive strength and 0.17 GPa modulus of elasticity, while sprayed samples exhibited 2 MPa compressive strength and 0.12 GPa modulus of elasticity. These enhancements in mechanical properties and hydraulic conductivity are attributed to the polymer's coverage of sand particles and the development of interconnecting ties between them, which effectively stabilize the sand structure and reduce erosion susceptibility.

Rosa L. Santoni et al. (2005) The effectiveness of two items used to quicken the strength enhancement of a silty sand (SM) material stabilized using unconventional stabilizers was assessed in a laboratory experiment. This investigation assessed nine non-conventional stabilizers, such as lignosulfonates, polymers, silicates, and tree resins**.** The analysis of nontraditional additives for stabilizing SM soils revealed key insights into their stabilization mechanisms. The unconfined compressive strength (UCS) generally increased as moisture content decreased and cure times lengthened, indicating that drying is crucial for strength gains in nontraditionally stabilized soils. Compared to cement-treated controls, many nontraditional additives resulted in lower UCS, suggesting that cement alone was more effective in short-term strength improvement. For certain combinations, like Polymer 3 and Silicate 1 with a cement accelerator, there was a UCS increase, but this was still less significant than the strength gain from cement alone. Polymers 2 and 4 showed notable strength improvements at 7-day cure times and wet conditions, and prior studies indicated significant gains for polymer-stabilized soils at 28 days, suggesting that polymers contribute to strength over longer periods as they form mechanical bonds upon drying. Silicate additives, being highly alkaline (pH > 9.1), enhanced cement hydration by providing additional silicates, aiding the stabilization process. However, further chemical analyses are needed to fully understand the reinforcement mechanisms of these additives.

Consoli et al. (2011) explained the mechanisms by which polymers bind sand particles, forming a cementitious matrix that improves soil strength. Triaxial compression tests were conducted to assess the impacts of fiber reinforcement and cement inclusion on sandy soil under load. Fiber lengths of 12.8 mm at 0% and 3% by weight of the dry soil-cement mix, as well as specimens with 0% and 1% cement by weight that had been cured for seven days, were included. According to the findings, adding cement increased the peak strength, brittleness, and stiffness of the soil. Fiber reinforcement changed the behavior of the soil from brittle to more ductile, increasing both peak and residual triaxial strengths and decreasing stiffness. Fiber addition was particularly effective in boosting peak strength in uncemented soil, while it significantly improved residual strength in cemented soil. The inclusion of fibers raised the friction angle from 35° to 46°, although their impact on cohesion was minimal, with cohesion largely depending on cementation.

Marto et al. (2014) This study explored the macro- and microstructural characteristics of laterite soil treated with non-traditional powder and liquid stabilizers, SH-85 and TX-85, through various analytical methods to understand their effects on engineering properties and stabilization mechanisms. Compaction tests showed that while both stabilizers altered the optimum moisture content and dry density, the changes were minor for the liquid stabilizer, suggesting flocculation and agglomeration of soil particles which reduced compatibility. Unconfined compressive strength tests identified 9% as the optimal concentration for both SH-85 and TX-85, enhancing soil strength. Thermal analysis indicated marginal impacts on the soil's thermal properties, with no significant new peaks or shifts, while FESEM observations revealed that the additives filled soil pores with a cementation gel, leading to denser, more robust soil aggregates. EDAX analysis confirmed the presence of cementitious compounds such as sodium aluminosilicate hydrate (N-A-S-H) and calcium aluminate hydrate (CAH), which contribute to the soil's enhanced stability. These findings highlight that treating laterite soil with SH-85 and TX-85 significantly improves its strength and erosion resistance, forming stronger inter-particle bonds and filling voids more effectively and efficiently than traditional stabilizers like lime and cement. This leads to better erosion control by stabilizing the soil structure and preventing particle detachment and erosion.

S. Premkumar et al. (2015) The study investigated contact erosion at the foundation of pavement embankments using a newly developed apparatus designed for testing under vertical groundwater movement. Experimental results revealed significant soil erosion at the interface, primarily due to clay dispersion failure, with no direct correlation between eroded soil mass and clay content. Modified granular soil (Soil 3) showed that even minimal dispersive clay leads to bonding failures. In magnesium-dominant soils with low sodium, erosion is influenced by calcium content and the Ca/Mg ratio, with small sodium amounts exacerbating erosion. Soils with low calcium and Ca/Na ratios dispersed rapidly, causing significant erosion even at low ESP values. The experiments indicated that mass loss increases with sodium content, especially during initial water exposure, suggesting quick deformation potential. Settlement measurement challenges due to material stiffness and friction suggested estimating settlement from changes in void volume. Erosion mass loss correlated with prolonged water contact and increased over multiple water cycles, though tests were limited to five cycles. The study emphasized the need for further research on contact erosion under pavement layers to better understand erosion failure modes and the impact of soil chemical properties, supporting chemical stabilization and filtration solutions for dispersive soils. This research could inform new guidelines for constructing pavement embankments in flood-prone and dispersive soil regions, particularly relevant in Australia where dispersive soils are common, enhancing their use in pavement construction.

Jang et al. (2016) focused on biopolymers like xanthan gum and their environmental benefits compared to synthetic polymers. Biopolymer Soil Treatment (BPST) has emerged in construction and geotechnical engineering as an eco-friendly method using natural binders like agar gum, xanthan gum, and chitosan to enhance soil properties. Studies demonstrate BPST significantly increases soil strength, primarily by boosting interparticle cohesion, leading to unconfined compressive strengths (UCS) ranging from 200 kPa to 12.6 MPa and cohesion from 40 to 235 kPa, while minimally affecting the friction angle. BPST also raises the soil's liquid limit by enhancing water adsorption and pore-fluid viscosity, thereby improving undrained shear strength. It effectively reduces erosion by enhancing cohesion and shear strength, making it valuable in arid regions. Biopolymers improve groundwater control by holding water well and reducing hydraulic conductivity in soils, notably reducing sand's permeability by up to 10^{-4}. These properties make BPST advantageous for ground improvement and as grouting materials, managing soil permeability and workability efficiently. Environmentally, biopolymers are sustainable, have low CO_2 emissions, and promote vegetation growth, supporting their use in slope stabilization and earthworks. Despite these benefits, further research is needed to bridge laboratory findings with field applications, and specialized construction equipment must evolve to handle the unique properties of biopolymers. However, the study lacked extensive field data on the performance of biopolymer-stabilized sands under different environmental conditions.

Liu et al. (2017) The study evaluated the permeability characteristics of sand reinforced with polyurethane soil stabilizer (PSS) through reinforcement layer form tests, single-hole permeability tests, and porous permeability tests. Results demonstrated that PSS significantly enhances sand's permeability resistance by forming a reinforcement layer on its surface, with layer thickness increasing with longer curing times and higher PSS concentrations; for example, at 24 hours of curing, layers were approximately 2.12 cm (3% PSS), 2.57 cm (5% PSS), 3.05 cm (7% PSS), and 3.56 cm (9% PSS). Permeability tests showed that the time for water to permeate the reinforcement layer increased with higher PSS concentration and longer curing time, while the water flow rate decreased. Along with longer curing times and higher PSS concentrations, the permeability coefficient likewise reduced but increased with specimen depth. When curing times were longer than three hours and PSS concentrations were higher than three percent, there were notable improvements in permeability resistance. A water-resistant layer formed after six hours of curing and at PSS concentrations of seven percent or more. According to microscale SEM studies, PSS strengthens sand's permeability resistance by encasing and connecting sand particles, filling gaps, and narrowing water flow channels. These results are especially relevant to surface protection in landfill, embankment, and slope engineering, where engineering considerations should be taken into account when choosing the best PSS concentration, curing duration, and reinforcement technique.

Rezaeimalek et al. (2017) This study examined the stabilization of sand using a moisture-activated polyurethane polymer precursor from the Methylene diphenyl diisocyanate (MDI) family, identifying an optimal curing procedure and mix design. Key findings include that the treated sand reaches maximum strength after a sequential curing of 4 days in air followed by 4 days in water, with heat curing having no impact on strength. Although the order of mixing is less important, it is nevertheless advisable to add water last to avoid early polymerization. The amount of polymer added increases strength linearly, and stabilized sand with a compressive strength of 5000 kPa is produced when the polymer to water ratio is 2:1. The stabilized sand's high strength and ductility were validated by static load testing. It also performed admirably under cyclic loading of 750 macrostrain for more than 1,000,000 cycles, demonstrating elastic behavior and efficient dynamic energy dissipation. Though more research needs cover soil types other than the poorly graded sand analyzed here to increase the findings' application, these results are probably relevant to other MDI-based liquid polymers.

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Karimi et al. (2018) discussed how polymer chains penetrate soil pores, reducing permeability and enhancing the durability of stabilized sand. The study concluded that using Polyacrylamide (PAM) as a stabilizing additive in soils resulted in increased dry density and unconfined compressive strength (UCS), with the effects varying based on soil type and compaction effort. The dry density increased by 0.8% to 1.3% compared to untreated samples, especially when the compaction effort was at least 35 blows per layer (BPL), with soils containing more fines showing the greatest density improvement. Similarly, PAM-treated soils exhibited UCS increases ranging from 22.9% to 95.2%, with the highest increases observed under the same 35 BPL compaction effort. Soils with moderate fines and higher sand content had the most significant UCS improvement, while those with the most fines and least sand had the smallest gains.

Sepehr et al. (2018) Through a comprehensive laboratory testing program, the curing of soil specimens treated with a liquid polymer soil stabilizer of the styrene acrylic family was investigated. In a controlled laboratory setting, this work developed mix design recommendations and curing protocols for stabilizing sand and clay with a liquid polymer soil stabilizer belonging to the styrene acrylic family. Important discoveries include the fact that, without sacrificing the unconfined compressive strength (UCS), heat curing at 100°C shortens the time needed for the treated soils to completely cure from air curing at 20°C to just 1-2 days. Sand's UCS increases linearly with increasing liquid polymer concentration, however compaction causes polymer bleeding if the void volume is exceeded. Clay gains strength with the addition of polymer up to its liquid limit; after that, the soil becomes too viscous for compaction. Sand and clay both shown susceptibility to moisture and below-freezing temperatures, although clay was more compromised. The polymer significantly decreased the treated soils' capacity for swelling, and a larger polymer concentration further minimized this potential. The treated soils showed good strength and ductility. Water addition had no positive impact on the stabilized specimens' strength.

Liu et al. (2018) The study assessed the efficacy of a polyurethane soil stabilizer on reinforced sand through unconfined compression, direct shear, and tensile tests, revealing significant improvements in strength characteristics with increasing polymer concentration and sand density. Specifically, the unconfined compressive strength, cohesion, and tensile strength of specimens rose with higher polymer content, with the highest tensile strength observed at a density of 1.50 g/cm^3, moderate at 1.40 g/cm^3, and lowest at 1.60 g/cm^3. When the polymer solution was applied to sand, it formed membranes that enveloped and bonded sand particles, creating a stable structure. This mechanism enhanced erosion control by filling voids and providing robust interlocking forces, which were most effective at optimal sand densities. As the polymer concentration increased, more extensive polymer membranes formed, further stabilizing the sand structure and improving erosion resistance by preventing particle detachment and maintaining structural integrity under stress. These findings offer a solid theoretical foundation for using polyurethane stabilizers in sand reinforcement to mitigate erosion.

Yang QW, Pei XJ, Huang RQ, et al. (2019) The results of the study showed that silty sand's characteristics were much enhanced by the addition of methyl carboxymethyl cellulose (M-CMC). While it decreased soil permeability, an increase in M-CMC concentration significantly increased water resistance and strengthened soil cohesiveness with little impact on friction angles. According to SEM pictures, M-CMC significantly altered the physicochemical cementation of the soil, resulting in changes to its strength, water susceptibility, permeability, and resistance to erosion. Tests using rainfall simulations verified that topsoil treated with M-CMC showed increased resistance to erosion and a notable decrease in soil loss. The stabilized soil also shown better water retention and lower rates of moisture intrusion. The efficacy of M-CMC in managing erosion on silty sand slopes for a prolonged duration was confirmed by field tests.

Song et al. (2019) The study evaluated the water-related and mechanical properties of soil stabilized with a vinyl acetate polymer solution through laboratory and field tests, focusing on its erosion control capabilities. Laboratory results showed that spraying the polymer on the soil surface effectively enhanced its water-retaining and erosion-resistant properties. Increased stabilizer concentration led to reduced soil evaporation and maintained higher moisture content, which supported better vegetation growth. Mechanically, higher polymer concentrations significantly improved the soil's unconfined compressive strength, cohesion, and shear strength, though the internal friction angle remained stable. Durability tests indicated that the soil retained high strength after 720 hours of illumination or 10 freeze-thaw cycles, demonstrating resilience. Additionally, the polymer had no negative impact on plant growth in the seed growth test. Field tests confirmed that the vinyl acetate polymer substantially reduced erosion and promoted healthy vegetation on treated slopes, indicating its effectiveness in controlling soil erosion by creating a protective layer that minimized soil loss and enhanced surface stability.

Yakupoğlu et al. (2019) The effectiveness of polyacrylamide (PAM) and polyvinyl alcohol (PVA) polymers in controlling soil erosion varies with aggregate size and rainfall conditions. In simulation experiments, both polymers reduced total runoff, sediment yield, and soil loss due to splash significantly, although they did not notably delay runoff generation compared to control plots. PAM, potentially due to its higher charge density and molecular weight, was more effective than PVA in minimizing soil and water losses. Results showed that soil and water losses increased during sequential rainfall simulations, likely because the aggregates did not reconnect properly due to insufficient drying time and higher antecedent soil moisture. Additionally, the effectiveness of polymer application improved with larger soil aggregates, particularly those over 6.4 mm. Therefore, while polymers are promising for erosion control, especially with larger aggregates, further research is needed to evaluate their economic and biophysical feasibility comprehensively.

Zomorodian SMA et al. (2020) The HET (Hydraulic Erosion Testing) testing program demonstrated that very small additions of MK10(Montmorillonite K10= Nano-clay based additive) additive can substantially improve the hydraulic erosion resistance of highly erodible SP compacted, very silty sand at bench scale. Compared to cement stabilization, MK10 at similar dry weight concentrations shows equal effectiveness but with potentially significantly lower embodied carbon. Among the MK10-soil mixtures tested, the 1% MK10 mixture was identified as optimal, showing moderately strong erosion resistance [mean I_{HET} (Erosion rate index) =4.1 for i(Hydraulic gradient)=3.3–10.3]. The erosion resistance of SP-compacted 1% MK10-soil specimens remained unaffected by variations in compaction density, molding water content within allowable ranges, and different hydraulic gradients tested (i = 0.43–10.3). Additionally, higher compaction densities, molding water contents towards the upper limit of allowable range, longer curing periods, and higher hydraulic gradients generally led to marginally greater erosion resistance, consistent with expectations from the study.

Sandesh Gautam et al. (2020) An expansive soil from Carrollton, Texas, primarily composed of 43% montmorillonite, 34% illite, and 23% kaolinite, was tested with a liquid ionic soil stabilizer. The stabilizer showed minimal impact on Atterberg's limits, with slight, inconsistent changes in the liquid limit. It increased the optimum moisture content (OMC) from 23% to 27% and decreased the maximum dry density (MDD) from 15.2 to 14.3 kN/m³ (1:300 ratio) and 14.5 kN/m³ (1:150 ratio). The soil exhibited a 53% swell reduction when compacted at its respective OMC and MDD;

however, when both treated and control soils were compacted at the control soil's OMC and MDD, the swell reduction was only 25%. This suggests the importance of using the treated soil's compaction curve for optimal swell reduction. The unconfined compressive strength of the treated soil decreased slightly when compacted to the treated soil's compaction curve but was similar to untreated soil when compacted to the untreated soil's curve. Despite this, the modulus E50 increased after 7 days of curing for both compaction methods. SEM analysis showed modifications in soil fabric and structure, including the disappearance of flaky structures and some mineralogical changes towards more stable phases, albeit minor. The relatively low mass application ratio in laboratory conditions might explain the lesser impact seen in lab results compared to the effective performance observed in field applications, where soil is wetted to near saturation.

Farooq et al. (2020) The best concentrations for strengthening and controlling erosion in silty clay soil were found to be 5% SD and 15% RH in a study on stabilizing soil embankment slopes with sawdust (SD) and rice husk (RH). Sawdust and rice husk significantly increased soil stability at these ratios. With SD, the soil's unconfined compressive strength (UCS) increased by 3.4 times (237%), while with RH, it increased by 2.4 times (138%). Shear strength measurements also demonstrated significant improvements; the angle of internal friction increased by 1.3 times (32%) with SD and 1.2 times (22%) with RH, while cohesiveness improved by over three times (220%) with SD and over two times (130%) with RH. At their respective ideal contents, both additions dramatically decreased soil erosion rates: SD by 62% and RH by 55%. Interestingly, sawdust outperformed rice husk in terms of strength and resistance to erosion, even at lower dosages, making it more efficient and cost-effective.

Yuxia Bai et al. (2021) In this work, a series of uniaxial compression (UC) and direct tensile (DT) experiments were conducted at various polyurethane polymer contents (PUC), dry densities (DD), and temperatures (TP) to examine the mechanical behavior of a polyurethane (PU) polymer-sand mixture. Unconfined compression (UC) and direct tensile (DT) tests on PU-sand mixtures across various temperatures revealed several insights into the mechanical behavior influenced by polyurethane content (PUC) and dry density (DD). With increasing PUC and positive temperatures, the stress-strain relationship (r-e) indicated a progressive drop in stress after peaking, which was associated with bulging failure with cracks. Conversely, higher DD and negative temperatures reduced ductility. Temperature had a beneficial impact on the linear connections between UCS, E50 (secant modulus at 50% UCS), and TS (tensile strength), which peaked at 1.44 MPa, 0.3 MPa, and 38.67 MPa, respectively, as PUC increased. The effects of the PU treatment were increased by both positive and negative temperatures, improving the strength-to-stiffness ratios. Positive temperatures predominantly improved strength and ductility, while negative temperatures enhanced strength and stiffness, but reduced ductility due to frozen water. SEM observations confirmed that PU created a three-dimensional network bonding the grains, with higher PUC strengthening this network by boosting connection strength and density, though higher DD reduced connection strength. Higher temperatures further enhanced the strength, stiffness, and ductility of the PU-sand mixture by contraction, while frozen water at lower temperatures increased strength and stiffness, yet decreased ductility.

Zhang et al. (2021) The Taguchi method is an effective and economical approach for studying soil erosion on slopes, as it significantly reduces the number of tests needed compared to a full-factorial design. This study, which used orthogonal design as a comparative tool, demonstrated that both methods can closely approximate the results of a full-factorial design in terms of statistical parameters for dependent variables. However, the Taguchi method provided results more aligned with the full-factorial design, particularly for complex variations and small-scale slopes, proving superior to the orthogonal design. Despite its advantages, including better handling of experimental error through S/N ratio analysis, the Taguchi method's results can still be influenced by nonquantifiable factors, the spacing between factor levels, the size of the soil box, and the nature of dependent variables. Therefore, applying the Taguchi method requires expert knowledge in soil erosion to appropriately select variables, factors, and levels for slope-scale experiments. While it can substitute for a full-factorial design in some cases, discrepancies remain in certain scenarios, necessitating professional judgment and experience.

Algadwi et al. (2021) The application of polymer to soil significantly enhances its resistance to wind and rain erosion, offering an effective alternative to traditional stabilization methods like marl. This polymer treatment not only extends the soil's lifespan but also reduces costs compared to capping techniques. However, the effectiveness of the polymer varies with soil type; in the observed project, sandy soil exhibited greater improvement in stability than sabkhah soil. This suggests that assessing soil type prior to polymer application is crucial for optimizing erosion control outcomes.

Prince Kumar et al. (2022) A research study was designed and conducted to investigate the effect of polymer emulsion treatment on permeability characteristics of subgrade soils. Taking into account the effects of polymer dose and curing time, this study assessed the efficacy of polymer emulsion in lowering the hydraulic conductivity of cohesive (CL) and cohesive (SM) soils. To monitor microstructural changes, FE-SEM imaging was used in conjunction with a variety of extensive laboratory studies, such as permeability testing employing a double-walled triaxial setup and soil characterization tests. The findings revealed that polymer emulsion significantly lowered the hydraulic conductivity in both soil types, with a more pronounced effect in SM soils. Increased polymer dosage and longer curing periods led to greater reductions in hydraulic conductivity. SEM images showed that polymer emulsion treatment created a more compact soil microstructure, binding soil particles and restricting water flow through the voids. These microstructural changes corroborated the observed decreases in hydraulic conductivity, confirming the efficacy of polymer emulsion treatment.

Boaventura et al. (2023) This study explored the application of a polymer-stabilized composite material for geotechnical structures in an environmentally protected sandy soil area. The soil, classified as A-3 (HRB) and SP (SUCS), exhibited granular behavior with no natural cementing elements. The mechanical qualities of the soil were improved by the addition of polymer at 2.5% and 5% concentrations. The polymer, which is an organic acrylic-styrene copolymer, was obtained at random and delivered as an anionic aqueous emulsion. Compaction experiments revealed that the addition of polymer increased dry density and slightly decreased ideal moisture content, while direct shear tests revealed that curing time bolstered the cohesive intercept and friction angle.

Permeability decreased due to the polymer filling void spaces between soil grains, reducing the potential for erosion. Microstructural analysis confirmed that the polymer formed a cementing film around grains, increasing rigidity through air exposure, which catalyzed the hardening process. The leachate analysis indicated no significant environmental contamination risk, validating the polymer's safe use in sensitive areas. Overall, the study demonstrated that both 2.5% and 5% polymer solutions are technically and environmentally viable for use in embankments, slopes, and pavement, with the 5% concentration yielding superior results. This composite's efficacy in erosion control is attributed to the polymer's ability to bind soil particles, reduce permeability, and enhance overall structural integrity.

Wang et al. (2023) Growing environmental consciousness and quickening social progress have led to the widespread application of organic polymer technology for ecological slope preservation. The importance of organic synthetic polymers and biopolymers for improving soil consolidation and encouraging vegetation growth on slopes is highlighted in this study, which is important for the development of sustainable infrastructure. It goes over the basic traits and ways in which these polymers interact with soil, focusing on how they affect mechanical qualities, infiltration, resistance to erosion, and vegetation support. In road slope ecological engineering, organic polymers offer substantial advantages over conventional protective techniques. Notwithstanding their benefits in accomplishing sustainable infrastructure objectives, their application presents certain technological difficulties.To establish standardized testing and design techniques for slopes changed by organic polymers, it is imperative to do further research in order to gain a deeper understanding of the mechanical mechanics behind these polymer-soil composites.

2.2.2 Cause of Erosion & Embankment Failure

Because surface runoff and erosion exacerbate the dangers of flooding and surface water pollution while also contributing to losses of water and soil fertility, they play a major role in land degradation in many regions of the world. On the other hand, the absence of soil stabilizers can lead to increased vulnerability of natural slopes to topsoil erosion, especially in areas where the surface lacks adequate plant cover. Soil stabilizers play a crucial role in reinforcing the soil structure, similar to how vegetation acts as natural reinforcement. Without these stabilizers, bare soil becomes more susceptible to erosion. Topsoil erosion in such conditions can occur through two primary mechanisms: wind erosion, which removes loose soil particles, and water erosion, where rain or runoff washes away the unprotected soil layers.

a) Raindrop impact energy loosens the top soil: After a rainfall over significant time raindrop impact energy may loosens the bond among the soil particles and becomes vulnerable to sheet erosion.

b) Surface runoff carries it downwards: the loosened soil mass is subjected to an additional hydraulic push by the surface runoff, carries it downwards and induces a failure surface **(Khan and Rahman, 2009)**.

Reduced soil infiltration rate could result in more runoff since runoff is produced when rainfall intensity surpasses both soil surface water holding capacity and soil infiltration rate. The primary element that reduces soil infiltration during precipitation in seal development occurs at the soil surface in arid and semi-arid environments **(Morin et al., 1981; Ben-Hur and Letey, 1989)**. According to **Wakindiki and Ben-Hur (2002)**, In comparison to the underlying soil, a surface seal is denser, thinner, and has a lower saturated hydraulic conductivity. Drill and interrail processes are the two primary categories of soil erosion processes. Runoff from a soil surface can collect in narrow, erodible channels called gullies or rills, which can cause damage to embankments and structures.

According to recent research conducted by the Center for Environment and Geographic Information Services (CEGIS) in Bangladesh, river erosion causes 0.1 million individuals in the nation to become homeless each year. Riverbank properties have been submerged for the past 34 years on 219286 acres in the Jamuna, 69135 acres in the Ganges, and 95119 acres in the Padma. worry that by 2007, the Jamuna's erosion will sink 3408 acres of land, 543 communities, 3360 meters of embankment, 5160 meters of roadways, 4 educational institutions, and 2 marketplaces. Between now and then, the Padma would result in 1600 acres of land, 370 acres of localities, 570 meters of roadways, and 1778 acres of land along the Ganges. 3930 m of roads, 9 educational institutions, 5 marketplaces and 1 Union Council office to be submerged in the river by the recent rate of erosion. The main areas of erosion in Bangladesh arepresented in Table 2.1

Year	Affected areas (Acres)	Affected population
1996	71680.4	10103635
1997	7756	173090
1998	41519	321000
1999	227755	899275
2000	219310	415870

Table 1: Main areas of erosion in Bangladesh **(Zaman, 1998)**

River	No. of location of bank/embankment erosion	Length of erosion (km)
Brahmaputra-Jamuna	41	162.60
Ganges-Padma	26	94.50
Meghna	8	72.00
Teesta	11	34.90
Minor river	112	92.30
Flashy river	75	23.00
Tidal river	32	85.80
Total	305	565.10

Table 2: Losses of river erosion between 1996 to 2000 **(Chowdhury et al., 2007)**

From the field survey and past studies, it was observed that, the most common causes

of embankment and river bank failure can be broadly classified into two major groups (**Arifuzzaman, 2011)**:

a) Natural forces (such as; rainfall impact, wave action, wind action etc)

b) Human interference (such as; travel paths for men and cattle, cattle grazing, unplanned forestation

Figure 1: Failure (a) river bank; (b) road embankment and (c) and hill slope (Drdrave,2012) of embankment slopes etc).

2.3 SURFACE EROSION

Mechanics of Erosion

For erosion to be prevented and controlled, it is imperative to comprehend the physics of the erosion process. Particle detachment and particle movement are the two distinct processes that comprise the two-step process that constitutes erosion.

Particle inertial or cohesive forces counteract the drag and tractive forces of the flowing stream. Erosion is caused by drag or tractive forces, which are influenced by particle form, roughness, discharge, and velocity. Erosion is, however, resisted by inertial, frictional, and cohesive forces arising from basic soil properties, soil structure, and physicochemical interactions.

In terms of soil stabilizers, erosion protection essentially consists of:

(1) Reducing the force of erosive agents like wind and water by decreasing the flow velocity over the soil surface or by dissipating the energy in areas treated with stabilizers, and
(2) Enhancing the soil's resistance to erosion by applying stabilizers that bind the soil particles together, thereby increasing the interparticle bond strength and reinforcing the surface, similar to how a protective layer of vegetation would work.

