

Performance Assessment of Polymer–Cement Stabilized Soil for Geotechnical Applications

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ABSTRACT

Soil stabilization is widely used to improve the engineering performance of weak and problematic soils for geotechnical and pavement applications. The present study investigates the performance of polymer–cement stabilized soil by evaluating the effects of different cement and polymer contents on plasticity characteristics, compaction behaviour, unconfined compressive strength (UCS), and California Bearing Ratio (CBR). An untreated soil was compared with mixtures containing 4% and 6% cement, 0.5% and 1.0% polymer, and their combined treatments. The effect of curing period on the strength development of cement-containing mixtures was also examined. The untreated soil exhibited a plasticity index of 26.6%, maximum dry density of 1.63 Mg/m³, unconfined compressive strength of 118 kPa at 28 days, and CBR of 3.8%. Stabilization resulted in a progressive improvement in the engineering properties of the soil. The 6% cement treatment increased the 28-day UCS to 278 kPa and the CBR to 9.4%, whereas the combined treatment containing 6% cement and 1.0% polymer increased the corresponding values to 367 kPa and 15.1%, respectively. Compared with the untreated soil, the 6% cement–1.0% polymer treatment resulted in approximately 211% improvement in 28-day UCS and 297% improvement in CBR. The plasticity index was also reduced from 26.6% for untreated soil to 14.2% after combined stabilization. The progressive increase in UCS with curing period indicates the development of cementitious bonding, while the improved performance of the combined treatment indicates the beneficial contribution of polymer modification to the stabilized soil matrix. The findings demonstrate the potential of polymer–cement stabilization for improving the strength, plasticity and bearing characteristics of soil for selected geotechnical applications. Further investigation involving durability, moisture susceptibility and field-scale validation is recommended before practical implementation.

Keywords: Soil stabilization; Polymer; Cement stabilization; Polymer–cement stabilized soil; Unconfined compressive strength; California Bearing Ratio; Plasticity index; Geotechnical applications.

INTRODUCTION

Soil is one of the fundamental materials supporting civil engineering infrastructure, and its engineering behaviour has a direct influence on the safety, serviceability and durability of constructed facilities. While many naturally occurring soils possess adequate engineering characteristics, problematic soils such as highly plastic and expansive soils may exhibit considerable volume change, low bearing capacity and inadequate strength under varying moisture conditions. Such behaviour can create difficulties in pavement subgrades, foundations, embankments and other geotechnical applications. Consequently, soil stabilization has become an important technique for modifying unfavourable soil properties and improving their suitability for engineering purposes. Ikeagwuani and Nwonu (2019) highlighted that expansive soils require stabilization because their shrink–swell behaviour can significantly restrict their direct use in construction.

Soil stabilization may be achieved through mechanical, chemical or additive-based techniques. Among conventional chemical stabilizers, cement and lime have been extensively investigated because of their ability to improve soil strength and reduce volume instability. Cement stabilization primarily involves hydration and the development of cementitious products within the soil matrix, resulting in improved particle bonding and strength. Barman et al. (2022) reported that the effectiveness of chemical stabilization is influenced by stabilizer type and dosage, soil mineralogy, curing period, moisture condition and other physicochemical factors. Their review also indicated that cement-based stabilization can provide substantial improvements in the strength and stiffness of clayey soils.

Although cement is an effective stabilizing agent, increasing attention has been directed towards alternative and complementary stabilizers because the performance of cement-treated soil is dependent on dosage, soil characteristics and curing conditions. Furthermore, the environmental implications associated with extensive cement production have encouraged research into alternative soil-improvement materials. Jang and Lee (2020) reviewed the application of polymeric materials in geotechnical engineering and reported that polymers can modify soil behaviour through interactions with soil particles and pore water.

Polymer-based stabilization has consequently emerged as an alternative approach for improving soil properties. Polymers can act through mechanisms that differ from those of conventional calcium-based stabilizers. Depending on polymer chemistry, concentration and soil characteristics, polymer treatment may improve particle bonding, modify water retention, reduce permeability or alter the interaction between soil particles and water. Huang et al. (2021), in their state-of-the-art review, emphasized that polymer effectiveness depends on characteristics such as polymer type, molecular structure, concentration, solubility, viscosity, pH and moisture behaviour. They also identified the need for further investigation into the practical application and long-term performance of polymer-stabilized soils.

