EXPERIMENTAL STUDY ON THE STABILIZATION OF GRANULAR SOILS USING REDISPERSIBLE POLYMER POWDER FOR FLEXIBLE PAVEMENT FOUNDATIONS SUBGRADE APPLICATIONS

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Abstract— The performance of pavement systems is strongly influenced by the engineering behaviour of subgrade soils. While granular soils are widely available, their inherent limitations in strength and durability often restrict their use in subgrade applications. Conventional stabilizers such as lime and cement raise concerns related to environmental impact and long-term performance, prompting the need for sustainable alternatives. This study investigates the use of Redispersible Polymer Powder (RPP) as an eco-friendly stabilizing additive for granular soils. An experimental program was conducted with RPP dosages of 2–10% by dry soil weight, assessing Unconfined Compressive Strength (UCS), California Bearing Ratio (CBR), compaction characteristics, durability, and microstructural behaviour. Results showed significant strength and stiffness improvements, with UCS and CBR values peaking at an 8% dosage, beyond which gains plateaued. Durability tests confirmed enhanced resistance to moisture-induced degradation, while Scanning Electron Microscopy revealed polymer film formation leading to dense particle bonding and reduced pore spaces. RPP treatment exhibited minimal effect on compaction parameters, ensuring field applicability without major procedural changes. Overall, RPP proved effective in enhancing strength, durability, and moisture resistance of granular subgrades, offering a sustainable alternative to cementitious stabilizers.

Keywords— Redispersible Polymer Powder (RPP), Soil Stabilization, Pavement Subgrade, Strength and Durability, Sustainable Infrastructure

I. INTRODUCTION

The rapid expansion of transportation infrastructure, especially in developing economies like India, has significantly increased the demand for sustainable and reliable pavement systems. A key component in any flexible or rigid pavement structure is the subgrade, which acts as the foundational support for the overlying pavement layers. The subgrade’s mechanical performance directly influences the overall service life, load-bearing capacity, and resistance to deformation of the pavement structure.

In many parts of the world, granular soils such as sandy soils, gravelly soils, or silty sands are abundantly available and frequently used as subgrade materials due to their natural occurrence, ease of excavation, and cost-effectiveness. However, these soils often exhibit low cohesive strength, high permeability, and poor resistance to environmental degradation, which make them vulnerable under heavy vehicular loads and extreme weather conditions. Consequently, such soils require stabilization to enhance their engineering properties and ensure long-term pavement performance.

Soil stabilization is a process that alters the physical and/or chemical properties of a soil to improve its performance characteristics. The traditional methods of soil stabilization include the use of cement, lime, bitumen, and fly ash. While these materials are effective in many cases, they are not always suitable for granular soils and are increasingly being scrutinized due to environmental and economic considerations. As infrastructure projects grow in scale and complexity, the industry is moving toward more sustainable, durable, and performance-efficient stabilization techniques.

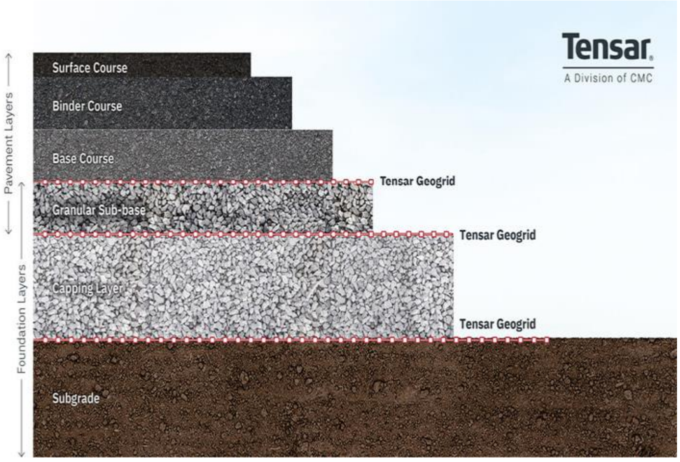

Figure 1. layers of foundation and pavement

1.1 CHALLENGES WITH GRANULAR SOILS IN SUBGRADE APPLICATIONS

Granular soils, by nature, are non-cohesive, which means they lack the interparticle bonding necessary to resist tensile and shear forces effectively. Although these soils can exhibit high friction angles and acceptable bearing capacity under compacted conditions, their structural integrity deteriorates significantly when exposed to moisture infiltration, freezing and thawing cycles, and cyclic traffic loading. Key challenges associated with using granular soils in subgrade applications include:

Susceptibility to Erosion: Due to their open-graded nature, granular soils are prone to water infiltration and erosion.

Poor Load Distribution: Lack of cohesion leads to stress concentration and differential settlements under repeated loading.

Moisture Sensitivity: Water infiltration reduces interparticle friction and results in softening of the subgrade.

Inconsistent Compaction: Achieving uniform compaction in large-scale projects can be challenging with sandy and silty materials. These limitations necessitate the adoption of stabilization methods that can modify the soil structure, enhance interparticle bonding, and increase overall strength and durability.

1.2 SOIL STABILIZATION METHODS

Stabilization of weak or problematic soils has long been practiced using materials such as lime, cement, fly ash, and other industrial byproducts. Each method offers specific benefits: Lime stabilization improves plasticity and reduces moisture sensitivity, particularly in clayey soils. Cement stabilization provides rapid strength gain and good load-bearing capacity but may lead to brittleness and shrinkage cracking. Fly ash, a pozzolanic material, can enhance strength and durability when combined with other stabilizers. Despite these advantages, conventional stabilizers have certain drawbacks:

Environmental Impact: High carbon emissions during production (especially for cement).

Chemical Incompatibility: Some stabilizers are ineffective in non-reactive granular soils. Long Curing Time: Slower strength development delays project execution.

Durability Concerns: Brittle failure, loss of strength in wet conditions, and crack propagation. The growing demand for sustainable and adaptable stabilization techniques has led researchers to explore polymer-based stabilizers, which offer unique benefits such as rapid strength gain, enhanced flexibility, and improved moisture resistance.

1.3 REDISPERSIBLE POLYMER POWDER (RPP) IN SOIL STABILIZATION

Redispersible Polymer Powder (RPP) represents a class of advanced construction additives increasingly utilized in modern civil engineering applications, particularly in modifying the properties of mortars, plasters, and concrete. These polymers are formulated by spray-drying polymer emulsions, most commonly based on vinyl acetate-ethylene (VAE), styrene-butadiene rubber (SBR), or acrylic-based systems. The spray-drying process transforms the liquid emulsion into a fine powder, which is easily transportable and can be stored for extended periods without degradation.

Figure 2 (a) Subgrade stabilization by cement (b) Subgrade stabilization by Lime

When mixed with water, RPP readily redisperses to reform the original polymer emulsion. This reversible process is key to its versatility. Upon drying, the dispersed polymer particles coalesce to form a continuous, flexible film that binds the surrounding matrix—be it cement particles, sand, or in the context of this study, soil grains. This mechanism of film formation imparts a range of enhanced mechanical and durability properties to the treated matrix, even in the absence of traditional cement hydration reactions.

1.3.1 MECHANISM OF RPP IN SOIL STABILIZATION

In the stabilization of granular soils, RPP acts primarily as a physical modifier rather than a chemical stabilizer. Unlike cement, lime, or fly ash, which rely on pozzolanic or hydration reactions to form rigid cementitious bonds, RPP modifies the soil behaviour through film-forming and binding effects.