Principal Factors Affecting Erosion

i) Erosion by Rainfall
Four fundamental factors—climate, soil type, terrain, and plant cover—control rainfall erosion. The intensity and duration of precipitation are the primary climatic factors influencing rainfall erosion. **Wischmeier and Smith (1978)** have shown that the most important 'single' measure of the erosion-producing.
The mechanism of top soil erosion is shown in Figure 2.5.

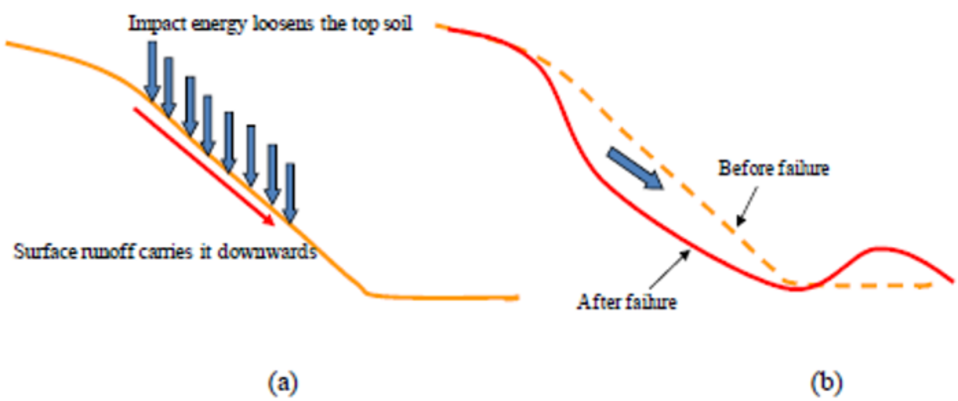

Figure 2: Mechanism of Top Soil Erosion (a) Impact of Rainfall on Slope & (b) After Slope failure due to rainfall

ii) Erosion by Wind
The same fundamental elements that govern rainfall erosion also govern wind erosion. In Figure 2.2, the dependency of wind erosion on these variables is schematically depicted.

Temperature, humidity, and the amount and distribution of rainfall have the most effects on soil moisture. Wind erosion is only possible on relatively dry soils. The wind's velocity, duration, direction, and degree of turbulence are its most crucial properties. Only fine silt-sized, or less than 0.1 mm, dry soil particles can be picked up and carried in suspension by the wind

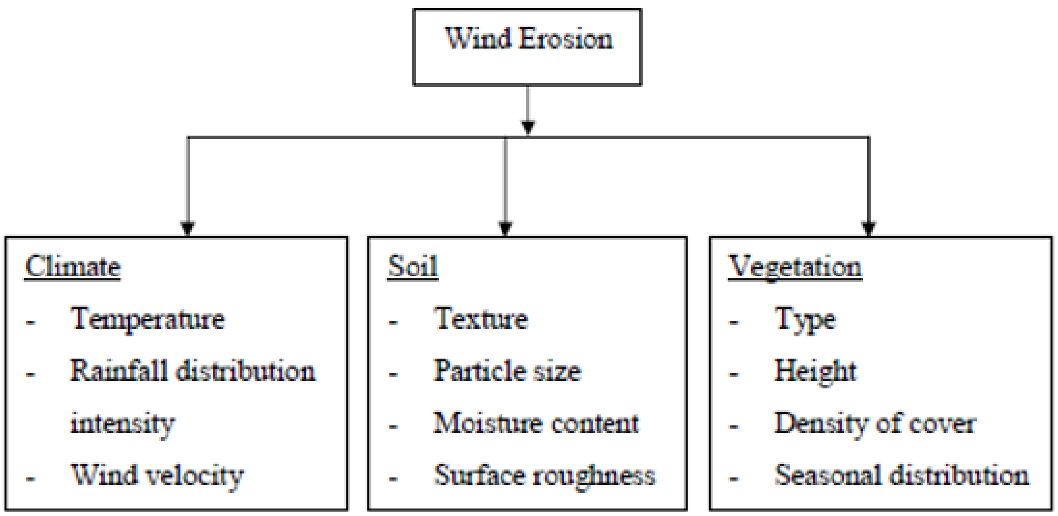

Figure 3: Schematic Diagram showing factors of wind erosion **(Gray & Sotir,1996)**

For wind erosion, soil stabilizers help in the following ways: Initiation of Movement: Soil stabilizers bind soil particles together, increasing their weight and cohesion, thus requiring higher wind velocity to initiate movement. Transport: Stabilizers reduce the detachment and airborne transport of soil particles by strengthening the soil matrix. Deposition: By making the soil heavier and more cohesive, stabilizers reduce the distance that particles can be transported by wind, keeping more soil in place.

Research has shown that most wind-eroded soil particles are transported close to the ground, within a zone under 1 meter in height. This suggests that applying soil stabilizers to create a robust surface layer can significantly impede soil particle movement in this critical zone. By enhancing the soil's inherent resistance to wind erosion, stabilizers serve a similar role to low barriers or windbreaks, preventing soil from becoming airborne and reducing erosion.

2.3.1 AVAILABLE PRACTICE TO PROTECT SLOPE FAILURE

The methods to protection slopes and embankments can generally be classified as:
(a) indigenous methods,
(b) gravity walls,
(c) RC-walls,
(d) sand bags as revetment or sand cement mixed bags and
(e) CC-blocks.
(f) Geosynthetics/Geotextile

a) Indigenous methods: grass, water hyacinths etc.

Grass:

When it comes to this kind of protective job, there are no hard and fast rules. Traditionally, chailla grass has been used. Chailla grass straw is spread out across the hill at a specific thickness and kept there with the assistance of broken bamboo. netting weaved. Pegs secure this bamboo net to the incline. The term "aar bandh" refers to what is technically called "soft protection." It must be built each year at the start of the monsoon and taken down at the conclusion of the monsoon, otherwise it will crumble during the dry season. When the wave height surpasses 0.6 m for an extended duration, it is unable to endure the force of the eroding waves (CIDA, 2002).

Water hyacinths:

The water hyacinth is a floating plant that thrives in an abundance of water and may survive on dry land. With the assistance of bamboo poles and fencing, the plants encircle the mound and float as the water level rises. Waves are therefore unable to immediately assault the slope. Only when the wave height takes the shape of ripples will the ck as well approach work effectively.

b) Gravity walls

Masonry walls are intended to function as gravity walls in order to both hold the earth at the back and provide protection from wave onslaught. It conserves land that would otherwise be needed to create slopes. However, it is not visually appealing or friendly to the environment. Its poor soil condition makes it quite expensive as well.

c) RC walls

As a wave barrier, RCC walls are employed. RCC walls, however, are not environmentally friendly.

d) Sand bags and sand-cement mixed bags

This kind of protection is inexpensive and only lasts temporarily. Low FM sand is filled into gunny or polyethylene bags with a capacity of approximately 1.25 cubic feet for this kind of protection job. The sand-filled bags are positioned in a rip-rap pattern across the inclines. Because polyethylene bags are more sustainable than gunny bags, they are preferable. This kind of labor is most appropriate for urgent repairs and emergencies that don't require a lot of time or money.

e) CC-block

Slope protection has recently used placed cement-concrete blocks with geotextile. However, it is quite expensive and not environmentally friendly. At Keraniganj, the protected embankment slopes made of cement concrete (CC) blocks crumbled, as seen in Figure 2.8. This failure may have been caused by improper CC block placement on the embankment slope, an existing soft layer or layers beneath the embankment, improper compaction of the embankment slope, high tidal surges that weaken the embankment and wash away the soil particles beneath the CC blocks, etc. But none of the aforementioned methods are cheap or environmentally friendly.

(f) Geosynthetics/Geotextile

Geosynthetics and geotextiles play a pivotal role in erosion control by reinforcing soil, providing separation and filtration, and protecting surfaces from erosive forces. These synthetic materials, typically made from polymers like polypropylene and polyester, are used to stabilize slopes, embankments, and shorelines. They enhance soil strength and prevent displacement by distributing loads more evenly, as shown in studies by **Vidal et al. (2017)** and **Shukla (2017)**, which highlight their effectiveness in improving embankment and slope stability. Additionally, geotextiles act as a filtration barrier, allowing water to pass through while retaining soil particles, thus preventing soil loss during heavy rains and surface runoff. They also shield soil surfaces from the direct impact of raindrops and flowing water, reducing erosion, as noted by **Gray and Sotir (1996)**. Furthermore, these materials aid in drainage and moisture control, managing water infiltration and preventing soil saturation that can lead to increased erosion risk, as described by **Koerner (2012)**. Their diverse applications in stabilizing slopes, protecting shorelines, and supporting road and railway embankments underscore their essential role in modern erosion control strategies.

Low-Cost Solutions to Protect Slope Failure

As the available practices which is available used in Bangladesh to protect the embankment is expensive and not eco-friendly that’s why some low-cost methods are also used for this purpose. The available low-cost solutions to protect slope failure are:

a) Vegetation by grass seeding
b) Compaction of embankments soil by layers.
c) Vegetation and plantation.
d) Soil Stabilization
e) Geosynthetics/Geotextile

Effect of Stabilizers in the stability & erosion control of Embankment: (References are listed accordingly)

To enhance the qualities of soil, chemical stabilizers like fly ash, cement, and lime have long been employed. By encouraging pozzolanic reactions, which improve the soil's load-bearing capacity and resistance to deformation and erosion, lime and cement stabilization raises the soil's shear strength and decreases its flexibility. Because of their adaptability and efficiency in a range of soil situations, polymers—both synthetic and natural—are being utilized more and more for soil stabilization. In addition to raising the pH of the soil, lime causes clay particles to clump together and flocculate, increasing the soil's shear strength and decreasing its permeability. Research indicates that soils treated with lime have better water erosion resistance and increased cohesiveness, both of which are good for slope stability. **(Little & Nair, 2009).** Cement works by hydrating and binding soil particles, significantly increasing compressive strength and reducing erodibility. The formation of calcium silicate hydrates (CSH) contributes to soil cementation, making it more resistant to disintegration under water flow **(Hausmann, 1990).** Fly ash, a by-product of coal combustion, enhances soil stability by filling voids and binding soil particles. Its pozzolanic properties improve soil's long-term durability and resistance to water-induced erosion **(Pandian, 2004).**

Polyacrylamide (PAM) and other synthetic polymers bind soil particles together, enhancing soil cohesion and reducing erosion. They form a viscous film around soil particles, which stabilizes the soil structure and decreases hydraulic conductivity (Tingle & Santoni, 2003). Biopolymers like xanthan gum, guar gum, and chitosan are eco-friendly alternatives that improve soil stability through similar binding mechanisms. These polymers increase soil cohesion and reduce permeability, thus controlling erosion effectively (Chang et al., 2015).

Effects on Erosion Control

2.3.2 Surface Erosion Resistance

Erosion control is vital for maintaining the surface integrity of embankments, preventing soil loss, and safeguarding structural foundations. Stabilizers play a significant role in enhancing surface erosion resistance.

- **Chemical Stabilizers**: Cement and lime treatments improve soil cohesion, which reduces the detachment of soil particles during rainfall or surface runoff. The hardened surface crust formed by these stabilizers acts as a protective layer, minimizing erosion rates **(Petry & Little, 2002**).

- **Polymers**: Synthetic and natural polymers create a cohesive layer on the soil surface, significantly reducing soil detachment and surface runoff. Studies have shown that polymer-treated soils can reduce erosion rates by up to 90% compared to untreated soils, making them effective for slope protection and embankment surfaces **(Zhang & Lei, 2014).**

2.3.2 Internal Erosion and Seepage Control

Internal erosion and seepage through embankments can lead to structural weakening and eventual failure. Stabilizers help in controlling these internal processes by reducing soil permeability and enhancing particle binding.

- **Chemical Stabilizers**: Lime and cement reduce soil permeability by filling voids and binding particles, thereby limiting water flow through the embankment. This reduction in permeability helps in controlling internal erosion and seepage, preserving the embankment's structural integrity

  (Al-Rawas & Goosen, 2006).

- **Polymers**: Polymers like PAM decrease hydraulic conductivity by creating a dense, interconnected matrix of soil particles. This matrix restricts water movement, reducing the potential for internal erosion and increasing the soil's resistance to seepage-related failures **(Green et al., 2000).**

PHYSICOCHEMICAL PROPERTIES OF POLYMERS

Based on their source and structure, polymers employed in soil stabilization fall into three categories: synthetic organic polymers, biopolymers, and geopolymers. Inorganic polymers called geopolymers are produced by activating amorphous aluminosilicates with alkali solutions. **(J. Davidovits-1991)**. Biopolymers, which include cellulose, lignin, and polysaccharides, are derived from natural sources such as biomass or bacteria. Polyacrylamide (PAM), polyacrylate, poly (vinyl alcohol) (PVA), and poly (vinyl acetate) (PVAc) are examples of man-made synthetic organic polymers. Because of their distinct physicochemical characteristics and compositions, each type interacts with soil minerals in a different way, which affects how efficient they are at stabilizing the soil.

2.3.3 Geopolymers: An Overview

An inorganic aluminosilicate material class recognized for its special qualities and uses is called geopolymers. They are created by reacting precursors rich in silica and alumina with alkali activators, which produces a strong three-dimensional network.

Chemical Structure and Formation

- **Polymerization Reaction:**
  - Alkali polyciliate react with precursors that are high in alumina and amorphous silica.
  - Polymeric Si-O-Al bonds are created by this reaction between Si and Al in a tetrahedron coordination with oxygen

- **Types of Poly(sialate) Structures:**
  - Poly(sialate): (-Si-O-Al-O-)

    - Poly(sialate-siloxo): (-Si-O-Al-O-Si-O-)
    - Poly(sialate-disiloxo): (-Si-O-Al-O-Si-O-Si-O-)
    - These structures are typically amorphous to semi-crystalline **(J. Davidovits-1991)**
- **Empirical Formula:**
    - General formula: Mn {−(SiO2) z−AlO2} n·wH2OMn
    - M: Alkali cation (e.g., Na^{+}, K^{+}, Ca^{2+})
    - n: Degree of polycondensation
    - z: Si/Al molar ratio (varies from <1 to >300) **(K.J.D. MacKenzie-2006)**
        - z<1: Mixtures contain crystalline phases.
        - 1<z<3: Rigid, brittle, three-dimensional network.
        - z>3: Two-dimensional, linear structure, adhesive properties.
        - z>15: Exhibits rubbery properties **(G.P. Zang-2010)**

2.3.4 Source Materials for Geopolymers

- **Common Precursors**:
    - Kaolinite
    - Metakaolin
    - Fly Ash
    - Furnace Slag
    - Rice Husk Ash
    - Red Mud **(J. He-2011)**
- **Alkali Activators**:
    - Sodium Hydroxide (NaOH)
    - Potassium Hydroxide (KOH)
    - Sodium Silicate (Water Glass)

Key Factors Influencing Properties

Factors	IMPACT ON GEOPOLYMER PROPERTIES
Si/Al Molar Ratio	Most significant effect on properties. Optimal performance typically between 1 and 3 **(M. Steveson-2005)**
Na/Al Molar Ratio	Best maintained at unity for optimal properties **(J. Davidovits-1991)**
Alkali Concentration	Affects pH, thus influencing solubility of silica and alumina. High pH enhances dissolution of precursors.

Table 3: Key Factors Influencing Properties

Physical and Chemical Properties

- **Common Properties:**
    - Excellent chemical durability against:

- Sea Water Attack
- Acid Attack
- High Temperature and Fire
- Frost Attack
- Sulphate Attack **[A. Fern´andez-Jim´enez-2009]**

- **Durability Considerations:**
    - The inclusion of calcium-containing precursors like slag, or the addition of cement and lime, may reduce resistance to sulphate attack. Calcium is vulnerable to sulphate, similar to traditional stabilizers such as lime and cement.

Visuals and Tables for Clarification

Si/AL RATIO (Z)	STRUCTURE TYPE	PROPERTIES
z<1	Contains crystalline phases	Hardens but may include gibbsite **(K.J.D. MacKenzie-2006)**
1<z<3	3D, Cross-linked	Rigid, brittle, cementitious and ceramic **(G.P. Zang-2010)**
z>3	2D, Linear linked	Adhesive properties **(G.P. Zang-2010)**
z>15	2D, Linear	Exhibits rubbery properties **(G.P. Zang-2010)**

Table 4**: Summary of Geopolymer Structures Based on Si/Al Ratio**

BIOPOLYMER IN SOIL STABILIZATION:

Introduction:

Biopolymers, also known as microbial-induced polymers, are a novel class of soil stabilizers. Actively researched for their potential in enhancing soil stability and controlling erosion.

Types and Properties of Biopolymers

1) Polysaccharides

- **Overview**:
  - Widely used in various industries due to their environmentally friendly nature.
  - Commonly used polysaccharides include agar gum, guar gum, gellan gum, beta-glucan, and xanthan gum.
- **Applications**:
  - Utilized as additives in food and medical sectors.
  - Serve as flocculants, foam stabilizers, water treatment agents, and filtration aids **(S. Kalia-2016) (T. Osmalek-2014) (I. Chang-2020)**

Polysaccharide	Key Properties	Typical Applications
Agar Gum	Gelling agent	Food industry, microbiological culture media
Gura Gum	High viscosity, thickening agent	Food, pharmaceuticals, hydraulic fracturing
Gellan Gum	Gelation under low temperatures	Food industry, drug delivery systems
Beta- Glucan	Immunomodulating, high viscosity	Medical applications, dietary supplements
Xanthan Gum	High viscosity, stability in various pH	Food industry, oil drilling, cosmetics

Table 5: Properties and Applications of Polysaccharides

2. Lignins

- Overview:
  - Lignins are abundant organic polymers, primarily found in the cell walls of woody plants and as byproducts in the papermaking industry.
- Types of Lignins:
  - Lignosulfonate: Byproduct of sulfite pulping; contains hydrophilic and hydrophobic groups.

- Kraft Lignin: Produced from the kraft pulping process; also known as sulfate lignins.
- Sulfur-Free Lignins: Derived from the bioethanol industry, these lignins are high in content and more similar to native lignin **(J.H. Lora-2002) (B. Chen-2004) (Y. Liu-2020)**

LIGNIN TYPE	SOURCE	KEY PROPERTIES
Lignosulfonate	Sulfite pulping	Hydrophilic groups, moderate size
Kraft Lignin	Kraft cooking process	Sulfur-containing, moderate to large size
Sulfur-Free Lignin	Bioethanol industry	High lignin content, moderate size

Table 6: Characteristics of Different Ligninsm

Interaction Mechanisms with Soil

- **Physical and Chemical Interactions**:
  - Biopolymers have large specific surface areas, varying charges, and different particle sizes.
  - They interact with fine soil particles (silt and clay) through ionic bonds and hydrogen bonds **(I. Chang-2016)**.
- **Behavior Under Moisture Variation**:
  - Biopolymers dehydrate when dried and swell upon rehydration.
  - The tensile strength and stiffness of biopolymer hydrogels decrease significantly with increasing water content **(I. Yakimets-2007)**
- **Effect on Soil Permeability**:
  - Swelled biopolymer hydrogels can coat large particles and fill the pores between them.
  - This reduces soil permeability drastically, which is beneficial for soil stabilization **(I. Chang-2016)**

CATEGORY	TYPE	MAJOR PHYSICAL AND CHEMICAL PROPERTIES COMPOSITION	REFERENCES
Lignin	Kraft lignin	- Wide Variety of types - strong reactivity with other substances	**(T. Zhang-2020)**
	lignosulfonate	- possess a high solubility and a multitude of active functional groups.	
	Hydrolyzed lignin	-Poor solubility in water - low chemical responsiveness	
	New lignin derivatives	- Properties change depending on the pulp-making techniques utilized.	
Polysaccharides	Xanthan gum	- Pseudo plasticity - Stable under a wide range of temperature and pH - Highly viscous, hydrophilic colloid - Anionic polysaccharide	**(A. Bouazza-2009)**
	Guar gum	- Hydrates quickly in water to generate extremely viscous solutions. - Non-ionic, pH and ionic strength have no effect on it - Disintegrate in extreme temperatures and pH	**(A. Bouazza-2009)**
	Agar Gum	- consists of two components: agaropectin, a weakly gelling charged polymer, and agarose, a strongly gelling complex sugar - Hydrophilic colloid - dissolve in 85 °C boiling water, and when cooled to 32–43 °C, it gels. - A chain of neutral polymers that is not very reactive to other substances - Although reduced, biodegradation is still susceptible to polymeric additions.	**(H.R. Khatami-2013)**
	Gellan gum	- Four-molecule polysaccharide with a high molecular weight - An anionic linear heteropolysaccharide - Thermo-gelation behavior	**(A. Bouazza-2009)**
	Sodium alginate	- Slowly dissolve in water to produce solutions that pour smoothly. - By reacting with sodium and calcium salts, gels are formed.	**(A. Bouazza-2009)**
	Beta-glucan	- Different types of natural formations - Molecular weight 250–3000 kDa - Naturally occurring beta-glucan is electrostatically neutral, but when altered, it can take on charges.	**(I. Chang-2012& 2014)**
New biopolymers	1)*R. tropici* EPS, 2)*L. mesenteroides* EPS,Astragalus, 3)Persian gum, Casein, 4)Sodium caseinate	Properties and compositions not thoroughly examined for soil stabilization	**(S. Larson-2012)** **(H.S. Aksoy-2017)** **(A.F. Cabalar-2018)** **(H. Ghasemzadeh-2020)**

Table 7: Compositions and properties of common biopolymers used in soil stabilization

2.3 Synthetic organic polymers

Many synthetic organic polymers have been used in soil stabilization in the past decades, including polyacrylamide (PAM), polyacrylates, poly (vinyl alcohol) (PVA), poly (vinyl acetate) (PVAc), polyurethane, aldehyde, propylene, etc. The most widely used synthetic organic polymers, along with a list of their characteristics, are given in **(Table)**

2.3.1. Derivatives of polyacrylamide (PAM)

PAM and its derivatives are the most often used synthetic polymers for stabilizing soil. PAM-based polymers were first used in agriculture to control and monitor erosion and infiltration. Afterwards, they were used for purposes other than agriculture control, such as preventing dust in helicopter landing zones, accelerating water clarification in storm water runoff ponds, reducing erosion on building sites, and a variety of other high-traffic military scenarios **[R.E. Sojka-2007]**. It is interesting to note that while anionic PAMs are typically innocuous to humans, animals, or plants, cationic or nonionic PAMs are frequently harmful **[C.A. Seybold-2008]**. As a result, anionic PAMs have been utilized in the majority of soil stabilizing applications. But it was also mentioned that cationic PAMs were utilized to stabilize soils **[H. Soltani-Jigheh-2019]**. Additionally, **Table 2** offers details on the various characteristics of PAMs that influence how they interact with soils, including surface charge, molecular weight, viscosity, and pH.

2.3.2. Derivatives of Polyacrylate

Often known as polyacrylics or acrylate polymers, polyacrylates are a family of acrylate- or acrylic-based polymers. The configurations and properties of polyacrylates can vary greatly depending on the functional groups—methyl, ethyl, butyl, and isobutyl acrylates—that are added to the basic acrylic acid structure **[T. Ohara-2020]**. The most basic of the acrylate polymers is poly (acrylic acid), among others.

The liquid polyacrylates, which include acrylic esters and acrylic acid, are flammable, volatile, colorless, and polymerize rapidly.

Acrylic acid polymers and their sodium counterparts are employed as dispersants and flocculants. Only acrylic esters are utilized in the synthesis of polymers, which are primarily utilized in binders, paints, coatings, and adhesives **[T. Ohara-2020]**.

2.3.3 Polymers based on poly (vinyl alcohol) and poly (vinyl acetate)

A synthetic aliphatic polymer possessing a strong cold flow and ease of polymerization is polyvinyl acetate (PVAc). PVAc is therefore commonly utilized in paints, adhesives, emulsion products, and textile finishing processes **[J.A. Brydson-1999]**. PVAc is also able to bind the soil particles together thanks to this adhesive quality. They can lessen the swell-shrinkage characteristics and increase the strength of expansive clays, according to several research **[(j. Liu-2017) (Z.Z. Song-2019)]**.

Polyvinyl alcohol, or PVA, is a man-made polymer that melts in water. PVAc can be used to make polyvinyl acetate since its ester groups are sensitive. Unlike PVAc, PVA is hydrophilic because it has hydroxyl groups. Studies reveal that adding PVA considerably enhances the characteristics of soft clays **[50,51]**.

2.3.4. Additional synthetic polymers

Other synthetic polymers have also been studied in addition to the ones that were previously covered. In terms of stabilizing soil, the properties of these polymers are not well understood. Polymers that possess in order to assess how various functional groups or compounds—such as ester **[(S. Arasan-2015) (J. Liu-2011)]**, propylene **[M. Ayeldeen-2017]**, urethane, carboxylic, and aldehyde —interact with various soil types, these groups and compounds have been investigated in the lab. There has also been research on other polymers, such as CBR PLUS **[H. Soltani-Jigheh-2019]**, resins, and methylene diphenyl diisocyanate. Because there hasn't been enough research done on these innovative polymers, they've been added to soils at different dosages—from 1% to 45%. Under some conditions, some of the polymers fail to significantly improve, while others have been claimed to have the ability to function as soil stabilizers.

Type of Polymer	Composition & Synthesis Method	Physiochemical Properties	References
Polyacrylamide (PAM) [CH2=CHCONH2] n	- produced by synthesizing acrylamide subunits with cross-linked or linear chains. - If any of the amide functional groups (-NH2) in the acrylamide subunits are released or replaced during polymerization, anionic PAMs are created. - Additionally synthesized as amphoteric, cationic, or neutral	- While linear-chained PAMs dissolve easily in water and remain linear after dissolving, they can coil or curl to variable degrees. Cross-linked PAMs are water absorbent but not water soluble. - Soil stabilization is the usual use for the linear-chained PAMs. - Through hydrolysis, PAMs' surface charge can be changed in different amounts. - Molecular weight is a function of component monomer count. Can have as low as 3.5 × 103 g/mol for a short-chained PAM molecule, or as high as 2 × 107 g/mol for high molecular weight anionic PAM. - Becomes highly viscous as molecular weight increases. - Viscosity rises as pH rises, particularly above pH 10.	**(W.P. Miller-1998)** **(H. Heller-2002)**
Polyacrylates	- Consists of acrylic acid monomers and esters (CH2=CHCOOR). - Different varieties can be created by substituting various functional groups for the H on the vinyl group (-CH=CH2) and/or the H of the carboxyl group (-COOH). - Possess different proportions based on the monomers.	- Monomers are colorless liquids, such as acrylic acid and acrylic esters. - Extremely reactive because of the carboxylic and vinyl groups. - Acrylic acid is miscible with alcohols and esters and hydrophilic. - Acrylates polymerize readily with various functional groups to create a variety of polymers. - Viscous and adhesive.	**(T. Ohara-2020)**
Poly (vinyl acetate) (PVAc) [CH2=CHOOCCH3]n	Produced by synthesizing vinyl acetate monomer and stirring equal amounts of vinyl acetate and water with emulsifiers	- Particle size, charge, and molecular weight vary according to the polymerization process. - Possess amorphous and atactic structures. - Insoluble in water, but soluble in acetone, benzene, and other solvents. - Have a high cold flow rate and a glass transition temperature of 28 ◦C, or even lower most of the time. - Strong adherence. -- Easily polymerizes in suspension, emulsion, bulk, and solution	**(J.A. Brydson-1999)**
Poly (vinyl alcohol) (PVA) [CH2=CH(OH)]	- produced by alcoholysing a poly (vinyl ester), while poly (vinyl acetate) is most commonly utilized.	- Are soluble in water. - Possess crystalline but aggressive structures. - Its molecular weight is less than that of PVAc, the raw material. - Extremely polar	

Table 8: Summary of the physicochemical properties of major synthetic organic polymers

2.4. Polymer-soil interaction

2.4 Mechanisms

2.4.1 Inorganic: geopolymers

The interaction between geopolymers and soil minerals involves a complex series of chemical reactions, leading to the stabilization of soil. This interaction is fundamentally different from that of organic polymers and is primarily driven by the geopolymerization process. Here's a detailed breakdown of this process, maintaining all critical information.
Geopolymerization Process

2.4.1.1 Phase 1: Dissolution

- **Reaction Initiation**: begins as soon as the alkali activator and precursor come into touch.
- **Dissolution of Aluminosilicates**: The extremely alkaline solution dissolves silica and alumina.
  - **Silica**: Dissolves into silicate ions.
  - **Alumina**: Converts from V- and VI-coordination to IV-coordination.