Experimental investigations have also demonstrated the potential of polymer treatment for problematic soils. Taher et al. (2020) compared commercially available polymer stabilizers with conventional treatments for expansive soil and evaluated parameters including swelling, unconfined compressive strength and hydraulic conductivity. Their results demonstrated that polymer treatment can modify the engineering behaviour of expansive soil, although its performance mechanism differs from conventional stabilizers such as lime and fly ash. Similarly, Zhang et al. (2019) reported that a combination of polyvinyl alcohol and potassium carbonate could reduce volume change and improve the strength characteristics of expansive soil, with microstructural observations indicating the development of a more homogeneous and denser treated structure.

The use of combined stabilizers provides another potential route for improving problematic soils. The combination of additives may enable different stabilization mechanisms to operate simultaneously. Barman et al. (2022) noted that combined additives can provide greater improvement than individual additives under suitable conditions. However, the effectiveness of combined treatment depends strongly on soil type, additive proportion, curing conditions and the interaction between the stabilizing materials.

Despite the growing body of research on cement and polymer stabilization individually, comparatively less attention has been directed toward systematically evaluating their combined effect using a common experimental framework involving plasticity, compaction, UCS and CBR. In addition, the selection of appropriate cement and polymer proportions requires consideration of both strength development and changes in basic engineering characteristics. Therefore, there is a need to evaluate polymer–cement stabilization using a controlled treatment matrix and to compare the performance of individual and combined stabilization.

The present study addresses this requirement by investigating the performance of polymer–cement stabilized soil using different proportions of cement and polymer. The study evaluates plasticity characteristics, compaction behaviour, unconfined compressive strength and California Bearing Ratio, with particular emphasis on the influence of curing period on strength development. The objective is to establish the extent to which

combined polymer–cement treatment can improve the engineering behaviour of problematic soil and to assess its potential for selected geotechnical applications.

LITERATURE REVIEWS AND RESEARCH GAP

Soil stabilization involves modifying the physical or chemical characteristics of soil to obtain improved engineering performance. Conventional approaches include compaction, mechanical reinforcement and chemical treatment. For problematic fine-grained soils, chemical stabilization is frequently adopted because chemical reactions can modify the soil fabric and improve strength and volume stability. Ikeagwuani and Nwonu (2019) reviewed several stabilization techniques for expansive soils and emphasized the importance of understanding the interaction between stabilizing agents and soil minerals before applying laboratory findings to field conditions.

Chemical stabilization using calcium-based materials such as cement and lime has been widely investigated. Jalal et al. (2020) reported that calcium-based stabilizers can improve clayey soils through mechanisms including hydration, cation exchange, flocculation, pozzolanic reactions and carbonation. The resulting improvement is affected by the stabilizer content, soil mineralogy, curing period, moisture condition and other environmental factors.

Cement stabilization is based primarily on hydration reactions that generate cementitious compounds capable of binding soil particles. The resulting modification generally increases soil strength and stiffness and may reduce plasticity and volume instability. Barman et al. (2022) identified cement as one of the principal conventional chemical stabilizers used for improving expansive and clayey soils. Their review indicates that cement-treated soils can exhibit greater compressive strength as cementitious compounds develop during curing.

The effectiveness of cement treatment is not solely dependent on cement content. Soil mineralogy, water content, compaction condition, curing temperature and curing duration can substantially influence the final performance. Therefore, evaluation of strength at different curing periods is important when cement is included in a stabilization programme.

Polymers have received increasing attention as soil stabilizing materials because they can interact with soil particles and water through mechanisms different from conventional cementitious stabilization. Huang et al. (2021) classified polymer applications in soil stabilization into several groups and highlighted the importance of polymer chemistry, molecular structure, concentration and moisture behaviour in determining stabilization effectiveness.

Polymer treatment may improve soil performance through particle binding, pore modification, water retention and changes in soil fabric. Jang and Lee (2020) reported that different polymer types produce different strengthening mechanisms and that the soil–polymer interaction is dependent on soil type, polymer concentration, water condition and other environmental factors.

Experimental evidence further demonstrates that polymer treatment can improve problematic soil behaviour. Taher et al. (2020) found that commercially available polymer stabilizers could reduce the swelling potential of expansive soil and alter its strength and hydraulic behaviour. However, the response varied considerably among polymer products, demonstrating that polymer stabilization cannot be treated as a single uniform technique.

Zhang et al. (2019) investigated polyvinyl alcohol combined with potassium carbonate for expansive soil stabilization and observed improvements in strength and volume-change behaviour. Their study also demonstrated the usefulness of microstructural investigation for understanding the changes produced by polymer-based treatment.