Once RPP is added to soil and subsequently mixed with water, the powder redisperses and begins to coat individual soil particles. As the mixture dries, a flexible polymer film forms over and between the particles. This film not only holds the grains together by creating continuous interparticle bridges but also partially fills micro voids within the soil structure, thereby enhancing compactness and reducing porosity. This mechanism does not alter the mineralogical composition of the soil but improves its engineering behaviour significantly.

1.3.2 KEY BENEFITS OF RPP-TREATED SOILS

The performance improvements offered by RPP stabilization stem largely from the nature of the polymer matrix formed upon drying. The key advantages observed in granular soil stabilization using RPP include:

(A) Improved Interparticle Bonding

The formation of a continuous polymer film enhances the cohesion between soil grains. This results in better structural integrity, even under shear stress. The flexible nature of the polymer also allows for better accommodation of minor particle movement without loss of strength, especially in cohesionless soils like sand.

(B) Enhanced Moisture Resistance

The hydrophobic properties of many RPP formulations (especially those based on vinyl acetate-ethylene) significantly reduce the water absorption capacity of treated soils. This moisture resistance is critical in preventing strength loss due to water infiltration, especially under soaked or flood-prone conditions. The reduced permeability also helps in maintaining long-term stability of subgrade layers.

(C) Increased Flexibility and Reduced Brittleness

Unlike cement-stabilized soils, which tend to become brittle and prone to cracking under loading or environmental cycling, RPP-treated soils exhibit better ductility and strain tolerance. This flexibility allows the subgrade or base material to absorb and redistribute stresses without sudden failure, a desirable trait in flexible pavement design.

(D) Long-Term Durability

Polymer-stabilized soils exhibit superior resistance to environmental degradation. Cyclic wetting and drying, as well as freezing and thawing cycles, often cause deterioration in traditional chemically stabilized soils. However, the polymer network created by RPP provides resilient, long-lasting binding that resists disintegration under such conditions.

These benefits collectively contribute to the superior performance of RPP-stabilized granular soils, making them suitable for flexible pavement foundations and other geotechnical applications.

1.3.3 RPP COMPARED TO TRADITIONAL STABILIZERS

Traditional soil stabilization methods largely rely on the chemical alteration of soil properties. Stabilizers such as lime and cement are reactive agents that form calcium silicate or aluminate hydrates when mixed with water and soil. While these materials have proven effective in a wide range of soils, they often exhibit limitations in granular, non-cohesive soils such as clean sands and silts, where adequate reaction or retention is difficult to achieve.

In contrast, RPP offers a non-reactive, film-based mechanism that works efficiently regardless of soil chemistry. Its use is particularly advantageous in soils with low clay content or those lacking sufficient cation exchange capacity to facilitate traditional stabilization. Moreover, RPP does not produce by-products like calcium hydroxide that may cause long-term durability concerns or environmental impacts.

Furthermore, RPP offers sustainability benefits. The production of polymer emulsions involves lower carbon emissions compared to cement or lime production. This makes RPP a more environmentally friendly alternative in projects where carbon footprint is a concern.

Bo Wang et al. (2023) conducted an experimental study to evaluate the effect of redispersible latex powder (RLP) on the mechanical and volumetric properties of cement-stabilized macadam mixtures, particularly those incorporating recycled aggregates. The study found that mixtures with recycled aggregates exhibited higher compressive and flexural strength compared to those with natural aggregates. With the addition of RLP, both flexural and tensile strengths increased, although a slight decrease in compressive strength was observed due to the flexible nature of the polymer film. The freeze-thaw resistance of the mixtures improved significantly, as indicated by higher Bond Durability Ratio (BDR) values, demonstrating enhanced frost resistance. Most notably, RLP greatly reduced the shrinkage strain and drying shrinkage coefficient of the mixtures—by over 50% in both 7-day and 14-day evaluations—owing to its dual function: the polymer filled pore spaces to limit water evaporation and formed an elastic network structure that absorbed internal stresses caused by shrinkage. Overall, the study concluded that the incorporation of RLP enhances the durability, crack resistance, and shrinkage performance of cement-stabilized macadam, especially when recycled aggregates are used, highlighting its potential as a sustainable and performance-enhancing additive in road base construction.

Salahudeen (2023) investigated the viability of utilizing biomass-derived inorganic polymer cements (IPCs) as substitutes for traditional cement in improving deficient BCS. The study focused on two waste-derived pozzolanic materials: Rice Husk Ash (RHA) and Sawdust Ash (SDA). Both materials are by-products of agricultural and wood processing activities and are rich in reactive silica, making them suitable candidates for alkali-activated binding systems. The black clay soil was treated with varying percentages (0%, 5%, 10%, 15%, and 20%) of RHA-IPC and SDA-IPC by dry weight. Laboratory tests were performed according to British Standards, assessing a range of geotechnical parameters including grain size distribution, unconfined compressive strength (UCS), California Bearing Ratio (CBR), and microstructural characteristics using Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS). The experimental outcomes demonstrated substantial improvements in soil behaviour following treatment. Specifically, the proportion of fine particles passing the No. 200 sieve decreased from 76.25% to 24.34% for RHA-IPC and to 35.51% for SDA-IPC at a 20% replacement level. In terms of strength development, UCS increased significantly with curing time, reaching 1123.56 kN/m² for RHA-IPC and 954.28 kN/m² for SDA-IPC at 28 days. These values represent a strength gain of over 800% and 675%, respectively, compared to untreated soil.The most remarkable performance was also observed in CBR values, where improvements of 1500% and 1233% were recorded for the RHA and SDA-based treatments. Microstructural observations confirmed a noticeable change in particle arrangement and bonding within the treated soils, with finer and denser matrix formation evident in SEM images. The EDS analysis corroborated the presence of cementitious gel formations contributing to improved mechanical properties.

Kumar et al. (2022) conducted a research study to evaluate the effectiveness of polymer emulsion treatment in enhancing the resilient characteristics of sandy soils commonly used in highway and airfield pavement construction. Recognizing that modern pavement design methods such as the Mechanistic-Empirical Pavement Design Guide (MEPDG) are highly dependent on the resilient modulus of subgrade materials, the study focused on characterizing both untreated and treated cohesionless soils. A commercially available polymer emulsion was utilized as a stabilizing agent, and the influence of varying polymer dosages and curing durations on the mechanical behaviour of the treated soil was systematically investigated. Laboratory experiments assessed improvements in unconfined compressive strength and resilient modulus, revealing that polymer emulsion significantly enhanced the mechanical properties of sandy soils. Furthermore, multiple regression models based on two- and three-parameter equations were applied to the test data, with the best-fit model effectively capturing the relationship between stress states and resilient behaviour. To validate the practical implications of the findings, a case study demonstrated how the increased resilient modulus of treated soils can reduce the required thickness of airfield pavements.

II. MATERIALS USED

SOIL

The primary material used in this study is a naturally occurring granular soil commonly known as Murrum, which is widely available and frequently utilized in subgrade construction for flexible pavements. The soil was procured from a designated borrow area selected specifically for its relevance and suitability in subgrade applications. Upon collection, the soil was air-dried to remove moisture and then manually broken down to eliminate any large clods.

