SUBGRADE STABILIZATION OF EXPANSIVE SOIL USING LIQUID POLYMER

[1]Deepak Singh ,[2]Sudhar Singh Rajput ,[3]Pushpraj Singraul,[4]Parshottam Sarathe

[1,2,3], Students Department of Civil Engineering, Oriental Institute Of Science and Technology, Bhopal (M.P), India

[4th] Assistant Professor, Department of Civil Engineering, Oriental Institute Of Science and Technology, Bhopal (M.P), India

Email.-satnadeepaksingh@gmail.com

Abstract

The stabilization of expansive soils is essential for enhancing the stability and load-bearing capacity of subgrades in construction projects. Expansive soils exhibit significant shrink-swell behavior, which can cause structural damage and foundation failures. This research explores the effectiveness of liquid polymers in stabilizing expansive soils by examining their mechanism of action, advantages, and overall performance in reducing swelling and shrinkage. Laboratory tests were conducted to assess how varying polymer concentrations influence soil properties such as plasticity index, shear strength, and compaction characteristics. The results indicate that liquid polymers substantially enhance the engineering properties of expansive soils, offering a cost-effective and environmentally friendly alternative to conventional stabilization techniques. Polymers consist of long chains of repeating molecular units, naturally known as macromolecules, which interlink to form the structural framework of plastics. The degree of interlinking determines the macroscopic properties and binding strength of the plastic material. This study also presents a literature review on soil stabilization using polymers. Among the promising methods for stabilizing expansive soils, chemical stabilizers like liquid polymers stand out. When incorporated into expansive soil, liquid polymers enhance its engineering properties, including strength, plasticity, and resistance to moisture.

Introduction :

Soil is one of the most fundamental materials encountered in civil engineering. Almost all structures, except those founded on solid rock, ultimately rest on soil. Geotechnical engineers worldwide face significant challenges when dealing with expansive soils, which contain clay minerals such as montmorillonite, illite, and kaolinite in substantial amounts. These minerals cause the soil to swell upon wetting and shrink upon drying, leading to instability. Expansive soils are typically unsaturated, making them problematic for construction projects.

The foundation plays a crucial role in any civil engineering structure, as it bears the entire load of the structure. Therefore, preparing a strong and stable base is essential. To ensure the proper transfer of loads onto the soil, it is necessary to improve its bearing capacity, which is not always naturally sufficient at every location. The process of enhancing soil strength through artificial means is known as soil stabilization. Soil stabilization involves modifying the physical properties of soil to improve its strength, durability, and other essential characteristics. This technique is widely used in road construction and infrastructure development. Common stabilizing agents include lime, coconut coir, fly ash, plastic fibers, and liquid polymers.

Subgrade failures in roads have long been a concern in highway engineering. Poor highway performance leads to increased maintenance costs, traffic disruptions, and accidents. Expansive soils exhibit unpredictable and non-uniform behavior under varying weather conditions, posing significant challenges in civil engineering, especially for road pavements, buildings, and other structures. Construction zones often experience extreme dry and wet conditions, further complicating soil treatment. Expansive soils are responsible for more damage than any other soil type due to their widespread occurrence and unpredictable nature. It is estimated that globally, nearly $30 billion in asset losses occur due to damage caused by expansive soils.

Subgrade stabilization of expansive soils is a crucial technique in civil engineering to improve the performance and longevity of foundations, roads, and other structures. These shrink-swell soils undergo significant volume changes due to fluctuations in moisture content, leading to cracks, shifts, and structural failures. An innovative solution for stabilizing expansive soils is the use of liquid polymers. When applied, liquid polymers enhance the soil's mechanical properties, reduce its shrink-swell potential, and increase its overall strength.

This method offers a promising approach to stabilizing problematic soils by modifying their behavior and improving their load-bearing capacity. Here's an overview of how liquid polymers can be effectively used for stabilizing expansive soils.

1. Polymer Soil Stabilization:

Liquid polymers, typically synthetic or organic polymers, are mixed with expansive soils to alter their physical and chemical properties. These polymers can form bonds with soil particles, enhancing cohesion and reducing the soil's tendency to expand or contract with moisture changes.

2. Types of Liquid Polymers Used:

- **Cationic Polymers:** These have positively charged ions that interact with the negatively charged particles of clay in expansive soils. This can help bind the particles together and reduce the swelling potential.
- **Acrylic Polymers:** Known for forming a gel-like structure that can improve soil strength, they help reduce water absorption and control swelling.
- **Epoxy Resins:** These are sometimes used to provide a durable and water-resistant stabilization layer, particularly in areas with extreme moisture variations.
- **Polyvinyl Alcohol (PVA):** A water-soluble synthetic polymer that can significantly improve soil's compaction and strength when applied correctly.

