Mtech report

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

Ground improvement through chemical stabilisation has long been a primary remediation strategy for weak and problematic subgrade soils in infrastructure development. Conventional stabilisers such as cement, lime, and fly ash have historically dominated this domain, offering reliable strength enhancement through pozzolanic and cementitious reactions. The environmental impact of these interventions is substantial; Ordinary Portland Cement production alone releases approximately 0.85 to 0.95 kg CO_2 per kilogram manufactured. This significant carbon burden arises from the twin processes of limestone calcination and high-temperature kiln firing, both of which are thermodynamically unavoidable in conventional clinker production. Concerns over greenhouse gas emissions, alkaline leachate risks, and groundwater chemistry alteration have catalysed widespread interest in bio-derived alternatives capable of matching engineering performance at a fraction of the carbon footprint.

Stabiliser families are receiving growing criticism in the geotechnical engineering application, Among them polysaccharide-based biopolymers have established themselves as increasingly well-characterised options. When compared to traditional cementitious binders, they are derived from renewable agricultural produce and leave a significantly small carbon footprint per cubic meter of soil treated. Their engineering strongpoints far exceed their environmental benefits, their range of soil-modifying actions applied simultaneously sets them apart from conventional additives [1]. "Viscosity enhancement of porewater, electrostatic and hydrogen bond affinity to clay platelet surface, permeability reduction by throat bridging of pores and gel network development across particles have been observed across diverse soil types and biopolymer chemistries [2]."

Researchers also stated "Xanthan gum has been among the most thoroughly investigated biopolymers in geotechnical contexts. Under controlled laboratory conditions, xanthan gum treatment has produced UCS enhancements exceeding 200% and CBR gains surpassing 300% relative to untreated soils, with the magnitude of improvement governed by biopolymer concentration and curing duration." These gains arise from progressive dehydration of the biopolymer matrix and densification of the polymer film bridging adjacent particles, transitions that simultaneously stiffen the soil skeleton and reduce macropore connectivity [3]. Guar gum, though less extensively characterised than xanthan gum in the geotechnical literature, achieves analogous performance trajectories through a subtly distinct hydrogel architecture attributable to its galactomannan structure [4].

Guar gum is a galactomannan polysaccharide recovered from the endosperm of Cyamopsis tetragonoloba, a drought-tolerant leguminous crop cultivated extensively in arid and semi-arid agricultural zones of Rajasthan and Haryana, India. Its molecular structure consists of a beta-(1 to 4)-linked D-mannose backbone decorated with alpha-(1 to 6)-linked D-galactose side chains at a mannose to galactose molar ratio of approximately 2:1. This architecture provides an abundance of hydroxyl groups capable of forming hydrogen bonds with soil particle surfaces and pore water molecules. Upon hydration, the polymer undergoes physical swelling and chain entanglement, generating a viscous hydrogel that progressively stiffens as free moisture dissipates during curing. “This mechanism restricts particle rearrangement, reduces effective pore sizes, and improves the efficiency of interparticle stress transfer, collectively elevating both strength and stiffness without irreversible chemical reactions [5].”

Collapsible alluvium along the Yamuna floodplain poses persistent geotechnical challenges in Delhi’s rapidly expanding urban environment. Characterised by low dry density, open fabric, and susceptibility to strength loss upon wetting, this deposit type is poorly served by conventional stabilisation strategies given the scale of infrastructure demand and the ecological sensitivity of the floodplain corridor. The convergence of these technical and environmental imperatives motivates the present investigation into guar gum as a sustainable stabilising agent for Yamuna Basin soil.

1.2 PROBLEM STATEMENT

Conventional soil stabilisation techniques predominantly rely on chemical additives such as cement and lime to improve the strength and load-bearing capacity of weak soils. Although these stabilisers are effective from an engineering perspective, their large-scale application poses significant environmental and sustainability challenges. The production of cement and lime is highly energy-intensive and contributes substantially to global carbon dioxide emissions, thereby increasing the carbon footprint of geotechnical construction activities. In addition, the use of chemical stabilisers can alter the natural soil chemistry, potentially affecting long-term soil health and groundwater quality, concerns that are particularly acute in ecologically sensitive settings such as active floodplains.

In the context of the Yamuna Basin region of Delhi, the presence of weak soils further aggravates geotechnical design challenges. These soils typically exhibit low natural strength, poor bearing capacity, and high compressibility. Upon wetting or loading, poorly graded sand is prone to sudden volume reduction, leading to excessive settlement and structural distress in foundations, pavements, and embankments. The fine-grained and low-cohesion nature of the deposit makes it susceptible to erosion and strength degradation under varying moisture conditions, limiting its direct use as a construction material without prior treatment.

Despite the extensive deployment of conventional stabilisers for improving such problematic soils, their environmental drawbacks and cost implications restrict their sustainable application, particularly in urban and environmentally sensitive regions. There exists, therefore, a pressing need to explore eco-friendly and cost-effective soil stabilisation alternatives that can enhance the mechanical performance of collapsible silts while minimising environmental impact. The present study addresses this gap by investigating guar gum biopolymer as a sustainable stabilising agent for Yamuna Basin soil.

1.3 AIM AND OBJECTIVES

The primary aim of this study is to evaluate the effectiveness of guar gum biopolymer as an eco-friendly stabilising agent for improving the engineering properties of poorly graded sand obtained from the Yamuna Basin, Delhi, with specific focus on compaction behaviour, unconfined compressive strength, California bearing ratio, and microstructural characteristics.

The specific objectives of the study are as follows:

- To characterise the index and compaction properties of untreated Yamuna Basin silt.
- To prepare guar gum-treated soil specimens at dosages of 1.0% and 1.5% by dry soil weight and cure them for periods of 3, 7, and 21 days.
- To determine the effect of guar gum dosage and curing duration on unconfined compressive strength and to analyse the stress-strain response of treated and untreated specimens.
- To evaluate the influence of biopolymer treatment on California Bearing Ratio and load-penetration behaviour under confined conditions.
- To conduct Scanning Electron Microscopy analysis to identify the microstructural bonding mechanisms responsible for observed macroscale performance improvements.
- To perform a theoretical carbon emission analysis comparing guar gum stabilisation with conventional cement-based ground improvement and to assess the environmental viability of the proposed approach.
- To identify the optimal guar gum dosage and curing duration for sustainable stabilisation of Yamuna Basin soil.

1.4 SIGNIFICANCE OF THE STUDY

This investigation contributes to the growing body of research on sustainable ground improvement by demonstrating the potential of guar gum biopolymer as an environmentally responsible alternative to conventional chemical stabilisers. By focusing on poorly graded sand from the Yamuna Basin, the research addresses a soil type that poses persistent challenges to geotechnical construction due to its low strength, high compressibility, and vulnerability to moisture-induced collapse. The findings provide region-specific insights directly applicable to foundation and pavement design in similar alluvial environments across the Indo-Gangetic Plain.

From an engineering perspective, the study establishes quantitative relationships between guar gum content, curing duration, and improvements in compaction characteristics, unconfined compressive strength, and bearing capacity.

These data can assist practising engineers in selecting appropriate biopolymer dosages and curing periods for field applications. The use of low biopolymer contents of 1.0% and 1.5% highlights the feasibility of achieving meaningful strength enhancement with minimal material addition, a consideration of practical significance for cost-sensitive infrastructure projects.

From a sustainability perspective, the inclusion of a theoretical carbon emission analysis provides a quantitative basis for comparing the environmental footprint of biopolymer and cement-based stabilisation. The results support the adoption of bio-based stabilisers that reduce dependence on energy-intensive and carbon-heavy materials, contributing to the broader goal of low-carbon infrastructure development in India and comparable developing economies.