The use of more than one stabilizing material can provide complementary mechanisms of soil improvement. Cement can contribute to cementitious bonding and strength development, whereas polymer treatment can influence particle interaction and moisture-related behaviour. Barman et al. (2022) observed that combined additives may produce more effective stabilization than individual additives under appropriate conditions.

However, the available literature indicates that the response to combined stabilization is highly dependent on the specific soil and additive system. A treatment that performs effectively for one soil may not produce the same response in another soil because of differences in mineralogy, plasticity, particle-size distribution and moisture condition. Therefore, experimental evaluation of specific polymer–cement combinations remains necessary.

The combined application of cement and polymer has received comparatively less attention than the individual use of these stabilizers. The two materials operate through different but potentially complementary mechanisms. Cement contributes to cementitious bonding and strength development, particularly with curing, whereas polymer treatment can contribute to particle bonding and modification of soil–water interaction. A combined treatment may therefore provide an opportunity to improve several engineering characteristics simultaneously. However, the interaction between the two stabilizers is dependent on their respective contents and the characteristics of the soil.

Previous experimental investigations involving combined stabilization have generally evaluated parameters such as Atterberg limits, compaction characteristics, UCS, CBR and swelling behaviour. Such studies indicate that the effectiveness of combined stabilization should be evaluated against suitable control specimens. Comparison between untreated soil, individual stabilizer treatment and combined treatment is particularly important because it permits the contribution of each stabilizing material to be examined.

For pavement and other geotechnical applications, strength-related parameters alone are insufficient to characterize the performance of a stabilized soil. Changes in plasticity and compaction behaviour can influence workability and moisture sensitivity, while CBR provides a useful indication of bearing performance for pavement subgrade applications. UCS, on the other hand, provides a direct measure of the compressive resistance of cohesive stabilized soil. A combined evaluation of these parameters therefore provides a more comprehensive assessment of stabilization effectiveness. Although considerable research has been undertaken on cement stabilization and polymer-based soil treatment, the performance of combined polymer–cement systems remains dependent on the specific soil and stabilizer characteristics. Published studies also demonstrate that the optimum dosage of a stabilizer cannot be generalized across different soils. Variations in soil mineralogy, initial plasticity, moisture condition and particle-size distribution can substantially alter the response to chemical treatment. In addition, curing conditions can influence the development of cementitious bonding and the final strength of treated specimens.

RESEARCH GAP

The review of previous investigations indicates that there is a need for systematic evaluation of polymer–cement stabilization under controlled laboratory conditions. In particular, further assessment is required to establish the relative performance of untreated soil, individual stabilizer treatment and combined polymer–cement treatment using a common experimental framework.

The present study addresses this requirement by evaluating the changes in selected engineering properties resulting from polymer–cement treatment. The investigation considers the influence of the stabilizing materials on index and compaction characteristics as well as strength-related properties. The performance of treated specimens is compared with untreated soil to determine the effectiveness of stabilization and to identify the treatment condition providing suitable engineering improvement.

The study is therefore intended to contribute experimental evidence on the use of polymer and cement in combination for soil improvement and to assess its potential applicability in geotechnical engineering works. The results are interpreted in terms of measurable changes in engineering properties rather than assuming that the combined treatment will necessarily provide greater improvement than individual stabilization.

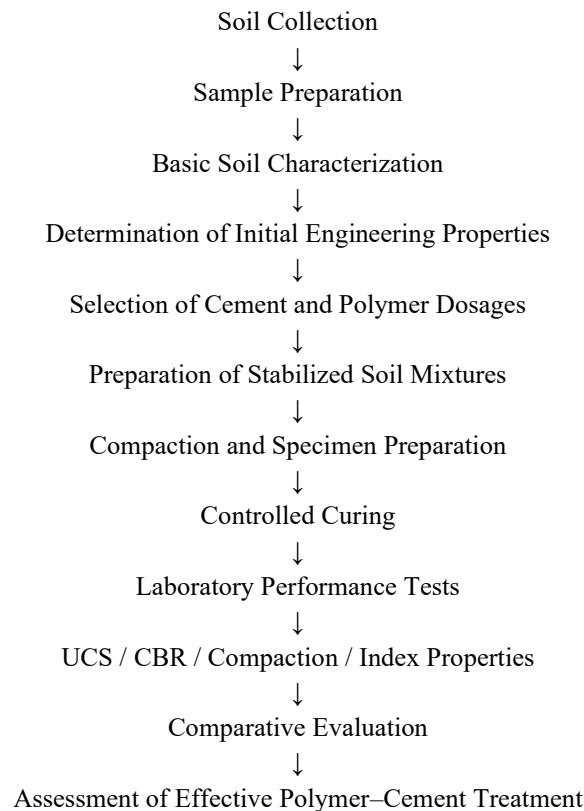
MATERIALS AND METHODS

RESEARCH APPROACH

The experimental program was designed to evaluate the effectiveness of polymer–cement treatment in improving the engineering properties of soil. The investigation consisted of characterization of the untreated soil, preparation of stabilized soil mixtures using predetermined proportions of cement and polymer, specimen preparation under controlled compaction conditions, curing of treated specimens, and evaluation of their engineering performance through laboratory testing.