Background : Explain the challenges posed by expansive soils in civil engineering, such as swelling and shrinkage with varying moisture content.

Importance of Soil Stabilization : Discuss the need for stabilizing expansive soils to ensure the durability and stability of foundations, roads, and other infrastructure.

Overview of Liquid Polymer Stabilization : Introduce liquid polymers as a potential solution, highlighting their ability to modify soil behavior by reducing moisture absorption and enhancing soil structure.

Literature Review :

Traditional Stabilization Methods : Provide an overview of common methods for stabilizing expansive soils, such as lime, cement, and fly ash.

Polymer-Based Stabilization : Review existing studies on the use of synthetic and bio-based polymers in soil stabilization. Highlight the advantages and limitations of polymers compared to other methods.

Research Gaps : Identify areas where liquid polymer stabilization has not been fully explored or optimized, which the current study aims to address.

Following literature were studied related to soil stabilization using polymers. This unit contains review of soil stabilization using polymers.

Reliance Private Ltd. (2010) conducted an evaluation report on the performance of a SoilTech-treated, stabilized base layer. The company, which specializes in construction for power generation, machinery installation, and tower erection, utilized SoilTech polymer to enhance the stability of the base layer. A case study was carried out to assess its effectiveness, with various tests conducted by Sudhakar Reddy from IIT Kharagpur. The results were highly positive, demonstrating that SoilTech is an effective soil stabilizer for industrial construction applications.

Basantadhakal et al. (2016) conducted a study on the effects of liquid acrylic polymer on the geotechnical properties of fine-grained soil. The research investigated the impact of commercially available acrylic polymer on the stabilization of natural Carbondale soil (Soil A) and a commercially available soil (Soil B). The polymer was mixed in varying percentages (2%, 3%, 4%, and 8.5%) of the dry weight of both soils. Tap water was added in accordance with the optimum moisture content (OMC) of each soil-polymer mixture, and the samples were compacted to achieve their maximum dry unit weight.

The compacted samples were cured for 7, 14, and 28 days in both confined and open-air environments. Unconfined compressive strength (UCS) tests were conducted to assess the strength improvement of the polymer-stabilized soil. The results indicated that for Soil B samples prepared at OMC, the UCS value increased by 30% to 75% in an open-air environment and by 12% to 14% in a confined air environment. However, Soil A samples prepared at OMC (23.50%) exhibited cracks during curing in an open-air environment, with only a minor strength increase (1.2%–13.8%) in a confined air environment.

When Soil A samples were prepared with moisture content lower than OMC (12.50%) and cured in an open-air environment, the UCS strength increased by 7% to 10%. Additionally, California Bearing Ratio (CBR) tests showed a marginal increase (14%) in CBR value for Soil A, whereas Soil B demonstrated a significant CBR improvement of 340%. These findings highlight the potential of liquid acrylic polymer in enhancing soil strength, particularly for commercially available fine-grained soils.

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P.K. Kolay et al. (2016) conducted a study titled *"The Effect of Liquid Polymer Stabilizer on Geotechnical Properties of Fine-Grained Soil."* The research aimed to assess the stabilization potential of a copolymer liquid stabilizer, *Soiltac*, on two different soil types:

1. **Carbondale soil (CH)** – Clay with high plasticity
2. **Galatia soil (ML)** – Silt with low plasticity

According to the manufacturer, *Soiltac* is a non-toxic and non-hazardous polymer with a pH value of 5.5. Typically, polymer stabilizers used in soil stabilization are vinyl acetates or acrylic copolymers, which are suspended in an emulsion with surfactants.

In this study, the polymer was mixed into both soil types at varying concentrations (0.5%, 1%, 1.5%, and 3%), followed by a series of geotechnical tests to evaluate its effects. The results demonstrated positive improvements in soil properties, confirming the effectiveness of liquid polymer stabilizers in enhancing the geotechnical characteristics of fine-grained soils. The findings support the use of polymer-based stabilization as a viable method for improving soil strength and stability.