1.5 SCOPE AND LIMITATIONS

The present investigation is confined to laboratory-scale testing of Yamuna Basin silt treated with guar gum at two dosage levels and three curing durations. The experimental programme encompasses Standard Proctor compaction testing, UCS testing, CBR testing, and SEM analysis. Field-scale performance, long-term durability under wetting-drying or freeze-thaw cycles, and behaviour under dynamic loading have not been evaluated in the current scope. The carbon emission analysis is theoretical in nature and based on published emission factors; site-specific logistical factors such as transport distances and local energy mixes are not incorporated. Results are specific to the soil type characterised and may not be directly extrapolated to other alluvial deposits without verification.

1.6 ORGANISATION OF THE REPORT

This report is structured into seven chapters. Chapter 1 presents the introduction, problem statement, objectives, and scope of the work. Chapter 2 reviews the relevant literature on soil stabilisation, biopolymer-based ground improvement, and the specific use of guar gum in geotechnical applications. Chapter 3 describes the materials used, including the characterisation of Yamuna Basin soil and the properties of the guar gum biopolymer. Chapter 4 provides detailed step-by-step procedures for the laboratory tests conducted, following the relevant Indian Standard codes. Chapter 5 outlines the experimental programme, including sample collection, preparation, and testing methodology. Chapter 6 presents results and discussion, covering compaction behaviour, UCS performance, CBR response, SEM analysis, and carbon emission assessment. Chapter 7 summarises the conclusions drawn from the study and provides recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 SOIL STABILISATION: AN OVERVIEW

Soil stabilisation refers to a class of physical, chemical, and mechanical treatments applied to geomaterials whose natural engineering properties are insufficient for a given construction context. Historical records indicate that chemical stabilisation was practised as early as the Roman period, when burnt lime-based materials were incorporated into local subgrade soils to enhance road-bearing capacity. In modern geotechnical engineering, the most widely used chemical stabilisers include ordinary Portland cement, hydrated lime, and pozzolanic by-products such as fly ash and ground granulated blast furnace slag (GGBS). Each of these agents modifies soil behaviour through a combination of physicochemical processes. Cation exchange reduces plasticity in fine-grained soils by replacing monovalent ions with higher-valency cations. Clay particles subsequently undergo flocculation and agglomeration, resulting in a coarser, more workable fabric. Over longer curing periods, pozzolanic reactions between siliceous or aluminous soil constituents and calcium hydroxide yield calcium silicate hydrates (CSH) and calcium aluminate hydrates (CAH), which bind particles into a denser, more rigid matrix. Carbonation contributes additional stiffening where atmospheric CO_2 reacts with the alkaline pore solution. These mechanisms do not operate in isolation; their relative contributions depend on stabiliser type, dosage, soil mineralogy, and curing conditions.

Cement stabilisation is particularly effective for improving the short- and long-term strength of cohesive soils. At typical field dosages of 4 to 8% by dry soil weight, cement-treated clays and silts commonly achieve UCS values in the range of 0.5 to 3.0 MPa following 28-day curing, depending on soil mineralogy, cement content, and compaction effort. Lime stabilisation, by contrast, is most beneficial for high-plasticity clays where the associated reduction in plasticity and swell potential offers immediate construction benefits alongside long-term strength development. However, both cement and lime impose significant carbon penalties. The production of ordinary Portland cement releases approximately 0.85 to 0.95 kg CO_2 per kilogram of cement produced, a consequence of the twin processes of limestone calcination and high-temperature kiln firing at temperatures exceeding 1,450 degrees Celsius.

Concerns over the environmental footprint of conventional stabilisers, combined with growing regulatory pressure to reduce embodied carbon in infrastructure construction, have driven exploration of alternative ground improvement agents. Fibrous inclusions such as polypropylene and basalt fibres, industrial by-products such as rice husk ash, enzymatic solutions, and more recently, biopolymers derived from plant or microbial sources have each been investigated as lower-impact alternatives to traditional chemical stabilisers. Among microbial approaches, Microbially Induced Carbonate Precipitation (MICP) has demonstrated capacity to augment soil cohesion through biogenic calcite cementation, though practical challenges related to scalability, treatment uniformity, and bacterial culture management continue to limit field deployment [6].

2.2 BIOPOLYMER-BASED STABILISATION

Biopolymers represent a diverse class of naturally derived macromolecules produced by living organisms through biological processes. For geotechnical applications, the biopolymers of primary interest fall into two broad families: polysaccharides, which include xanthan gum, guar gum, beta-1,3/1,6-glucan, and starch, and microbially synthesised polymers such as polyhydroxyalkanoates. Polysaccharides are the most extensively investigated family for soil improvement, owing to their commercial availability, established safety profiles, biodegradability, and demonstrated ability to modify soil fabric at low dosages.

The geotechnical literature documents several overlapping mechanisms through which polysaccharide biopolymers modify soil behaviour. First, upon hydration, polysaccharide chains absorb pore water and undergo physical swelling, generating a viscous hydrogel within the pore space. This gel increases the viscosity of pore fluid, impedes drainage, and partially fills interparticle voids, reducing porosity and effective pore diameter. Second, the abundant hydroxyl groups present in most polysaccharide chains enable hydrogen-bond formation with soil particle surfaces, particularly the siloxane and aluminol surfaces of clay minerals. This interfacial bonding creates a coating layer around individual particles that stiffens relative particle movement. Third, upon progressive desiccation during curing, the hydrogel undergoes densification: water is expelled from the gel network, polymer chains undergo increased chain entanglement, and the gel transitions from a viscous to a viscoelastic and ultimately gel-glass state. The resulting material bridges adjacent particles across pore throats, creating load-bearing filaments and membrane-like structures that contribute to both cohesion and stiffness.

Xanthan gum, produced by fermentation of Xanthomonas campestris, has been the most thoroughly characterised biopolymer in geotechnical research. Published studies document UCS improvements ranging from 100% to over 300% relative to untreated soils, depending on xanthan gum concentration, soil type, and curing duration. The strong anionic character of xanthan gum enables additional electrostatic attraction to positively charged clay mineral edges, augmenting the hydrogen-bond-mediated coating mechanism. A consistent finding across xanthan gum studies is the strong dependence of strength gain on curing duration, with longer curing periods producing progressively higher UCS and CBR values as progressive dehydration densifies the interparticle gel network.

Chitosan, derived from the deacetylation of chitin present in crustacean shells, has shown effectiveness particularly in cohesive soils under wet conditions, where its cationic character enables strong electrostatic bonding to negatively charged clay surfaces. However, its performance in dry conditions and under prolonged curing has been reported to diminish due to hydro-degradability and a tendency to form brittle fibres rather than flexible gel networks. Sodium alginate, derived from brown seaweed, has demonstrated compressive strength improvements comparable to guar gum at optimum dosages, though its ionic cross-linking mechanism makes its performance more sensitive to the ionic strength of the pore fluid. Beta-glucan has shown promise in sandy soils, where its distinctive capacity to cross-link and form rigid gel structures provides bridging across coarser pore geometries where smaller-molecular-weight biopolymers may be less effective.

2.3 GUAR GUM IN GEOTECHNICAL APPLICATIONS

Guar gum, derived from the endosperm of Cyamopsis tetragonoloba, is one of the most commercially available and cost-effective natural polysaccharides worldwide. India accounts for approximately 80% of global guar production, with the crop extensively cultivated in Rajasthan, Haryana, and Gujarat. The powder form in which guar gum is typically supplied to industry is obtained by mechanically separating, grinding, and screening the endosperm fraction of the seed. Commercially, guar gum finds extensive application as a thickener and stabiliser in food processing, as a viscosifier in hydraulic fracturing fluids, and as a binder in textile and paper industries. The substantial volumes of off-specification or by-product guar gum generated across these industries represent an economically attractive, low-cost feedstock for geotechnical applications.