2.4.1.2 Phase 2: Gelation and Reorientation

- **Formation of Oligomers**: Dissolved species form aluminosilicate oligomers by sharing oxygen atoms at their corners.
- **Gel Formation**: When the solution becomes saturated, aluminosilicate gel begins to form.
  - **N-A-S-H Gel**: Formation of sodium aluminosilicate hydrate, analogous to C-S-H in Portland cement.
  - **(N, C)-A-S-H Gel**: When calcium is introduced, forming more complex phases involving both C-S-H and N-A-S-H gels.

2.4.1.3 Phase 3: Polycondensation

- **Reorganization**: The gel diffuses, migrates, reorganizes, and eventually precipitates into a denser, stable matrix.
- **Charge Balancing**: Cations (Na+, K+, Ca2^2+) fill cavities to balance the negative charge of Al3+
- **Setting and Hardening**: The geopolymer sets at ambient temperatures, forming a semi-crystalline structure. The setting time can vary from instantaneous to several days.

2.5 Geopolymer-Soil Interaction

2.5.1 Interaction Mechanisms:

- **Binding Soil Particles**: Cementitious geopolymer products (N-A-S-H or (N, C)-A-S-H gels) bind soil particles, enhancing soil strength and stability.
- **Alkaline Environment**: High alkalinity may alter soil properties by dissolving Si and Al from soil minerals.
- **Cation Exchange**: Potential cation exchange reactions, especially with calcium-rich precursors or KOH activators.

2.5.2 Factors Affecting Interaction:

- **Soil Mineralogy**: Different soil types (varying in Si and Al content) can behave differently when treated with the same geopolymer.
- **Alkaline Concentration**: Influences the dissolution rate of aluminosilicates and the stability of the gel.
- **Silica and Alumina Source**: Different sources (e.g., fly ash, slag) affect the geopolymerization process.
- **Moisture Content**: Water content in the soil affects the setting and hardening of the geopolymer.

4. Geopolymer Applications in Soil Stabilization

2.5.3 Practical Applications:

- **Grouting**: Replacement of cement in grouting techniques, improving soil strength.
    - **Example**: Fly ash used in geopolymers can achieve significant strength improvements in both laboratory and field applications.
- **Stabilization Materials**: Use of various aluminosilicate materials (e.g., metakaolin, Class C and F fly ash, slag).
- **New Research**: Exploration of alternative materials like palm fuel ash for cost-effective stabilization.

2.5.4 Challenges and Considerations:

- **Complex Interactions**: Understanding the multifaceted interactions between geopolymer and soil minerals is essential.
- **Cost-Effectiveness**: High dosages of geopolymer are not cost-effective; optimizing the geopolymer-soil mix is critical.
- **Quality Control**: Ensuring consistent quality in geopolymer-soil systems is challenging due to soil variability and reaction sensitivity

PHASE	PROCESS	DETAILSE
Dissolution	Dissolution of alumina and silica	Silica and alumina dissolve in alkaline conditions.

Gelation	Formation of aluminosilicate gel	Gel forms as the solution saturates with aluminosilicates.
Polycondensation	Reorganization into stable matrix	Gel reorients, diffuses, and hardens into a solid structure.

Table 9: Phase of Geopolymerization

Gel Type	Compositions	Properties
N-A-S-H	Sodium aluminosilicate hydrate	Analogous to C-S-H in cement, strong
(N, C)-A-S-H	Sodium-calcium aluminosilicate hydrate	Complex reactions, dual phase system

Table 10: Comparison of N-A-S-H and (N, C)-A-S-H Gels

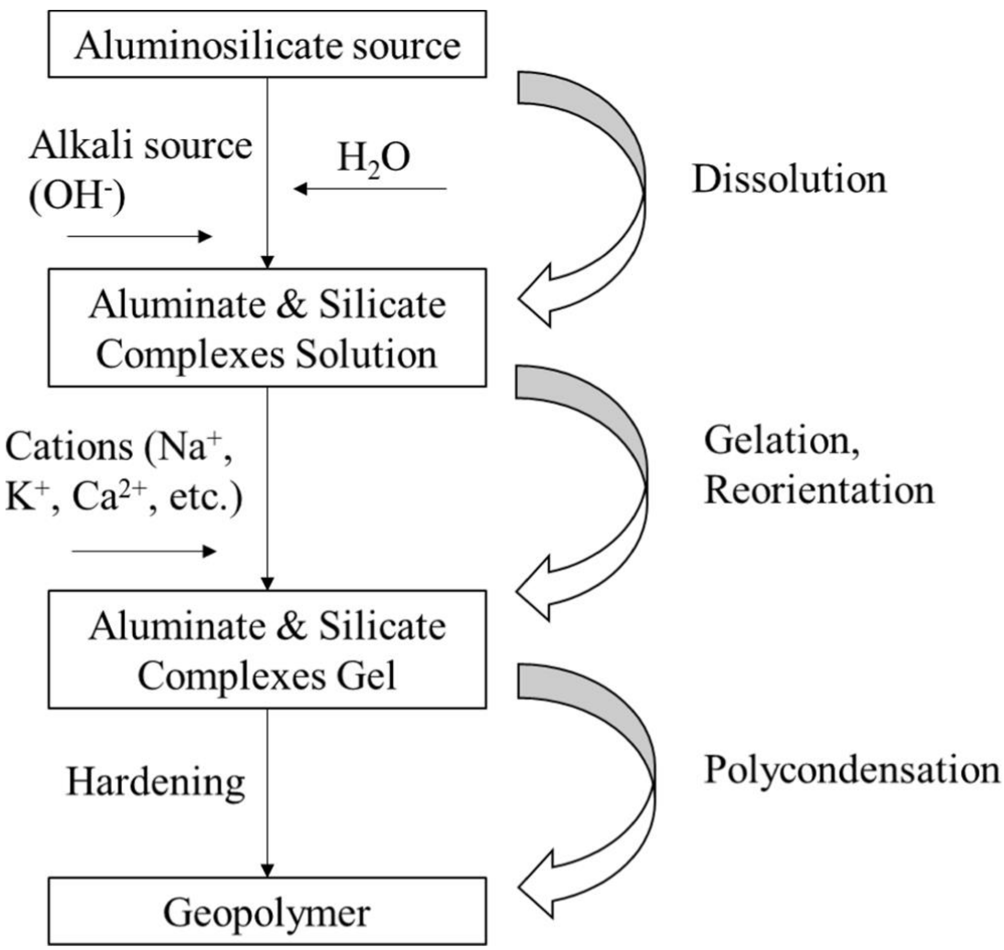

Figure 4: Schematic diagram of geopolymerization. Revised after Duxson et al. **[73].**

2.5.6 Organic: biopolymers and synthesized polymers

Understanding how organic polymers interact with soil minerals is essential for applications in soil stabilization. This interaction varies depending on the type of polymer (cationic, neutral, or anionic) and the soil mineral involved (clay or sand).

1. Basic Principles of Polymer Interaction with Soil

Functional Group Variability:

- **Polymer Conformation**: Different conformations and characteristics of polymers are produced when functional groups in monomers are changed.
- **Complex Interactions**: The interactions between each functional group and soil minerals can be complex, making it challenging to predict how each polymer will behave.

General Interaction Mechanisms:

- **Electrostatic Interactions:** These are crucial for polymers interacting with soil minerals, especially for charged polymers.
- **Entropy-Driven Adsorption:** Uncharged polymers interact mainly through changes in entropy, driven by adsorption on the soil surface and desorption of water.

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2. Interaction Mechanisms for Specific Polymers

A. Cationic Polymers (Polycations)

Mechanism:

1. Electrostatic Attraction: Polycations are positively charged and are attracted to the generally negatively charged surfaces of clay minerals.
2. Adsorption: These polycations readily adsorb onto the clay particles' edges and surfaces.
3. Water Sorption Modification: Large, stable flocculated particles are formed as a result of their modification of the water sorption close to the clay surface.

Outcome:

- Stable Flocculation: The interaction results in the stabilization of clay particles, enhancing soil structure.

B. Neutral Polymers

Mechanism:

1. Entropy-Driven Adsorption: An rise in entropy plays a major role in the adsorption of uncharged polymers on clay surfaces.
   - Water Desorption: Water molecules desorb as a result of the polymer's adsorption on the clay surface, rupturing the water molecules' successive hydrogen bonding that extends from the clay surface.
   - Surface Conformation: The polymer sequences together into contiguous adsorbed segments ("trains") that finish in free-dangling tails after alternating with loops that stretch away from the surface.
2. Low Desorption Rate: Due to the many adsorbed segments, the energy of adsorption is high, making desorption a low-probability event.

Outcome:

- Irreversible Adsorption: The adsorption process is generally considered irreversible, resulting in a stable attachment of polymers to the clay surface.

C. Anionic Polymers (Polyanions)

Mechanism:

1. Electrostatic Repulsion: Anionic polymers are negatively charged and repelled by the negatively charged clay surfaces under neutral or basic conditions.
2. Interparticle Bridging: They develop long loops and tails, facilitating a large "grappling distance" which enhances the interparticle bridging effect.
3. Cation Bridging:
   - Acidic Conditions: Anionic polymers have the ability to intercalate into clay layers in acidic environments and interact with positively charged spots on metal edges
   - Alkaline Conditions: Cation bridging, in which polyvalent cations (provided externally or removed from the interlayer) span the anionic polymer and clay surface, is how binding takes place.

Outcome:

- Strong Clay-Polymer Complexes: These interactions result in strong complexes and significant stabilization of the soil structure.

---

3. Polymer Interaction with Coarse Grains (Sands)

Mechanism:

1. Surface Neutrality: Unlike clay, sand particles typically have neutral surfaces.
2. Structural Changes:
   - Film Formation: Polymers can cover sand particles with a thin film.
   - Polymer Ties: They can form polymer ties connecting neighboring sand particles not in direct contact.
   - Adhesion Development: They can develop adhesion between neighboring sand particles in direct contact.
3. Reinforcement Mechanisms:
   - Filling: Sand particles are filled with polymer solutions.
   - Chemical Reaction: The surfaces of sand particles and polymer molecules establish physicochemical connections.
   - Enwrapping: Long-chain macromolecules form elastic and viscous membranes around sand particles.

Outcome:

- Enhanced Soil Properties: These interactions improve the hydraulic conductivity, mechanical strength, elasticity, and flexibility of the sand.

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4. Hydrogel Formation and Evaporation

Mechanism:

1. Hydrogel Formation: Through hydrogen bonds and intermolecular interactions, the polymer and water combine to produce a hydrogel on the surface of the sand grains.
2. Water Evaporation: As water evaporates, the hydrogel gradually hardens into a thin polymer membrane.

Outcome:

- Improved Soil Structure: This process results in a more elastic, flexible, and stronger soil structure.

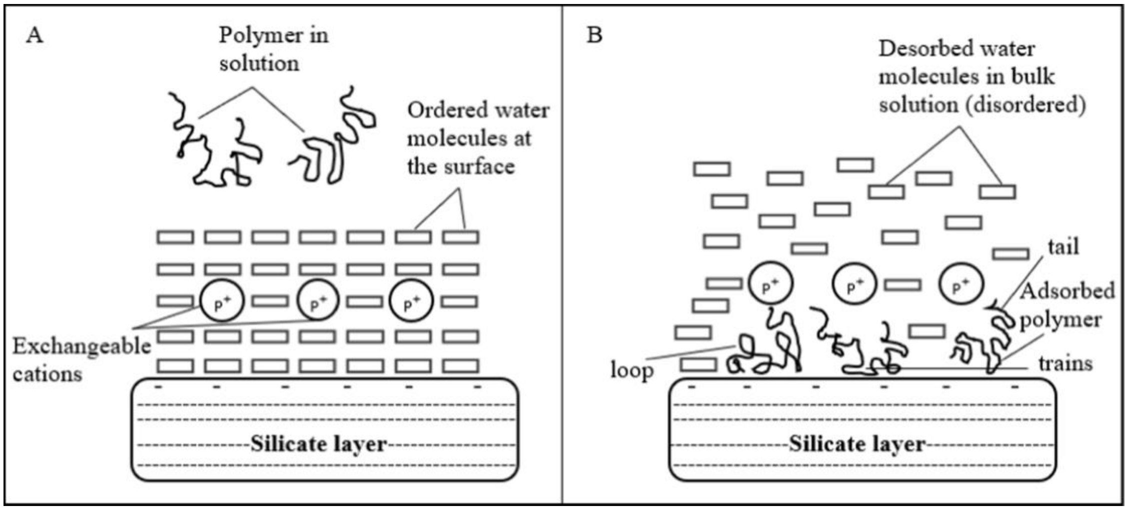


Figure 5: Diagram illustrating the adsorption of neutral polymer molecules onto a clay surface and change in conformation of polymers and the desorption of water molecules. (A) Before adsorption; (B) After adsorption. Adapted from Theng **[B.K.G. Theng-1982]**

4. ENGINEERING PROPERTIES OF POLYMER-STABILIZED SOILS

The main goals of soil stabilization are to improve mechanical properties, control permeability, resolve volumetric instability and enhance durability. The major properties and tests investigated in the literature for evaluating polymer stabilization quality are summarized in Fig. 3**.**

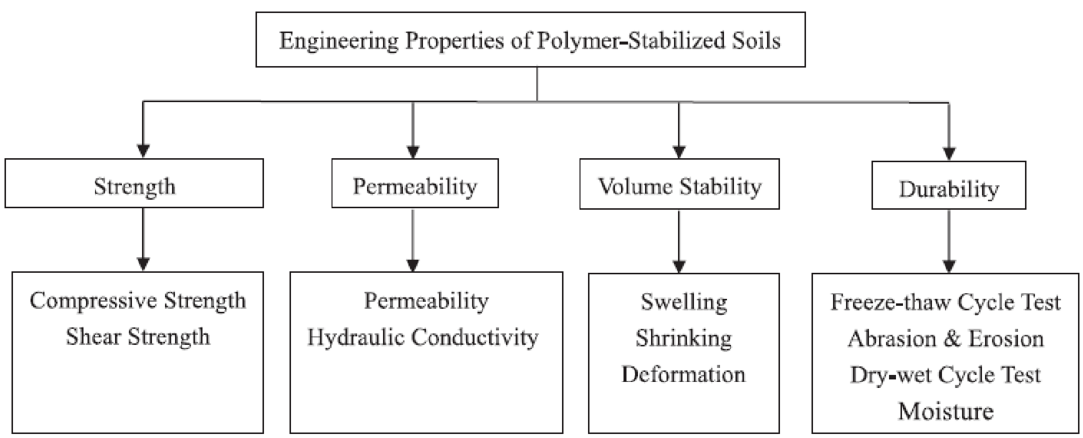


Figure 6: Tests for evaluating the effectiveness of polymer-stabilized soils

2.6 SOIL STRENGTHNING

2.6.1 Compressive Strength

Soil stabilization using organic polymers and geopolymers has been shown to substantially enhance the strength and durability of soils across various types. Organic polymers, such as synthetic acrylic polymers and natural biopolymers like guar gum or lignosulfonates, provide immediate strength improvements by forming bonds with soil particles. For instance, synthetic acrylic polymers have been reported to increase the unconfined compressive strength (UCS) of sand by up to 1000%, transforming weak soils into more stable structures capable of supporting heavier loads. Similarly, biopolymers like xanthan gum can significantly enhance the strength of clay soils, as seen in studies where xanthan gum-treated soils demonstrated a strength increase of up to 12 MPa under dry conditions. However, it's important to note that under wet conditions, the strength of polymer-treated soils can drastically decrease, sometimes dropping from 12 MPa to just 220 kPa, as observed in gellan gum-treated clays. This highlights the need for thorough testing in conditions that simulate the field environment to fully understand the behavior and durability of polymer-stabilized soils under varying moisture levels.

Geopolymers, which are inorganic binders formed from aluminosilicate materials such as fly ash, metakaolin, and slag, provide another effective method for soil stabilization. When these materials are activated with alkaline solutions, they undergo a chemical reaction known as geopolymerization, forming a cementitious matrix that binds soil particles together. For example, Cristelo et al. used a Class F fly ash-based geopolymer to treat sandy clays, achieving a UCS of 11.4 MPa. This demonstrates how geopolymer treatments can transform soils with low initial strength into robust materials suitable for construction. Similarly, Zhang et al. found that metakaolin-based geopolymers could increase the strength of clay soils to up to 4 MPa. The choice of precursor material and the concentration of the alkaline activator are critical factors in determining the effectiveness of geopolymer stabilization. High alkaline concentrations generally improve the stabilization process by dissolving more silica and alumina from the precursors, but there is a threshold beyond which additional increases in concentration do not significantly enhance soil strength.

Innovative research is continually exploring new materials for geopolymer stabilization. For example, combining fly ash with slag has shown promising results, leveraging the benefits of both materials. Other potential precursors, such as palm fuel ash, volcanic ash, and rice husk ash, are being investigated for their feasibility in creating strong and durable geopolymers. These alternative materials could offer more sustainable and cost-effective solutions for soil stabilization in various environmental conditions.

In summary, both organic polymers and geopolymers provide effective means of stabilizing soils, but their performance can vary significantly based on environmental conditions and material compositions. Real-world examples, like the dramatic strength improvements seen with polymers and the robust binding effects of geopolymers, understand the importance of selecting the right stabilization method.

Reference	Polymer Type	Polymer Dosage	Soil Type	Compressive strength
[71]	Acrylic	2%	Silty Clay	2.82-3.57Mps(7d)
[72]	Styrene-acrylic / Vinyl-acrylic emulsions	0.5, 1, 1.5, 2, 3, 5%	SP	0.8-10.2Mpa (7d)
[73]	Acrylic-Acrylamide Co-polymer	0.5, 1% + 5% calcium carbide	clay	434.4 kPa, 468.9 kPa
[74]	Acrylate emulsion	0.25, 0.5, 1, 2%	GM-GC	2–3 MPa (7d);
[75,76]	PAM	0.002%	GM	7.7 Mpa
			SC	7.9 Mpa
			GC	5.9 Mpa
[77]	Acrylic polymer	2, 3, 4, 5%	CH	868.88–898.39 kPa (7d)
			MH	3199.79–3901.47 kPa (28d)
[78]	Acrylic copolymer + ionic stabilizer	0.25, 0.375, 0.5% P + 0.5, 0.75, 1% Ionic	CI (IS1498)	1.7–7.0 MPa (>7d)
[79]	Styrene acrylic emulsion	10, 15, 20, 22.5, 30, 35%	SP	6Mpa
[80]	PAM	0.1, 0.2, 0.4, 0.6 g/L	CH	96.87–138.34 kPa (1-14d)
	PAM + Ground rubber	0.2% PAM + 5, 10, 20, 30% GR	CH	106.18–211.09 kPa (7d)
[81]	Acrylate polymer	0.3, 0.6, 0.69, 1.2, 1.5%	Saline soil	1085–1561 kPa (7d);
				1453–1930 kPa (28d)
[82]	Epoxy resin	6, 7, 8%	Saline soil	419–897 kPa
[52]	Polyester	10, 20, 30%	SP	10–45 MPa (1-28d)
[156]	SS 299	3, 6, 9,12, 15%	MH	221–377 kPa (7d);
				224–385 kPa (28d
[83]	Epoxy resin	1, 2, 3, 4, 5%	Sand	2–10 MPa
[67]	Polyvinyl chloride;polyethylene	3, 6%	Clay	600–2700 kPa
[84]	HPAM	2%	GM-GC	1700 kPa (7d)
				3700 kPa (28d)

Table 11: Summary of the compressive strength of soils treated with *synthetic organic polymers*

Reference	Polymer Type	Polymer dosage	Soil type	Compressive Strength
[85]	Glucan	0.05, 2.46, 4.92 g/kg	Residual Clay	1–4.4 MPa (28d)
[52]	Gellan gum	0.5, 1, 1.5, 2, 5%	SP	130.2–434.6 kPa (28d)
[51]	Xanthan gum	0.5, 1, 1.5, 2, 3%	CL	470.52–569.55 kPa (7d);
				612.74–823.19 kPa (28d)
[86]	Casein and sodium caseinate	0.5, 1, 2, 3, 5%	Dune sand	450–1700 kPa (14d)
[87]	Sodium alginate	1, 2, 4% of OMC	CH	830 kPa
		2, 4, 6% of OMC	ML	390 kPa
[89]	Xanthan gum	0.5, 1, 1.5%	Laterite soil	220–335 kPa (7d);
[90]	R. tropici exopolysaccharide	0.3, 1, 3, 10, 15, 20 mg/mL	Silt	120–1560 kPa (4d)
[55]	Agar only	1, 2, 4%	Sand	158–487 kPa
	Agar + starch	1% agar + 0.5% starch		
[90]	Xanthan gum	0.5, 1, 1.5, 2, 2.5%	Organic peat	15–100 kPa
			Bentonite	286–2580 kPa
			kaolinite	150–1180 kPa
[91]	Chitosan	0.02, 0.04, 0.08, 0.16%	CL	1500-3000 Kpa(7d)
[92]	Xanthan gum	0.5, 1, 1.5, 2, 2.5%	CH	600–1800 kPa (7d)
				600–2941 kPa (28d)
[93]	Xanthan gum	1, 1.5, 2%	SM	4200–4900 kPa (28d)
[94]	Guar gum	0.5, 1, 1.5, 2%	MH-CH	170–390 kPa (7d)
				196–418 kPa (28d)
[95]	Biofuel coproduct A	1, 3, 6, 12, 15%	CL	300–1000 kPa (7d)
	Biofuel coproduct B	1, 6, 12%	CL	300–600 kPa (7d)
[96]	Lignin	2, 5, 8, 12, 15%	ML	180–330 kPa (7d)
				220–680 kPa (28d)

Table 12: Summary of the compressive strength of soils treated with *biopolymers*

2.5.2. Shear strength

The triaxial shear test and the standard direct shear test are also commonly used to assess the effectiveness of polymer stabilization. Numerous earlier investigations have demonstrated that polymers can increase soil shear strength [**B. Indraratna et al. 2013]** utilized lignosulfonate to treat sands and silts; shear strength improvements were seen right away with just 1.2% addition for silty sand and 2% addition for sandy silts **[Q.S. Ghenet al 2014]**. **[I. Chang et al 2016]** peak shear strength in sandy soils was considerably raised when 0.5–5% gellan gum was added. Additionally, the authors note that the treated sand's cohesiveness and friction angles increased substantially, which they attribute to the gellan gum hydrogels' binding properties. Through interparticle interactions and interparticle bridging, the viscous biopolymer creates interparticle cohesion that eventually intensifies with condensation and binds particles into agglomerates. Additionally, it was confirmed that sand, kaolinite, bentonite, and organic peat soil all significantly improved cohesiveness **[S. Lee et al 2017]**. In the presence of xanthan gum , A recent review paper by provides more information on how different biopolymers can be used to improve the shear strength, cohesion, and friction angle of diverse soils **[I. Chang et al 2020].**

2.6 Permeability and hydraulic conductivity

One of the most important characteristics of soil is permeability, which describes how well fluids may permeate the soil's network of interconnected voids. In terms of water flow, this property is measured by the coefficient of permeability, which is also referred to as hydraulic conductivity.

Reduction of Permeability in Polymer-Treated Soils

Several studies have demonstrated that treating soils with polymers can significantly and immediately reduce their permeability. This is particularly evident in research by **Al-Khanbashi and Abdalla [100]**, who treated sandy soil with three types of acrylic emulsions. Even at a low polymer concentration of 0.5%, a notable decrease in permeability was observed. At a higher concentration of 5%, the soil's coefficient of permeability decreased by two orders of magnitude. This dramatic reduction indicates the effectiveness of polymers in sealing the soil pores and reducing fluid flow.

Similarly, it has been demonstrated that the hydraulic conductivity of treated silty sand can be greatly decreased by using biopolymers like sodium alginate, guar gum, and xanthan gum. For instance, after 7 days of curing, the permeability of silty sand treated with these biopolymers at a concentration of 0.5% decreased significantly from 1 × 10^-6 m/s to 2 × 10^-7 m/s for guar gum, 2 × 10^-9 m/s for xanthan gum, and 4 × 10^-11 m/s for sodium alginate [36]. These decreases are explained by the pore-plugging effect, in which the organic polymers raise the pore fluid's viscosity, obstructing the soil's voids and impeding water flow.

This permeability reduction mechanism is consistent across various synthetic organic polymers, such as polyacrylamide (PAM), and numerous biopolymers. These polymers enhance soil microstructure by increasing pore fluid viscosity and physically blocking small pores, leading to decreased permeability. For instance, **Huang et al. [101]** reported that adding a polyvinyl acetate-based polymer to soil improved its microstructure and pore uniformity, thereby increasing the soil's water retention capacity and reducing its permeability.

Permeability in Geopolymer-Stabilized Soils

In contrast, the effects of geopolymers on soil permeability are less documented and require further research. **Du et al. [102**] compared the permeability of soil treated with slag-based geopolymers to soil stabilized with lightweight cement. They discovered that the soil treated with geopolymer had ten times higher coefficient of permeability than the soil treated with cement due to bigger air holes (>10 μm) in the former. This was unexpected considering that the soil treated with geopolymer had a greater quantity of hydration product covering the soil aggregate.

The behavior of geopolymer-stabilized soils can be likened to lime stabilization effects. Lime significantly increases soil strength but also alters the texture of clay soils by causing flocculation of clay plates. This flocculation opens up the soil structure, reducing the water layers surrounding the clay plates and increasing permeability. Although the permeability may decrease over time as pozzolanic products fill the voids, it never returns to the pre-stabilization level. Similarly, the initial increase in permeability in geopolymer-treated soils due to structural changes might reduce over time but needs further investigation to fully understand the long-term effects.