- Atterberg limit for Carbondale soil (CH) and Galatia soil (ML) were slightly decreased with the addition of polymer, and no significant changes were observed for both soil.
- With the addition of polymer, MDD increases and OMC decreases for Carbondale soil (CH) and Galatia soil (ML).
- For Carbondale soil (CH), UCS values increases upto the addition of 1.5 % of polymer by weight thereafter decreases for 3.0 % polymer addition. Also, UCS values increases with the increase in curing period for all soil-polymer mixture. The maximum increase in UCS value (with 1.5 % polymer stabilizer and 28-days of curing period) was 220% with polymer. For Galatia soil (ML), no significant changes in UCS were observed for all soil-polymer mixture at any curing periods. Maximum increase in UCS value was approximately 23% with polymer.
- Unsoaked CBR value for Carbondale soil (CH) increases upto 1.5% of polymer addition and then decreases with 3.0% polymer stabilizer. The increases in unsoaked CBR values from untreated soil are 200% for 2.54 mm deformation and 195.5% for 5.08 mm deformation with 3-days of curing. Almost similar unsoaked CBR values are obtained for 7 and 28 days of curing.

Athulya P.V. et al. (2015) conducted a study titled *"Stabilization of Subgrade Soil Using Additives – A Case Study."* The objective was to experimentally analyze and compare the strength properties of plain soil, soil treated with *Terrasil*, and soil stabilized with *cement kiln dust (CKD)*. Various tests, including the **consistency limit test, California Bearing Ratio (CBR) test, triaxial test, and permeability test**, were performed to assess the effectiveness of these additives in stabilizing weak soils.

The study found that the behavior of soil changed significantly with the introduction of stabilizers. Key findings include:

- **Decrease in consistency limits**: As the dosage of stabilizers increased, the soil became stiffer, indicating improved stability.
- **Increase in CBR values**: The strength of the soil improved with higher stabilizer content, with an optimum dosage providing the best results.
- **Economic benefits of CKD**: Since cement kiln dust is a waste product, its use in soil stabilization is cost-effective while also enhancing soil strength.
- **Waterproofing effect of Terrasil**: Terrasil showed a significant improvement in the water resistance of the soil compared to CKD.
- **Increase in elastic modulus**: Soils treated with additives exhibited a significant improvement in their elastic modulus compared to untreated soil, indicating enhanced load-bearing capacity.

Sameer Vyas et al. (2016) conducted a study on the **stabilization of dispersive soil by blending polymers.** The research focused on stabilizing dispersive soil from Udaipur by incorporating various polymer-based additives, including:

- **0.5% and 1% Polyvinyl Alcohol (PVA) and Urea Formaldehyde Resin (UFR)**
- **0.5% Polyurethane (PU) and Epoxy Resin (ER)**
- **1% Styrene Butadiene Rubber (SBR) Latex**
  The **mechanical analysis** of polymer-treated soil was performed to assess improvements in **soil aggregation**, while **Atterberg's limit tests** were conducted to evaluate changes in **cohesion properties**.
  For testing:
- The **mechanical analysis and Atterberg's limit tests** were conducted on soil samples passing **4.75 mm and 425-micron sieves, respectively**.
- To compare the effectiveness of polymers with **conventional stabilizers**, the researchers also treated soil with **1.0% sodium aluminate, 9% calcium aluminate, and calcium hydroxide**, followed by mechanical analysis and index property evaluation.
- Sepehr Rezaeimalek1,,et.al(2017) studies on Mixing Methods Evaluation of a Styrene-Acrylic Based Liquid Polymer for Sand and Clay Stabilization in this paper ,focused on applications andprovided promising results. This study focuses on the application of a lowviscosity liquid polymer for shallow soil improvement. The mixing method ofsoil specimens treated with the liquid polymer soil stabilizer, which belongs toStyrene Acrylic family, was studied through an experimental testing program.The tested soils included poorly graded sand and sulphate rich clay. The water, liquid polymer and dry soil were mixed with different sequence to assess theeffect on strength. The specimens were cured in controlled environment for upto 35 days before tested. It was found that the curing of the polymer stabilizer in sand and clay were time consuming and took to a month to reach their full strength.
- Plasticity Reduction: One of the key benefits of liquid polymer stabilization is the reduction in plasticity. Pujari et al. (2020) found that the addition of liquid polymer decreased the plasticity index of expansive soils, making them less prone to volumetric changes due to moisture variation.