The geotechnical literature on guar gum stabilisation, while less extensive than that on xanthan gum, has expanded considerably in the past decade. A study by Banne, Kulkarni, and Baldovino evaluated guar gum treatment of laterite soil at contents ranging from 0.5% to 2.0% for subgrade applications, finding optimal CBR improvement at 1.5% dosage following extended curing. The observed CBR gains were attributed to gel network formation filling laterite pore spaces and augmenting the natural cementation between iron oxide-coated particles. A comparative investigation by Azimi, Soltani, and colleagues evaluating sodium alginate, xanthan gum, guar gum, and chitosan on high-plasticity clay found that guar gum achieved an optimal UCS improvement at a dosage of approximately 0.5%, somewhat lower than the other biopolymers investigated, consistent with its higher molecular weight and more rapid gel formation. Chandraprakash investigated the curing condition sensitivity of both xanthan gum and guar gum-treated black cotton soil, demonstrating that laboratory curing conditions producing progressive moisture loss yielded substantially higher strength gains than field curing with exposure to ambient humidity, underlining the importance of moisture management in biopolymer-treated subgrade applications.

Microstructural investigations using SEM have consistently confirmed that the macroscale strength improvements observed in biopolymer-treated soils are underpinned by identifiable changes in particle arrangement and interparticle contact character. Gel coating of individual particle surfaces, pore-throat bridging by desiccated polymer filaments, and aggregate cluster formation through biopolymer-mediated flocculation have been documented across multiple soil-biopolymer combinations.

These microstructural features collectively produce a hierarchical bonding architecture operating across multiple length scales simultaneously, from individual particle-scale hydrogen-bond coatings to aggregate-scale gel-filled pore networks, providing a physically coherent explanation for the observed enhancement in both stiffness and peak resistance.

The carbon footprint advantage of guar gum over conventional stabilisers has been highlighted in several recent life-cycle assessments. Published estimates place the embodied carbon of guar gum production in the range of 0.2 to 0.4 kg CO_2 per kilogram, accounting for cultivation, harvesting, processing, milling, and transport. At typical geotechnical treatment dosages of 1 to 2% by dry soil weight, this translates to per-cubic-metre emissions of 3 to 13 kg CO_2, compared with 72 to 115 kg CO_2 for cement stabilisation at conventional dosages. This order of magnitude reduction in embodied carbon positions guar gum stabilisation as a compelling candidate for low-carbon ground improvement, particularly in ecologically sensitive settings where the long-term soil alkalinity increases associated with cement and lime application are additionally concerning.

2.4 RESEARCH GAP AND PRESENT CONTRIBUTION

Despite the growing body of evidence supporting guar gum as an effective and sustainable stabiliser for fine-grained soils, several gaps in the existing literature motivate the present investigation. Studies specifically targeting Yamuna Basin alluvial weak poorly graded sand are sparse: the deposit's characteristically low dry density, open fabric, and susceptibility to collapse upon wetting distinguish it from the expansive clays, laterites, and loessic soils most commonly examined in biopolymer stabilisation literature. The applicability of performance trends documented for other soil types cannot be assumed without direct experimental verification. Furthermore, most existing guar gum studies have not combined mechanical performance assessment with SEM characterisation and carbon emission analysis within a single integrated investigation, limiting the completeness of conclusions that can be drawn regarding both technical and environmental performance. The present study addresses these gaps by providing a systematic, multi-criterion evaluation of guar gum stabilisation specifically for Yamuna Basin soil, integrating mechanical testing, microstructural analysis, and environmental assessment within a coherent experimental framework.

CHAPTER 3

MATERIALS

3.1 YAMUNA FLOODPLAIN SOIL

The soil used throughout this investigation was collected from the Yamuna floodplain in Delhi, India, where near-surface alluvial deposits are routinely encountered during geotechnical construction. The Yamuna floodplain in Delhi represents a geomorphologically active sedimentary environment where repeated cycles of deposition during seasonal flood events have produced stratified alluvial sequences dominated by poorly graded sand and silt with limited clay mineral content. The absence of significant mineralogical cementing agents and the characteristically open, low-density fabric of these deposits make them susceptible to collapse upon saturation, a behaviour of direct relevance to their performance as pavement subgrades and building foundation soils.

Disturbed surface soil was discarded, and sampling was excavated from a depth of approximately 0.5 m below ground level to minimise organic matter contamination and to obtain material representative of the near-surface alluvial stratum encountered in shallow foundation and pavement construction contexts. Retrieved bulk samples, totalling approximately 30 kg, were sealed in polyethylene bags and transported promptly to the laboratory to preserve in-situ moisture state.

Laboratory preparation involved air-drying in trays under ambient conditions until constant mass was attained, gentle manual disaggregation of dried lumps without crushing individual particles, and sieving through a 4.75 mm IS sieve to remove any coarse gravel and debris. The specific gravity of the soil solids, determined using the pycnometer method, measured 2.54, indicating the dominance of quartz and feldspar mineral fractions typical of alluvial origin. The natural bulk unit weight was approximately 1.6 g per cubic centimetre. Standard Proctor compaction testing in accordance [7] established a maximum dry density of 1.6 g per cubic centimetre at an optimum moisture content of 7.2%. Particle size distribution, determined by sieve analysis, confirmed a gradation dominated by poorly graded sand and silt fractions [8]. The overall index and compaction characteristics are consistent with collapsible alluvial silt exhibiting low dry density, open particle arrangement, and susceptibility to sudden volume reduction upon saturation.

Fig. 3.1 Sample collection site

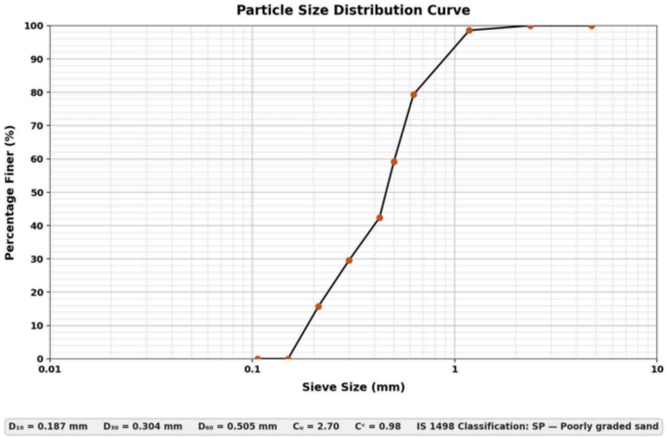


Fig. 3.2 Particle size distribution curve

3.2 GUAR GUM BIOPOLYMER

Commercially available guar gum in dry powdered form was procured from a local supplier and used without any chemical pre-treatment or modification. The material was derived from the endosperm of Cyamopsis tetragonoloba and conformed to food and industrial grade specifications, consistent with the biopolymer source employed in comparable geotechnical investigations reported in the literature. Food-grade guar gum powder is particularly suitable for geotechnical research applications because its production specifications ensure controlled molecular weight distribution and consistent viscosity characteristics, reducing batch-to-batch variability relative to lower-grade industrial products.

The molecular structure of guar gum comprises a linear backbone of beta-(1 to 4)-linked D-mannose units with alpha-(1 to 6)-linked D-galactose side chains at a mannose to galactose ratio of approximately 2:1. This galactomannan architecture provides an abundance of hydroxyl groups along both the backbone and side chains, enabling strong hydrogen-bond interactions with soil particle surfaces and pore water molecules. The high molecular weight of guar gum, typically in the range of 1 to 2 million Daltons, contributes to rapid viscosity development upon hydration and effective pore space occupation at relatively low dosage levels.