2.7 Durability

The durability of polymer-stabilized soils is a critical factor in their practical applications, particularly in environments subject to harsh weather conditions and mechanical wear. Various tests, such as freeze-thaw cycles, dry-wet cycles, abrasion tests, and erosion tests, have been employed to assess how well these treatments hold up over time.

Freeze-Thaw Cycle Test

Freeze-thaw cycles simulate the impact of water freezing and thawing within the soil, which can lead to expansion and contraction, potentially damaging the soil structure. **Fungaroli and Prager [103]** found that, in comparison to untreated cement-treated soils, soil-cement specimens modified with acrylic polymers had increased resilience to freeze-thaw cycles. Improvements were reported following curing times ranging from 7 to 91 days. In another study, **Arasan et al. [64]** reported that adding 10-30% polyester to sand by dry weight effectively neutralized the effects of 20 freeze-thaw cycles after a 28-day curing period.

Dry-Wet Cycle Test

Dry-wet cycles mimic the natural process of soil drying and subsequent re-wetting, which can cause cracking and strength reduction. **Rezaeimalek et al. (2019)** reported a significant strength and weight loss in acrylic emulsion-treated sand after 24 dry-wet cycles, with a 39% reduction in strength and a 7% weight loss. However, despite these reductions, the remaining strength was still substantial, suggesting that polymer stabilization can provide lasting benefits even under severe weathering conditions.

Abrasion and Erosion Tests

Tests for erosion and abrasion determine how resilient the soil is to physical deterioration and water-induced particle separation. Research has demonstrated that the erosion resilience of treated soils is markedly improved by polymers. Ayeldeen et al. [104] discovered that biopolymers such as modified starches, guar gum, xanthan gum, and carrageenan could endure five wet-dry cycles and increase the wind erosion resistance of silty sand at a 0.5% concentration. Similar to this, Indraratna et al. (2008)] showed that even at a low concentration of 0.6%, treating silty sand with lignosulfonate significantly decreased the soil erosion coefficient, from 0.181 to 0.0021.

When Chang et al. [105] investigated how resistant silty loam was to erosion, they discovered that the biopolymers xanthan gum and β-glucan greatly decreased the soil's erodibility under conditions of both short- and long-term water erosion. Other polymers, such as polyacrylamide (PAM), polysaccharides, casein, and polyvinyl acetate (PVAc), have also been reported to increase erosion resistance across different soil types [5,48,192,193].

Moisture Susceptibility

Moisture intrusion is a common challenge for polymer-stabilized soils, often leading to strength degradation. Many researchers have noted a decrease in strength when polymer-treated soils are exposed to water during testing. Despite this, the wet strength of polymer-stabilized soils often remains higher than that of untreated or even lime-treated soils under similar conditions. For instance, **Azzam [106**] observed no detrimental effects on polypropylene-stabilized clay after 24 hours of water submersion, attributing this resilience to the hydrophobic properties of the polymer components. However, the performance of polymers with both hydrophilic and hydrophobic segments under wet conditions requires further investigation

Chapter Three

EXPERIMENTAL PROGRAM

3.1 General

This chapter aims to detail the experimental program conducted for our research. It outlines the locations where tests were conducted, the procedures used for field and laboratory testing, and the collection of disturbed samples during field investigations. All samples were subsequently analyzed and tested at the Geotechnical Laboratory of the Department of Civil & Environmental Engineering at Islamic University of Technology (IUT).

3.2 Study Areas

Riverbank erosion and coastal land submergence are widespread national phenomena and major natural disasters. The most common type of degradation, accounting for 25% of Bangladesh's agricultural land, is water erosion. Bangladesh is experiencing landslides, riverbank erosion, coastal erosion, sheet, rill, and gully erosion, among other types of soil erosion. Approximately 1.7 million hectares of the country's hilly regions have seen accelerated soil erosion. Total soil loss of 2.0 to 4.7 ton/ha per year was noted in a study conducted at the Bangladesh Agricultural Research Institute's (BARI) Ramgati site. Tackling cost-effective, eco-friendly road embankments construction amidst material scarcity involves investigating alternative, locally sourced stabilization methods. Addressing soil erosion's multifaceted challenges necessitates understanding and managing factors like soil type, slope, rainfall, and human activities. Therefore, efficient techniques to enhance the qualities of slope topsoil are crucial for managing slope erosion. Biological stabilization, chemical stabilization, and physical stabilization are three categories of soil improvement approaches that have been used in recent years to alter soil qualities like strength, permeability, water stability, and durability. Figure 3.1 depicts the study area's location (Board bazar, Gazipur). Sandy Soil has been collected from the area. For erosion control test, a prototype of the embankment has been made with the sandy soil and the chemical stabilizers SB-95 and TX-95 have been used. Figure 3.2 shows the Prototype of Embankment for Soil Erosion Test.

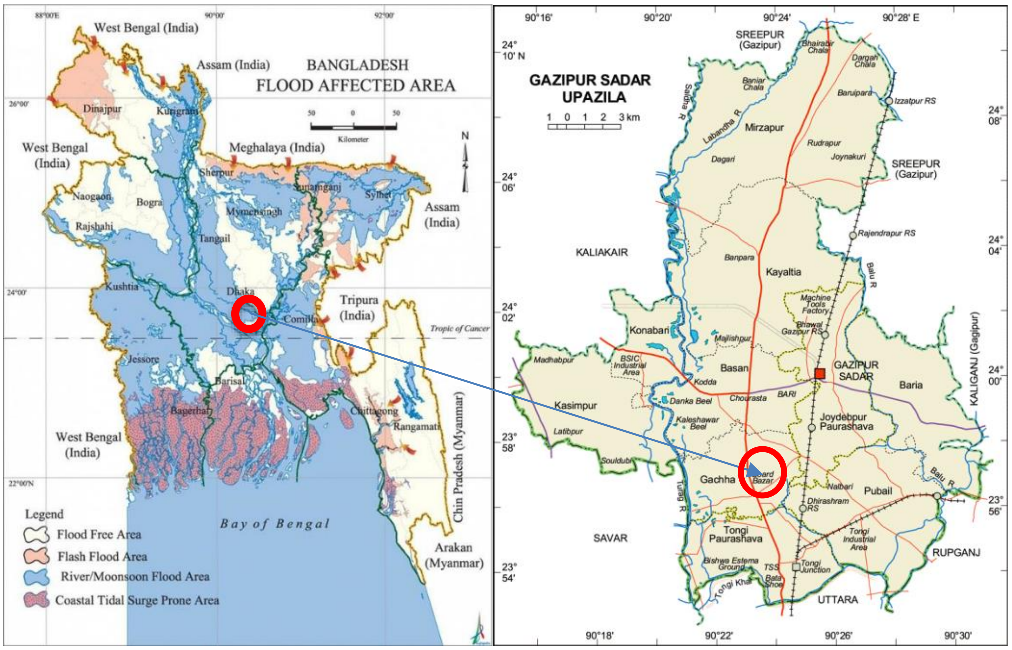


Figure 7: Location map of the study area for field test

Figure 8: Prototype of Embankment for Erosion Test

3.3 Experimental Program

We have collected the soil from the area and did some tests. Sieve analysis, Hydrometer Analysis, Specific Gravity Test, Compaction Test, Permeability Test were done before mixing the stabilizers. After using the stabilizers, Unconfined Compressive Strength Test was done making blocks of different percentage of the Stabilizers. After getting the proper ratio of Chemical Stabilizers, the embankment model has been made. We have also used moisture sensor for getting the data of the quantity of moisture inside the soil.

3.3.1 Pre-experimental Set Up & Making of Blocks

(a) Test Set up: A box was made with acrylic glass with the dimension of 120 cm x 75 cm x 45 cm. This box was used for holding the whole embankment prototype. The embankment prototype consists of stabilized soil. Figure 3.3 shows the plan of our schematic model.

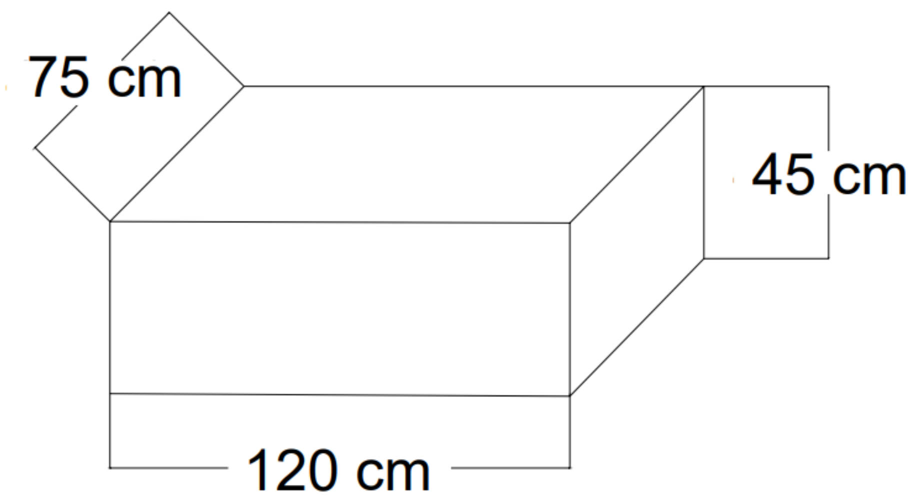


Figure 9: Plan of the box where our embankment model will be set

(b) Mixing & Making Blocks: We have used 4 ratios of percentages for our experiments. We made molds of 7.5% SB-95, 10% SB-95, 12.5% SB-95, 15% SB-95 of soil & then made blocks with those. We have also kept the blocks in 3,7,14 & 28 Days. After those days, the blocks were kept out from the mold by the help of a hydraulic jack. Then the blocks were cut into cylindrical shapes for UCS test. For perfect scrutiny, we have tested for 2 blocks for each percentage.

Figure 10 (a): Curing of Blocks before Demolding. (b) Curing of Blocks in Lab condition

Figure 11: Demolding the blocks with Hydraulic Jack

3.3.2 Unconfined Compressive Strength Test

a) Calculations:

Sample = 6 kgs

For 7.5%:

SB-95 = 7.5 % of Sample
= 7.5 % of 6 kgs
= 0.45 kgs = 450 gm

Water = 12.5% (as it is the optimum moisture content) of sample soil
= 12.5% of 6 kgs
= 750 mL

TX-95 = 1.3 kgs for 1 m^3 Soil
Volume = 6/ (16.048 x 1000/9.81) = 3.67 x 10^{-3} m^3
TX-95 Weight = 3.67 x 10^{-3} x 1.3 x 1000 = 4.76 gm

For 10%:

SB-95 = 10 % of Sample
= 10 % of 6 kgs
= 0.6 kgs = 600 gm

Water = 12.5% (as it is the optimum moisture content) of sample soil
= 12.5% of 6 kgs
= 750 mL

TX-95 = 1.3 kgs for 1 m^3 Soil
Volume = 6/ (16.048 x 1000/9.81) = 3.67 x 10^{-3} m^3
TX-95 Weight = 3.67 x 10^{-3} x 1.3 x 1000 = 4.76 gm

For 12.5%:

SB-95 = 12.5 % of Sample
= 12.5 % of 6 kgs
= 0.75 kgs = 750 gm

Water = 12.5% (as it is the optimum moisture content) of sample soil
= 12.5% of 6 kgs
= 750 mL

TX-95 = 1.3 kgs for 1 m^3 Soil
Volume = 6/ (16.048 x 1000/9.81) = 3.67 x 10^{-3} m^3
TX-95 Weight = 3.67 x 10^{-3} x 1.3 x 1000 = 4.76 gm

For 15%:

SB-95 = 15 % of Sample

= 15 % of 6 kgs
= 0.9 kgs = 900 gm
Water = 12.5% (as it is the optimum moisture content) of sample soil
= 12.5% of 6 kgs
= 750 mL

TX-95 = 1.3 kgs for 1 m^3 Soil
Volume = 6/ (16.048 x 1000/9.81) = 3.67 x 10^{-3} m^3
TX-95 Weight = 3.67 x 10^{-3} x 1.3 x 1000 = 4.76 gm

b) UCS Test: Total 8 blocks are made with different percentages of ratios. Then the blocks were demolded and made ready for UCS test. The outcomes of UCS test of different percentage are generated in graphs which are shown below:

7.5 % SB-95

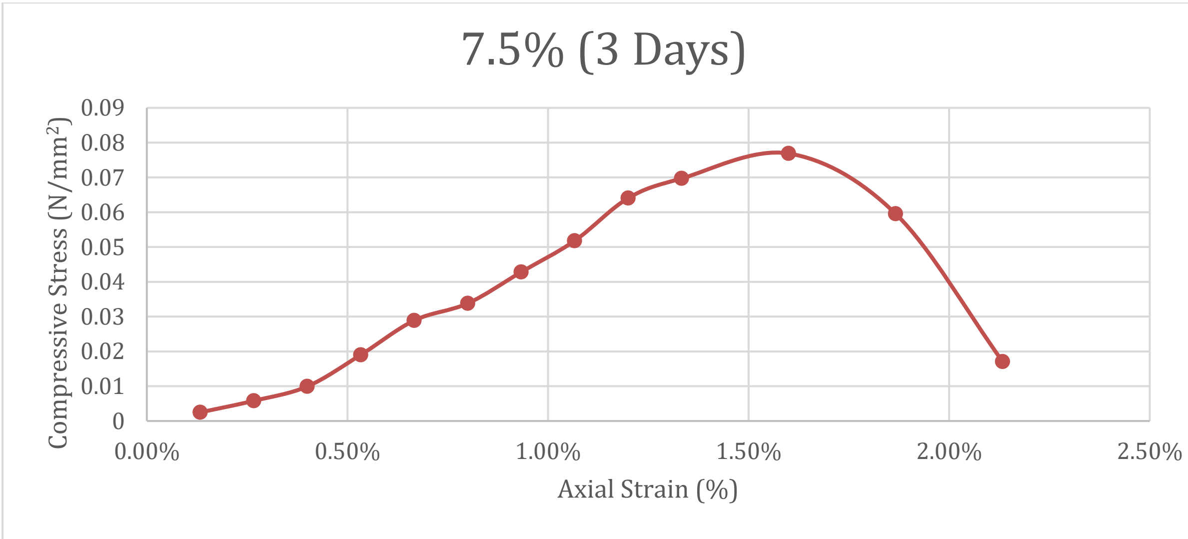
1.0132	calibration factor

7.5 % for 3 Days

Area of the mold =	1194.5934	sqmm
Volume=	89594.505	cubmm

load dial	calibrated (kg)	displacement dial gauge reading	unit strain L_0/L	corrected $A=A_0/(1-(L_0/L))$	stress Kg/mm^2	stress N/mm2
0.3	0.30396	0.1	0.13%	1196.188318	0.000254107	0.00249025
0.7	0.70924	0.2	0.27%	1197.7875	0.000592125	0.005802826
1.2	1.21584	0.3	0.40%	1199.390964	0.001013714	0.009934402
2.3	2.33036	0.4	0.53%	1200.998727	0.001940352	0.019015447
3.5	3.5462	0.5	0.67%	1202.610805	0.002948751	0.028897761
4.1	4.15412	0.6	0.80%	1204.227218	0.003449615	0.033806225
5.2	5.26864	0.7	0.93%	1205.847981	0.004369241	0.042818558
6.3	6.38316	0.8	1.07%	1207.473113	0.005286379	0.05180651
7.8	7.90296	0.9	1.20%	1209.102632	0.006536219	0.064054949
8.5	8.6122	1	1.33%	1210.736554	0.007113191	0.069709269
9.4	9.52408	1.2	1.60%	1214.017683	0.007845092	0.076881898
7.3	7.39636	1.4	1.87%	1217.316644	0.006075954	0.05954435
2.1	2.12772	1.6	2.13%	1220.633583	0.001743128	0.01708265

Table 13: UCS Test result of 7.5% for 3 Days



Graph 1: Compressive Stress Vs Axial Strain Graph for 7.5% (3 Days)

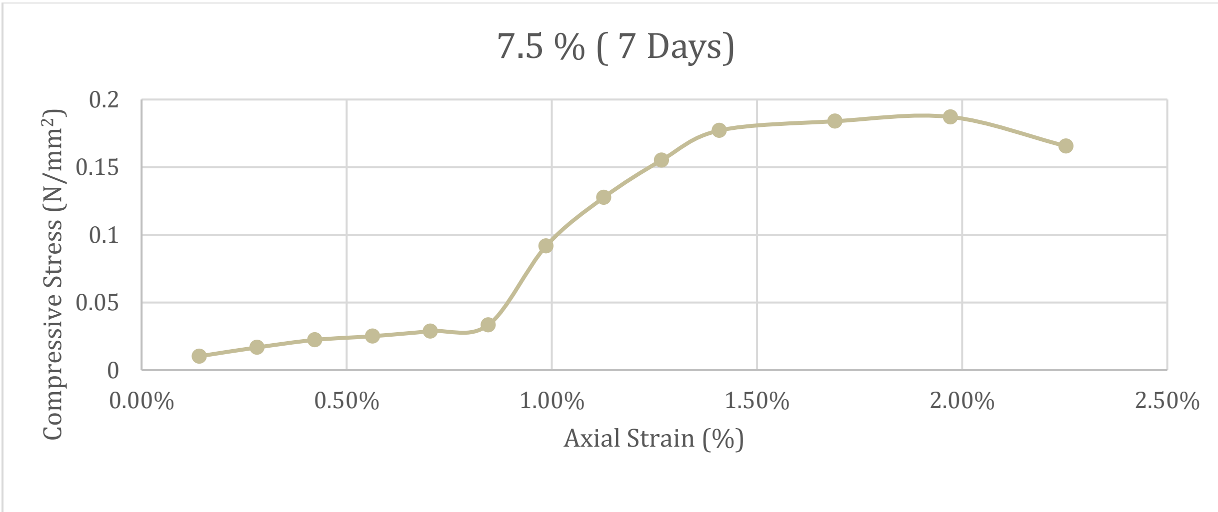
1.0132	calibration factor

7.5 % for 7 Days

Area of the mold =	1061.309135	sqmm
Volume=	75352.94859	cubmm

load dial	calibrated (kg)	displacement dial gauge reading	unit strain L_0/L	corrected $A=A_0/(1-(L_0/L))$	stress Kg/mm^2	stress N/mm2
1.1	1.11452	0.1	0.14%	1062.806045	0.001048658	0.010276848
1.8	1.82376	0.2	0.28%	1064.307183	0.001713565	0.016792941
2.4	2.43168	0.3	0.42%	1065.812568	0.002281527	0.022358963
2.7	2.73564	0.4	0.56%	1067.322218	0.002563087	0.025118255
3.1	3.14092	0.5	0.70%	1068.83615	0.002938636	0.028798629
3.6	3.64752	0.6	0.85%	1070.354383	0.003407769	0.033396132
9.9	10.03068	0.7	0.99%	1071.876936	0.009358052	0.091708909
13.8	13.98216	0.8	1.13%	1073.403826	0.013026002	0.127654816
16.8	17.02176	0.9	1.27%	1074.935073	0.015835152	0.155184487
19.2	19.45344	1	1.41%	1076.470694	0.0180715	0.177100699
20	20.264	1.2	1.69%	1079.555137	0.018770695	0.183952809
20.4	20.66928	1.4	1.97%	1082.657307	0.019091249	0.187094238
18.1	18.33892	1.6	2.25%	1085.777357	0.016890129	0.165523268

Table 14: UCS Test result of 7.5% for 7 Days



Graph 2: Compressive Stress Vs Axial Strain Graph for 7.5% (7 Days)

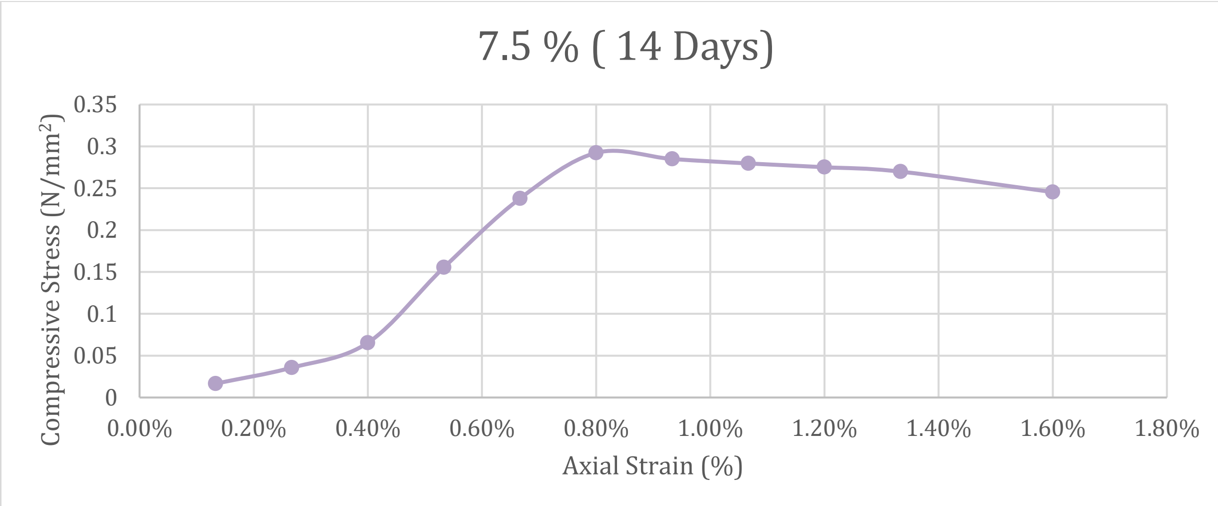
1.0132	calibration factor

7.5 % for 14 Days

Area of the mold =	1194.5934	sqmm
Volume=	89594.505	cubmm

load dial	calibrated (kg)	displacement dial gauge reading	unit strain L_0/L	corrected $A=A_0/(1-(L_0/L))$	stress Kg/mm^2	stress N/mm2
2	2.0264	0.1	0.13%	1196.188318	0.001694048	0.016601667
4.3	4.35676	0.2	0.27%	1197.7875	0.00363734	0.035645929
7.9	8.00428	0.3	0.40%	1199.390964	0.00667362	0.06540148
18.8	19.04816	0.4	0.53%	1200.998727	0.015860267	0.155430613
28.8	29.18016	0.5	0.67%	1202.610805	0.024264009	0.237787293
35.44	35.907808	0.6	0.80%	1204.227218	0.029818134	0.292217709
34.6	35.05672	0.7	0.93%	1205.847981	0.029072255	0.284908099
34	34.4488	0.8	1.07%	1207.473113	0.028529662	0.279590689
33.5	33.9422	0.9	1.20%	1209.102632	0.028072224	0.275107796
32.9	33.33428	1	1.33%	1210.736554	0.027532232	0.269815876
30	30.396	1.2	1.60%	1214.017683	0.025037527	0.24536776

Table 15: UCS Test result of 7.5% for 14 Days



Graph 3: Compressive Stress Vs Axial Strain Graph for 7.5% (14 Days)

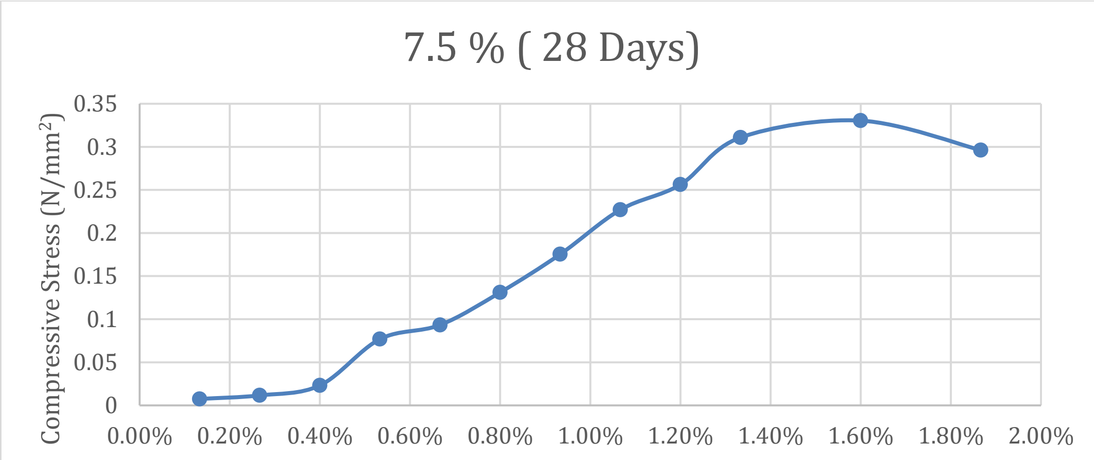
1.0132	calibration factor

7.5 % for 28 Days

Area of the mold =	1194.5934	sqmm
Volume=	89594.505	cubmm

load dial	calibrated (kg)	displacement dial gauge reading	unit strain L_0/L	corrected $A=A_0/(1-(L_0/L))$	stress Kg/mm^2	stress N/mm2
0.9	0.91188	0.1	0.13%	1196.188318	0.000762321	0.00747075
1.4	1.41848	0.2	0.27%	1197.7875	0.00118425	0.011605651
2.8	2.83696	0.3	0.40%	1199.390964	0.002365334	0.023180271
9.3	9.42276	0.4	0.53%	1200.998727	0.00784577	0.076888548
11.3	11.44916	0.5	0.67%	1202.610805	0.009520254	0.093298487
15.9	16.10988	0.6	0.80%	1204.227218	0.013377774	0.131102189
21.3	21.58116	0.7	0.93%	1205.847981	0.017897082	0.175391402
27.6	27.96432	0.8	1.07%	1207.473113	0.023159373	0.226961854
31.2	31.61184	0.9	1.20%	1209.102632	0.026144877	0.256219798
37.9	38.40028	1	1.33%	1210.736554	0.031716462	0.310821328
40.4	40.93328	1.2	1.60%	1214.017683	0.033717202	0.330428584
36.3	36.77916	1.4	1.87%	1217.316644	0.030213306	0.296090397

Table 16: UCS Test result of 7.5% for 28 Days



Graph 4 : Compressive Stress Vs Axial Strain Graph for 7.5% (28 Days)