- **Mechanisms and Microstructural Changes (2022) –**

1. Mechanism of Polymer Action – Research in 2022 delved deeper into understanding the mechanism through which liquid polymers interact with expansive soils.
   Ghosh et al. (2022) conducted a study on the **microstructural changes in expansive soils stabilized with liquid polymers** using **Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) techniques**. Their key findings were:

- **SEM Analysis:** The images revealed that the **polymers formed a thin film around soil particles**, leading to **reduced plasticity** and **enhanced particle bonding**. This resulted in a **denser, more uniform soil structure**, which improved **compaction** and reduced **swelling potential**.
- **XRD Analysis:** The study indicated that **the polymers did not alter the mineralogical composition of the soil**. Instead, they **modified the physical structure of clay particles**, leading to **better cohesion** and **reduced water absorption**.
  These findings suggest that **liquid polymers enhance the engineering properties of expansive soils** by **modifying their physical structure rather than their chemical composition**, making them an effective stabilization method for improving soil stability and reducing moisture-related issues.

- Raman and Sharma (2022) conducted a study on the molecular interactions between soil minerals and liquid polymers. They found that the polymers interacted with the mineral layers of clay, reducing the attraction between water molecules and clay minerals, which in turn lowered the soil's ability to absorb moisture and swell. This insight into the chemical mechanism helped in understanding why polymer-treated soils showed improved resistance to volumetric changes with moisture fluctuations.

2. Performance Under Field Conditions –
   Verma et al. (2022) conducted **field trials** to evaluate the **long-term effectiveness** of **polymer-treated expansive soils** in **road construction** under real-world conditions. Their findings highlighted several advantages of polymer stabilization:

- **Improved Load-Bearing Capacity:** The polymer-treated subgrade soils exhibited **higher strength** and **greater resistance to deformation** under traffic loads compared to untreated soils.
- **Reduced Moisture Susceptibility:** The treated soils showed **better resistance to moisture-induced volume changes**, minimizing the risks of **swelling and shrinkage** that typically affect expansive soils.

- **Sustainable Infrastructure Development:** The study concluded that **polymer stabilization is a viable and durable solution** for enhancing the **performance and longevity** of infrastructure in regions with problematic soils.
  These findings reinforce the **practical benefits of polymer-based soil stabilization**, making it a **cost-effective and sustainable** alternative to traditional soil improvement techniques.

Kumar et al. (2023) conducted a **comparative study** on the effectiveness of **liquid polymers, lime, and cement** in stabilizing **expansive soils**. Their findings indicated:

- **Reduction in Swelling Potential: Polymer stabilization** was more effective than lime and cement in **minimizing soil expansion**, making it ideal for regions with **fluctuating moisture levels**.
- **Improved Shear Strength:** Soils treated with polymers exhibited **higher shear strength**, providing better structural support.
- **Better Moisture Resistance:** Unlike lime and cement, which can **degrade over time due to leaching**, polymers maintained **long-term stability** even in **high-moisture conditions**.
  Key Takeaway:
  While **lime and cement** remain effective in improving soil strength, **liquid polymer stabilization** offers superior **moisture resistance, durability, and swelling control**, making it a **sustainable alternative for infrastructure projects in moisture-sensitive regions**.

Material and method :

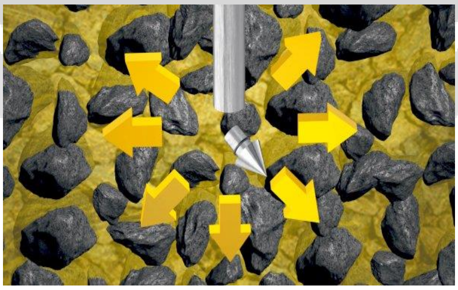
Soil Sample Collection : Describe the characteristics of the expansive soil used in the study, including the soil classification (e.g., clay content, plasticity index).

Polymer Selection : Outline the types of liquid polymers tested (e.g., synthetic polyacrylamide, polyvinyl alcohol, etc.) and their properties.

Subgrade stabilization of expansive soils using liquid polymers is an innovative method to enhance the engineering properties of problematic soils, such as shrink-swell behavior and low strength. Here's how liquid polymers can be used for stabilizing expansive soils:

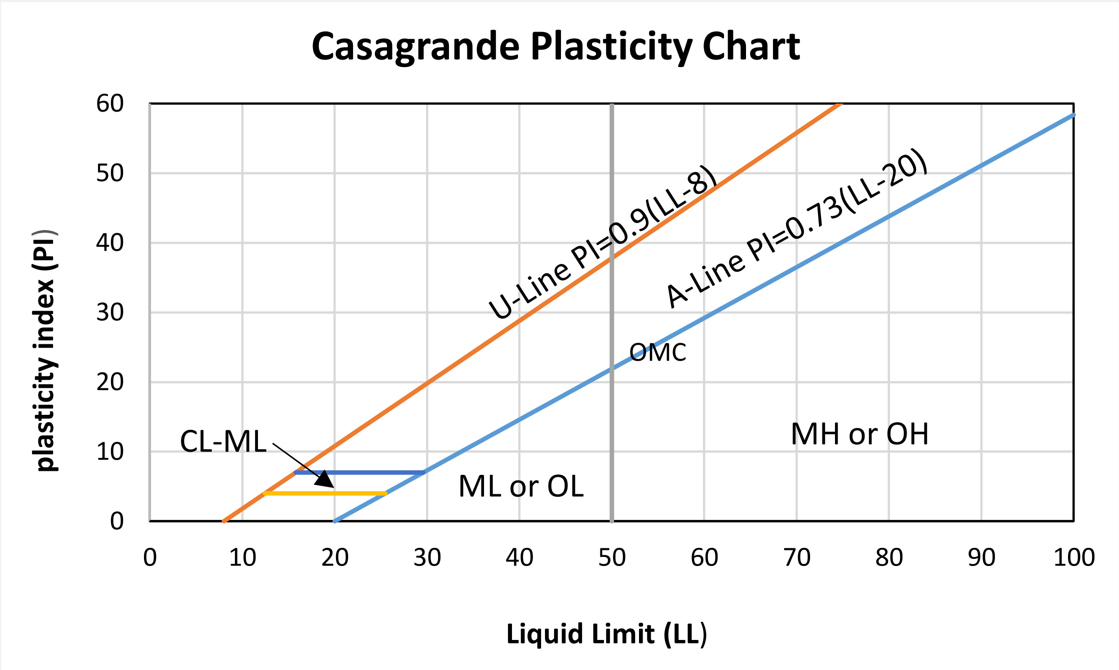
Polymer application techniques refer to various methods used to process, shape, or apply polymers in different industries. These techniques are essential for fabricating products with specific properties, from packaging materials to medical devices. Here are some common polymer application techniques:

1. **Injection Molding:** A process where molten polymer is injected into a mold under high pressure. It's widely used for producing parts with intricate shapes, such as automotive components, containers, and toys.