Upon contact with water, guar gum rapidly hydrates and swells, forming a viscous hydrogel through the absorption of free water into its polymeric network. This hydration process is physical in nature and involves no chemical degradation or exothermic reactions. The hydrated guar gum increases the effective viscosity of pore fluid and forms a continuous gel matrix within the soil pores. Unlike ionic biopolymers, guar gum does not rely on cation exchange or electrostatic attraction; instead, it stabilises soil primarily through polymer entanglement and viscous gel-mediated bonding, contributing to improved ductility and toughness alongside enhanced peak strength.

The powder was incorporated into the soil in dry form prior to moisture conditioning. This dry-mixing protocol was adopted to ensure uniform distribution throughout the soil matrix before water addition initiated hydration and gel formation, a preparation sequence demonstrated to produce more homogeneous treatment than wet-slurry methods at the dosage levels considered. Treatment dosages of 1.0% and 1.5% by dry soil weight were selected based on the effective concentration range reported in the biopolymer stabilisation literature for silt-dominated soils; dosages below 1.0% have generally yielded marginal strength gains, while concentrations above 2.0% have been associated with diminishing returns or localised polymer agglomeration. No supplementary binders, fibres, or chemical activators were used in combination with the biopolymer.

CHAPTER 4

TEST PROCEDURES AS PER INDIAN STANDARD CODES

The three principal mechanical laboratory tests employed in this study, namely the Standard Proctor Compaction Test, the Unconfined Compressive Strength Test, and the California Bearing Ratio Test, were each conducted strictly in accordance with the corresponding Indian Standard codes. The procedures described below provide a comprehensive step-by-step account of each test as performed by a geotechnical engineer, including apparatus requirements, specimen preparation, testing protocol, and calculation methodology. Adherence to standardised procedures ensures reproducibility, enables comparison with published data, and provides a defensible basis for drawing conclusions regarding the engineering performance of treated and untreated specimens.

4.1 STANDARD PROCTOR COMPACTION TEST (IS 2720 PART 7: 1980)

4.1.1 Objective and Relevance

The compaction behavior of the soil samples was determined using the Standard Proctor Compaction Test in accordance [7]. Initially, the collected soil was air-dried under laboratory conditions and crushed manually to break down the soil lumps without altering the natural grain size. The processed soil was then passed through the 4.75 mm sieve to obtain a uniform sample suitable for testing.

Predetermined quantity of water was added to the dry soil to get known moisture content to initiate the test. The soil-water mixture was thoroughly blended to ensure uniform distribution of moisture throughout the sample. After mixing, the prepared soil was kept in a sealed condition for sufficient time to allow moisture equilibrium.

The compaction mould was brushed cleaned properly and weight was recorded before placing the soil. The moist soil was filled into the mould in 3 equal layers. Each layer was compacted uniformly by applying the 25 number of hammer blows using the 2.5 kg rammer dropped from 310 mm height. Care was taken to distribute the blows evenly over the entire surface of each layer to achieve uniform compaction.

After compaction of the final layer, the excess soil projecting above the mould was trimmed carefully using a straight edge. The total weight of the mould along with compacted soil was measured. A representative soil sample was collected from the compacted specimen for moisture content determination.

The same procedure was repeated for different moisture contents in order to obtain the variation between dry density and water content. Using the experimental observations, the dry density corresponding to each moisture content was calculated and the compaction curve was plotted. From the resulting curve, the optimum moisture content (OMC) and maximum dry density (MDD) of the soil were determined.

4.2 UNCONFINED COMPRESSIVE STRENGTH TEST (IS 2720 PART 10: 1991)

4.2.1 Objective and Relevance

The unconfined compressive strength behaviour of the untreated and treated soil specimens was evaluated through laboratory testing conducted as per [9]. Initially, the required quantity of dry soil was mixed thoroughly with water to achieve working moisture condition. For treated specimens, the required percentage of Guar Gum was added carefully and mixed uniformly to ensure proper distribution throughout the soil matrix.

The prepared soil mixture was compacted into cylindrical moulds having dia 38 mm and height 76 mm satisfying the ratio of 2 to 1. The specimens were extracted carefully from the moulds to avoid disturbance and were then subjected to loading.

Before testing, the dimensions and weight of each specimen were measured. The specimen was then placed centrally on the loading platform of the unconfined compression testing machine. Axial load was applied vertically at a constant strain rate without any lateral confinement.

During loading, the deformation and corresponding load values were recorded continuously until the specimen exhibited clear failure or reduction in load carrying capacity. The maximum axial load sustained by the specimen was noted for determining the unconfined compressive strength.

The compressive strength of each specimen was calculated by dividing the peak load by the corrected cross-sectional area of the specimen. The observed failure patterns and deformation characteristics were also noted during the testing process. Multiple specimens were tested under similar conditions and the average value was considered for analysis and interpretation.

4.2.2 Calculations

For each data point, calculate the corrected cross-sectional area using the formula: $A = A_0 / (1 - \varepsilon)$, where A_0 is the initial cross-sectional area and ε is the axial strain (deformation divided by initial height). Calculate the axial stress at each point as the measured load divided by the corrected area. Plot the stress-strain curve and identify the peak stress as the UCS. Calculate the percentage improvement in UCS for treated specimens relative to the untreated baseline as: % improvement = 100 × (UCS$_{tr}^{eated}$ − UCS$_{u}^{ntReated}$) / UCS$_{u}^{ntReated}$.

4.3 CALIFORNIA BEARING RATIO TEST (IS 2720 PART 16: 1987)

4.3.1 Objective and Relevance

The California Bearing Ratio test was conducted to evaluate the load-deformation behavior of the soil under simulated field conditions. The test procedure was carried out in accordance with . Initially, the soil sample was prepared by air drying and manual crushing to remove lumps and achieve uniformity. Water corresponding to optimum moisture condition was added gradually and mixed thoroughly with the soil.

The prepared soil was compacted into the CBR mould in 5 layers using 2.6 kg rammer. Each layer was compacted uniformly to ensure proper density throughout the specimen. After completion of compaction, the top surface was levelled carefully and surcharge weights were placed over the specimen to simulate field overburden conditions.

The penetration test was then performed using the CBR testing machine. The loading plunger was allowed to penetrate the soil specimen at a constant rate of penetration. The load values corresponding to different penetration depths were recorded continuously throughout the test.

The CBR value was calculated as the ratio of the experimentally obtained load to the standard load corresponding to the same penetration level. Generally, the values at 2.5 mm and 5 mm penetrations were determined, and the higher appropriate value was adopted for analysis. The obtained results were further used to evaluate the suitability of the soil for pavement and subgrade applications.

4.3.2 Reporting

Report the load at each standard penetration depth (2.5 mm and 5.0 mm) along with the corresponding CBR values and the adopted CBR. For comparative biopolymer stabilisation studies, report the full load-penetration curves for treated and untreated specimens on the same axes, as the shape of the curve carries information about stiffness, brittleness, and ductility that the CBR index value alone does not capture. Calculate percentage improvement in load at each penetration depth relative to the untreated reference.

CHAPTER 5

EXPERIMENTAL PROGRAMME

5.1 SAMPLE COLLECTION AND PREPARATION

The soil sample used in the experimental programme was collected from the Yamuna Basin region of Delhi, India. The sampling site was located within the active floodplain zone, where near-surface alluvial deposits are regularly encountered during geotechnical investigations for urban infrastructure projects. Sampling was conducted manually by excavating the ground to a depth of approximately 0.5 m below the existing ground surface, ensuring that the sampled material was representative of the in-situ near-surface stratum and uninfluenced by surface vegetation, root zone organics, or loose disturbed fill. Approximately 30 kg of bulk soil was collected in batches, placed in sealed polyethylene bags immediately after extraction, and transported to the geotechnical engineering laboratory at Delhi Technological University without unnecessary delay to preserve the in-situ moisture condition.