Subsequently, the dried soil was sieved through a 4.75 mm Indian Standard (IS) sieve to remove coarser particles and to obtain a representative sample for laboratory testing. This process ensured uniformity in the sample preparation and enhanced the reliability of test results.

The characterization of the soil was carried out in accordance with the procedures outlined in the Indian Standard (IS) 2720 series, which includes various methods for testing soils. These tests provided essential information on the physical properties of the soil, including its particle size distribution, compaction behaviour, strength parameters, and plasticity characteristics.

Grain size distribution was determined as part of the classification process. The results of this analysis are illustrated in Figure 4, which shows the gradation curve of the untreated soil. The curve helps identify the soil's classification under the Unified Soil Classification System (USCS) or Indian Standard Soil Classification System (ISSCS) and provides insight into its suitability for use as subgrade material. The soil was found to be well-graded with a significant proportion of sand-sized particles, confirming its granular nature.

Table 1 Properties of soil used

Properties of Soil

S.No	Properties	
1.	Specific gravity (G_s)	2.67
2.	Gravel (%)	5.2
3.	Sand (%)	93.82
4.	Co-efficient of uniformity (C_u)	39.407
5.	Co-efficient of curvature (C_c)	1.489
6.	Liquid Limit	25
7.	Plastic Limit	22.23
8	Plasticity index	2.77

REDISPERSIBLE POLYMER POWDER (RPP)

A commercial-grade Redispersible Polymer Powder (RPP) based on Vinyl Acetate Ethylene (VAE) was used as the stabilizing agent. The polymer was white in colour, free-flowing, and stored in airtight. A systematic experimental program was designed to analyse soil behavior under varying RPP contents (0%, 2%, 4%, 6%, 8%, and 10%) and curing periods (7, 14, and 28 days). The methodology ensures reproducibility, accuracy, and reliability of results through consistent procedures, controlled conditions, and appropriate testing standards, primarily derived from Indian Standard codes and relevant international guidelines.

Table 2 Properties of RPP

Property	Value
Chemical base	Vinyl Acetate–Ethylene
Appearance	White powder
Minimum film-forming temperature (MFFT)	~5°C
Bulk density	400–600 kg/m³
pH	5.0–7.0
Redispersibility	Excellent

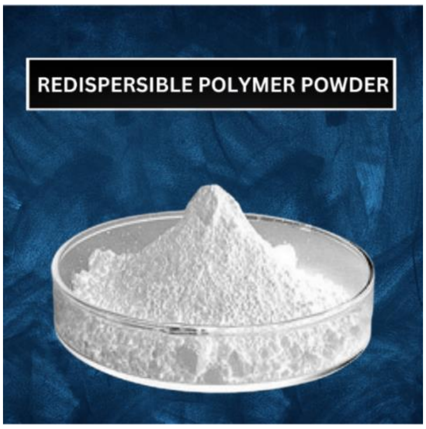

Figure 3. Redispersible Polymer Powder (RPP)

III EXPERIMENTAL DESIGN AND TEST PROGRAM

The experimental program was planned to evaluate the impact of RPP on the geotechnical behavior of granular soil. The tests conducted include:

- Standard Proctor Compaction Test
- California Bearing Ratio (CBR) Test (Unsoaked and Soaked)
- Unconfined Compressive Strength (UCS) Test at 7, 14, and 28 days of curing
- Microstructural Evaluation using SEM and EDS

Each test was conducted on soil samples treated with six different dosages of RPP, ensuring that all dosages were tested under identical conditions. All tests were performed in triplicate to eliminate random errors and improve the statistical significance of the results. The average of three trials was considered for all evaluations.

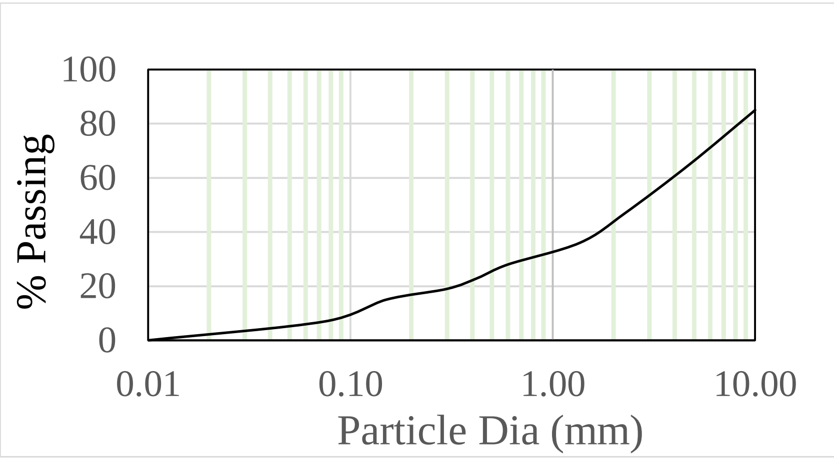

Figure 4. Particle size distribution curve of tested soil

IV RESULTS AND DISCUSSIONS

COMPACTION CHARACTERISTICS OF RPP-STABILIZED SOIL

Compaction characteristics play a critical role in subgrade performance, directly influencing strength, stiffness, and settlement behaviour. The effectiveness of RPP in enhancing the compatibility of granular soil was evaluated using the Standard Proctor Compaction Test. The relationship between dry density and moisture content for different RPP dosages (0%, 2%, 4%, 6%, 8%, and 10%) is presented. The results exhibit a typical parabolic trend in all curves, with each mixture reaching a Maximum Dry Density (MDD) at its respective Optimum Moisture Content (OMC). However, with increasing RPP content, a consistent increase in MDD is observed, indicating enhanced packing and densification behaviour due to polymer treatment. Figure 5. clearly shows that all soil samples, irrespective of RPP content, follow a typical bell-shaped compaction curve. This is characteristic of granular soils, where dry density increases with water content up to a certain point (OMC) and then decreases with further water addition due to excessive pore water occupying potential void spaces. A closer analysis reveals that as the percentage of RPP increases, the MDD also increases steadily, indicating a favourable response to polymer addition. Concurrently, the OMC shifts from lower to slightly higher values, implying that the treated soil requires more water for effective compaction.