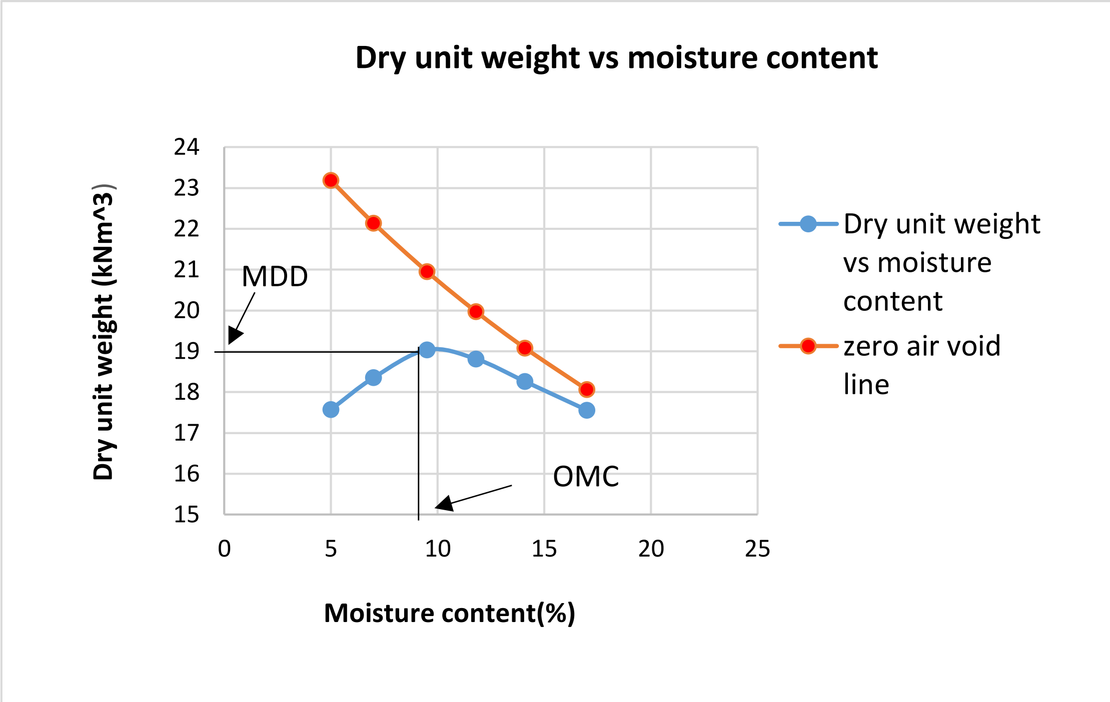


2. **Thermoforming**: This technique involves heating a polymer sheet until it becomes soft and pliable, then forming it over a mold to create products such as food packaging, disposable cups, or trays.
3. **Compression Molding:** A preheated polymer is placed into a mold cavity, and pressure is applied to shape the material. This technique is often used for producing automotive parts, electrical components, and rubber products.
4. **Film and Sheet Extrusion**: Polymers are melted and formed into thin films or sheets. This is used in food packaging, textiles, and electronics.
5. **3D Printing (Additive Manufacturing):** Polymers are used as filaments to create three-dimensional objects layer by layer. It's increasingly used for rapid prototyping, customized parts, and medical implants.
6. **Coating and Laminating**: Polymers can be used to coat or laminate surfaces for added protection, aesthetics, or functionality, such as in protective coatings, paint, or composite materials.

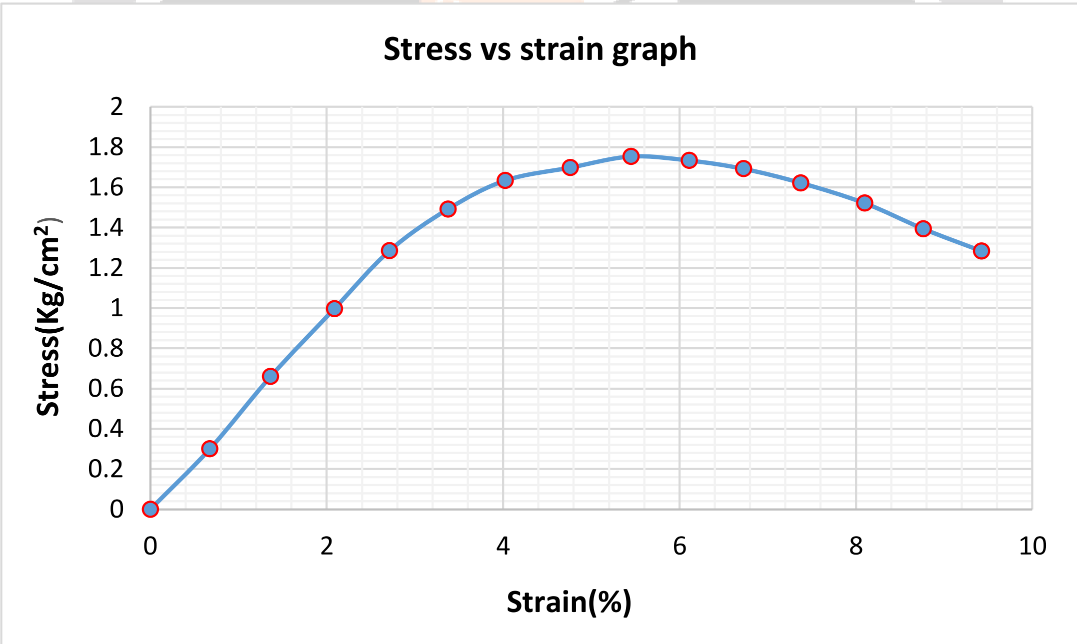
Experimental Setup : Detail the laboratory procedures, including:
- Preparation of soil-polymer mixtures with different polymer concentrations.
- Tests conducted, such as:
- Atterberg Limits (Plasticity Index)
- Compaction Test (Standard Proctor Test)
- Unconfined Compression Test (to evaluate strength)
- Swelling Tests (to measure reduction in swelling potential)
- Curing Time: Specify the curing periods for the soil-polymer mixtures before testing.