In the laboratory, the collected bulk sample was air-dried by spreading it in thin layers in large galvanised trays under ambient laboratory conditions until constant mass was attained, typically over a period of 48 to 72 hours. Following air-drying, the soil was gently disaggregated by hand and passed through a 4.75 mm IS sieve to remove any coarse gravel, root fragments, or debris. The air-dried, sieved soil was stored in sealed containers for use in subsequent testing.

Basic index and compaction properties were determined from representative sub-samples: specific gravity by the pycnometer method (IS 2720 Part 3), grain size distribution by dry sieve analysis (IS 2720 Part 4), and compaction characteristics by the Standard Proctor test (IS 2720 Part 7). These characterisation tests established the properties summarised in Table 1, which served as the reference baseline for all subsequent stabilisation investigations.

Table 5.1: Index and Compaction Properties of Yamuna Basin Soil

Property	Value
Specific Gravity	2.54
Natural Bulk Unit Weight (g/cm³)	1.6
Maximum Dry Density, MDD (g/cm³)	1.6
Optimum Moisture Content, OMC (%)	7.2
Predominant Particle Size	Poorly graded sand
Classification	Collapsible alluvial sand

5.2 SPECIMEN FABRICATION PROTOCOL

The guar gum biopolymer powder was weighed accurately using an electronic balance with 0.01 g resolution to achieve target dosages of 1.0% and 1.5% by dry soil weight. For each batch, the required quantity of guar gum was first dry-blended with the oven-dried soil in a clean tray using a spatula and manual kneading, ensuring uniform distribution of the biopolymer throughout the soil mass before any water was introduced. This dry-mixing sequence was maintained consistently across all batches to prevent premature localised hydration of the biopolymer that could result in gel agglomerates and non-uniform treatment.

Following dry-mixing, water was added gradually to the soil-biopolymer blend to attain the target moisture content of 7.2% (the OMC of untreated soil). The mixture was blended continuously during water addition and then transferred to sealed polyethylene bags for a minimum equilibration period of 30 minutes to allow uniform moisture distribution and initial hydration of the biopolymer. After equilibration, specimens were prepared for UCS and CBR testing following the procedures described in Chapter 4.

Prepared and sealed specimens were cured for designated periods of 3, 7, and 21 days at ambient laboratory temperature of approximately 25 degrees Celsius. Three replicate specimens were prepared for each treatment condition and curing period to assess reproducibility, and the mean of three replicate test results was reported for each condition. Following the curing period, specimens were unwrapped immediately prior to testing to minimise surface moisture loss between unwrapping and test commencement.

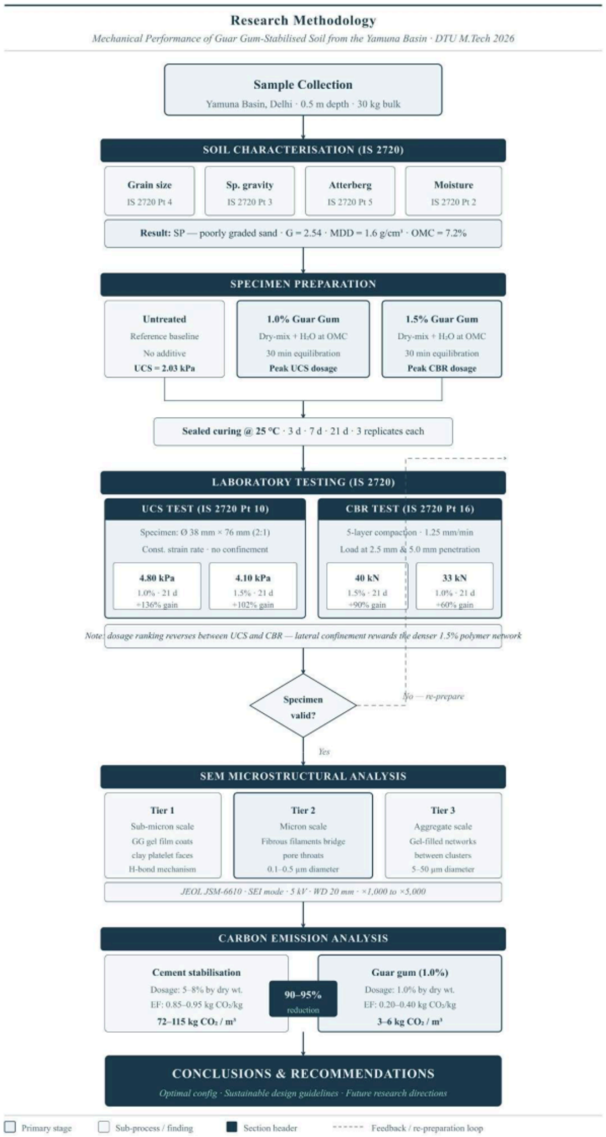


Fig. 5.1 Research Methodology

CHAPTER 6

RESULTS AND DISCUSSION

6.1 COMPACTION CHARACTERISTICS

Standard Proctor compaction testing of both untreated and guar gum-treated specimens revealed that biopolymer addition at dosages of 1.0% and 1.5% produced only marginal shifts in compaction behaviour. For untreated Yamuna Basin silt, the maximum dry density (MDD) was established at 1.6 g per cm^3 at an optimum moisture content (OMC) of 7.2%. These values are characteristic of poorly graded silty alluvium with low clay mineral activity and limited capacity for water-holding at the capillary scale.

The insensitivity of compaction characteristics to biopolymer addition at these dosage levels is consistent with the non-cementitious, physically reversible bonding mechanism of guar gum. Unlike cementitious stabilisers, which alter the packing geometry of particles through flocculation and the formation of cementitious bridges that stiffen the soil matrix before compaction, guar gum acts primarily after compaction during the curing phase. During compaction itself, the hydrated guar gum gel behaves as a viscous pore fluid that does not mechanically stiffen the soil matrix sufficiently to alter the soil's compaction response at these low dosage levels. This behaviour favourably distinguishes guar gum from cementitious stabilisers, which often require modification of field compaction protocols to accommodate altered OMC and MDD values.

6.2 UNCONFINED COMPRESSIVE STRENGTH

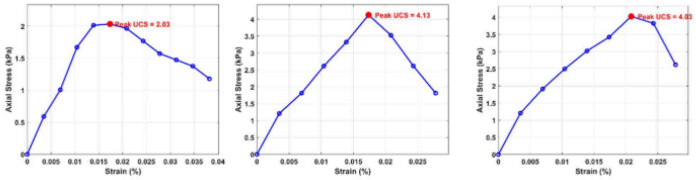
6.2.1 Untreated Soil

Prior to biopolymer addition, the untreated Yamuna Basin silt was tested to establish a baseline. The stress-strain response exhibited gradual, diffuse yielding without a well-defined peak, consistent with the loose, unbonded fabric of collapsible alluvium. A peak UCS of 2.03 kPa was recorded. This relatively modest strength value reflects the open, low-density fabric typical of collapsible silty alluvium: without mineralogical cementing agents or clay mineral-mediated cohesion to bridge interparticle contacts, the soil relies primarily on frictional resistance at particle contacts for its limited load-carrying capacity [10].

6.2.2 Effect of Curing at 3 Days

At 3 days of curing, both dosage levels produced measurable UCS gains relative to the untreated control, confirming that early-stage biopolymer-soil interaction is sufficient to initiate meaningful strength development. The 1.0% guar gum specimens achieved a UCS of approximately 3.11 kPa, representing an improvement of approximately 53% relative to the untreated baseline. This early-stage gain is attributable to the onset of hydrogen bonding between guar gum hydroxyl groups and particle surfaces, progressive gel formation within pore spaces, and incipient interparticle cross-bridging.