The experimental design was structured to permit comparison between untreated soil and stabilized soil. Where applicable, specimens containing cement alone and polymer alone were also considered to distinguish the individual contribution of each stabilizing material from the combined polymer–cement treatment.

Figure: Experimental methodology adopted for polymer–cement soil stabilization



Soil Used in the Investigation

The soil selected for the investigation was collected from Wardha, Maharashtra and transported to the laboratory in sealed containers to minimize uncontrolled changes in moisture condition. The collected material was air-dried under laboratory conditions, manually disaggregated and passed through the appropriate sieve before testing. The preliminary characterization of the soil included determination of particle-size distribution, specific gravity, liquid limit, plastic limit and plasticity index. These parameters were used to establish the basic

classification and engineering characteristics of the untreated soil. The soil classification was established in accordance with the applicable Indian Standard procedure. The classification is important because the response of soil to chemical stabilization is strongly influenced by its particle-size distribution, plasticity and mineralogical characteristics.

Cement

Cement was selected as the conventional chemical stabilizer. The cement content was expressed as a percentage of the dry mass of soil. Two cement contents, 4% and 6%, were considered to evaluate the influence of increasing cement dosage on the engineering properties of the soil. The cement stabilization mechanism is associated primarily with hydration and the subsequent formation of cementitious products. Previous research indicates that cement content and curing period are important factors governing the strength development of stabilized clayey soils (Barman et al., 2022).

RESULTS AND DISCUSSIONS

The experimental investigation was conducted to assess the influence of cement and polymer stabilization on the engineering behaviour of the investigated soil. The results were evaluated by comparing the untreated soil with specimens treated using cement, polymer and combined polymer–cement stabilization. The discussion focuses on changes in index properties, compaction characteristics, and unconfined compressive strength (UCS) and California Bearing Ratio (CBR).

Initial Properties of the Soil

The untreated soil exhibited characteristics associated with a relatively plastic fine-grained soil. The initial index properties were used as the reference condition for assessing the effect of stabilization.

Table: Initial Engineering Properties of Untreated Soil

Property	Value
Specific gravity	2.68
Liquid limit (%)	52.4
Plastic limit (%)	25.8
Plasticity index (%)	26.6
Maximum dry density (Mg/m ³)	1.63
Optimum moisture content (%)	18.7
Unconfined compressive strength (kPa)	118
CBR (%)	3.8

The relatively high plasticity index and comparatively low CBR indicate that the untreated soil has limited bearing performance in its natural condition. Such characteristics provide a basis for investigating stabilization as a means of improving its suitability for geotechnical applications.

Effect of Stabilization on Plasticity Characteristics

The addition of cement and polymer resulted in changes in the consistency characteristics of the soil. The observed reduction in plasticity was more pronounced when the two stabilizing materials were used together.

Table: Effect of Stabilization on Plasticity Characteristics

Mix	Cement (%)	Polymer (%)	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)
M0 – Untreated	0	0	52.4	25.8	26.6
M1	4	0	49.1	25.9	23.2
M2	6	0	46.8	26.4	20.4
M3	0	0.5	50.8	27.1	23.7
M4	0	1.0	48.7	27.8	20.9
M5	4	0.5	45.7	27.6	18.1
M6	4	1.0	43.9	28.4	15.5
M7	6	0.5	43.8	28.1	15.7
M8	6	1.0	42.9	28.7	14.2