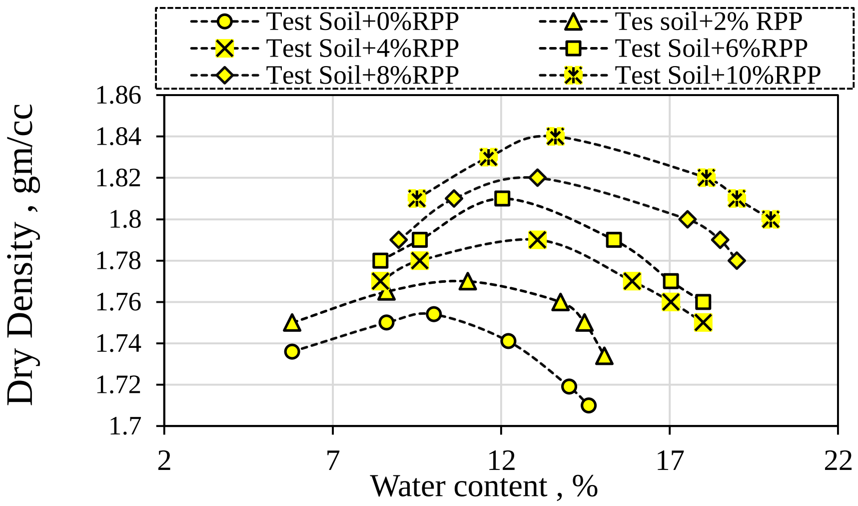

Figure 5. Standard Proctor Compaction curves of test soil with different percentages of RPP

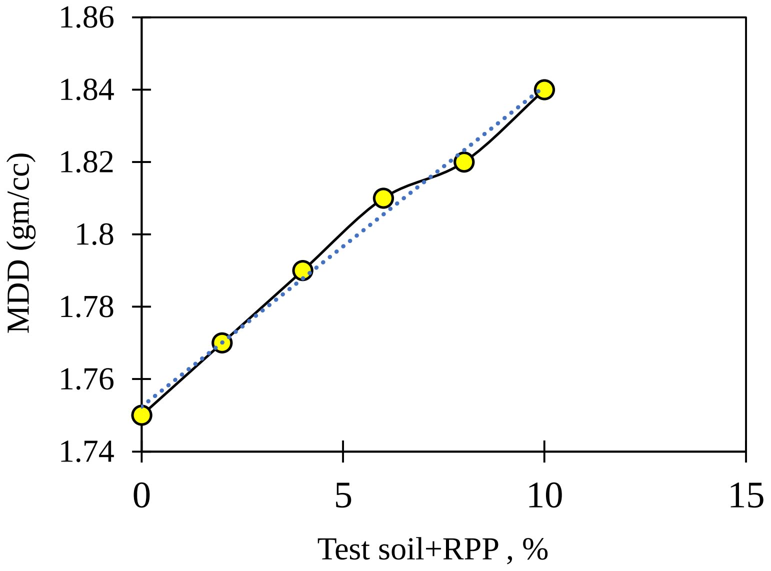

Figure 6. Variation of MDD for test soil with different percentages of RPP

EFFECT OF RPP ON MAXIMUM DRY DENSITY (MDD)

As illustrated in Figure 6, the MDD of the untreated soil is recorded at 1.75 g/cc, which serves as the baseline. With the incremental addition of RPP:

- 2% RPP led to a modest increase in MDD to 1.77 g/cc,
- 4% RPP further raised it to 1.79 g/cc,
- 6% RPP yielded 1.81 g/cc,
- 8% RPP slightly improved MDD to 1.82 g/cc, and
- 10% RPP resulted in the highest MDD of 1.84 g/cc.

This consistent rise in MDD can be attributed to the polymer's film-forming ability. Upon compaction and drying, RPP disperses and binds soil particles through interparticle adhesion, reducing intergranular voids and increasing soil matrix density. The polymer also reduces internal friction temporarily during compaction, allowing soil grains to rearrange more densely under standard Proctor energy.

EFFECT OF RPP ON OPTIMUM MOISTURE CONTENT (OMC)

From Figure 5, it is evident that the OMC increases with the addition of RPP, rising from 10% in untreated soil to 14% in samples with higher polymer content. This shift is due to the hydrophilic nature of RPP, which temporarily retains water molecules during mixing and compaction.

Key observations include:

- A jump from 10% to 12% OMC at 2% RPP,
- A further rise to 14% at 4% and 8–10%, indicating consistent behaviour,
- A slight reduction to 13% OMC at 6% RPP, possibly due to batch variation or early film formation limiting water retention.

The elevated OMC values imply that RPP-treated soil requires more moisture for effective compaction, but the gain in MDD offsets the additional water demand. In field applications, this suggests that moisture conditioning must be carefully controlled when using RPP, as too little water may prevent proper dispersion and bonding, while too much may lead to reduced dry density.

CALIFORNIA BEARING RATIO (CBR) – UNSOAKED CONDITION

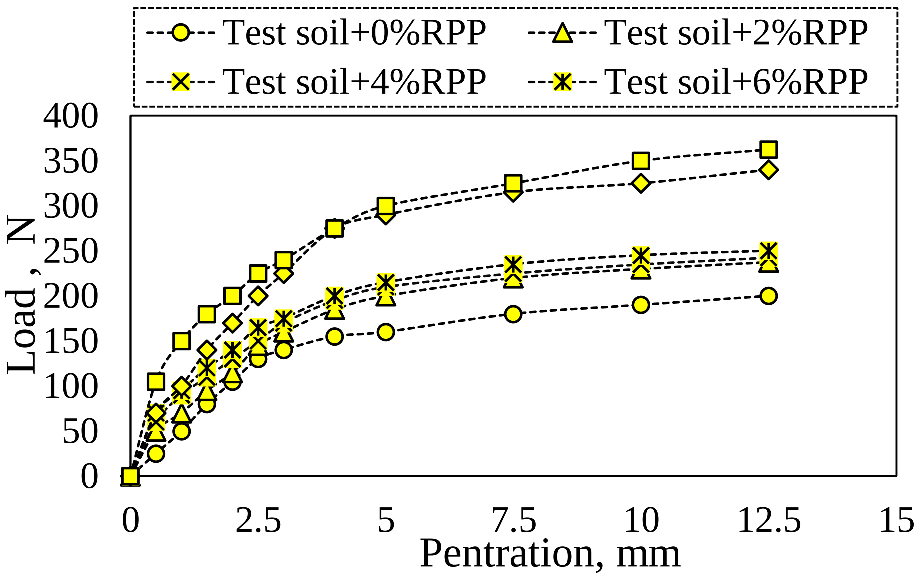

Figure 7. Variation of pressure and penetration of the CBR(Unsoaked) test for test soil with different percentages of RPP

The California Bearing Ratio (CBR) test is a critical evaluation technique used to determine the strength of subgrade materials and their capacity to support pavement layers. In this study, unsoaked and soaked (96 hours) CBR tests were conducted on untreated and RPP-treated granular soil samples with RPP contents of 0%, 2%, 4%, 6%, 8%, and 10%. The results provide insight into the improvement in load-bearing capacity of soil due to the addition of RPP.

VARIATION IN CBR WITH RPP CONTENT

As observed from Figure 7, the unsoaked CBR values exhibit a consistent and significant increase with the addition of RPP:

- The untreated soil (0% RPP) recorded a base CBR value of 9.48%.
- A modest increase to 10.58% was observed at 2% RPP.
- At 4% and 6%, the CBR rose to 10.98% and 12.04%, respectively.
- A more pronounced improvement was noted at 8% RPP, reaching 14.80%.
- The peak CBR value of 16.40% was achieved at 10% RPP, marking a total increase of approximately 73% compared to untreated soil.

This variation clearly demonstrates that RPP enhances the load-bearing capacity of granular soils in unsoaked conditions.