At 1.5% guar gum, the 3-day UCS reached approximately 3.02 kPa, corresponding to an improvement of approximately 49%, marginally below the 1.0% result. Despite this slight reduction in peak strength, specimens at the higher dosage displayed greater post-peak ductility and a more gradual load-shedding trajectory. This behaviour indicates that the denser polymer network formed at elevated concentrations distributes deformation more uniformly across the soil-polymer composite [11].



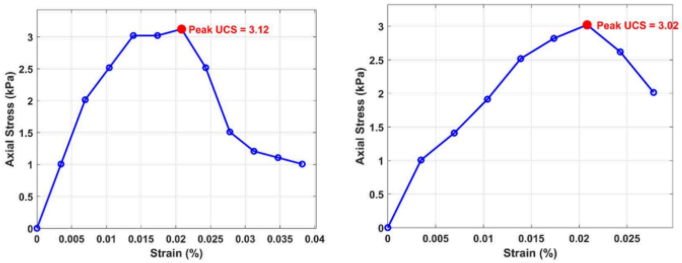
(a) (b) (c)

Fig. 6.1 UCS stress-strain curves: (a) untreated soil; (b) 1% GG at 3 days; (c) 1.5% GG at 3 days.

6.2.3 Effect of Curing at 7 Days

Extending curing to 7 days yielded substantially higher UCS values at both dosages, reflecting time-dependent densification of the soil-polymer matrix as free moisture progressively dissipates and polymer chains develop increased entanglement and stiffness. The 1.0% guar gum specimens achieved a peak UCS of 4.13 kPa, an improvement of approximately 103% over the untreated baseline. The corresponding stress-strain curves display a markedly steeper pre-peak gradient and a more pronounced peak compared to 3-day specimens.

The 1.5% guar gum mix produced a 7-day UCS of approximately 4.03 kPa, corresponding to an improvement of approximately 99%. While the absolute peak strength falls slightly below that of the 1.0% specimens, the 1.5% treatment conferred superior post-peak ductility and strain accommodation, consistent with the dosage-dependent trade-off between peak-strength optimisation and enhanced deformation tolerance documented in recent biopolymer optimisation studies [12].



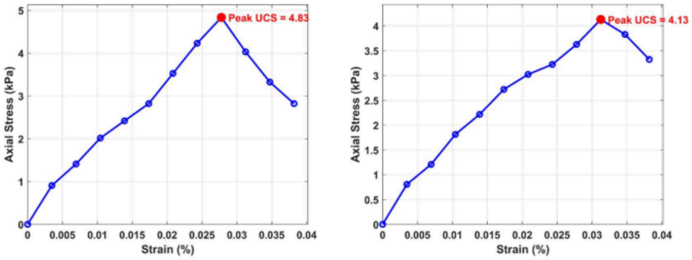
(a) (b)

Fig. 6.2 UCS stress-strain curves at 7 days: (a) 1% GG; (b) 1.5% GG.

6.2.4 Effect of Curing at 21 Days

The 21-day curing period produced the highest UCS values recorded across all treatment conditions. For the 1.0% guar gum mix, peak strength reached approximately 4.80 kPa, a 136% improvement over the untreated soil. Three weeks of curing represents a meaningful threshold for this soil-polymer system: as specimens progressively lost pore moisture, the initially viscous guar gum gel underwent gradual densification, stiffening at particle contact points and tightening its anchorage within the irregular geometry of pore channels.

At 1.5% guar gum, the 21-day UCS reached approximately 4.10 kPa, a 102% improvement. The slightly lower peak strength compared to the 1.0% treatment is consistent with the hypothesis of localised polymer accumulation at higher dosages, where excess gel may partially decouple adjacent particles rather than uniformly reinforce the matrix. Despite this, the 1.5% specimens exhibited greater strain energy capacity and improved post-peak stability [13].



(a) (b)

Fig. 6.3 UCS stress-strain curves at 21 days: (a) 1% GG; (b) 1.5% GG.

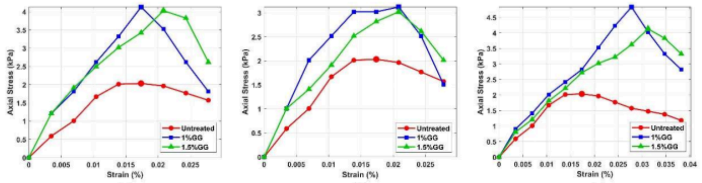


Fig. 6.4 UCS comparison: untreated vs. GG-treated at (a) 3 days; (b) 7 days; (c) 21 days.

Table 6.1: Summary of Unconfined Compressive Strength Results

Curing Period (days)	Guar Gum Dosage (%)	UCS (kPa)	Improvement over Untreated (%)
0	0 (Untreated)	2.03	0
3	1.0	3.11	53
3	1.5	3.02	49
7	1.0	4.13	103
7	1.5	4.03	99
21	1.0	4.80	136
21	1.5	4.10	102

6.3 CALIFORNIA BEARING RATIO

6.3.1 Untreated Soil

The untreated Yamuna Basin silt exhibited a load-penetration response characteristic of weakly bonded, low-density alluvium. Load increased gradually and approximately linearly with penetration across the 0 to 6 mm penetration range, reaching approximately 21 kN at 6 mm. There was no distinct peak or plateau in the load-penetration response of untreated soil, consistent with a frictionally dominated, unbonded granular-silt assembly.

6.3.2 Results at 3-Day Curing

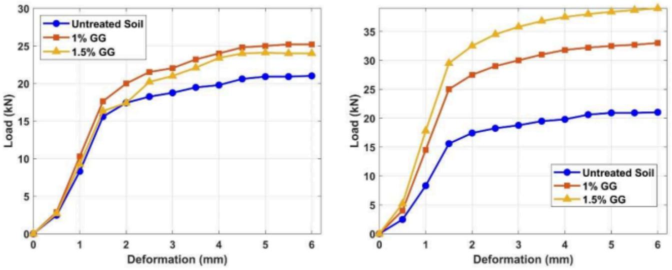
After 3 days of curing, both treatment levels produced discernible improvements in load resistance across the 0–6 mm penetration range (Fig. 8(a)). The 1.0% guar gum mix reached approximately 25 kN at 6 mm penetration, a 24% improvement over the untreated baseline, with the enhanced stiffness becoming particularly evident beyond 1 mm penetration. This early-stage improvement reflects the initial development of the biopolymer network, wherein partial hydration and gel formation begin reinforcing the soil matrix and improve stress transfer capacity [14].

The 1.5% treatment achieved approximately 26 kN at 6 mm, a marginally greater improvement (approximately 27%), though the difference between the two dosages at this early curing stage was modest. Ongoing dehydration and polymer chain densification with continued curing are expected to amplify these initial gains, a trajectory consistent with observations from biopolymer-treated soils in the literature [15].

6.3.3 Results at 21-Day Curing

By 21 days, the divergence between treated and untreated specimens had grown substantially. The untreated soil response remained essentially unchanged from its 3-day behaviour, confirming that unassisted curing produces negligible strength gain in this deposit. In contrast, the 1.0% guar gum treatment reached approximately 33 kN at 6 mm penetration, a 60% improvement. The load-penetration curve for this mix displays a relatively steep initial gradient up to approximately 2.5 to 3.0 mm, indicating that the matured biopolymer matrix mobilises penetration resistance at lower strain levels than untreated soil.

The 1.5% guar gum mix at 21 days achieved the highest measured load resistance of all CBR specimens, approaching 40 kN at 6 mm penetration, an improvement of approximately 90% over the untreated reference. The reversal of the dosage ranking between CBR and UCS reflects the multiaxial confinement conditions inherent in CBR testing. Under lateral confinement, the more flexible and strain-tolerant polymer network formed at higher dosage accommodates deformation while sustaining elevated load, an attribute that becomes more pronounced as the matured gel network at 21 days reaches its full load-carrying capacity [16].