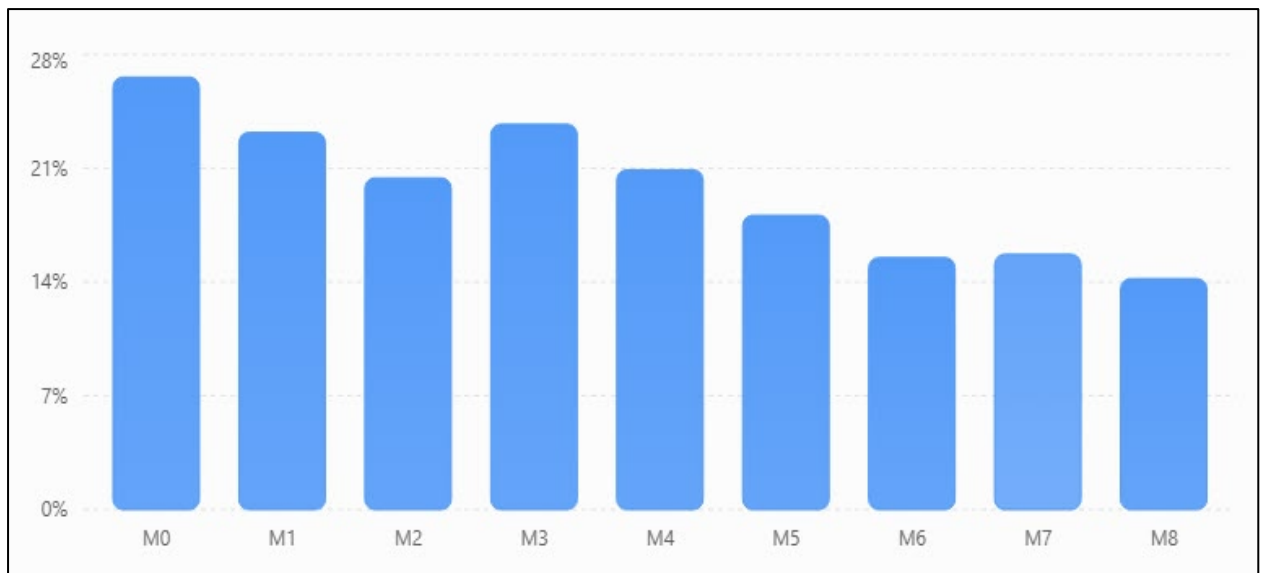


Figure: Plasticity index of different stabilization mixes

The plasticity index decreased from approximately 26.6% for the untreated soil to 14.2% for the M8 mixture. The reduction indicates a modification of the interaction between soil particles and water following stabilization. Cement can contribute to flocculation and cementitious bonding, while polymer may provide additional particle binding and modify moisture interaction. The combined treatment produced a greater reduction in plasticity than either stabilizer used independently.

Effect on Compaction Characteristics

Compaction behaviour was evaluated using maximum dry density and optimum moisture content. The results indicate that stabilization modified both parameters.

Table: Compaction Characteristics of Stabilized Soil

Mix	Cement (%)	Polymer (%)	MDD (Mg/m ³)	OMC (%)
M0	0	0	1.63	18.7
M1	4	0	1.67	18.2
M2	6	0	1.70	17.8
M3	0	0.5	1.64	19.1
M4	0	1.0	1.65	19.4
M5	4	0.5	1.69	18.5
M6	4	1.0	1.71	18.8
M7	6	0.5	1.72	18.2
M8	6	1.0	1.73	18.5