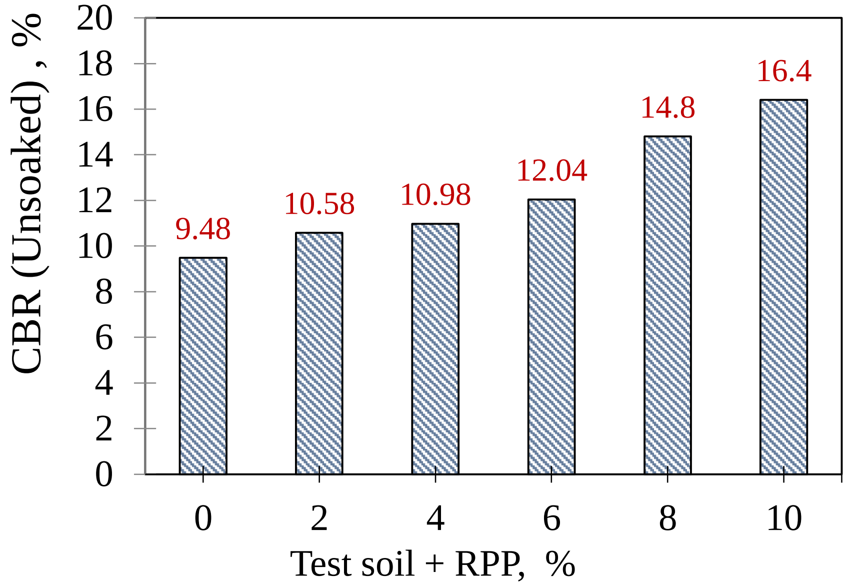

Figure 8. CBR (Unsoaked) values for the test soil with different percentages of RPP

INTERPRETATION OF LOAD-PENETRATION BEHAVIOR

Figure 7 illustrates the load-penetration curves for the various RPP dosages. Key observations from this figure include:

- The initial stiffness (slope of the load vs. penetration curve) increases with increasing RPP content, indicating improved resistance to deformation under loading.
- The peak loads sustained at 2.5 mm and 5 mm penetrations increase proportionally with RPP dosage.
- Untreated soil (0% RPP) shows the lowest load-carrying response throughout the penetration range.
- Soil treated with 10% RPP exhibits the highest load capacity, crossing 350 N at peak penetration, almost double that of untreated soil.

The increase in penetration resistance is due to the polymer's binding action, which forms a thin film around soil grains, increases cohesion, and reduces particle displacement under load.

CALIFORNIA BEARING RATIO (CBR) – SOAKED CONDITION (96 HOURS)

The soaked California Bearing Ratio (CBR) test is a vital parameter used to assess the long-term bearing capacity of subgrade soils subjected to water ingress. Subgrades in pavement systems are frequently exposed to seasonal moisture, rainwater, and groundwater. Therefore, the soaked CBR provides a realistic estimate of field performance under worst-case scenarios. This test simulates 96 hours of water saturation, followed by a penetration test to evaluate the soil's strength.

In this study, RPP-treated soil specimens were tested at varying dosages: 0%, 2%, 4%, 6%, 8%, and 10% by dry weight of soil. The results are represented graphically in Figure 7 and Figure 8.

EFFECT OF RPP CONTENT ON SOAKED CBR

As seen in Figures, the soaked CBR values exhibit a clear and steady increase with increasing RPP content:

- The untreated soil sample (0% RPP) recorded a base soaked CBR of 7.66%.
- A mild improvement is observed with 2% RPP (8.75%), followed by consistent increases at 4% (9.12%), 6% (10.21%), and 8% (11.60%).
- The maximum strength is achieved at 10% RPP, with a soaked CBR value of 12.70%, reflecting an overall improvement of approximately 66% over untreated soil.

This improvement indicates that RPP is effective not only under dry conditions but also under sustained moisture exposure, which is critical for long-term pavement performance.

SOIL BEHAVIOR AND STRENGTHENING MECHANISM IN SOAKED CONDITIONS

The soaked CBR values typically reflect the ability of the soil to retain strength and resist disintegration or softening after saturation. The following mechanisms explain the strength gain observed in RPP-treated samples:

- Water-Resistant Polymer Matrix: Once cured, RPP forms a hydrophobic and elastic film around soil grains. This film resists water ingress and maintains inter-particle bonding even after prolonged soaking.
- Reduction in Loss of Cohesion: In untreated soil, water dislodges particles and weakens the matrix. RPP-treated soils maintain particle contact due to the adhesive bonding, leading to better stress transfer and load resistance.
- Limited Swelling and Softening: The addition of RPP reduces the affinity of the soil matrix to absorb and swell excessively. This results in better dimensional stability and prevents loss of load-bearing capacity.

Thus, RPP functions as a moisture-insensitive stabilizer, protecting granular soil structure against disintegration under saturated conditions.

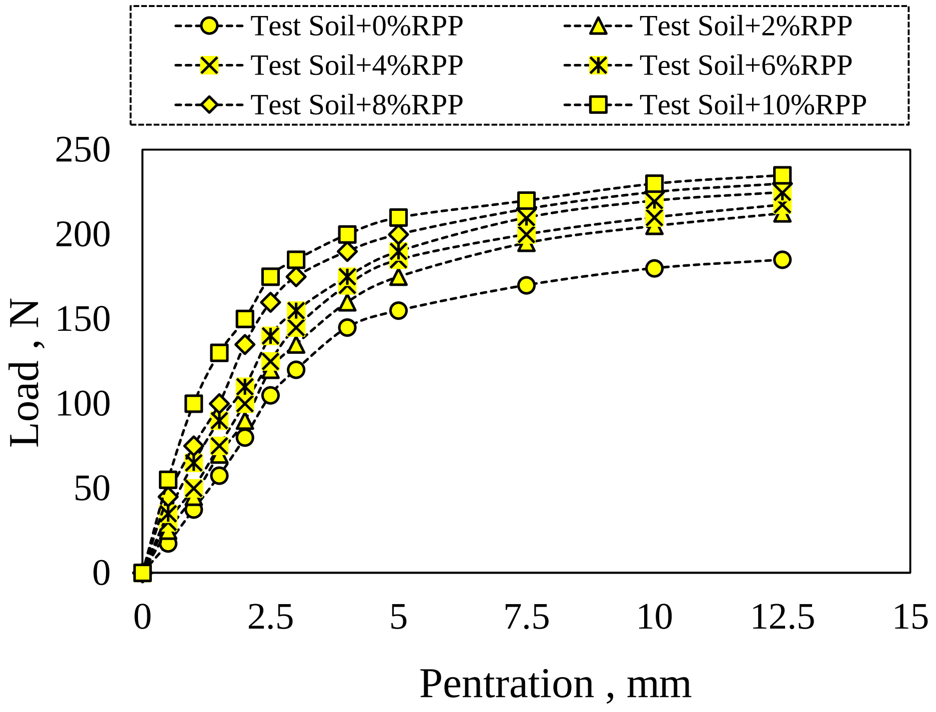

Figure 9. Variation of pressure and penetration of CBR (Soaked-96 hours) test for test soil with different percentages of RPP

ENGINEERING IMPLICATIONS FOR PAVEMENT DESIGN

The improvement in soaked CBR values demonstrates the suitability of RPP-treated soil for wet climate regions, where pavements are frequently subjected to high moisture conditions. The implications include:

- Higher soaked strength translates to reduced subgrade thickness and smaller base layers, lowering total construction costs.
- With 12.70% soaked CBR at 10% RPP, the soil meets IRC and MoRTH subgrade standards for moderate to heavy traffic loading.
- Improved moisture durability increases the lifespan of flexible pavements, reducing maintenance frequency and enhancing sustainability.