(a)

(b)

Fig. 6.5 CBR load–penetration curves: (a) untreated vs. GG-treated at 3 days; (b) untreated vs. GG-treated at 21 days.

Table 6.2: Summary of California Bearing Ratio Load-Penetration Results

Curing Period (days)	Guar Gum Dosage (%)	Load at 6 mm Penetration (kN)	Improvement over Untreated (%)
0	0 (Untreated)	21	0
3	1.0	25	24
3	1.5	26	27
21	1.0	33	60
21	1.5	40	90

6.4 SCANNING ELECTRON MICROSCOPY ANALYSIS

Scanning Electron Microscopy analysis was conducted on 1.0% guar gum-treated specimens cured for 21 days using a JEOL JSM-6610 instrument in secondary electron imaging (SEI) mode at an accelerating voltage of 5 kV and a working distance of 20 mm. Magnifications ranging from 1,000× to 5,000× were selected to characterise bonding features operating across multiple length scales simultaneously. SEM imaging of the untreated soil was also conducted as a reference.

At 1,000× magnification (Fig. 9a), the overall aggregate fabric of the 21-day treated specimen is visible. Compared to the untreated reference, which shows a loose assemblage of angular to sub-angular silt and sand particles with large unfilled pore spaces, the treated specimen exhibits a more consolidated aggregate structure in which particle clusters are interconnected by continuous material filling inter-aggregate pore spaces.

At 5,000× magnification focusing on clay platelet regions (Fig. 9b), thin translucent films are visible coating the faces of individual clay-sized mineral particles. These coatings are identifiable as desiccated guar gum gel layers, consistent with the hydrogen-bonding interaction between the biopolymer's abundant hydroxyl groups and the siloxane and aluminol surfaces of clay platelets [17]. This sub-micron coating is the first level of the hierarchical bonding structure identified in the treated specimen.

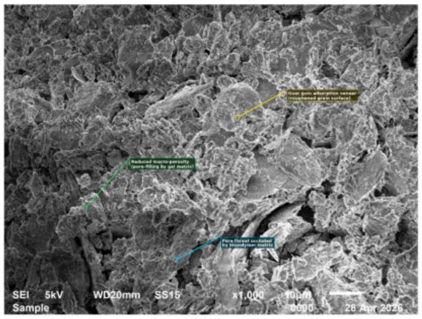
At 3,500× magnification at the aggregate-pore interface (Fig. 9c), the boundary between a silt-particle aggregate cluster and an adjacent pore space shows a continuous gel membrane spanning the pore opening. This membrane acts simultaneously as a physical barrier to plunger-induced pore compression and as a tensile element resisting separation of adjacent aggregate clusters.

At 5,000× magnification in regions of higher local polymer concentration (Fig. 9d), a three-dimensional fibrous skeleton is visible spanning inter-aggregate voids. This fibrous network represents the desiccated remnant of a load-bearing hydrogel that occupied those voids during the cured-wet state. The fibre diameters, ranging from approximately 0.1 to 0.5 micrometres, are consistent with polymer chains or small bundles thereof that have undergone chain entanglement and cross-linking during progressive dehydration.

At 5,000× magnification examining slender bridging features across pore throats (Fig. 8e), extremely thin dried filaments are visible tethering adjacent cluster faces. These ultra-thin filaments, estimated at 50 to 200 nanometres in diameter, simultaneously narrow the effective pore aperture and add tensile resistance against separation of bonded units.

At 1,500× magnification over a broader field of view (Fig. 8f), the macro-scale flocculated fabric produced by biopolymer-mediated inter-aggregate bonding is apparent. Multiple aggregate clusters of 5 to 50 micrometres in diameter are visible, separated by partially filled pore spaces, and interconnected at their boundaries by the gel network features described above.

The microstructural evidence collectively supports a three-tier hierarchical bonding model for the guar gum-treated Yamuna silt at 21 days of curing. At the sub-micron scale, hydrogen-bonded gel coatings on individual particle surfaces modify the surface energy and create a bonded rather than purely frictional contact at each interparticle junction. At the micron scale, fibrous gel filaments bridge pore throats and contribute tensile resistance and pore-size reduction. At the aggregate scale, gel-filled or gel-bridged pore networks between flocculated particle clusters produce macroscopic cohesion and stiffness enhancement. It is the simultaneous operation of bonding mechanisms at all three length scales that underlies the 136% UCS gain and the 60 to 90% CBR improvement measured at 21 days.



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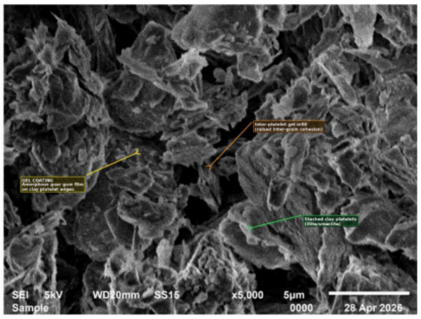

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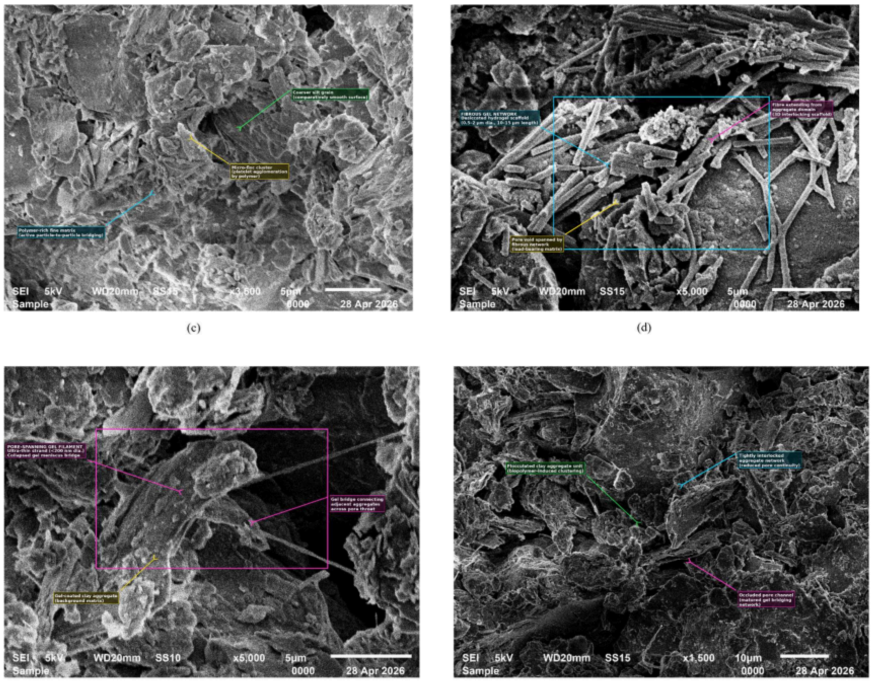

(c) (d)

(e) (e)

Fig. 6.6 SEM micrographs of 1% guar gum-treated Yamuna silt cured for 21 days: (a) overall aggregate fabric at ×1,000; (b) clay platelet morphology and gel coating at ×5,000; (c) aggregate-pore interface at ×3,500; (d) fibrous gel network in pore space at ×5,000; (e) ultra-thin gel filament bridging at ×5,000; (f) macro-scale flocculated fabric at ×1,500. All images acquired using JEOL JSM-6610, SEI mode, 5 kV, WD 20 mm.

6.5 THEORETICAL CARBON EMISSION AND SUSTAINABILITY ASSESSMENT

A theoretical carbon emission analysis was undertaken alongside the mechanical performance evaluation to quantify the environmental benefit of substituting conventional cementitious stabilisers with guar gum. This analysis follows a simplified cradle-to-treated-ground boundary, accounting for the embodied carbon in the stabiliser material itself without incorporating construction machinery emissions or end-of-life considerations, consistent with the scope adopted in comparable published life-cycle assessments.