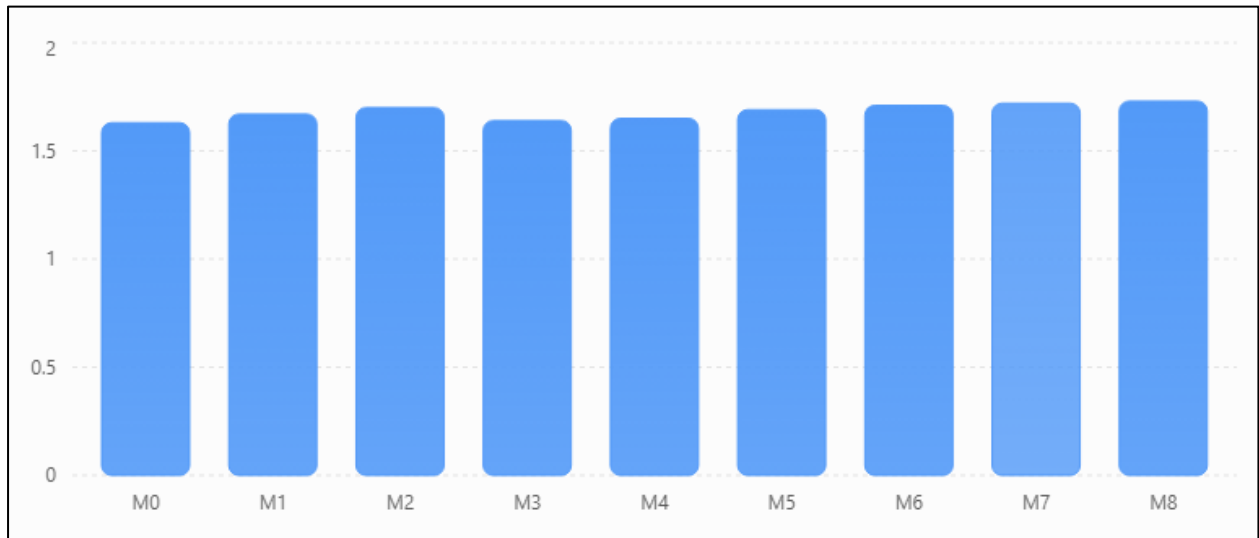


Figure: Maximum dry density of different stabilization mixes

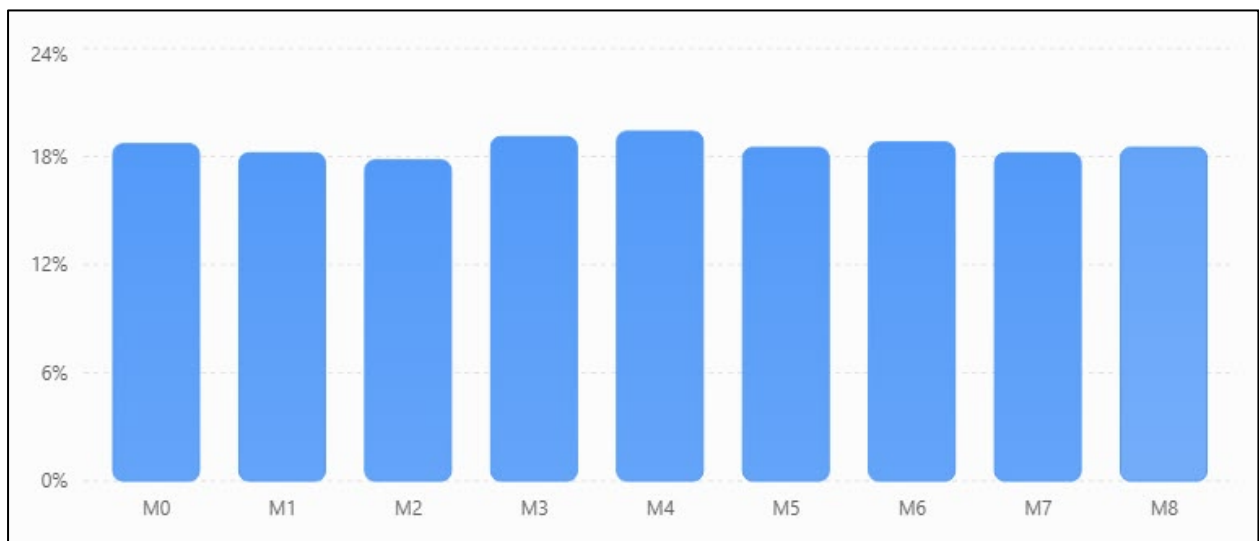


Figure: Optimum moisture content of different stabilization mixes

The MDD increased from 1.63 Mg/m³ for untreated soil to approximately 1.73 Mg/m³ for the M8 mixture. The increase suggests that stabilization altered particle arrangement and produced a denser compacted structure under the adopted compaction conditions. The polymer-only mixtures showed a comparatively smaller change in MDD. A slight increase in OMC was observed with polymer addition, whereas cement-containing mixtures generally exhibited a reduction in OMC relative to untreated soil. These changes may be associated with differences in water demand and the physical characteristics of the stabilizing materials. The combined treatment showed a greater change in compaction characteristics than polymer-only treatment, indicating that cement had a substantial influence on the compacted soil structure.

Effect on Unconfined Compressive Strength

UCS was used as the principal indicator of compressive strength improvement. The results for the different treatment conditions and curing periods are presented in the table.