From a design perspective, 6–10% RPP treatment provides a significant balance between performance and cost, offering enough strength to withstand seasonal saturation cycles.

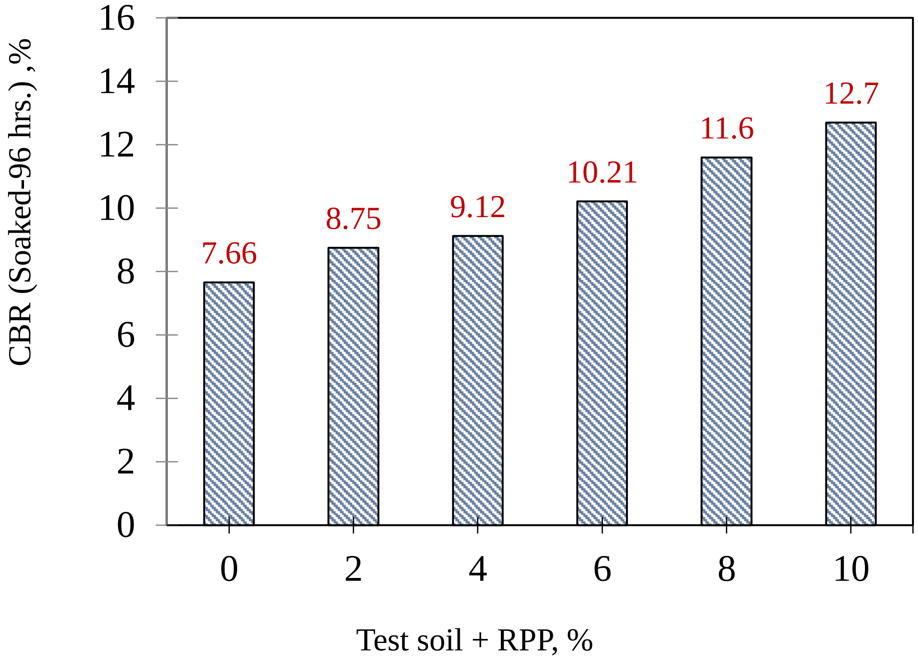

Figure 10. CBR (Soaked-96 hrs.) values for test soil with different percentages of RPP

COMPARISON BETWEEN SOAKED AND UNSOAKED CBR RESULTS

To evaluate the durability and moisture resistance of RPP-treated soils, a comparative analysis was carried out between unsoaked and soaked CBR values. Strength retention under saturation was calculated to assess the effectiveness of Redispersible Polymer Powder (RPP) in maintaining subgrade performance in water-exposed environments.

Table 3. Comparison of soaked and unsoaked CBR and strength retention

RPP (%)	Unsoaked CBR (%)	Soaked CBR (%)	Strength Retention (%)
0	9.48	7.66	80.80
2	10.58	8.75	82.70
4	10.98	9.12	83.06
6	12.04	10.21	84.82
8	14.80	11.60	78.38
10	16.40	12.70	77.44

The results indicate that the inclusion of RPP enhances the soaked CBR values across all dosages, confirming improved moisture resistance compared to untreated soil. Strength retention values range from approximately 77% to 85%, demonstrating that even under fully saturated conditions, the treated soils maintain a substantial portion of their dry strength.

The maximum strength retention (84.82%) was observed at 6% RPP, suggesting this dosage provides optimal interaction between the polymer and soil particles. This peak performance can be attributed to improved bonding and matrix formation, which effectively resists disintegration under wet conditions.

However, a decline in strength retention is noted at higher RPP dosages (8% and 10%). While the absolute CBR values continue to increase with higher polymer content, the relative strength retention decreases. This phenomenon may be due to polymer film saturation, where excess polymer forms weaker, more flexible films that reduce overall matrix stiffness. It is also possible that at higher concentrations, the uniform dispersion of RPP is compromised, leading to inconsistencies in stabilization.

EFFECT OF RPP ON UNCONFINED COMPRESSIVE STRENGTH (UCS)

The Unconfined Compressive Strength (UCS) test is an essential parameter for evaluating the load-bearing capacity and strength behaviour of treated and untreated soils in subgrade and subbase applications. This test helps assess the effect of stabilization on the soil's ability to resist axial loads without any lateral confinement, which is particularly relevant for pavement subgrades and embankments.

In this study, UCS tests were performed on specimens treated with varying percentages of RPP ranging from 0% to 10%. The influence of polymer dosage and curing time (7, 14, and 28 days) on UCS behaviour was thoroughly investigated.

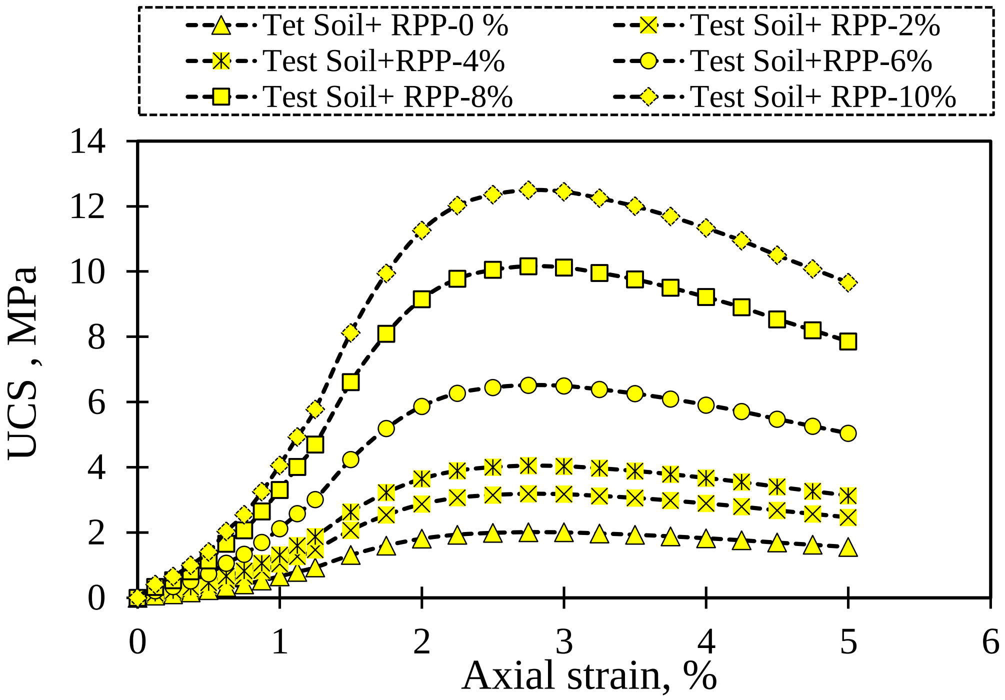

Figure 11. The results of UCS tests of test soil treated with different percentages of RPP of 7- Days curing

Figure 11. Presents the stress–strain behaviour of soil specimens treated with different RPP contents. It is evident from the curves that the peak UCS value and strain energy increased significantly with increasing RPP content:

- Untreated soil (0% RPP) exhibited a peak strength of 2.0 MPa, with low strain energy and early failure.
- As RPP content increased to 2% and 4%, the UCS rose to 3.2 MPa and 4.0 MPa, respectively.
- At 6% RPP, a substantial improvement was recorded, with the UCS reaching 6.5 MPa.
- The highest values were observed at 8% and 10% RPP, achieving 10.2 MPa and 12.5 MPa, respectively, marking more than a 6-fold improvement compared to untreated soil.