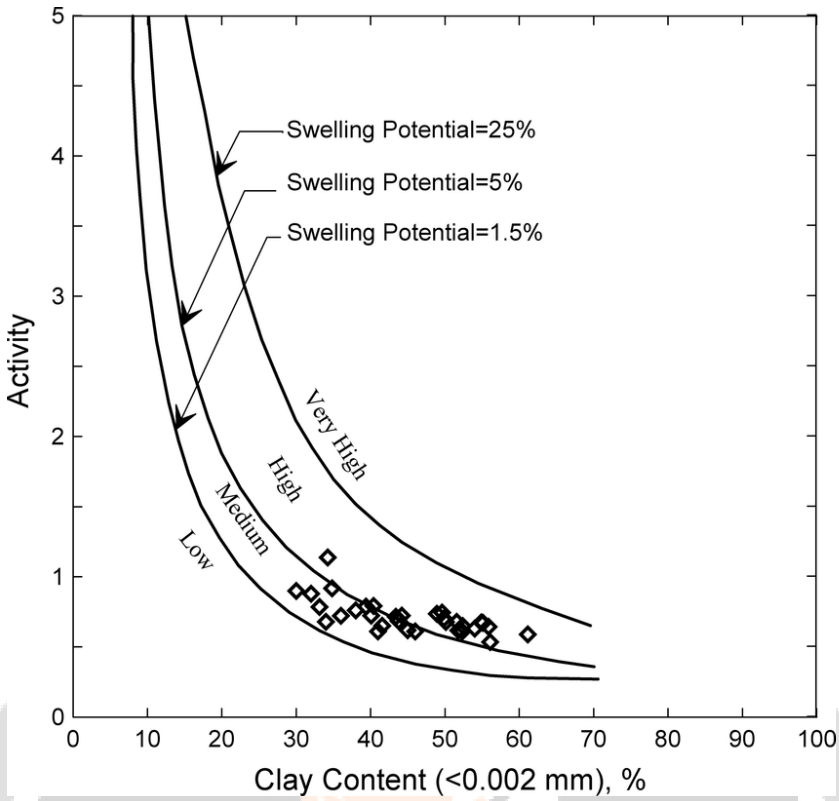
atterberg limits (plasticity index)



standard proctor compaction test



unconfined compression test



swelling tests

Results and Discussion :

Effect of Polymer Concentration on Soil Properties : Present data on how varying polymer concentrations affected soil properties such as plasticity, shear strength, and swelling potential.

Comparison with Control Sample : Compare the properties of the treated soils with untreated expansive soil (control sample).

Mechanism of Polymer Action : Discuss how the polymer interacts with soil particles, reducing moisture absorption and enhancing bonding between clay particles.

Effect on Compaction and Shear Strength : Analyze the compaction curves and unconfined compressive strength results, showing the improvements in soil density and strength.

Environmental Considerations : Briefly touch on the potential environmental impact of using synthetic polymers, including concerns about biodegradability and leaching.

Conclusion :

- Summary of Findings

The incorporation of liquid polymers into expansive soils has proven to be an effective stabilization technique. Research indicates that this treatment can **significantly enhance soil properties** by minimizing **swelling**, improving **compaction characteristics**, and increasing **strength**. Experimental studies help determine the **optimal polymer dosage**, demonstrating that polymer-based stabilization can serve as a **sustainable, cost-efficient, and eco-friendly** alternative to conventional methods. Furthermore, polymers have emerged as **versatile materials** with widespread applications worldwide. Additionally, utilizing **waste fibers or plastics** for soil stabilization presents an opportunity to leverage their **durability, high strength, and cost-effectiveness** while addressing environmental concerns related to waste disposal.

- Implications for Civil Engineering

The application of liquid polymer stabilization has **practical significance** in civil engineering projects. This technique can be effectively utilized in **road construction, foundation design, and pavement development** to enhance **soil stability and load-bearing capacity**. By mitigating **moisture-induced volume changes**, polymer stabilization ensures **durable and resilient infrastructure**, making it particularly beneficial in regions with **expansive or problematic soils**.

- Future Research Directions

Further research should focus on **developing eco-friendly polymer alternatives**, optimizing **dosage levels for maximum effectiveness**, and conducting **long-term performance evaluations**. Investigations into **the environmental impact, biodegradability, and durability** of polymer-stabilized soils will be crucial in advancing sustainable **soil stabilization techniques** for future infrastructure projects.

FUTURE SCOPE :

Field Testing : Conducting field trials to verify the laboratory results in real-world conditions.

Environmental Impact Assessment : A more detailed investigation into the environmental impact of using liquid polymers in largescale applications.

Long-Term Performance : Studying the long-term performance and durability of the polymer-treated expansive soil under varying climatic conditions.

Optimal Dosage and Long-Term Performance : Determining the ideal polymer concentration for **enhancing expansive soil properties** requires further investigation. **Patil et al. (2020)** highlighted that the **required polymer dosage varies based on soil type**, emphasizing the need for **detailed analysis**. Additionally, the **long-term effectiveness** of polymer-treated soils under **real-world conditions** remains an area that requires **further exploration**.