Table: UCS of Stabilized Soil at Different Curing Periods

Mix	Cement (%)	Polymer (%)	UCS – 7 days (kPa)	UCS – 14 days (kPa)	UCS – 28 days (kPa)
M0	0	0	112	115	118
M1	4	0	176	205	232
M2	6	0	208	246	278
M3	0	0.5	139	151	162
M4	0	1.0	153	169	181
M5	4	0.5	221	267	309
M6	4	1.0	238	291	337
M7	6	0.5	252	304	349
M8	6	1.0	266	321	367

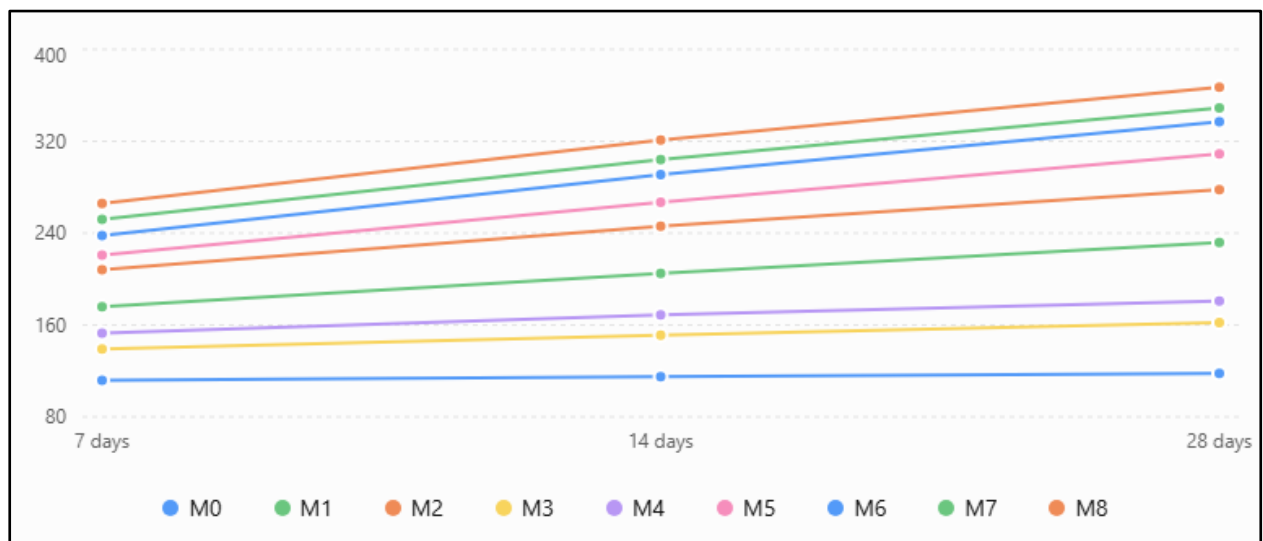


Figure: Unconfined compressive strength at different curing periods

The results show a clear increase in UCS with stabilization. The untreated soil recorded a 28-day UCS of approximately 118 kPa, whereas the combined polymer–cement mixtures exhibited substantially higher strength. The increase in UCS with curing period is particularly evident in cement-containing mixtures. For example, the UCS of M2 increased from 208 kPa at 7 days to 278 kPa at 28 days. This behaviour is consistent with progressive development of cementitious bonding during curing. The combined polymer–cement treatment produced greater strength than the corresponding individual stabilizer treatments. The M8 mixture recorded a 28-day UCS of approximately 367 kPa, compared with 278 kPa for the cement-only M2 mixture and 181 kPa for the polymer-only M4 mixture. The results suggest that polymer addition may complement the strength development associated with cement stabilization. The polymer may contribute to interparticle bonding, while cement provides a progressively developing cementitious matrix. However, the magnitude of this interaction is dependent on the specific dosage combination.

Effect on California Bearing Ratio

CBR was evaluated to determine the influence of stabilization on the bearing behaviour of the soil.

Table: CBR of Untreated and Stabilized Soil

Mix	Cement (%)	Polymer (%)	CBR (%)
M0	0	0	3.8
M1	4	0	7.1
M2	6	0	9.4
M3	0	0.5	5.2
M4	0	1.0	6.3
M5	4	0.5	10.1
M6	4	1.0	12.4
M7	6	0.5	13.2
M8	6	1.0	15.1