10% SB-95

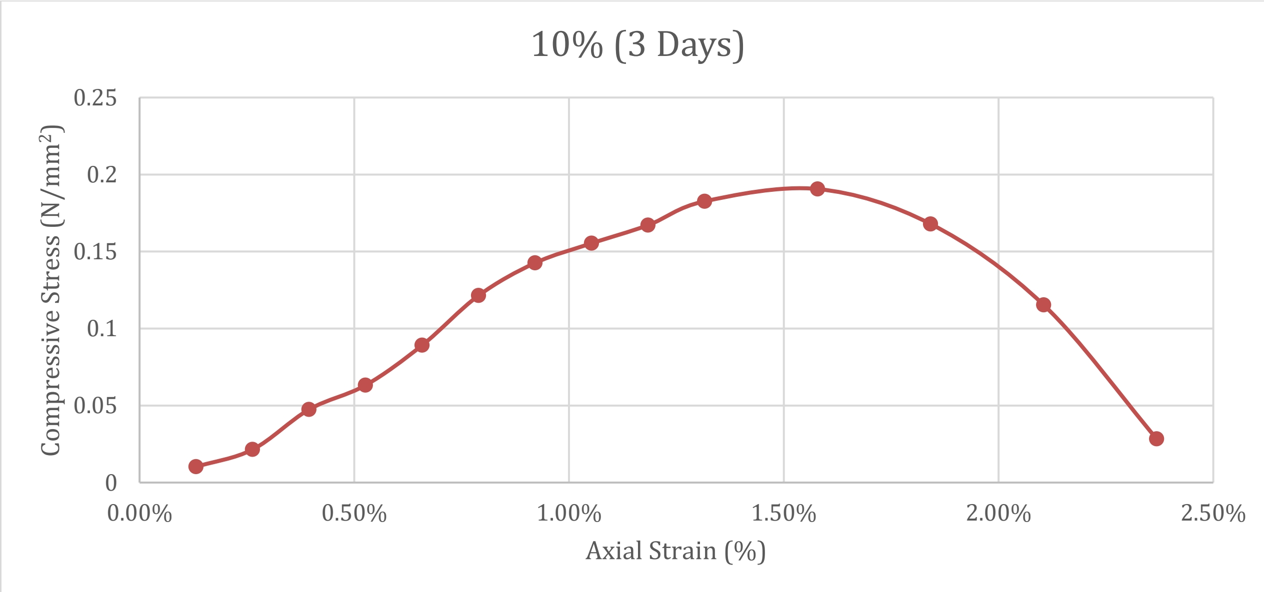
1.0132	calibration factor

10 % for 3 Days

Area of the mold =	1062.464301	sqmm
Volume=	80747.2869	cubmm

load dial	calibrated (kg)	displacement dial gauge reading	unit strain L_0/L	corrected $A=A_0/(1-(L_0/L))$	stress Kg/mm^2	stress N/mm2
1.1	1.11452	0.1	0.13%	1063.864123	0.001047615	0.010266627
2.3	2.33036	0.2	0.26%	1065.267637	0.002187582	0.021438301
5.1	5.16732	0.3	0.39%	1066.67486	0.004844325	0.047474388
6.8	6.88976	0.4	0.53%	1068.085806	0.006450568	0.063215565
9.6	9.72672	0.5	0.66%	1069.500489	0.009094638	0.089127454
13.1	13.27292	0.6	0.79%	1070.918924	0.012393954	0.12146075
15.4	15.60328	0.7	0.92%	1072.341128	0.014550668	0.142596549
16.8	17.02176	0.8	1.05%	1073.767113	0.015852376	0.155353285
18.1	18.33892	0.9	1.18%	1075.196896	0.017056336	0.167152097
19.8	20.06136	1	1.32%	1076.630492	0.018633468	0.182607988
20.72	20.993504	1.2	1.58%	1079.509183	0.019447268	0.190583223
18.3	18.54156	1.4	1.84%	1082.40331	0.017129992	0.167873921
12.6	12.76632	1.6	2.11%	1085.312996	0.0117628	0.115275443
3.1	3.14092	1.8	2.37%	1088.238368	0.002886243	0.028285178

Table 17: UCS Test result of 10% for 3Days



Graph 5: Compressive Stress Vs Axial Strain Graph for 10% (3 Days)

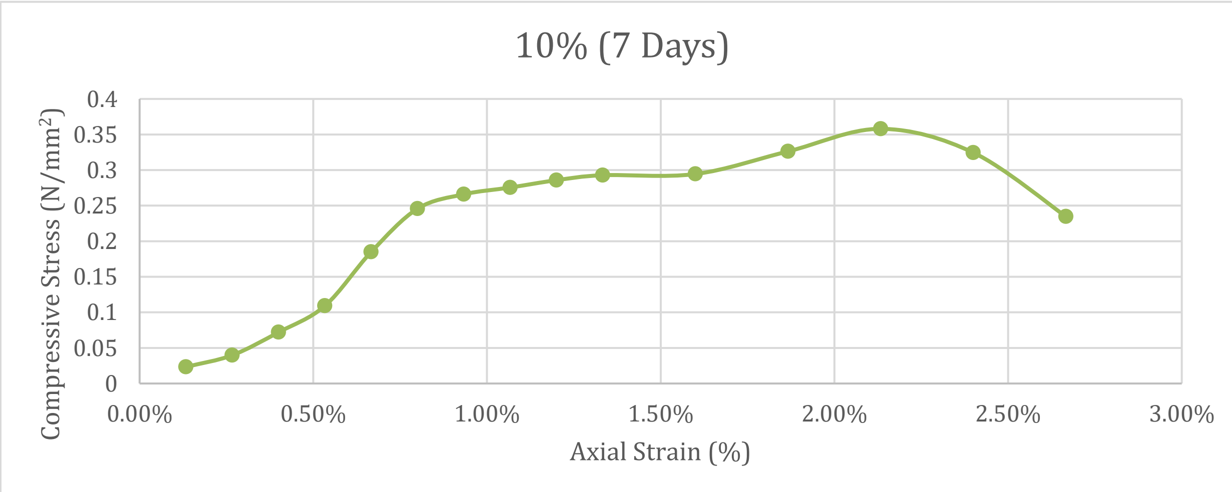
1.0132	calibration factor

10 % for 7 Days

Area of the mold =	1194.5934	sqmm
Volume=	89594.505	cubmm

load dial	calibrated (kg)	displacement dial gauge reading	unit strain L_0/L	corrected $A=A_0/(1-(L_0/L))$	stress Kg/mm^2	stress N/mm2
2.8	2.83696	0.1	0.13%	1196.188318	0.002371667	0.023242334
4.8	4.86336	0.2	0.27%	1197.7875	0.004060286	0.039790804
8.7	8.81484	0.3	0.40%	1199.390964	0.00734943	0.072024415
13.2	13.37424	0.4	0.53%	1200.998727	0.011135932	0.109132132
22.4	22.69568	0.5	0.67%	1202.610805	0.018872007	0.184945672
29.8	30.19336	0.6	0.80%	1204.227218	0.02507281	0.245713536
32.3	32.72636	0.7	0.93%	1205.847981	0.027139706	0.265969121
33.5	33.9422	0.8	1.07%	1207.473113	0.028110108	0.275479061
34.8	35.25936	0.9	1.20%	1209.102632	0.029161594	0.285783621
35.7	36.17124	1	1.33%	1210.736554	0.029875401	0.292778929
36	36.4752	1.2	1.60%	1214.017683	0.030045032	0.294441313
40	40.528	1.4	1.87%	1217.316644	0.033292899	0.32627041
44	44.5808	1.6	2.13%	1220.633583	0.036522672	0.357922186
40	40.528	1.8	2.40%	1223.968648	0.033111959	0.324497201
29	29.3828	2	2.67%	1227.321986	0.02394058	0.234617682

Table 18: UCS Test result of 10% for 7 Days



Graph 6: Compressive Stress Vs Axial Strain Graph for 10% (7 Days)

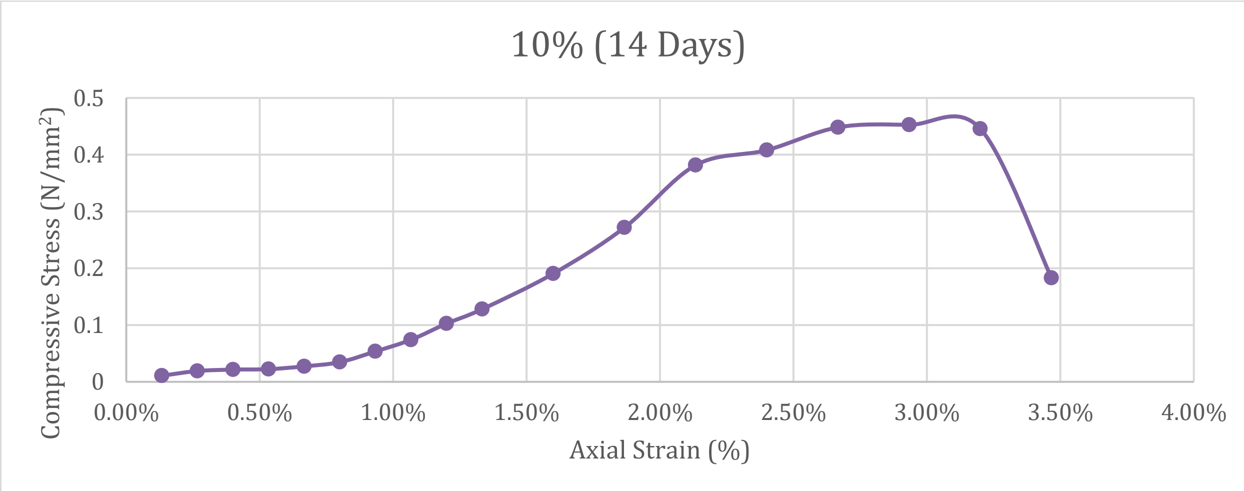
1.0132	calibration factor

10 % for 14 Days

Area of the mold =	1194.5934	sqmm
Volume=	89594.505	cubmm

load dial	calibrated (kg)	displacement dial gauge reading	unit strain L_0/L	corrected $A=A_0/(1-(L_0/L))$	stress Kg/mm^2	stress N/mm2
1.3	1.31716	0.1	0.13%	1196.188318	0.001101131	0.010791083
2.3	2.33036	0.2	0.27%	1197.7875	0.001945554	0.019066427
2.6	2.63432	0.3	0.40%	1199.390964	0.002196381	0.021524538
2.7	2.73564	0.4	0.53%	1200.998727	0.002277804	0.022322482
3.3	3.34356	0.5	0.67%	1202.610805	0.002780251	0.027246461
4.2	4.25544	0.6	0.80%	1204.227218	0.003533752	0.034630767
6.5	6.5858	0.7	0.93%	1205.847981	0.005461551	0.053523198
9	9.1188	0.8	1.07%	1207.473113	0.007551969	0.0740093
12.5	12.665	0.9	1.20%	1209.102632	0.01047471	0.102652163
15.6	15.80592	1	1.33%	1210.736554	0.013054797	0.127937011
23.3	23.60756	1.2	1.60%	1214.017683	0.019445812	0.190568961
33.3	33.73956	1.4	1.87%	1217.316644	0.027716338	0.271620116
46.9	47.51908	1.6	2.13%	1220.633583	0.038929848	0.381512512
50.3	50.96396	1.8	2.40%	1223.968648	0.041638289	0.40805523
55.4	56.13128	2	2.67%	1227.321986	0.045734763	0.448200676
56.1	56.84052	2.2	2.93%	1230.69375	0.046185755	0.452620399
55.4	56.13128	2.4	3.20%	1234.084091	0.045484161	0.445744782
22.8	23.10096	2.6	3.47%	1237.493163	0.018667546	0.182941946

Table 19: UCS Test result of 10% for 14 Days



Graph 7: Compressive Stress Vs Axial Strain Graph for 10% (14 Days)

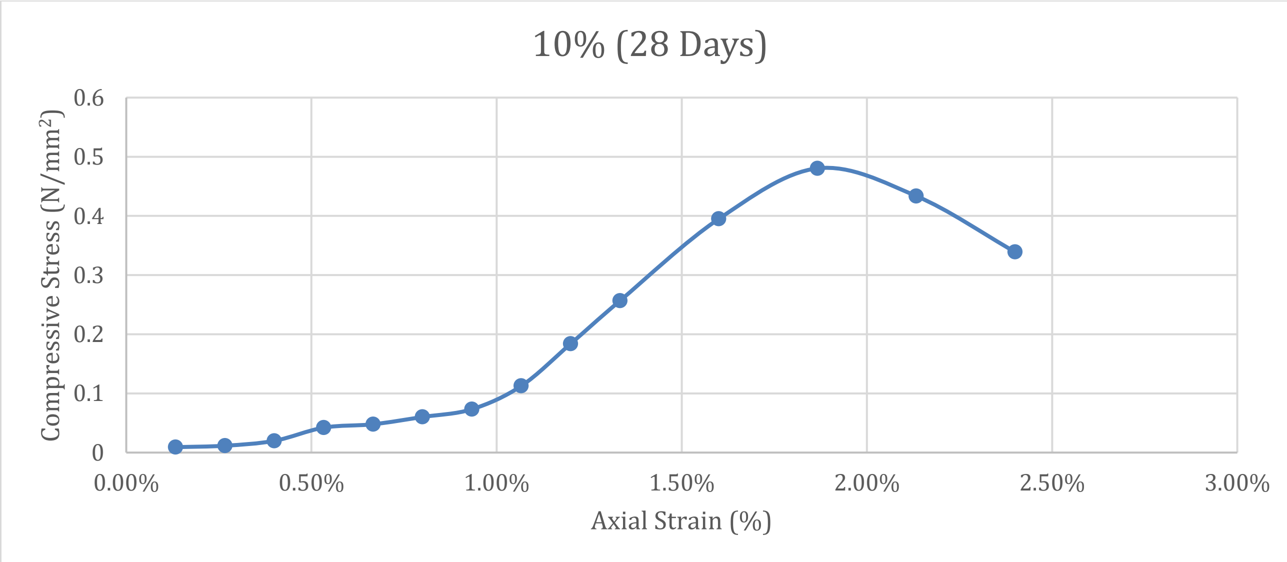
1.0132	calibration factor

10 % for 28 Days

Area of the mold =	1194.5934	sqmm
Volume=	89594.505	cubmm

load dial	calibrated (kg)	displacement dial gauge reading	unit strain L_0/L	corrected $A=A_0/(1-(L_0/L))$	stress Kg/mm^2	stress N/mm2
1.1	1.11452	0.1	0.13%	1196.188318	0.000931726	0.009130917
1.4	1.41848	0.2	0.27%	1197.7875	0.00118425	0.011605651
2.4	2.43168	0.3	0.40%	1199.390964	0.002027429	0.019868804
5.1	5.16732	0.4	0.53%	1200.998727	0.004302519	0.042164688
5.8	5.87656	0.5	0.67%	1202.610805	0.004886502	0.047887719
7.3	7.39636	0.6	0.80%	1204.227218	0.006141997	0.060191571
8.9	9.01748	0.7	0.93%	1205.847981	0.007478123	0.073285609
13.7	13.88084	0.8	1.07%	1207.473113	0.011495776	0.112658601
22.4	22.69568	0.9	1.20%	1209.102632	0.018770681	0.183952675
31.3	31.71316	1	1.33%	1210.736554	0.026193279	0.256694131
48.3	48.93756	1.2	1.60%	1214.017683	0.040310418	0.395042094
58.9	59.67748	1.4	1.87%	1217.316644	0.049023794	0.480433178
53.3	54.00356	1.6	2.13%	1220.633583	0.044242237	0.43357392
41.8	42.35176	1.8	2.40%	1223.968648	0.034601997	0.339099575

Table 20: UCS Test result of 10% for 28 Days



Graph 8: Compressive Stress Vs Axial Strain Graph for 10% (28 Days)

12.5% SB-95

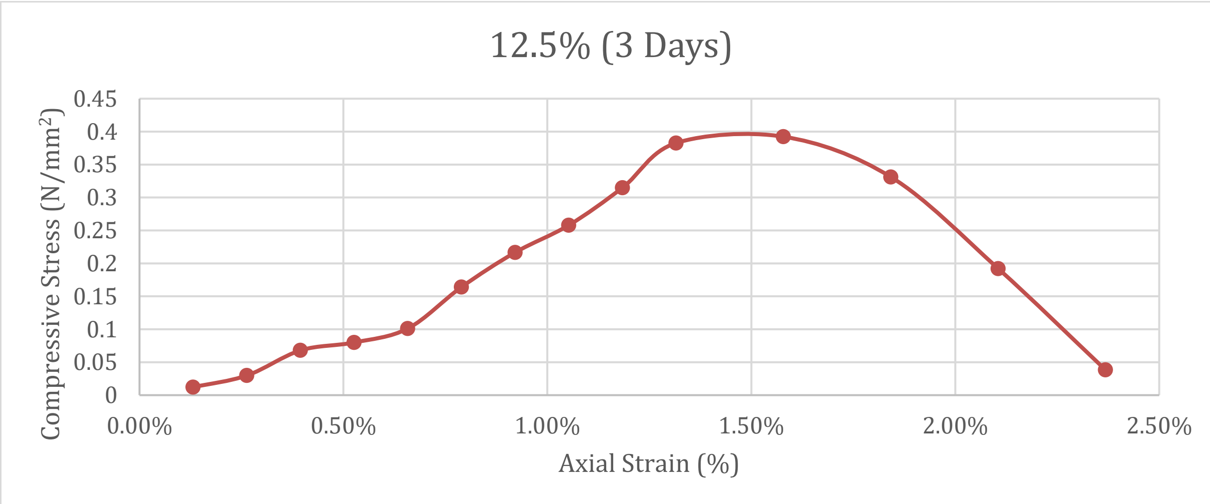
1.0132	calibration factor

12.5 % for 3 Days

Area of the mold =	1062.464301	sqmm
Volume=	80747.2869	cubmm

load dial	calibrated (kg)	displacement dial gauge reading	unit strain L_0/L	corrected $A=A_0/(1-(L_0/L))$	stress Kg/mm^2	stress N/mm2
1.3	1.31716	0.1	0.13%	1063.864123	0.00123809	0.012133286
3.2	3.24224	0.2	0.26%	1065.267637	0.003043592	0.029827201
7.3	7.39636	0.3	0.39%	1066.67486	0.006934034	0.067953536
8.6	8.71352	0.4	0.53%	1068.085806	0.008158071	0.079949097
10.9	11.04388	0.5	0.66%	1069.500489	0.010326204	0.101196797
17.7	17.93364	0.6	0.79%	1070.918924	0.01674603	0.16411109
23.4	23.70888	0.7	0.92%	1072.341128	0.022109457	0.216672678
27.9	28.26828	0.8	1.05%	1073.767113	0.026326267	0.257997419
34.1	34.55012	0.9	1.18%	1075.196896	0.032133761	0.314910857
41.5	42.0478	1	1.32%	1076.630492	0.039054996	0.382738965
42.65	43.21298	1.2	1.58%	1079.509183	0.040030211	0.392296064
36.1	36.57652	1.4	1.84%	1082.40331	0.033791951	0.331161123
21	21.2772	1.6	2.11%	1085.312996	0.019604667	0.192125738
4.2	4.25544	1.8	2.37%	1088.238368	0.003910393	0.038321854

Table 21: UCS Test result of 12.5% for 3 Days



Graph 9: Compressive Stress Vs Axial Strain Graph for 12.5% (3 Days)

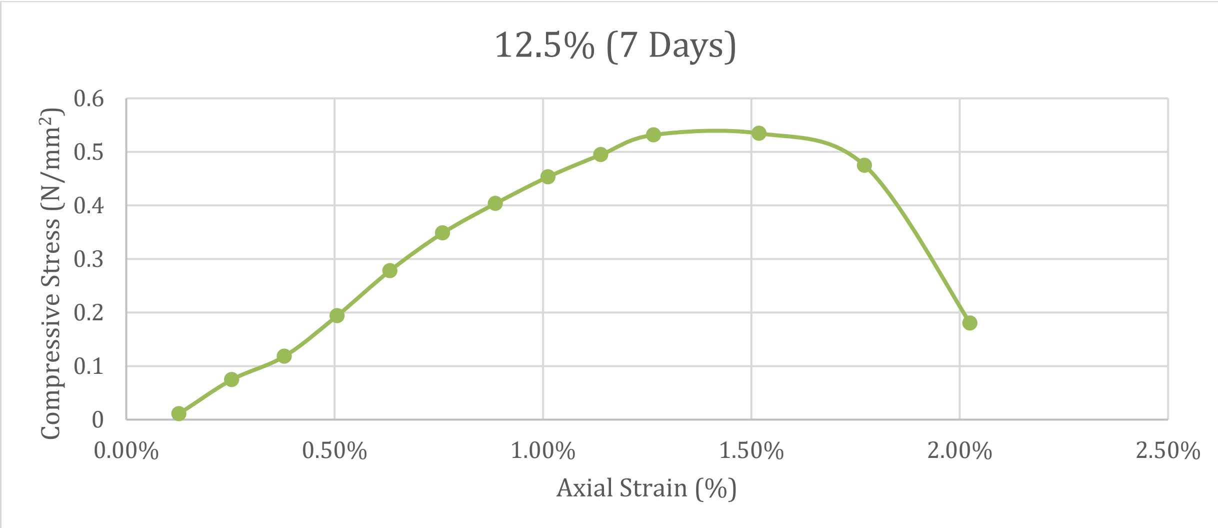
1.0132	calibration factor

12.5 % for 7 Days

Area of the mold =	1170.820991	sqmm
Volume=	92518.27474	cubmm

load dial	calibrated (kg)	displacement dial gauge reading	unit strain L_0/L	corrected $A=A_0/(1-(L_0/L))$	stress Kg/mm^2	stress N/mm2
1.3	1.31716	0.1	0.13%	1172.304546	0.001123565	0.011010934
8.8	8.91616	0.2	0.25%	1173.791864	0.007596032	0.074441109
14	14.1848	0.3	0.38%	1175.282962	0.012069264	0.118278784
23	23.3036	0.4	0.51%	1176.777852	0.019802888	0.194068302
33	33.4356	0.5	0.63%	1178.27655	0.0283767	0.278091658
41.4	41.94648	0.6	0.76%	1179.779071	0.035554521	0.348434308
48	48.6336	0.7	0.89%	1181.285428	0.041170067	0.403466655
54	54.7128	0.8	1.01%	1182.795637	0.046257188	0.453320441
59	59.7788	0.9	1.14%	1184.309712	0.050475648	0.494661349
63.5	64.3382	1	1.27%	1185.827669	0.054255944	0.531708254
64	64.8448	1.2	1.52%	1188.875286	0.054542979	0.534521196
57	57.7524	1.4	1.77%	1191.938608	0.048452495	0.474834456
21.7	21.98644	1.6	2.02%	1195.017757	0.018398421	0.180304527

Table 22: UCS Test result of 12.5% for 7 Days



Graph 10: Compressive Stress Vs Axial Strain Graph for 12.5% (7 Days)

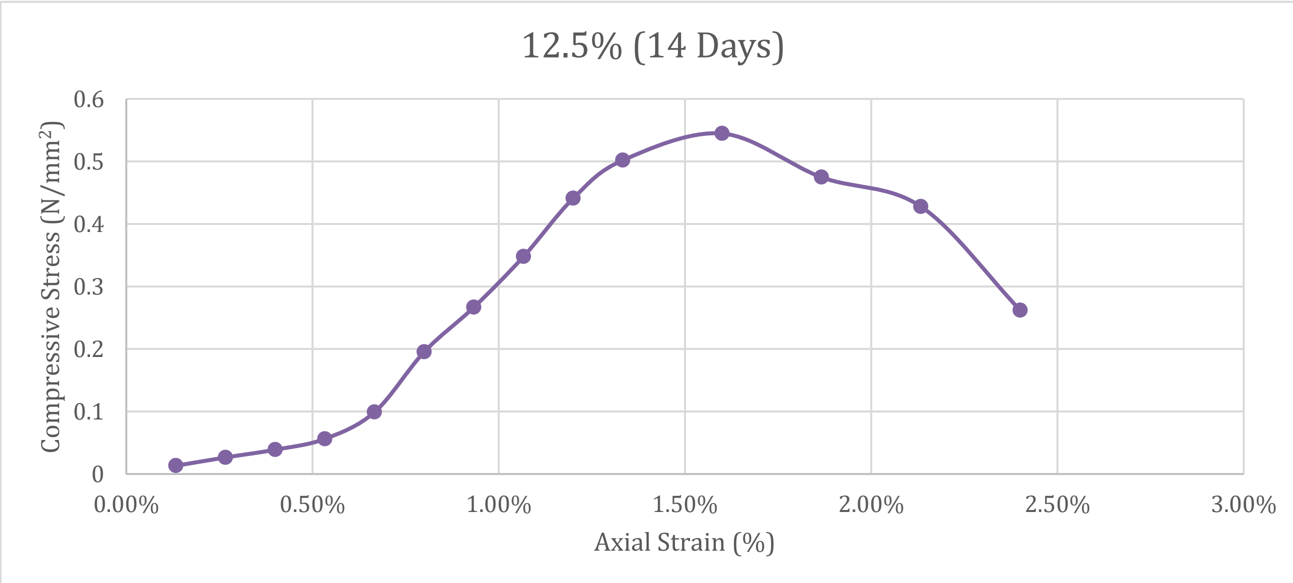
1.0132	calibration factor

12.5 % for 14 Days

Area of the mold =	1194.5934	sqmm
Volume=	89594.505	cubmm

load dial	calibrated (kg)	displacement dial gauge reading	unit strain L_0/L	corrected $A=A_0/(1-(L_0/L))$	stress Kg/mm^2	stress N/mm2
1.6	1.62112	0.1	0.13%	1196.188318	0.00135524	0.013281334
3.2	3.24224	0.2	0.27%	1197.7875	0.00270686	0.026527203
4.7	4.76204	0.3	0.40%	1199.390964	0.00397038	0.038909741
6.8	6.88976	0.4	0.53%	1200.998727	0.00573669	0.056219583
12	12.1584	0.5	0.67%	1202.610805	0.01011	0.099078039
23.7	24.01284	0.6	0.80%	1204.227218	0.01994046	0.19541647
32.4	32.82768	0.7	0.93%	1205.847981	0.02722373	0.266792555
42.3	42.85836	0.8	1.07%	1207.473113	0.03549426	0.34784371
53.7	54.40884	0.9	1.20%	1209.102632	0.04499936	0.440993691
61.2	62.00784	1	1.33%	1210.736554	0.05121497	0.501906736
66.6	67.47912	1.2	1.60%	1214.017683	0.05558331	0.544716428
58.2	58.96824	1.4	1.87%	1217.316644	0.04844117	0.474723446
52.6	53.29432	1.6	2.13%	1220.633583	0.04366119	0.427879704
32.3	32.72636	1.8	2.40%	1223.968648	0.02673791	0.26203149

Table 23: UCS Test result of 12.5% for 14 Days



Graph 11: Compressive Stress Vs Axial Strain Graph for 12.5% (14 Days)