The stress–strain behaviour also demonstrated a shift from brittle to more ductile failure patterns with increasing RPP content, as evidenced by the broader curves in higher RPP-treated specimens.

VARIATION OF PEAK UCS WITH REDISPERSIBLE POLYMER POWDER (RPP) CONTENT

Figure 12 provides a visual summary of the peak UCS values for each RPP content for 7 days curing samples. The trend shows a clear and consistent increase, affirming the effectiveness of RPP in enhancing soil strength

The results reflect a non-linear increase, where the strength gain is modest up to 4% but becomes much more prominent beyond 6%, indicating an optimal interaction between polymer film formation and soil particle bonding. This performance improvement is attributed to the formation of a flexible yet strong polymer network that binds soil particles and resists crack propagation.

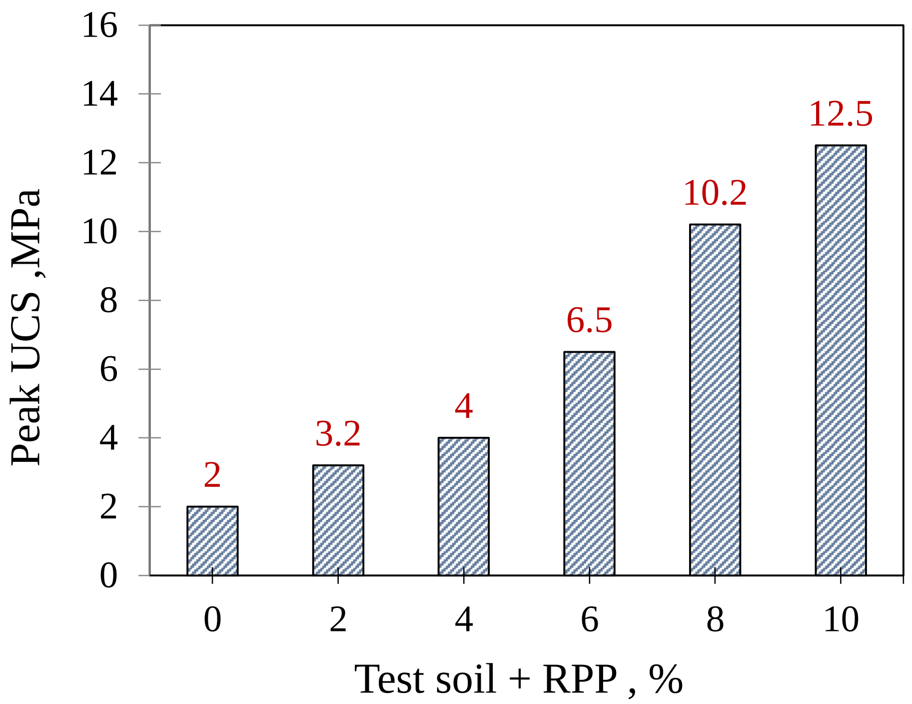

Figure 12. Peak UCS values of test soil treated with different percentages of RPP of 7- Days curing

INFLUENCE OF CURING DAYS ON UCS STRENGTH

Figure 13 presents the unconfined compressive strength (UCS) of soils treated with varying percentages of Redispersible Polymer Powder (RPP) across different curing periods 7, 14, and 28 days. The results reveal a clear and consistent trend: longer curing durations significantly enhance the strength of polymer-treated soils, particularly at higher RPP dosages. For untreated soil (0% RPP), the UCS values increased only marginally from 1.9 MPa at 7 days to 2.3 MPa at 28 days. This slight improvement can be attributed to basic moisture loss and minor structural rearrangements among soil particles, with no chemical bonding or stabilisation mechanisms at play. The lack of substantial strength development in untreated samples highlights the inherent limitations of granular soils in achieving strength through natural curing alone.

In contrast, RPP-treated specimens demonstrated a remarkable improvement in strength with increased curing time. For instance, the soil treated with 10% RPP showed a UCS of 11.7 MPa at 7 days, which increased to 12.9 MPa at 14 days and further to 13.6 MPa at 28 days. This progressive gain indicates that the stabilisation effect of RPP continues to develop over time. The observed strength improvement is primarily due to the hydration and subsequent film-forming action of the polymer, which enhances interparticle bonding and creates a cohesive and durable matrix. As curing progresses, the polymer particles coalesce to form continuous films that bind soil grains together, reducing void spaces and increasing the load-bearing capacity of the composite material.

Moreover, the gradual evaporation of moisture during curing facilitates closer packing of soil particles and promotes stronger interactions between the polymer chains and the soil matrix. This interlocking mechanism significantly improves the mechanical integrity of the stabilized soil. The chemical nature of the RPP also contributes to strength development, as the polymer reacts with soil minerals and water to form durable bonds over time. The longer the curing period, the more complete these reactions become, resulting in a stiffer and more resilient structure.

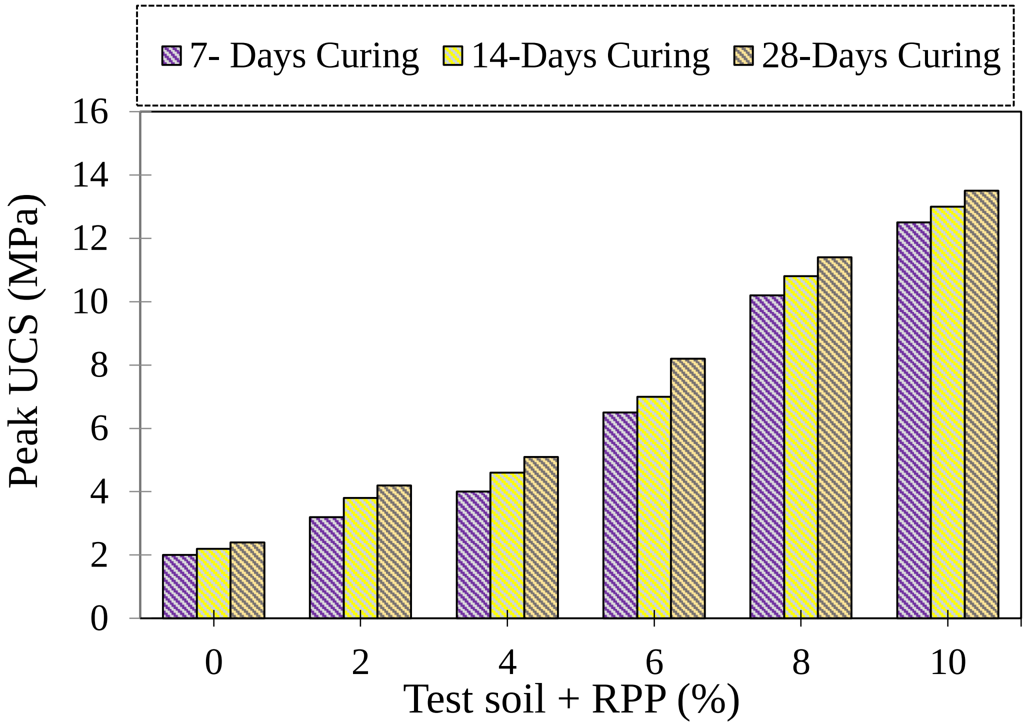

Figure 13. Peak UCS values of test soil treated with different percentages of RPP of 7 ,14 and 28 Days curing

The results clearly demonstrate that curing time is a critical factor in achieving the desired strength in polymer-stabilised soils. While the initial strength gain is noticeable within the first 7 days, the continuation of the curing process up to 28 days allows the soil-polymer system to mature fully, leading to maximum performance. This finding underscores the importance of allowing adequate curing duration in field applications to ensure long-term durability and effectiveness of the stabilization process, particularly when higher percentages of RPP are used. Therefore, the development of UCS over time highlights the time-dependent nature of polymer-soil interactions and the essential role of curing in unlocking the full potential of RPP as a soil stabilizer.