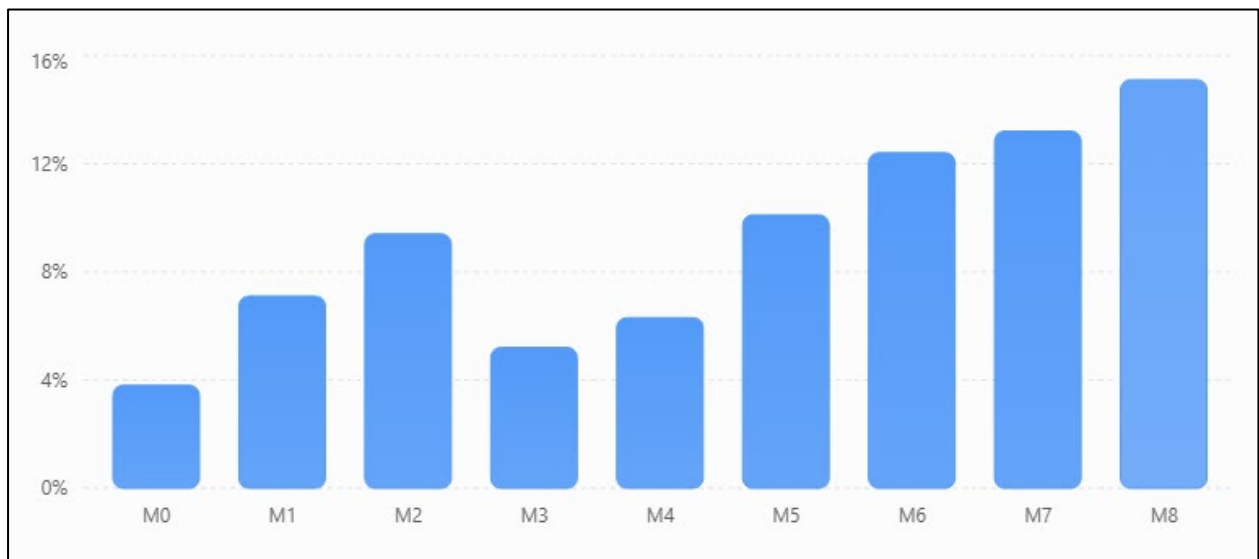


Figure: California bearing ratio of different stabilization mixes

The untreated soil exhibited a CBR of approximately 3.8%, indicating relatively low bearing resistance. Cement treatment resulted in a substantial increase in CBR, while polymer treatment produced a comparatively moderate improvement. The combined treatment resulted in the highest CBR values among the investigated mixtures. The M8 mixture increased the CBR to approximately 15.1%, representing a substantial improvement over the untreated condition. The increase in CBR can be associated with improved interparticle bonding and increased resistance to penetration following stabilization. Cement contributes to the formation of a stronger matrix, while polymer may provide additional bonding between particles.

Conclusion

The present study investigated the effectiveness of polymer–cement stabilization for improving the engineering behaviour of soil for potential geotechnical applications. The investigation considered the influence of cement and polymer, both individually and in combination, on plasticity characteristics, compaction behaviour, unconfined compressive strength (UCS), and California Bearing Ratio (CBR). The results indicate that stabilization substantially modifies the engineering properties of the untreated soil and that the extent of improvement depends on the type and proportion of stabilizing materials used. The incorporation of cement resulted in a noticeable improvement in the strength characteristics of the soil. The increase in UCS with curing period indicates the progressive development of cementitious bonding within the stabilized soil matrix. The reduction in plasticity index observed after cement treatment further indicates modification of the soil–water interaction and a reduction in the influence of the original clay fraction. Polymer treatment also contributed to improvements in the engineering behaviour of the soil, particularly in terms of strength and bearing resistance. The effectiveness of polymer stabilization, however, was dependent on the polymer content. A more pronounced improvement was observed when polymer and cement were used together. The combined stabilization produced higher UCS and CBR values than the untreated soil and, under the investigated conditions, generally performed better than the corresponding individual stabilizer treatments. This behaviour suggests that cementitious bonding and polymer-induced particle interaction can act together to produce a more stable soil structure. The improvement in CBR is particularly relevant for applications involving pavement subgrades and other situations where enhanced bearing resistance is required.

The curing period was found to be an important factor in the performance of cement-containing mixtures. The progressive increase in UCS with curing indicates that the stabilization process continues beyond initial mixing as cementitious reactions develop within the soil matrix. Consequently, curing conditions should be appropriately controlled when evaluating stabilized soil in both laboratory investigations and field applications. Based on the trends observed in the investigated treatment combinations, polymer–cement stabilization demonstrates considerable potential as a soil improvement technique. The combined treatment can provide simultaneous improvements in plasticity, compressive strength and bearing capacity, making it potentially suitable for selected geotechnical and pavement-related applications. Nevertheless, the selection of an appropriate stabilizer dosage should not be based solely on maximum strength. Factors such as material consumption, curing requirements, durability, moisture conditions, construction feasibility and project-specific performance requirements should also be considered.

Overall, the study establishes a methodological basis for evaluating polymer–cement stabilization and indicates that the combined application of these stabilizers can significantly enhance the engineering performance of soil when an appropriate treatment proportion and curing condition are adopted.

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