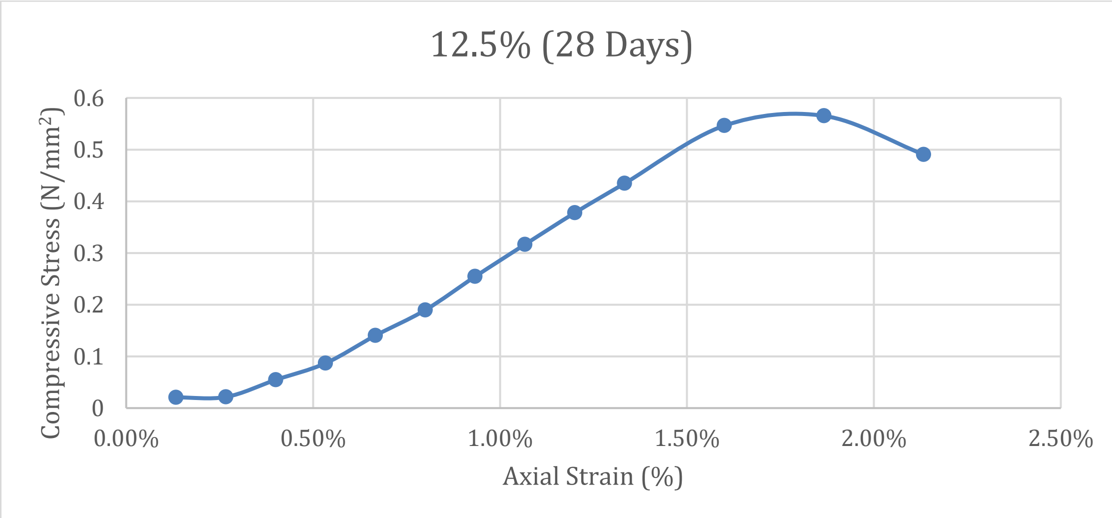
1.0132	calibration factor

12.5 % for 28 Days

Area of the mold =	1194.5934	sqmm
Volume=	89594.505	cubmm

load dial	calibrated (kg)	displacement dial gauge reading	unit strain L_0/L	corrected $A=A_0/(1-(L_0/L))$	stress Kg/mm^2	stress N/mm2
2.5	2.533	0.1	0.13%	1196.188318	0.00211756	0.020752084
2.6	2.63432	0.2	0.27%	1197.7875	0.002199322	0.021553352
6.6	6.68712	0.3	0.40%	1199.390964	0.00557543	0.054639211
10.5	10.6386	0.4	0.53%	1200.998727	0.008858128	0.086809651
17	17.2244	0.5	0.67%	1202.610805	0.014322506	0.140360555
23	23.3036	0.6	0.80%	1204.227218	0.019351498	0.189644676
30.9	31.30788	0.7	0.93%	1205.847981	0.025963372	0.254441048
38.5	39.0082	0.8	1.07%	1207.473113	0.032305647	0.316595339
46	46.6072	0.9	1.20%	1209.102632	0.038546935	0.377759959
53	53.6996	1	1.33%	1210.736554	0.044352836	0.434657794
66.8	67.68176	1.2	1.60%	1214.017683	0.055750226	0.546352213
69.3	70.21476	1.4	1.87%	1217.316644	0.057679947	0.565263485
60.3	61.09596	1.6	2.13%	1220.633583	0.050052662	0.490516086

Table 24: UCS Test result of 12.5% for 28 Days



Graph 12: Compressive Stress Vs Axial Strain Graph for 12.5% (28 Days)

15% SB-95

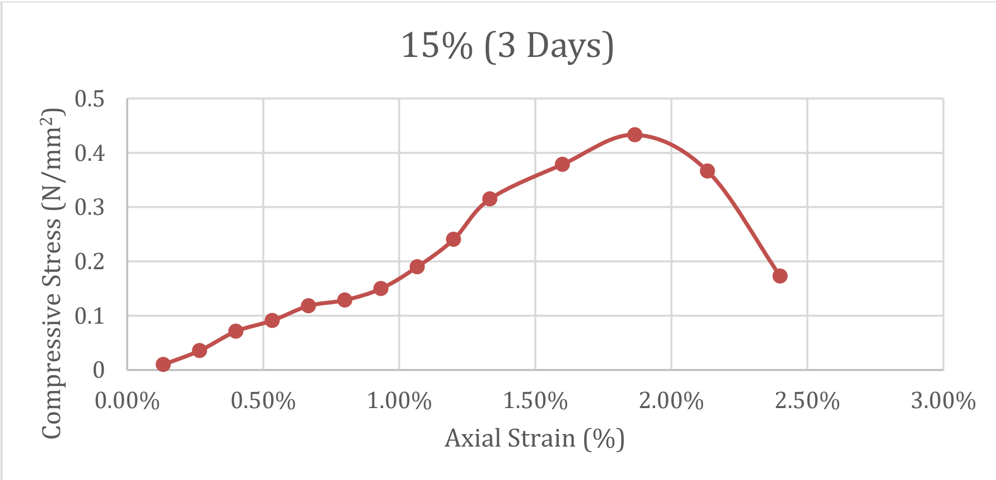
1.0132	calibration factor

15 % for 3 Days

Area of the mold =	1194.5934	sqmm
Volume=	89594.505	cubmm

load dial	calibrated (kg)	displacement dial gauge reading	unit strain L_0/L	corrected $A=A_0/(1-(L_0/L))$	stress Kg/mm^2	stress N/mm2
1.2	1.21584	0.1	0.13%	1196.188318	0.001016429	0.009961
4.3	4.35676	0.2	0.27%	1197.7875	0.00363734	0.035645929
8.6	8.71352	0.3	0.40%	1199.390964	0.007264954	0.071196548
11	11.1452	0.4	0.53%	1200.998727	0.009279943	0.090943444
14.3	14.48876	0.5	0.67%	1202.610805	0.012047755	0.118067996
15.6	15.80592	0.6	0.80%	1204.227218	0.013125364	0.128628563
18.2	18.44024	0.7	0.93%	1205.847981	0.015292342	0.149864954
23.1	23.40492	0.8	1.07%	1207.473113	0.019383388	0.189957204
29.3	29.68676	0.9	1.20%	1209.102632	0.024552721	0.240616669
38.4	38.90688	1	1.33%	1210.736554	0.032134885	0.314921874
46.3	46.91116	1.2	1.60%	1214.017683	0.038641249	0.378684244
53.1	53.80092	1.4	1.87%	1217.316644	0.044196323	0.433123969
45	45.594	1.6	2.13%	1220.633583	0.037352733	0.366056781
21.3	21.58116	1.8	2.40%	1223.968648	0.017632118	0.172794759

Table 25: UCS Test result of 15% for 3 Days



Graph 13: Compressive Stress Vs Axial Strain Graph for 15% (3 Days)

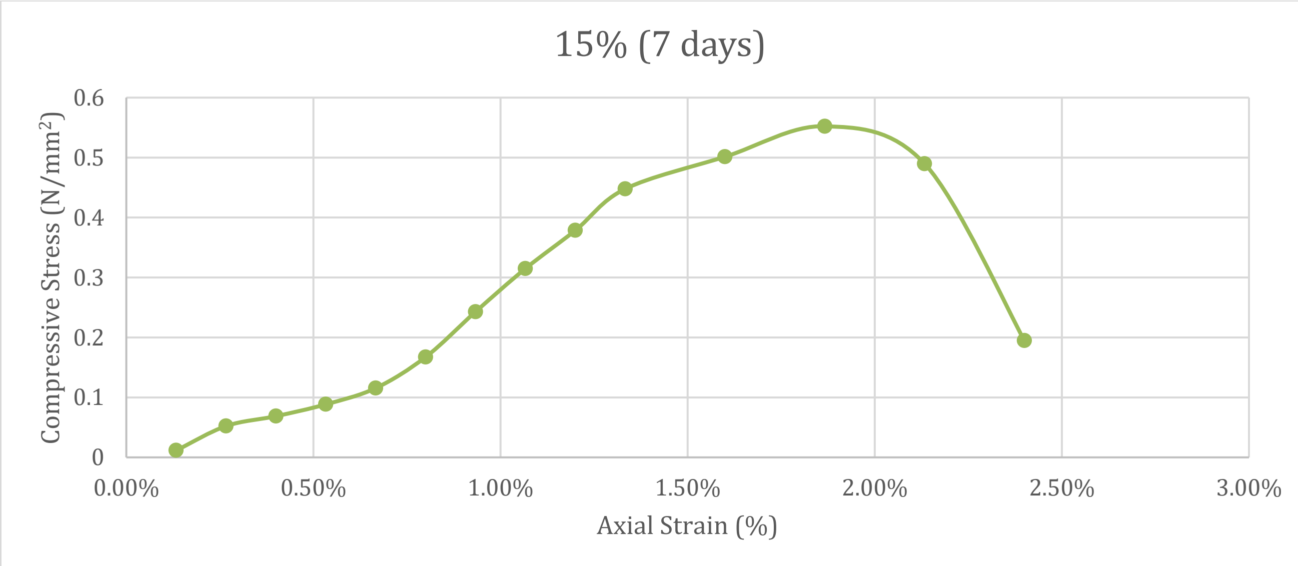
1.0132	calibration factor

15 % for 7 Days

Area of the mold =	1194.5934	sqmm
Volume=	89594.505	cubmm

load dial	calibrated (kg)	displacement dial gauge reading	unit strain L_0/L	corrected $A=A_0/(1-(L_0/L))$	stress Kg/mm^2	stress N/mm2
1.4	1.41848	0.1	0.13%	1196.188318	0.001185833	0.011621167
6.3	6.38316	0.2	0.27%	1197.7875	0.005329126	0.052225431
8.3	8.40956	0.3	0.40%	1199.390964	0.007011525	0.068712947
10.7	10.84124	0.4	0.53%	1200.998727	0.009026854	0.088463168
14	14.1848	0.5	0.67%	1202.610805	0.011795005	0.115591045
20.3	20.56796	0.6	0.80%	1204.227218	0.0170798	0.16738204
29.5	29.8894	0.7	0.93%	1205.847981	0.024787038	0.242912975
38.3	38.80556	0.8	1.07%	1207.473113	0.032137825	0.314950688
46.1	46.70852	0.9	1.20%	1209.102632	0.038630732	0.378581176
54.6	55.32072	1	1.33%	1210.736554	0.04569179	0.447779539
61.3	62.10916	1.2	1.60%	1214.017683	0.051160013	0.501368124
67.7	68.59364	1.4	1.87%	1217.316644	0.056348231	0.552212668
60.2	60.99464	1.6	2.13%	1220.633583	0.049969656	0.489702627
24	24.3168	1.8	2.40%	1223.968648	0.019867176	0.19469832

Table 26: UCS Test result of 15% for 7 Days



Graph 14: Compressive Stress Vs Axial Strain Graph for 15% (7 Days)

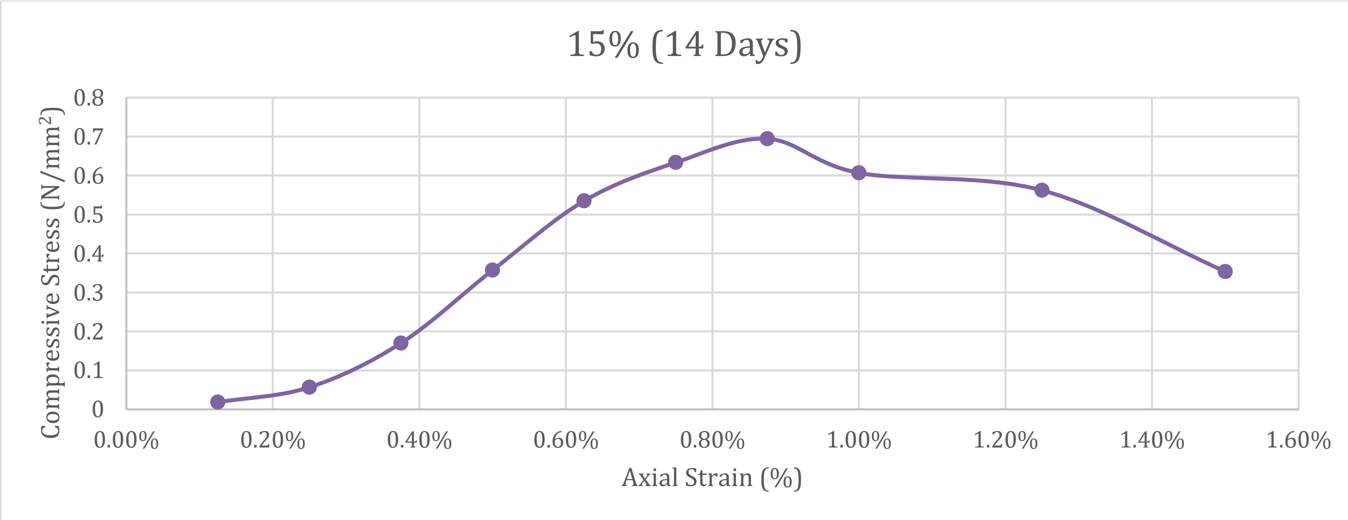
1.0132	calibration factor

15 % for 14 Days

Area of the mold =	1134.1176	sqmm
Volume=	90729.408	cubmm

load dial	calibrated (kg)	displacement dial gauge reading	unit strain L_0/L	corrected $A=A_0/(1-(L_0/L))$	stress Kg/mm^2	stress N/mm2
2.1	2.12772	0.1	0.13%	1135.537021	0.001873757	0.018362815
6.5	6.5858	0.2	0.25%	1136.96	0.005792464	0.056766148
19.5	19.7574	0.3	0.38%	1138.38655	0.017355616	0.170085038
41	41.5412	0.4	0.50%	1139.816683	0.03644551	0.357165995
61.5	62.3118	0.5	0.63%	1141.250415	0.054599586	0.535075941
72.9	73.86228	0.6	0.75%	1142.687758	0.064639075	0.633462938
80	81.056	0.7	0.88%	1144.128726	0.070845175	0.694282716
70	70.924	0.8	1.00%	1145.573333	0.061911357	0.606731302
65	65.858	1	1.25%	1148.473519	0.057343943	0.561970641
41	41.5412	1.2	1.50%	1151.388426	0.036079223	0.353576387

Table 27: UCS Test result of 15% for 14 Days



Graph 15: Compressive Stress Vs Axial Strain Graph for 15% (14 Days)

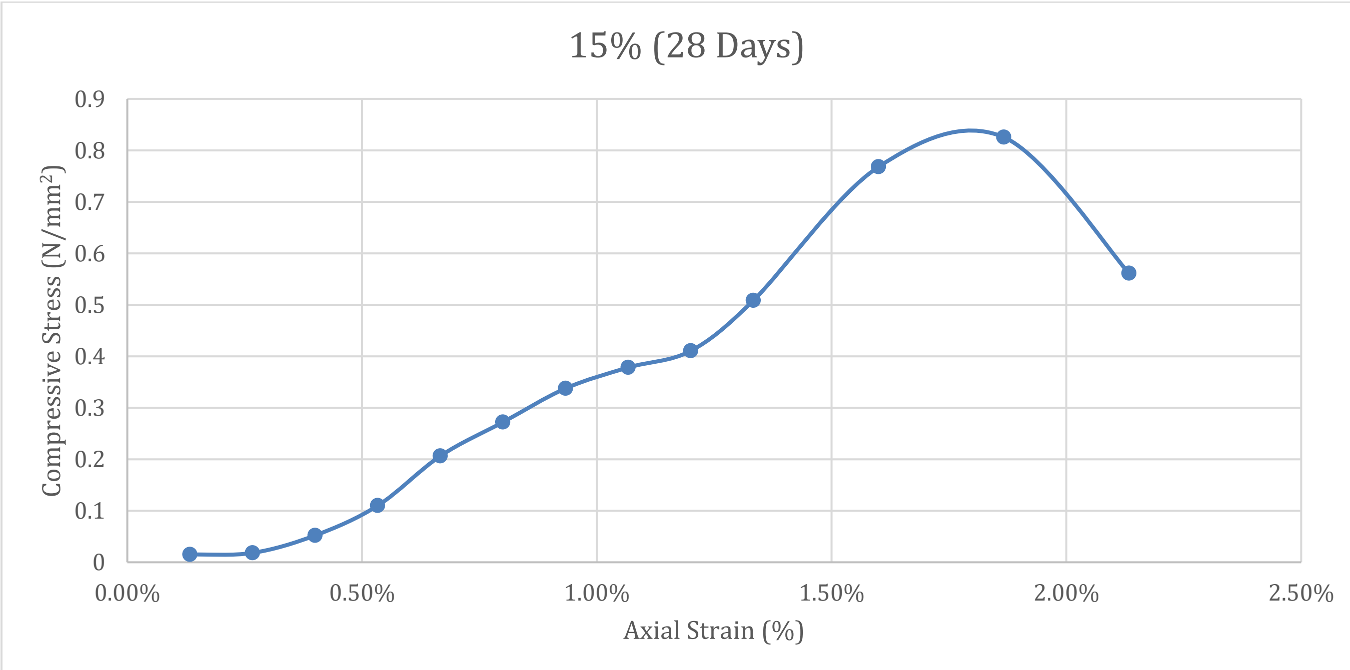
1.0132	calibration factor

15 % for 28 Days

Area of the mold =	1194.5934	sqmm
Volume=	89594.505	cubmm

load dial	calibrated (kg)	displacement dial gauge reading	unit strain L_0/L	corrected $A=A_0/(1-(L_0/L))$	stress Kg/mm^2	stress N/mm2
1.8	1.82376	0.1	0.13%	1196.188318	0.001524643	0.0149415
2.2	2.22904	0.2	0.27%	1197.7875	0.001860964	0.018237452
6.3	6.38316	0.3	0.40%	1199.390964	0.005322001	0.052155611
13.3	13.47556	0.4	0.53%	1200.998727	0.011220295	0.109958891
25	25.33	0.5	0.67%	1202.610805	0.021062508	0.206412581
33	33.4356	0.6	0.80%	1204.227218	0.027765192	0.272098882
41	41.5412	0.7	0.93%	1205.847981	0.034449782	0.337607863
46	46.6072	0.8	1.07%	1207.473113	0.038598955	0.378269756
50	50.66	0.9	1.20%	1209.102632	0.041898842	0.410608651
62	62.8184	1	1.33%	1210.736554	0.05188445	0.508467608
93.9	95.13948	1.2	1.60%	1214.017683	0.078367458	0.76800109
101.2	102.53584	1.4	1.87%	1217.316644	0.084231034	0.825464136
69	69.9108	1.6	2.13%	1220.633583	0.05727419	0.561287064

Table 28: UCS Test result of 10% for 28 Days



Graph 16: Compressive Stress Vs Axial Strain Graph for 15% (28 Days)

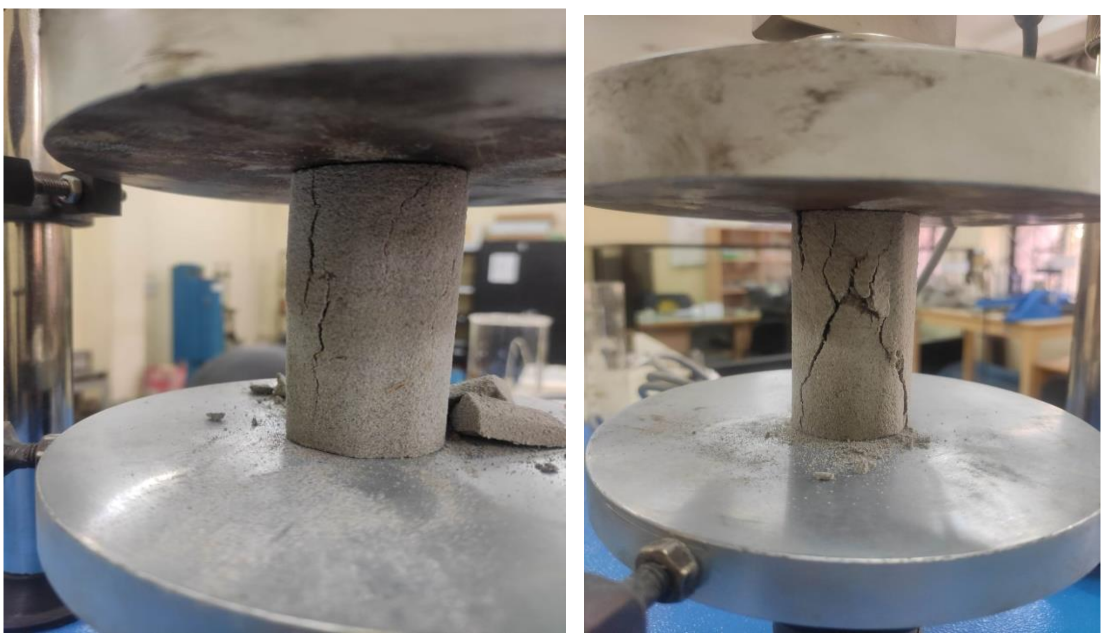


Figure 12 (a): UCS Tests of Cylindrical Sample. (b) UCS Tests of Cylindrical Sample

Submerged Embankment Test

In this test, our embankment model filled with sand which was mixed with the feasible percent of SB-95 (10%) and filled with water. Through this, we were able to measure the quality of water under the pores of the soil. Also, the percentage of SB-95 was perfect or not for erosion control had also been measured.

a) Test Set up: A box made with acrylic glass has been made which was in the dimension of 120 cm x 75 cm x 45 cm. In this box, at first in the base we have kept 200 kgs saturated sand. After that, on the slope 150 kgs treated (mixed with 10% SB-95) sand were kept upon the base. It was a 2:1 slope. After air drying for 24 hours, we placed approximately 350 L water in the box and after 24 hours we pumped out the water from the Box. We measured the quantity of water on the water on the surface, upon 1.5 inches depth and upon 4 inches depth afterwards by a sensor which was run by Arduino.

b) Sensor Data Processing: A moisture sensor has been made with the help of Arduino. With that we have added a temperature and humidity sensor so that we can measure the water quantity in the surface, 1.5 inches depth and 4 inches depth with the perspective to temperature and humidity. With the help of the Sensor, we were able to take the data in excel before and after placing water. A curve is also generated based upon the moisture content on before and after water placing.

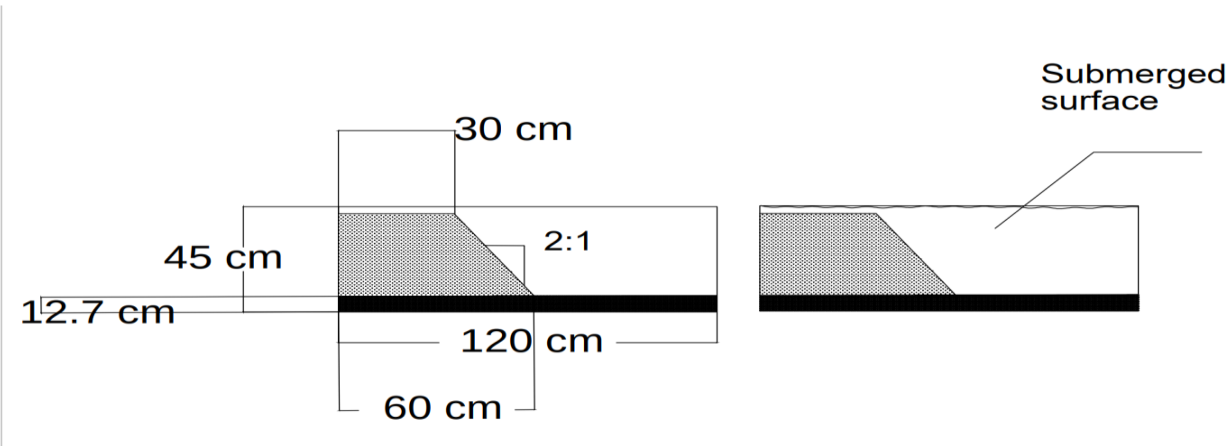


Figure 13 (a): Submerged Embankment Test (Before Placing Water). (b) Submerged Embankment Test (After Placing Water) (c) Schematic design of embankment model

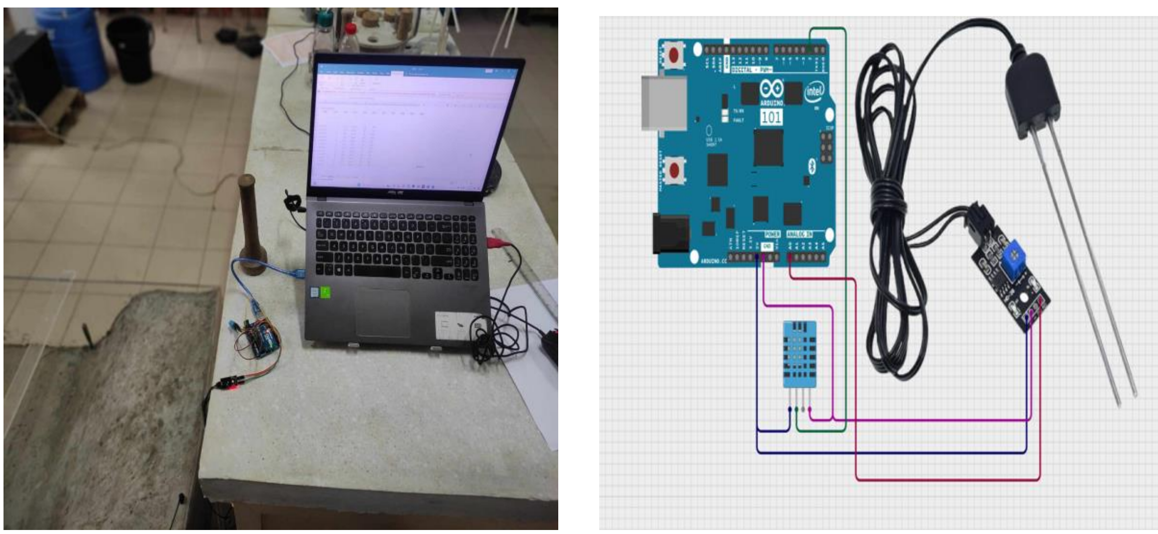


Figure 14(a): Data taking by Soil Moisture Sensor (b) Circuit design of Soil Moisture Sensor with Temperature and Humidity Sensor

Summary

This chapter details the experimental program conducted to study soil stabilization for erosion control. The research covers locations, procedures for field and laboratory testing, and collection of disturbed samples, all of which were analyzed and tested at the Geotechnical Laboratory of the Islamic University of Technology (IUT).

i. The research focuses on riverbank erosion and soil erosion issues in Bangladesh, particularly at Board Bazar, Gazipur. Water erosion affects 25% of agricultural land in Bangladesh, with various types of erosion occurring across the country. Sandy soil from Board Bazar was used to create a prototype embankment stabilized with chemical additives SB-95 and TX-95. The study investigates eco-friendly and cost-effective methods for constructing road embankments using locally sourced stabilization techniques.
ii. Initial soil tests included sieve analysis, hydrometer analysis, specific gravity test, compaction test, and permeability test. After obtaining baseline data, chemical stabilizers were mixed with the soil in varying ratios. Unconfined Compressive Strength (UCS) tests were then conducted on soil blocks made with different percentages of SB-95 (7.5%, 10%, 12.5%, and 15%). These blocks were cured for 3, 7, 14, and 28 days before testing. The UCS tests involved calculating the amount of SB-95 and TX-95, as well as water content, for each soil sample.
iii. A box made of acrylic glass, measuring 120 cm x 75 cm x 45 cm, was used to hold the embankment prototype. The soil blocks were made by mixing different percentages of SB-95 with soil and water. After curing, the blocks were removed from molds using a hydraulic jack and cut into cylindrical shapes for UCS testing. Each percentage was tested on two blocks to ensure accuracy.

iv. The UCS tests were conducted on the prepared blocks to determine their strength. Calculations were made for each sample to ensure the correct number of stabilizers and water. The test results were plotted on graphs, showing the strength of blocks with different SB-95 percentages over various curing periods.

v. A submerged embankment test was conducted to assess the effectiveness of the stabilizers in controlling erosion. A box made of acrylic glass was filled with a base of 200 kg saturated sand, followed by 150 kg treated sand (mixed with 10% SB-95) on a 2:1 slope. After air drying for 24 hours, 350 liters of water were added, and the water content was measured at different depths using a moisture sensor connected to an Arduino. This sensor measured water quantity before and after saturation, providing data on the stabilizer's effectiveness.

vi. The moisture sensor, along with a temperature and humidity sensor, provided data on the water content at the surface, 1.5 inches depth, and 4 inches depth. The data, recorded in

Excel, was used to generate curves showing moisture content before and after water addition, confirming the stabilizer's performance in controlling erosion.