Portland cement production releases approximately 0.85 to 0.95 kg CO_2 per kilogram manufactured, a consequence of the coupled energy demands of high-temperature clinker production at approximately 1,450 degrees Celsius and the release of CO_2 during limestone calcination, which alone accounts for approximately 60% of total cement production emissions. With global cement demand projected to grow in tandem with infrastructure expansion in developing economies, the cumulative climate burden of cement-based ground improvement is substantial and growing [18].

For quantitative comparison, emission estimates were computed for one cubic metre of stabilised soil under each stabiliser scenario. In conventional practice, cement is typically applied at 5 to 8% by dry soil weight for soft soil improvement. At a representative dry soil density of 1,600 kg per cubic metre, this corresponds to a cement mass of 80 to 128 kg per cubic metre of treated soil. Applying an average emission factor of 0.90 kg CO_2 per kg cement yields estimated emissions of 72 to 115 kg CO_2 per cubic metre of stabilised ground [19].

Guar gum's agricultural origin and comparatively simple processing chain result in substantially lower embodied carbon. Published life-cycle estimates place guar gum production emissions in the range of 0.2 to 0.4 kg CO_2 per kilogram. At the optimal 1.0% dosage established in this study, guar gum consumption amounts to approximately 16 kg per cubic metre of treated soil (1,600 $kg/m^3 \times 0.01$). Accordingly, total estimated CO_2 output for guar gum stabilisation ranges from approximately 3.2 to 6.4 kg per cubic metre, a reduction of 90 to 95% relative to cement stabilisation.

Table 6.3: Comparative Carbon Emission Analysis – Cement vs. Guar Gum Stabilisation

Parameter	Cement Stabilisation	Guar Gum Stabilisation (1.0%)
Typical dosage (% by dry soil weight)	5–8%	1.0%
Stabiliser mass per m^3 (kg)	80–128	16
Emission factor (kg CO_2/kg stabiliser)	0.85–0.95	0.20–0.40
Estimated CO_2 per m^3 (kg)	72–115	3–6
Relative CO_2 reduction	—	90–95%

Several additional environmental attributes reinforce the case for guar gum as a sustainable stabiliser. Being biodegradable and derived from a renewable agricultural crop, its use avoids the long-term soil alkalinity increases and potential groundwater quality impacts associated with cementitious stabilisation. Cement treatment permanently elevates the pH of stabilised soil, sometimes exceeding pH 12 in the immediate post-treatment period, creating alkaline conditions that are hostile to native soil microbial communities and may mobilise heavy metal contaminants into groundwater. Guar gum, by contrast, leaves no persistent ionic or pH signature in the treated soil after its eventual biodegradation. The stabilisation mechanism is predominantly physical, based on hydrogen bonding and gel network formation, rather than irreversible mineral transformation, making guar gum stabilisation particularly appropriate in ecologically sensitive floodplain settings.

The mechanical and environmental data collectively indicate that guar gum stabilisation at dosages of 1.0 to 1.5% significantly enhances the compressive strength and bearing capacity of Yamuna Basin soil, while substantially reducing embodied carbon relative to cement-based alternatives. The method is therefore well-positioned for application in pavement subgrade and low- to moderate-load-bearing foundation contexts where the ecological profile of the stabiliser is a relevant design constraint alongside engineering performance.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

This study systematically evaluated guar gum, a naturally derived galactomannan polysaccharide, as a sustainable stabilising agent for weak alluvium from the Yamuna floodplain in Delhi. A laboratory investigation encompassing Standard Proctor compaction testing, Unconfined Compressive Strength testing, California Bearing Ratio testing, Scanning Electron Microscopy, and a theoretical carbon emission analysis was conducted on specimens treated with 1.0% and 1.5% guar gum by dry soil weight, cured for periods of 3, 7, and 21 days. The principal conclusions drawn from this investigation are as follows:

- Compaction behaviour proved notably resistant to biopolymer addition. Maximum dry density and optimum moisture content remained within experimental reproducibility ranges of the untreated reference values of 1.6 g per cm³ and 7.2%, respectively, across both dosage levels. This insensitivity confirms that guar gum-treated subgrades can be compacted to the same field specification as untreated fill without recalibrating compaction targets or modifying field equipment selection.
- UCS results revealed a consistent, curing-dependent strength trajectory for both dosages. The 1.0% guar gum treatment achieved the highest peak strength of approximately 4.80 kPa at 21 days, representing a 136% improvement over the untreated baseline of 2.03 kPa. Strength development was progressive, with UCS at 3, 7, and 21 days increasing from 3.11 kPa to 4.13 kPa to 4.80 kPa for the 1.0% mix.
- The 1.5% dosage produced marginally lower peak UCS values than the 1.0% mix at all curing ages, attributed to localised polymer-rich zones introducing concentration gradients that redistribute axial stress non-uniformly. However, the 1.5% specimens consistently exhibited superior post-peak ductility and strain energy capacity.
- CBR test results revealed a dosage-response reversal relative to UCS under the confined loading conditions of the CBR test. The 1.5% guar gum treatment achieved the highest load resistance of approximately 40 kN at 6 mm penetration

at 21 days, an improvement of approximately 90%, compared to 60% for the 1.0% mix.

- SEM analysis confirmed a hierarchical, three-tier bonding structure in 1.0% guar gum-treated specimens cured for 21 days. Sub-micron hydrogen-bonded gel coatings on individual particle surfaces, micron-scale fibrous gel filaments bridging pore throats, and aggregate-scale gel-filled pore networks between flocculated particle clusters operate simultaneously to produce the macroscale cohesion and stiffness enhancements measured in mechanical testing.
- The theoretical carbon emission analysis demonstrated that guar gum stabilisation at 1.0% dosage produces an estimated 3 to 6 kg CO_2 per cubic metre of treated soil, compared with 72 to 115 kg CO_2 per cubic metre for conventional cement stabilisation. This represents a reduction of 90 to 95%, establishing a compelling environmental advantage for the biopolymer approach.
- These results collectively position guar gum as a technically sound and environmentally responsible alternative to conventional stabilisers for geotechnical improvement of collapsible Yamuna Basin silt in pavement subgrade and shallow foundation applications [20].

7.2 RECOMMENDATIONS FOR FUTURE RESEARCH

Based on the findings and limitations of the present investigation, the following directions are recommended for future research:

- Field-scale pilot studies should be conducted to validate laboratory performance trends under actual construction conditions, including variability in natural soil moisture, ambient temperature during curing, and compaction equipment effects.
- The durability of guar gum-treated Yamuna silt under repeated wetting and drying cycles and under sustained load should be investigated to assess performance in subgrade and embankment applications subject to monsoon-driven moisture cycling.
- The performance of guar gum treatment at additional dosage levels, including dosages below 1.0% and above 1.5%, should be evaluated to define the full dosage-response relationship and to confirm the optimal concentration for Yamuna Basin silt more precisely.
- Extended curing periods beyond 21 days, particularly 28, 60, and 90 days, should be investigated to characterise the long-term strength development trajectory and to determine whether a performance plateau is reached or whether progressive strength gain continues.
- The potential biodegradation of guar gum under field conditions, including the influence of soil microbial activity and moisture availability on the rate and extent of biopolymer degradation, should be characterised to assess the long-term durability of treated subgrades.
- The combination of guar gum with other low-carbon additives such as fly ash, ground granulated blast furnace slag, or nano-silica should be explored to assess whether synergistic interactions can further enhance performance while maintaining the environmental advantages of biopolymer stabilisation.
- A full life-cycle assessment incorporating field-scale construction logistics, transport distances, and end-of-life scenarios should be conducted to provide a

more comprehensive comparison of the environmental footprint of guar gum and cement-based stabilisation.

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