Field Trials: While laboratory studies have shown significant improvements, Singh et al. **(2021)** suggested the need for field trials to verify the practical applications and behavior of polymer-treated soils in real-world conditions, such as exposure to cyclic moisture changes and heavy traffic

References :

- Relience private ltd. (2010) companies make the evaluation report of SoilTech treated soil stabilised base layer.
- Basantadhakal et.al (2016) studies effect of liquid acrylic polymer on geotechnical properties of fine graned soil.
- P.K.KOLAY, et.al (2016) studies" the effect of liquid polymer stabilozer on geotechnical properties of fine grained soil"
- Sameervyas et.al (2016)studies stabilisation of dispersive soil by blending polymer.
- Sepehr Rezaeimalek1,,et.al(2017) studies on Mixing Methods Evaluation of a Styrene-Acrylic Based Liquid Polymer for Sand and Clay Stabilization in this paper
- Mechanism of Polymer Action – Research in 2022 delved deeper into understanding the mechanism through which liquid polymers interact with expansive soils.
- Ghosh et al. (2022) used scanning electron microscopy (SEM) and X-ray diffraction (XRD) techniques to study the changes in the microstructure of expansive soils treated with liquid polymers.
- Raman and Sharma (2022) conducted a study on the molecular interactions between soil minerals and liquid polymers.
- Verma et al. (2022) conducted a series of field trials to assess the long-term effectiveness of polymer-treated expansive soils.

- Athulya P.V. et.al (2015) studies stabilization of sub grade soil using additives – a case study
- Kumar et al. (2023) compared the effectiveness of liquid polymers with lime and cement in improving the engineering properties of expansive soils
- Kumar, P., & Sharma, S. (2017). "Effect of Polymer on Stabilization of Expansive Soil." Geotechnical Testing Journal.
- Rao, K. R., & Sahu, P. K. (2018). "Stabilization of Expansive Soils with Synthetic Polymers." Journal of Civil Engineering Research.
- T.Raghvendra, B.Rohini, G.Divya,"Stabilization of black cotton soil using terrasil and zycobond" IJCRT 2018 , ISSN:2320-2882(PAPER) National Conference Proceeding NTSET feb 2018.
- P.K.Kolay ,A.Pant ,V.K.Puri ,"Effect of liqyid polymer stabilizer on geotechnical properties of fine-grained soil", Indian Geotechnical Conference IGC 2016 IIT madras, Chennai.
- Samer Vyas, NeelamPhaugal , Pankaj Sharma , "stabilisation of dispersive soil by blending polymers", International Journal of earth science and Engineering ISSN:0974-5904, VOLUME 04, No. 06 SPL, PP 52- 54, 2011.
- N.Sohaib , M. SarfrazFaiz , G.Sana "Use of acrylic polymer for stabilisation of clayey soil" International Journal of Scientific and engineering research, Vol.9 ,Issue 11, ISSN 2229-5518, 2018.
- LarisaChabdris , Dan Paul, LaelislauRandermanchere "Expansive soil stabilisation – genral consideration " Internatinal Multidisciplinary scientific Geo conference SGEM 2017.
- J.Ranjitha, Supriya D.K., Hitaishi.P, Pratik kumR , " Experimental Study On Black Cotton Soil Stabilised Using Soiltechmk 3 Polymer " e-ISSN :2319-1163 , p-ISSN :2321-7308 IJRET.
- Qassun S. mohammadShafiqu and Safe H Bdan "improvement on expansive soil using polymethacrylate polymer " International Conference on material Engineering and Science 454 (2018) , 012138
- Anjaneyappa, Dr. M.S. Amarnath and B.R. Shrinivasamurthy" Characterisation of polymer stabilised soil for [avment " Indian Road Congress Polymer Paper.
- BibhaMahto, A.K.Duggal " Areveve paper on important of subgrade by RBI grade 81 and ash pond " eISSN:2395-0056 , P-ISSN:2395-0075 , IRJET 2015
- Chandra, S., & Agarwal, P. (2021). The Effectiveness of Cationic and Anionic Polymers for Stabilizing Expansive Soils. Journal of Geotechnical Engineering, 147(8), 06021001.
- Patel, R., & Saha, D. (2023). Cost-Effectiveness and Environmental Benefits of Liquid Polymer Stabilization. Construction and Building Materials, 321, 126377.
- Ghosh, S., et al. (2022). Microstructural Changes in Expansive Soils Stabilized with Liquid Polymers: An SEM and XRD Study. Geotechnical Testing Journal, 45(2), 314-324.
- Reddy, P., et al. (2023). Long-Term Durability and Performance of Polymer-Treated Soils in Road Construction. Transportation Geotechnics, 33, 100698.