This comprehensive experimental program demonstrated the potential of using chemical stabilizers for effective and eco-friendly soil stabilization in erosion-prone areas of Bangladesh.

Chapter Four

RESULTS AND DISCUSSION

4.1 Introduction

The primary goal of this chapter is to provide comprehensive findings from both field and laboratory investigations conducted during the study. Laboratory UCS tests were conducted for 4 different percentages. Submerged Embankment Test has also been conducted for measuring the moisture quantity of soil in the case of dry and wet condition. The Moisture Quantity of the slope with dry condition has been compared with that of dry condition. By those, the power of Stabilization of SB-95 and TX-95 has been confirmed. Finally, the erosion control of Soil has been estimated has been estimated by all the test result.

4.2 Selection of Study Areas

The issue of soil erosion is pervasive in Bangladesh, affecting both agricultural land and hilly regions where erosion rates are high. Various types of erosion, including riverbank and coastal erosion, are prominent natural disasters nationwide. Addressing these challenges requires cost-effective and eco-friendly approaches to road embankment construction, particularly in the face of material scarcity. The choice of Gazipur (Board bazar) for soil stabilization testing is strategic due to its susceptibility to various forms of soil erosion, including water erosion affecting a significant portion of agricultural land. Gazipur's hilly regions, covering a substantial area, experience accelerated soil erosion, making it a critical location for studying effective erosion control methods. The region's diverse soil types and terrain provide an ideal setting to investigate and implement cost-effective and environmentally friendly stabilization techniques. This research aims to address the multifaceted challenges of soil erosion by enhancing slope topsoil properties through innovative approaches like biological, chemical, and physical stabilization methods, such as those involving SB-95 and TX-95 chemical stabilizers.

4.2.1 Metrological Condition of the Study Areas

With a mean annual rainfall of approximately 2376 mm, Board bazar receives substantial precipitation throughout the year, contributing significantly to its water resources and agricultural productivity. The highest average temperature reaching 36°C indicates warm climatic conditions during certain periods, while the lowest average temperature of 12.7°C reflects cooler periods that impact crop growth and seasonal activities.

Similar to Dhaka, Board bazar experiences a pronounced monsoon season from May to September, accounting for about 80% of its annual average rainfall. This seasonal pattern influences planting and harvesting schedules, as well as water management strategies for agricultural activities. The annual average temperature of 25°C, with monthly variations between 18°C in January and 32°C in May, underscores the region's diverse climatic conditions and their implications for crop selection and growth cycles.

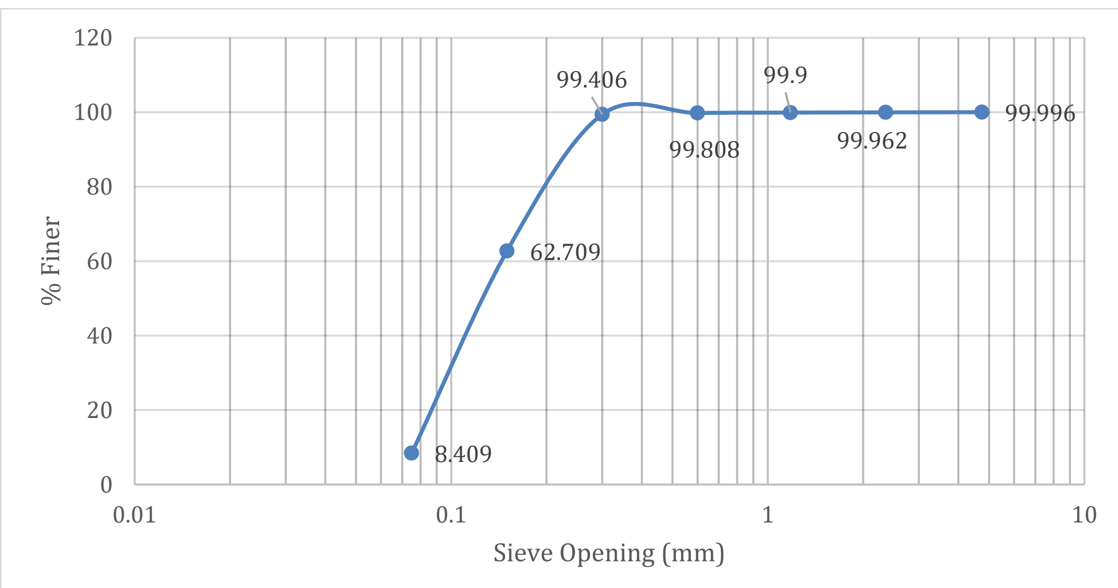
These meteorological factors necessitate adaptive agricultural practices and infrastructure planning to optimize water usage, mitigate climate risks, and sustainably manage natural resources in Board bazar, Gazipur.

4.2.2 Physical and Index Properties of Site Soil

a) Sieve Analysis:

Sieve No.	Sieve Opening (mm)	Wt. of Sieve (gm)	Wt. of Sieve+Soil (gm)	Wt. of soil Retained (gm)	% of Soil Retained	Cumulative % Retained	% Finer
#4	4.75	335.63	335.65	0.02	0.004	0.004	99.996
#8	2.36	326.56	326.73	0.17	0.034	0.038	99.962
#16	1.18	314.75	315.06	0.31	0.062	0.1	99.9
#30	0.6	313.4	313.86	0.46	0.092	0.192	99.808
#150	0.3	302.3	304.31	2.01	0.402	0.594	99.406
#100	0.15	295.5	478.985	183.485	36.697	37.291	62.709
#200	0.075	288.65	560.15	271.5	54.3	91.591	8.409
Pan		213.6	254.87	41.27	8.254	99.845	0.155

Table 29: Sieve Analysis of Sample Soil

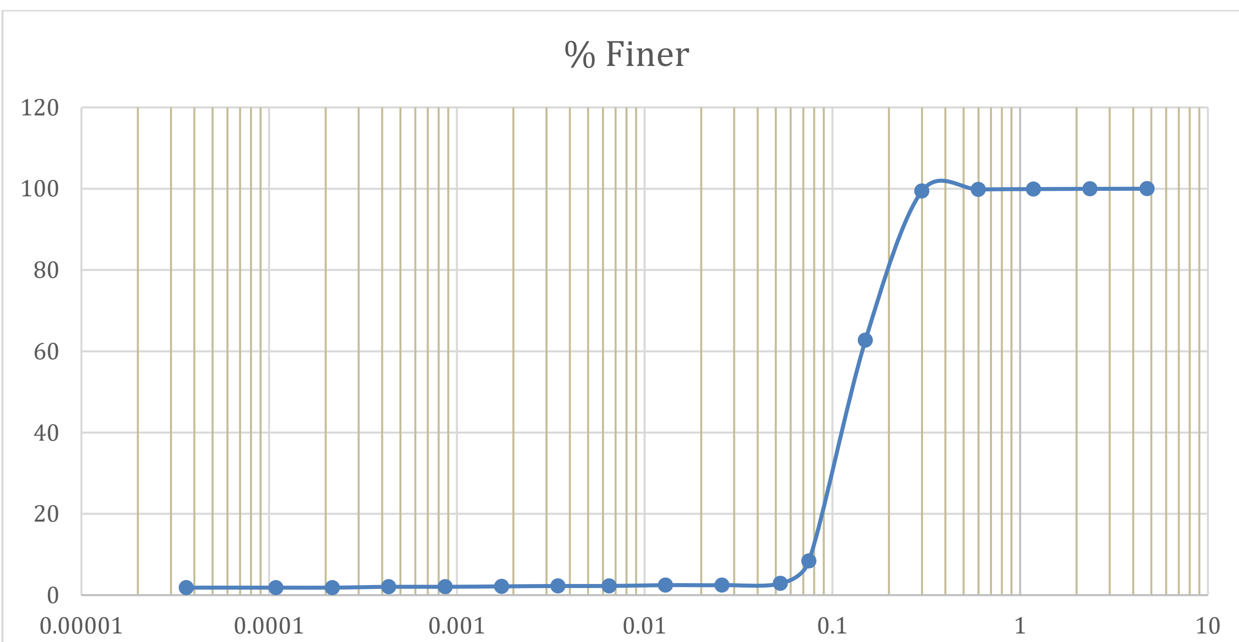


Graph 17: Particle Size Distribution Curve

b) Hydrometer Analysis:

Elapsed time, t (min)	Room Temp. (C)	Actual Hydro Rdg, R_a	Reading after meniscus correction, $R = R_a - C_m$	Effective Depth, L (cm)	Value of K	D in mm = k√L/t	C_t	a	Corrected Hydrometre Reading, $R_c = R_a - C_z \pm C_t$	Percent Finer = R_c*a/W_s
0.25	27	10.5	9.5	14.6	0.0131	0.20022012	2	1.032	7.5	3.07142857
0.5		6	5	15.704	0.0131	0.10382607	2	1.032	8	3.27619048
1		5	4	16.3	0.0131	0.05288897	2	1.032	7	2.86666667
2		4	3	15.6	0.0131	0.02587043	2	1.032	6	2.45714286
4		4	3	15.6	0.0131	0.01293521	2	1.032	6	2.45714286
8		3.5	2.5	15.7	0.0131	0.0064883	2	1.032	5.5	2.25238095
15		3.5	2.5	15.7	0.0131	0.00346043	2	1.032	5.5	2.25238095
30		3.25	2.25	15.75	0.0131	0.00173297	2	1.032	5.25	2.15
60		3	2	15.8	0.0131	0.00086786	2	1.032	5	2.04761905
120		3	2	15.8	0.0131	0.00043393	2	1.032	5	2.04761905
240		2.5	1.5	15.9	0.0131	0.00021765	2	1.032	4.5	1.84285714
480		2.5	1.5	15.9	0.0131	0.00010882	2	1.032	4.5	1.84285714
1440		2.5	1.5	15.9	0.0131	3.6275E-05	2	1.032	4.5	1.84285714

Table 30: Hydrometer Analysis of Sample Soil



Graph 18: Hydrometer Analysis Curve

c) Compaction Test:

Sample No.	1	2	3	4	5	6
Can No.	3	55	125	21	53	133
Wt. of Can (kg)	0.026	0.029	0.046	0.027	0.033	0.027
(Wt. of Can+ Wet soil) kg	0.071	0.069	0.086	0.071	0.079	0.061
(Wt. of Can + Dry Soil) kg	0.069	0.067	0.084	0.067	0.067	0.055
Wt. of Dry Soil (kg)	0.043	0.038	0.038	0.04	0.034	0.028
Wt. of Moisture (kg)	0.045	0.04	0.04	0.044	0.046	0.034
Moisture Content (%)	2.5	5	7.5	10	12.5	15
Wt. of Mold (kg)	4.234	4.234	4.234	4.234	4.234	4.234
(Wt. of Mold + Compacted Soil) kg	5.649	5.692	5.742	5.794	5.836	5.687
Wt. of Compacted Soil (kg)	1.415	1.458	1.508	1.56	1.602	1.453
Wet Density	1533.709	1580.316	1634.511	1690.874	1736.397	1574.897
Dry Density	1496.302	1505.063	1520.476	1537.158	1543.464	1369.476
Void Ratio,e	0.684977	0.675168	0.658188	0.640192	0.63349	0.841021
γd, Dry Unit Weight	14.67872	14.76467	14.91586	15.07952	15.14138	13.43456

Table 31: Compaction Test of Sample Soil

d) Specific Gravity Test:

Wt. of Dry Soil, Ws (gm)	Wt. of Pycnometre + Water = W_1 (gm)	Temperature of Water, °C	Wt. of Pycnometre + Water + Soil = W_2 (gm)	Wt. of equal volume of water as the soil solids , $W_w=W_1+W_s-W_2$	Specific Gravity of Water = G_T at T°C	G_s at T°C = $(W_s/W_w)*G_T$
50	354.68	30	384.9	19.78	0.9974	2.521233569

Table 32: Specific Gravity Test of Sample Soil

e) Permeability Test:

Test No.	1	2	3
Average Flow, Q (cm^3)	500	700	1000
Time of Collection, t (s)	61 s	241 s	329 s
Temperature of water, T (°C)	30	30	30
Head Difference, h (cm)	103	103	103
Diametre of Specimen, D (cm)	7.8	7.8	7.8
Length of Specimen, L (cm)	20.5	20.5	20.5
Area of Specimen, A = ¼*π*D^2 (cm^2)	47.783736	47.783736	47.783736
$k = \frac{QL}{Aht}$ (cm/s)	1347754.6	7454629.5	14538074
Average k (cm/s)	7780152.784		
$k_{20} = k_T \frac{n_T}{n_{20}}$ (cm/s)	6200781.769		

Table 33: Permeability Test of Sample Soil

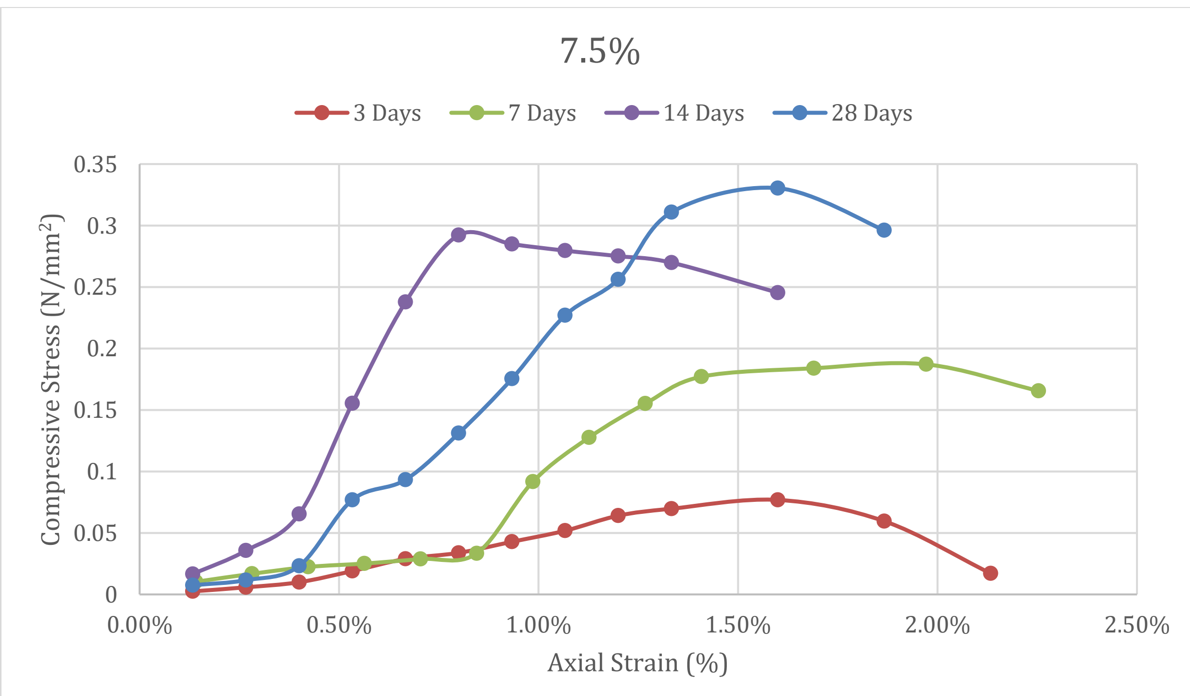
The Previous tests depict important soil Properties of our sample soil. From those tests, we have found that, our soil is a type of silty sand. This is obtained from our sieve analysis test. The

Specific Gravity of the soil is 2.521. Dry Unit Weight of Soil was 15.14 kN/m^3 . All the test were conducted in room temperature.

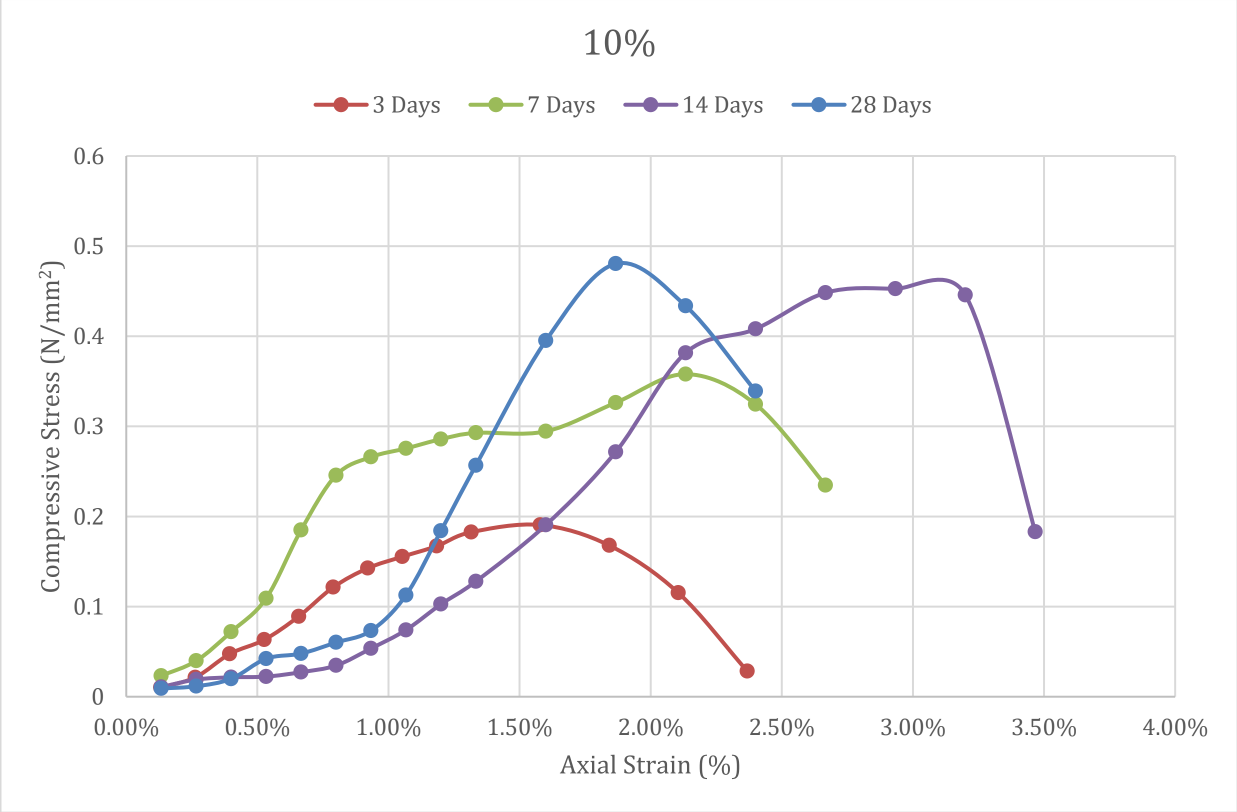
4.3 Results from UCS Test

Percentage	Days	Compressive Stress (Kpa)	Bearing Strength (Kpa)
7.50%	3	76.8	38.4
	7	187	93.5
	14	292	146
	28	330	165
10%	3	178	89
	7	381	190.5
	14	446	223
	28	480	240
12.50%	3	392	196
	7	545	272.5
	14	552	276
	28	565	282.5
15%	3	433	216.5
	7	552	276
	14	694	347
	28	825	412.5

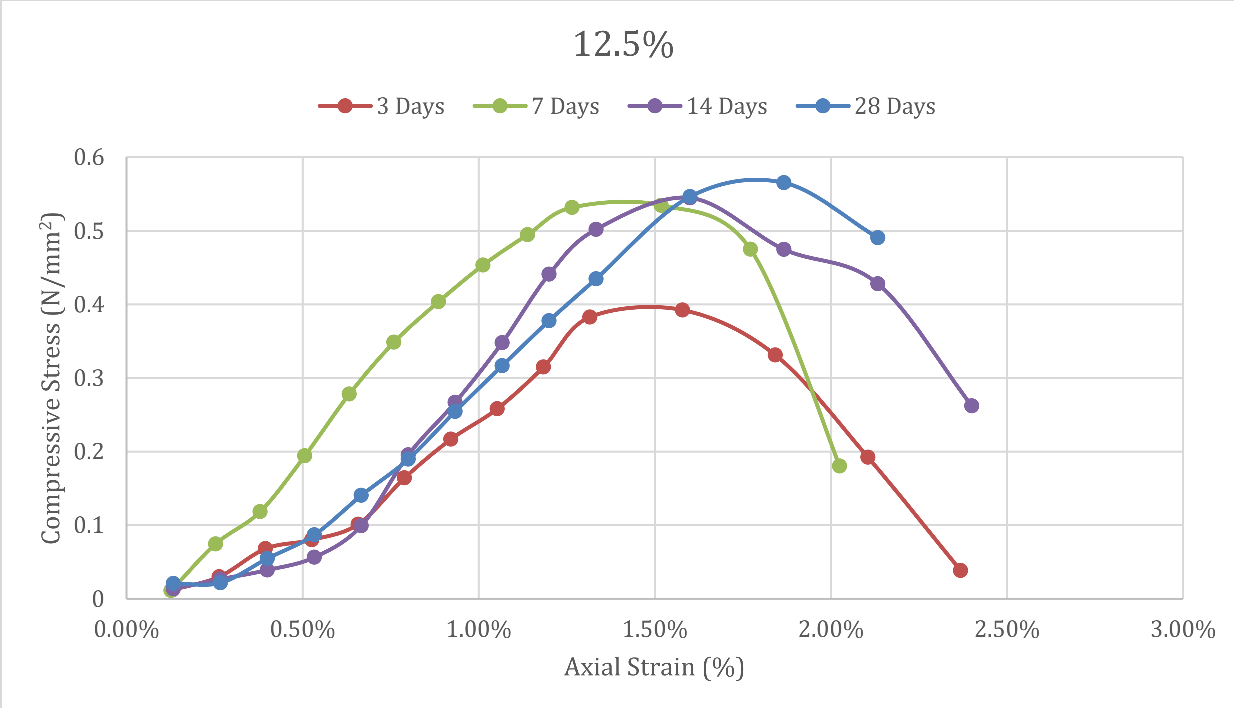
Table 34: Result Table from UCS Test



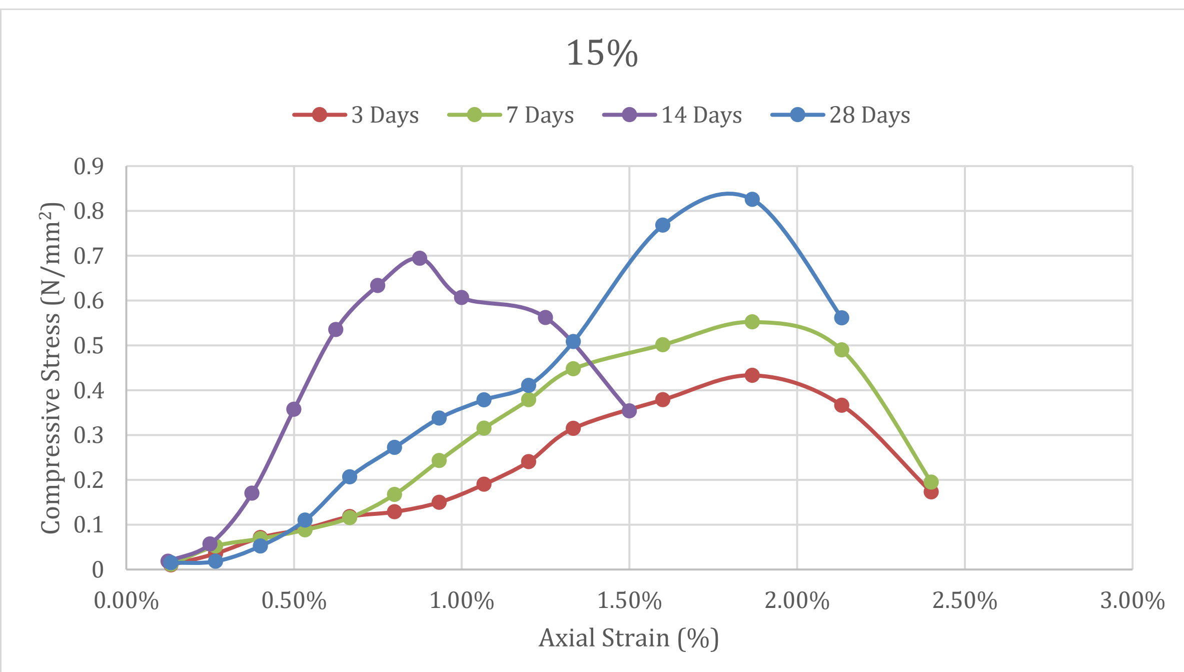
Graph 19: Compressive Stress Vs Axial Strain Graph for 7.5%



Graph 20: Compressive Stress Vs Axial Strain Graph for 10%



Graph 21: Compressive Stress Vs Axial Strain Graph for 12.5%



Graph 22: Compressive Stress Vs Axial Strain Graph for 15%

From all the Graphs and the Result Table we can see the compressive strengths of 3,7,14 and 28 days for 7.5%, 10%, 12.5% & 15% of the samples mixed with SB-95 & TX-95. For every percentage, the strength is getting higher day by day. The higher the percentage of SB-95 and

TX-95, the stronger the strength. But the co-relation of SB-95 and TX-95 can make a change when the SB-95 mixes in more than 12.5% with TX-95 the brittleness of the material increases. That's why, after 12.5% of SB-95, the quantity of TX-95 should be increased according to the calculation.