MICROSTRUCTURE ANALYSIS (SEM ANALYSIS)

Understanding the microstructural changes that occur within treated soil matrices provides crucial insights into the mechanisms responsible for performance enhancement. In this study, High-Resolution Scanning Electron Microscopy (HR-SEM) was employed to examine the microstructure of gravelly sand stabilized with 10% Redispersible Polymer Powder (RPP). The analysis was aimed at visualizing the effects of polymer modification at the particle scale, particularly in terms of coating behaviour, interparticle bonding, void reduction, and matrix integrity.

The SEM image shown in Figure 17, taken at 250× magnification, illustrates the morphological evolution of the soil system due to polymer interaction. These micro-level observations support the macro-scale improvements noted in mechanical tests such as CBR, UCS, and compaction.

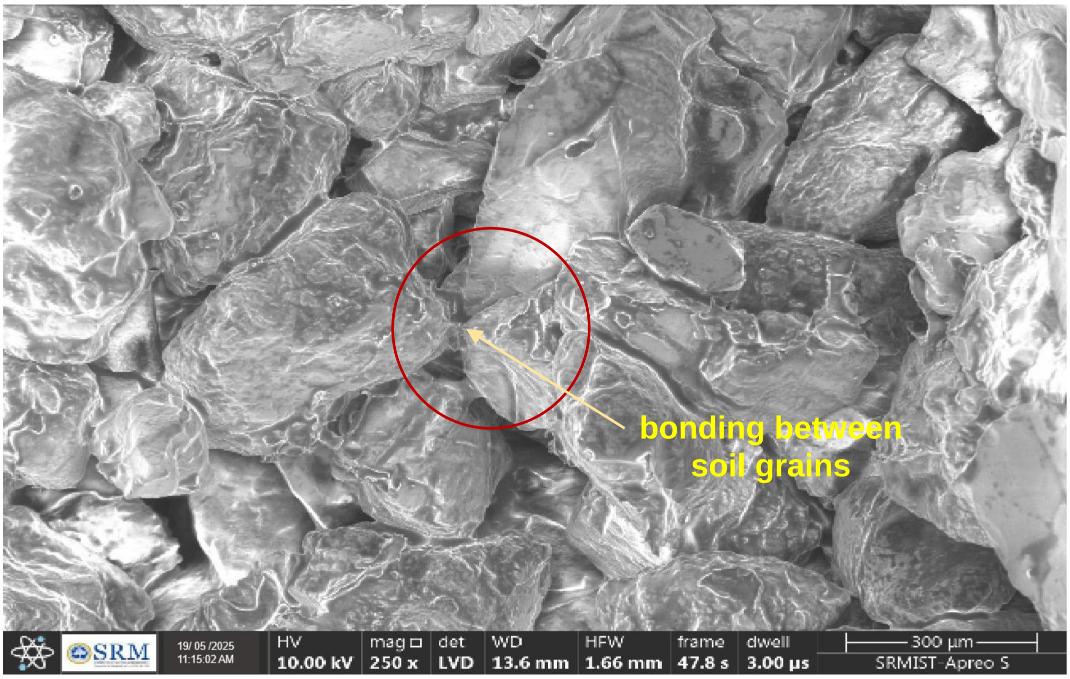

Figure 14. Scanning Electron Microscopy (SEM) image of soil treated *with 10 %* RPP (Redispersible Polymer Powder)

V. Conclusions

This study aimed to evaluate the potential of Redispersible Polymer Powder (RPP) as a stabilizing agent for granular soils intended for use in pavement subgrades. A comprehensive experimental program was conducted, involving compaction characteristics, California Bearing Ratio (CBR) tests under both unsoaked and soaked conditions, Unconfined Compressive Strength (UCS) analysis, stress-strain behavior evaluation, and microstructural examination through Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS).

1. Practical RPP Dosage Range: The results suggest that a polymer dosage between 6% and 10% offers an effective balance between strength enhancement, ductility, moisture resistance, and economic feasibility. Beyond this range, marginal gains in strength may not justify additional material cost.
2. Long-Term Curing Effects: Curing time was observed to be a critical factor in strength development. RPP-treated samples showed continuous strength gain up to 28 days, emphasizing the need for adequate curing periods in field applications to fully harness the stabilizing potential of RPP.
3. Microstructural Validation: SEM analysis confirmed improved bonding and reduced voids in the soil matrix, while EDS results verified the presence and uniform distribution of polymeric material in the treated samples, supporting the mechanical test outcomes.

SPECIFIC CONCLUSIONS

Based on the detailed experimental results presented, the following specific conclusions can be drawn:

COMPACTION CHARACTERISTICS

- The addition of RPP increased the Maximum Dry Density (MDD) from 1.75 g/cc to 1.84 g/cc, indicating improved packing and densification of soil particles.
- The Optimum Moisture Content (OMC) increased from 10% to 14% with RPP addition due to the hydrophilic nature of the polymer, which temporarily retains water during compaction.

CALIFORNIA BEARING RATIO (CBR)

- Unsoaked CBR values improved from 9.48% (untreated) to 16.40% at 10% RPP, representing a 73% increase in load-bearing capacity.
- Soaked CBR values also rose from 7.66% to 12.70% across the same RPP range, indicating a 66% improvement under saturated conditions.
- Strength retention values ranged from 77% to 85%, with peak retention observed at 6% RPP, highlighting the optimum interaction between soil particles and polymer.

UNCONFINED COMPRESSIVE STRENGTH (UCS)

- UCS increased from 2.0 MPa in untreated soil to 12.5 MPa at 10% RPP, showing more than a six-fold improvement.
- Peak strength gain was most significant beyond 6% RPP content, indicating a non-linear but favourable trend with increasing polymer dosage.
- The stress-strain curves revealed a shift from brittle to ductile behavior, enhancing the material's resilience under loading.

CURING TIME INFLUENCE

- Curing time significantly affected UCS results. For example, 10% RPP samples showed an increase from 11.7 MPa (7 days) to 13.6 MPa (28 days).
- This trend suggests continued hydration and bonding processes that strengthen the soil matrix over time.

MICROSTRUCTURAL AND ELEMENTAL ANALYSIS

- SEM analysis of the treated soil revealed a denser, more cohesive matrix with visible polymer bridging between particles.
- EDS analysis confirmed the presence of elements like carbon, silicon, and oxygen, validating the integration of RPP into the soil.

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