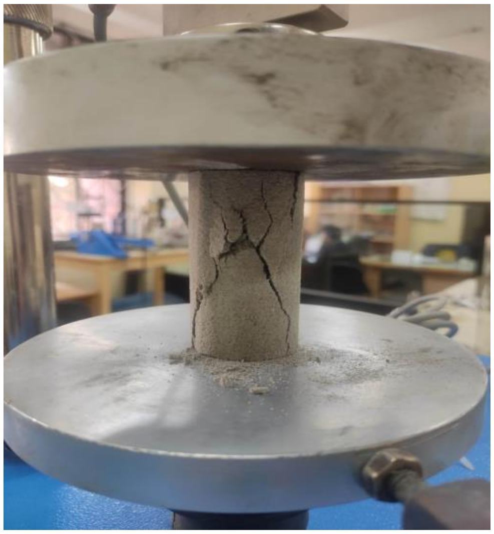
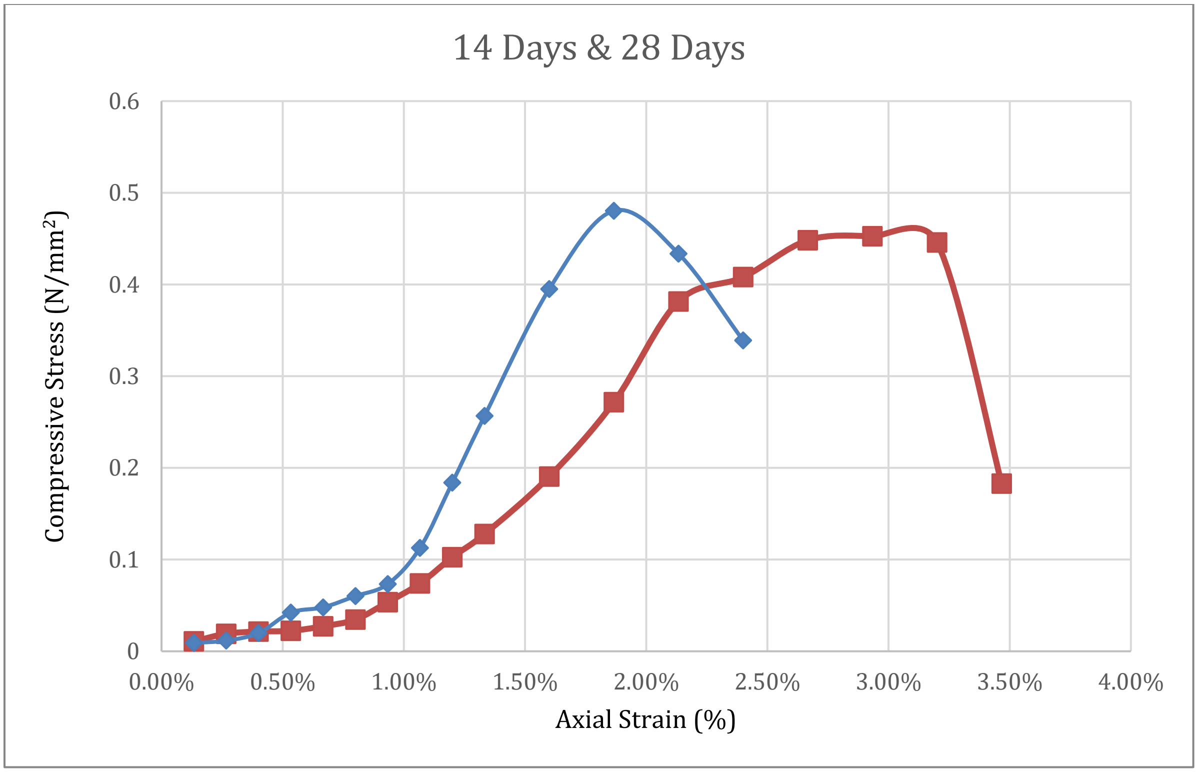


Figure 15(a): Crack gained from UCS Test (b) Brittle condition of 15% Mixture

4.4 Reason of taking 10% SB-95

From the analysis of UCS data, its noticeable that the soil reaches 446 KPa within 14 days & 480 KPa within 28 days of curing which also shows tensile crack in soil. So, this percentage is cost feasible and high performing for our future end over.



Graph 23: Compressive Stress Vs Axial Strain Graph for 10% (14 Days & 28 Days)

For any construction areas, we need bearing strength of at least 200 KPa but for 10% SB-95 we have got 223 KPa in just 14 Days and 240 KPa in 28 Days. Therefore, only 10% of SB-95 is enough for erosion control of an Embankment.

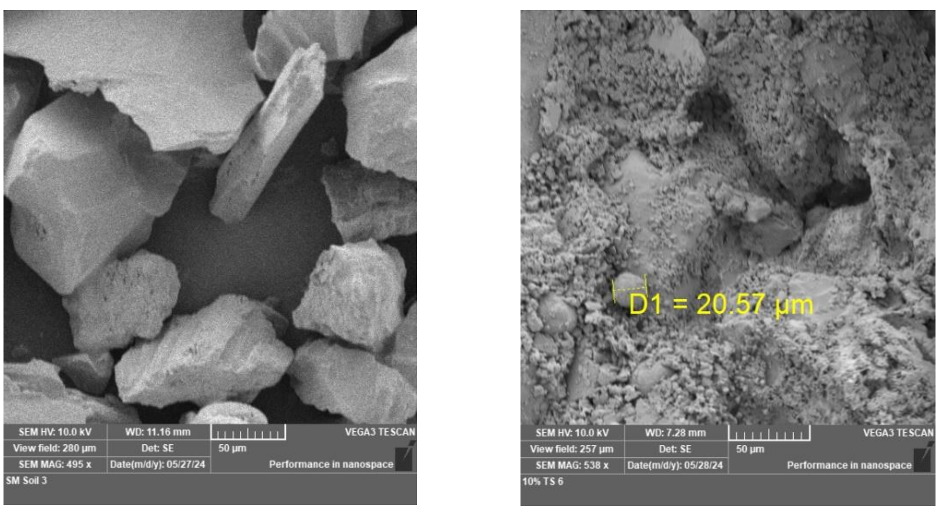


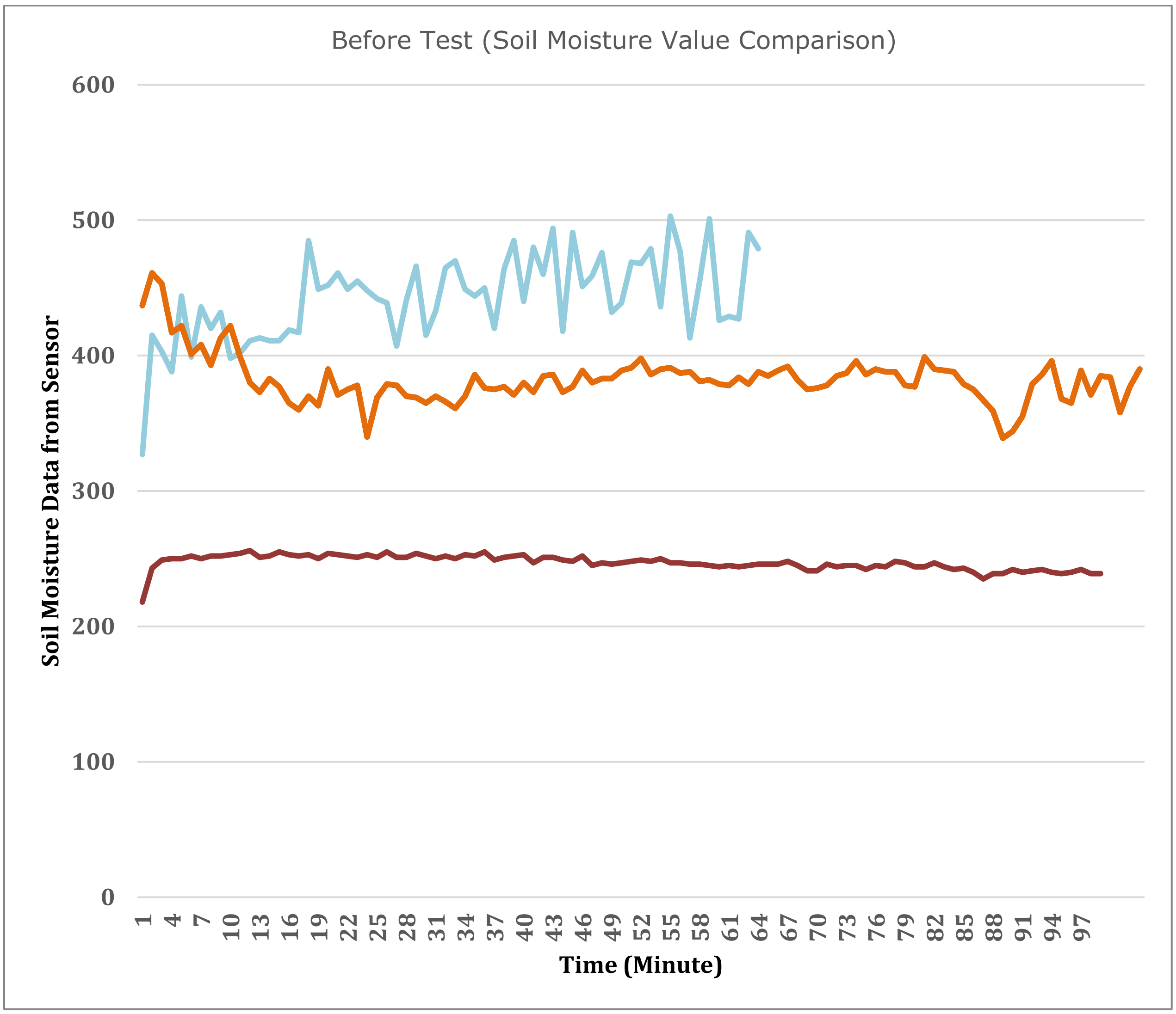
Figure 16 (a) SEM Image of Base Soil (b) SEM image of Treated soil (10%)

Based on SEM pictures, the interactions between the soil stabilizer and soil particles lead to bond formation, enhancing permeability, reducing erosion susceptibility, and strengthening sandy soil. Observing thin film fragments around soil particles indicates successful coating, thereby improving erosion resistance. Throughout testing, temperature variations demonstrated a notable impact, with higher temperatures correlating to increased strength gain rates.

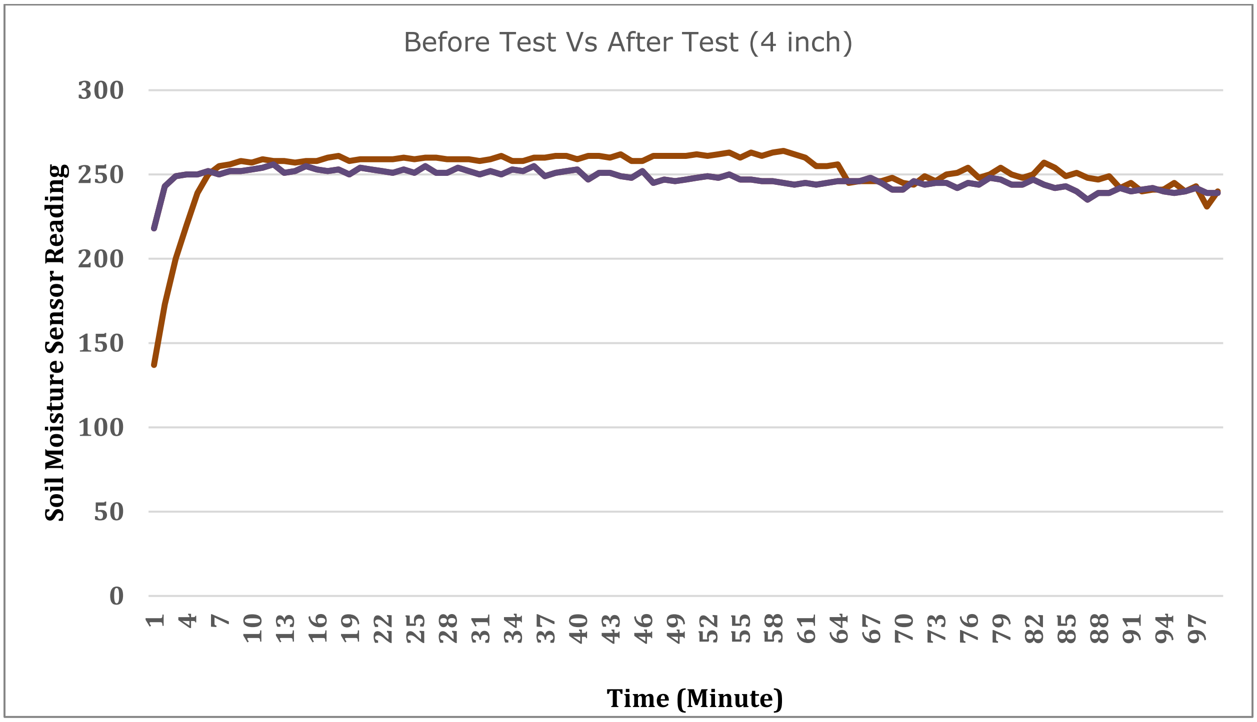
4.5 Sensor Data Analysis & Result

By using the sensor, we can analyze the quantity of water in the surface of the soil, in 1.5 inches depth and in 4 inches depth of the soil. The sensor works with the help of Arduino and can show data through excel files with the perspective of temperature and humidity.

The curves below show data generated by the sensor.



Graph 24: Soil moisture Data Vs Time (on Surface, in 1.5 in depth, in 4 inch dept



Graph 25: Soil moisture Data Vs Time (Before submerging Vs After submerging)

The data from excel defines the water quantity in that place. The sensor is made in such a way that, the higher the number, the lesser amount of water is present on that place. From the first graph, the upper blue curve is of the base soil's, the green middle one is of the 1.5-inch depths and the last orange one is of the 4-inch depths. The first graph was generated before saturation.

The second graph depicts the comparison of the values of before and after placement the of water in 4 inches depth. We have found that the values are almost same which identifies that not much extra water is penetrated after keeping the water for 24 hours. Therefore, SB-95 is working properly for the control of seepage which will be able to reduce erosion in river embankment.

4.6 Efficiency of SB-95 & TX-95

<u>Qualities of SB-95 & TX-95:</u>

SB-95	**TX-95**
Physical State: Solid	Physical State: Liquid
Solubility: Slightly Soluble in Water (0.1%-1%)	Solubility: Soluble in Ethylene Glycol (40%-43%)
Appearance: Powder	Appearance: Viscous Liquid
Color: Grey	Color: Pale Yellow
pH: 12-14	pH: 8-9

Ecotoxicity: None	Ecotoxicity: None
Bulk Density:0.7105 kg/L	Dynamic Viscosity: 100-400 cP

Efficiency: Soil stabilizers such as SB-95 and TX-95 are valued for their ability to effectively control erosion. Their efficiency is evaluated based on several key qualities. Firstly, they should securely bind soil particles together to prevent erosion caused by water or wind. At the same time, they must balance this binding strength with adequate water permeability, ensuring that soil moisture and drainage remain optimal. Additionally, these stabilizers should be durable, capable of withstanding environmental factors like weather conditions and UV exposure over extended periods. Their compatibility with various soil types, including sandy, clayey, and loamy soils, is crucial for universal applicability. Furthermore, efficient stabilizers are non-toxic and environmentally safe, posing no harm to plants, animals, or humans. They should also integrate seamlessly with vegetation, supporting plant growth to further enhance erosion control. Ease of application and compliance with regulatory standards are further indicators of their efficiency. By encompassing these qualities, SB-95 and TX-95 demonstrate their effectiveness in maintaining soil stability and preventing erosion across diverse environmental conditions.

Binding Strength: Both SB-95 and TX-95 should form strong bonds with soil particles to prevent them from being washed away or blown by wind.

Durability: The stabilizers should maintain their effectiveness over time, resisting degradation from weather conditions and environmental factors.

Environmental Impact: Their impact on the surrounding environment should be minimal, ideally biodegrading safely over time without introducing harmful chemicals.

Ease of Application: Efficiency also includes how easy they are to apply and integrate into soil management practices.

Cost-effectiveness: Evaluating efficiency also involves considering the cost of the stabilizers relative to the benefits they provide in erosion control.

Water Permeability: Efficient soil stabilizers should strike a balance between stabilizing the soil and allowing water to permeate through. This ensures that they prevent erosion while still facilitating healthy soil moisture levels and drainage.

Compatibility with Soil Types: The effectiveness of stabilizers can vary depending on the type of soil they are applied to. Good stabilizers should work effectively across different soil compositions, including sandy, clayey, or loamy soils.

Longevity: They should provide long-lasting protection against erosion, reducing the need for frequent reapplication and maintenance.

Resistance to Environmental Factors: Efficiency includes resistance to environmental stresses such as rain, wind, freeze-thaw cycles, and UV exposure, which can degrade stabilizers over time.

Non-Toxicity and Safety: Stabilizers should be non-toxic to plants, animals, and humans, ensuring they do not pose environmental or health risks.

Ease of Integration with Vegetation: Some stabilizers are designed to promote vegetation growth by providing a stable base for seeds or plants to root and thrive, further enhancing erosion control.

Regulatory Compliance: Efficient stabilizers should meet relevant regulatory standards and guidelines for erosion control in the region where they are used.

4.7 Summary

i. In this chapter, the primary focus is to present comprehensive findings derived from both field and laboratory investigations aimed at assessing the efficacy of SB-95 and TX-95 soil stabilizers in controlling erosion. Laboratory tests included rigorous Unconfined Compressive Strength (UCS) assessments across varying percentages of stabilizer mixes. These tests were complemented by Submerged Embankment Tests, which measured soil moisture levels under dry and wet conditions, comparing stabilized slopes. The study area selected for these investigations, Gazipur (specifically Board Bazar), was chosen due to its vulnerability to multiple forms of soil erosion, particularly water erosion affecting significant agricultural regions. This location provided an ideal setting to explore cost-effective and environmentally sustainable methods for constructing road embankments, given the region's challenges with material scarcity.

ii. Meteorological conditions in Gazipur played a crucial role in shaping the study's context, with the region experiencing substantial annual rainfall averaging 2376 mm and variable temperatures ranging from 12.7°C to 36°C throughout the year. The pronounced monsoon season from May to September contributes about 80% of the annual rainfall, influencing agricultural cycles and necessitating strategic water management practices. These environmental factors underscore the importance of adopting adaptive agricultural strategies and resilient infrastructure planning to optimize water use and mitigate climate-related risks in Gazipur.

iii. Analysis of soil properties conducted during the study confirmed Gazipur's soil composition as predominantly silty sand, characterized by a specific gravity of 2.521 and a dry unit weight of 15.14 kN/m^3. These findings provided foundational data essential for understanding soil behavior and guiding the selection of appropriate stabilization methods.

iv. From the UCS data analysis, it was evident that a 10% mix of SB-95 achieved notable compressive strength gains, reaching 223 KPa in 14 days and 240 KPa in 28 days. These results indicated that a modest percentage of SB-95 could significantly enhance the stability and bearing capacity of embankments, making it a cost-effective and high-performing solution for erosion control in Gazipur's challenging terrain. Sensor data further validated these findings by demonstrating SB-95's efficacy in reducing water infiltration and controlling seepage, critical factors in mitigating erosion risks along river embankments and other vulnerable areas.

v. The SEM analysis revealed that the soil stabilizer interacts with soil particles to form bonds, thereby increasing permeability, reducing erosion, and strengthening sandy soil. Thin film fragments observed around soil particles indicate effective coating, enhancing erosion resistance. Temperature variations during testing showed higher temperatures leading to accelerated strength gain.

vi. The efficiency criteria for soil stabilizers, exemplified by SB-95 and TX-95, encompassed strong binding capabilities, durability against environmental stressors such as weather fluctuations and UV exposure, compatibility across diverse soil types (including sandy, clayey, and loamy soils), non-toxicity to flora and fauna, and seamless integration with vegetation to enhance erosion control measures. These attributes ensure long-term effectiveness while adhering to regulatory standards for environmental safety and sustainability. Overall, SB-95 and TX-95 emerge as robust solutions capable of maintaining soil stability and effectively managing erosion challenges across Gazipur's varied climatic and geographical conditions, underscoring their practical utility in erosion-prone regions.

Chapter Five

CONCLUSIONS & RECOMMENDATIONS

5.1 General

The primary aim of this chapter is to present comprehensive findings derived from both field experiments and laboratory analyses conducted throughout the study. Laboratory tests included UCS tests conducted across four different compositions. Additionally, a Submerged Embankment Test was carried out to measure soil moisture under dry and wet conditions. A comparison was made between the moisture content of slopes in dry and wet conditions to assess the effectiveness of stabilization using SB-95 and TX-95. Finally, erosion control measures for soil were estimated based on the results of all conducted tests.

5.2 Summary

I. The research conducted focuses on addressing riverbank and soil erosion issues in Bangladesh, particularly at Board Bazar, Gazipur. Water erosion affects a significant portion, approximately 25%, of Bangladesh's agricultural land, prompting the study to explore sustainable methods for constructing road embankments using locally sourced stabilization techniques. Sandy soil from Board Bazar was utilized to create a prototype embankment stabilized with chemical additives SB-95 and TX-95. These additives are intended to enhance soil stability and mitigate erosion effectively.

II. The study area of Gazipur, particularly Board Bazar, was chosen due to its susceptibility to various forms of soil erosion, especially water erosion affecting significant agricultural regions. Analysis of soil properties in Gazipur confirmed the predominant composition as silty sand, with specific gravity and dry unit weight measurements providing foundational data essential for selecting appropriate stabilization methods.

III. Initial soil testing involved comprehensive analyses such as sieve analysis, hydrometer analysis, specific gravity test, compaction test, and permeability test to establish baseline characteristics of the soil. Following this, SB-95 and TX-95 were mixed with the soil in varying ratios, and Unconfined Compressive Strength (UCS) tests were conducted on soil blocks cured for different periods (3, 7, 14, and 28 days). These tests aimed to assess the strength development of the stabilized soil blocks over time, crucial for determining the efficacy of the chemical stabilizers.

IV. A prototype embankment was constructed in a box made of acrylic glass, utilizing soil blocks mixed with different percentages of SB-95. The embankment was subjected to UCS testing to measure its strength under controlled conditions. Results were plotted on graphs to visualize the strength development of the embankment blocks with varying percentages of SB-95 over different curing periods, providing clear insights into the stabilizers' performance.

V. To evaluate the effectiveness of SB-95 in controlling erosion, a submerged embankment test was conducted. This test involved constructing a slope with treated sand mixed with 10% SB-95 in a box filled with saturated sand. After air-drying, water was added, and moisture levels were measured using sensors at different depths. Data collected from the sensors, including those for moisture, temperature, and humidity, were analyzed to assess how well SB-95 reduced water infiltration and managed erosion, crucial for real-world applications.

VI. UCS data analysis revealed that a 10% mix of SB-95 notably enhanced compressive strength, demonstrating its potential effectiveness in stabilizing embankments. Results indicated significant strength gains over curing periods, highlighting SB-95 as a cost-effective solution for erosion control in Gazipur's challenging terrain. Sensor data further corroborated these findings by demonstrating SB-95's ability to mitigate water infiltration and control seepage, critical factors in reducing erosion risks along river embankments and other vulnerable areas.

VII. Efficiency criteria for soil stabilizers like SB-95 and TX-95 were assessed, focusing on their strong binding capabilities, durability against environmental stressors, compatibility with diverse soil types, and environmental safety. These attributes underscore their long-term effectiveness and adherence to regulatory standards for sustainability. Overall, SB-95 and TX-95 emerge as robust solutions capable of maintaining soil stability and effectively managing erosion challenges across Gazipur's varied climatic and geographical conditions, making them invaluable tools in erosion-prone regions.

VIII. In conclusion, the research provides comprehensive findings from both field and laboratory investigations, offering insights into the efficacy of SB-95 and TX-95 as soil stabilizers. These findings not only validate the performance of these stabilizers in controlling erosion but also emphasize their practical utility in sustainable infrastructure development, particularly in regions like Gazipur where erosion poses significant challenges to agricultural productivity and environmental sustainability.

5.3 Conclusions

Based on this investigation, the Stabilizer SB-95 & TX-95 have shown effective protection of embankment slopes against seepage, soil erosion, and runoff. They exhibit promising performance in areas prone to wave action and provide mitigation against shallow depth failures. The application of SB-95 and TX-95 represents a potentially cost-effective, sustainable, and environmentally friendly method for erosion control in various settings, including Bangladesh.

5.4 Recommendations for Future Studies

1. Long-term Field Monitoring: Longitudinal studies to monitor the performance of stabilized embankments over extended periods (e.g., several years) may be conducted. This would provide insights into the durability and long-term effectiveness of SB-95 and TX-95 in real-world conditions, considering seasonal variations and environmental stressors.

2. Impact of Climate Variability: How climate change and variability affect the performance of stabilized embankments may be studied. The resilience of SB-95 and TX-95 against extreme weather events, such as intense rainfall and prolonged droughts, which may exacerbate erosion risks can be evaluated.

3. Comparative Studies: Comparative studies with other types of soil stabilizers and traditional construction materials (e.g., cement, lime) to benchmark the performance, cost-effectiveness, and environmental impact of SB-95 and TX-95 can be conducted. This would provide a broader perspective on their advantages and disadvantages.

4. Field Trials in Diverse Geographical Settings: Field trials to diverse geographical settings beyond Gazipur to validate the findings in different climatic and geological conditions may be expanded. This could include coastal areas, mountainous regions, and urban environments where erosion poses significant challenges.

4. **Ecological Impact Assessment:** The ecological impact of SB-95 and TX-95 on soil microbiota, vegetation, and nearby water bodies can be investigated. Assess their compatibility with local flora and fauna to ensure minimal ecological disturbance and promote sustainable land use practices.

   6. Development of Guidelines: Practical guidelines and recommendations for engineers, planners, and policymakers regarding the application of SB-95 and TX-95 in soil stabilization projects can be developed.

   7. Cost-Benefit Analysis: Thorough cost-benefit analysis to evaluate the economic feasibility of using SB-95 and TX-95 compared to conventional stabilization methods can be conducted. Lifecycle costs, maintenance requirements, and long-term savings associated with erosion prevention and infrastructure longevity may be considered.

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Appendix

Appendix A: Experimental Procedures

This section provides detailed descriptions of the experimental procedures conducted during the study to evaluate the effectiveness of chemical stabilizers in enhancing soil properties.

1. **Laboratory Testing Protocols**
   - **Sample Preparation:** Detailed steps followed for collecting and preparing soil samples from erosion-prone areas in Bangladesh.
   - **Unconfined Compressive Strength (UCS) Testing:** Procedures for conducting UCS tests to assess the strength of stabilized soils using SB-95, TX-95, and K-31 stabilizers.
   - **Moisture Content Monitoring:** Methodology for monitoring moisture content changes in stabilized soils over time.
   - **Scanning Electron Microscopy (SEM) Analysis:** Techniques employed to analyze microstructural changes and particle bonding in stabilized soils.
2. **Field Trial Methodologies**
   - **Site Selection:** Criteria used for selecting field trial sites representative of real-world embankment conditions in Bangladesh.
   - **Application of Stabilizers:** Details on the application techniques and dosage of SB-95, TX-95, and K-31 stabilizers in field trials.
   - **Monitoring and Data Collection:** Procedures for monitoring soil stability, erosion resistance, and environmental factors during field trials.

Appendix B: Data and Results

This section presents supplementary data and detailed results obtained from laboratory tests and field trials conducted during the research.

1. **Laboratory Test Results**
    - **UCS Test Data:** Tables or figures showing UCS test results for soil samples treated with SB-95, TX-95, and K-31 stabilizers.
    - **Moisture Content Data:** Graphs illustrating changes in moisture content of stabilized soils over the experimental period.
    - **SEM Images:** SEM images depicting microstructural changes and particle bonding in stabilized soil samples.
2. **Field Trial Observations**
    - **Erosion Monitoring Data:** Charts or graphs presenting erosion rates and stability observations from field trials.
    - **Comparative Analysis:** Comparative analysis of field trial results highlighting the performance of different stabilizers under real-world conditions.

Appendix C: Supporting Documentation

This section includes any additional documentation, raw data sheets, or detailed calculations, which provide further context or support for the study findings.