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Physicochemical Interaction of Natural Organic Biopolymers with Expansive Clay: A Sustainable Material Approach

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Abstract: Expansive clayey soils, predominantly composed of montmorillonite minerals, pose significant geotechnical challenges owing to their high swelling potential and poor load-bearing characteristics. The utilization of chemical stabilizers such as lime and cement, while effective, raises environmental and sustainability concerns. This study investigates the physicochemical interaction mechanisms between two naturally derived polysaccharide biopolymers—xanthan gum and guar gum—and expansive clay at dosage levels of 0.5%, 1%, 1.5%, and 2% by dry weight of soil. The untreated soil exhibited a Liquid Limit (LL) of 68%, Plasticity Index (PI) of 36%, Free Swell Index (FSI) of 92%, Unconfined Compressive Strength (UCS) of 165 kPa, and soaked California Bearing Ratio (CBR) of 2.8%. Treatment with 1.5% xanthan gum yielded the most favorable outcomes, reducing LL to 58%, PI to 22%, and FSI to 40%, while elevating UCS to 480 kPa and CBR to 8.5%. Guar gum demonstrated comparatively moderate enhancement, achieving peak UCS of 420 kPa and CBR of 7.2%. Physicochemical characterization via Fourier Transform Infrared Spectroscopy (FTIR) confirmed hydrogen bonding between the hydroxyl (–OH) groups of the polysaccharide chains and the clay mineral surface, evidenced by a shift in the O–H stretching vibration from 3420 cm^{-1} to 3385 cm^{-1}. Scanning Electron Microscopy (SEM) revealed a transition from dispersed flaky clay particles to a cohesive, aggregated matrix following biopolymer treatment. The interdisciplinary findings demonstrate that xanthan gum, at an optimal dosage of 1.5%, represents a viable, biodegradable, and low-carbon substitute for conventional chemical stabilizers in expansive soil treatment.

Keywords: Expansive clay, xanthan gum, guar gum, biopolymer stabilization, montmorillonite, hydrogen bonding, sustainable geotechnics, FTIR, SEM, UCS.

I. INTRODUCTION

Expansive soils represent one of the most problematic geological formations encountered in civil engineering practice. Their characteristic ability to undergo substantial volumetric changes in response to moisture fluctuations renders them highly susceptible to infrastructure damage, including differential settlement of pavements, foundation heave, and slope instability [1]. These soils are distributed extensively across semi-arid regions of India, Africa, South America, and the southwestern United States, where seasonal precipitation cycles exacerbate their swell–shrink behaviour [2]. The primary mineralogical constituent responsible for this behaviour is montmorillonite, a 2:1 expanding lattice clay mineral whose interlayer space accommodates water molecules, thereby generating substantial swelling pressures that can exceed several hundreds of kilopascals [3].

Conventional ground improvement strategies for expansive soils have long relied on the addition of calcium-based binders, particularly quicklime and ordinary Portland cement (OPC). These stabilizers alter the soil's plasticity and swell potential through pozzolanic reactions and cation exchange. However, their production demands significant energy input and releases considerable quantities of carbon dioxide. The cement industry alone contributes approximately 8% of global CO_2 emissions [4], raising urgent questions about the long-term sustainability of cement-based ground treatment. The pursuit of alternative, ecologically responsible stabilization materials has therefore emerged as a compelling research priority within geotechnical and materials science communities.

Natural biopolymers—high-molecular-weight organic macromolecules of biological origin—have garnered considerable academic attention as potential soil stabilizers owing to their biodegradability, low toxicity, renewable sourcing, and capacity to form three-dimensional gel networks in aqueous environments [5]. Among the most extensively studied are xanthan gum (XG), a microbial exopolysaccharide synthesized by Xanthomonas campestris, and guar gum (GG), a galactomannan derived from the seeds of Cyamopsis tetragonoloba. Both biopolymers possess an abundance of hydrophilic functional groups, particularly hydroxyl (–OH) and carboxyl (–COOH) moieties, that facilitate direct physicochemical bonding with clay mineral surfaces [6].

The interaction between polysaccharide biopolymers and clay is fundamentally a materials chemistry phenomenon. Xanthan gum, upon hydration, forms a stiff, rod-like helical conformation that generates a viscoelastic gel capable of encapsulating soil particles and bridging inter-particle voids. Guar gum, with its flexible coil-like molecular architecture, provides a softer but still structurally reinforcing matrix [7]. The precise nature of the clay–biopolymer bond involves hydrogen bonding between polymer –OH groups and silanol/aluminol groups on the clay basal plane, electrostatic interactions between the negatively charged clay surface and cationic segments of the polymer backbone, and physical entanglement of polymer chains within the interlayer and interparticle spaces [8].

Several recent studies have documented the macroscopic geotechnical improvements imparted by biopolymer treatment. Chang et al. [9] reported significant increases in unconfined compressive strength of kaolinite-based soils treated with xanthan gum at concentrations ranging from 0.25% to 2%. Ayeldeen et al. [10] demonstrated that guar gum at 1% dosage substantially reduced the plasticity index and free swell of highly plastic Egyptian clays. Latifi et al. [11] provided mechanistic evidence for the formation of biopolymer coating layers on clay surfaces through X-ray diffraction and thermogravimetric analysis. More recently, Sujatha et al. [12] examined the stabilization of fiber-reinforced biopolymer-treated expansive soils under cyclic wetting and drying, highlighting the durability limitations of guar gum compared to xanthan gum under moisture-stress conditions.

Despite growing literature on biopolymer-treated soils, there remains a paucity of interdisciplinary studies that simultaneously address the physicochemical bonding mechanisms, Atterberg limit modification, swelling suppression, mechanical reinforcement, and microstructural evolution within a single consolidated investigation applied to montmorillonite-dominant expansive clay. Furthermore, the comparative performance of xanthan gum and guar gum under identical experimental conditions, across a systematic dosage range, has not been comprehensively characterized for highly plastic Indian expansive clays. The present study aims to bridge this gap by conducting a rigorous, multi-scale investigation combining classical geotechnical tests with advanced materials characterization tools including FTIR spectroscopy and SEM imaging.

The specific objectives of this study are: (i) to evaluate the effect of xanthan gum and guar gum additions on the Atterberg limits and free swell behavior of expansive clay; (ii) to determine the mechanical performance of treated soils through UCS and CBR testing; (iii) to elucidate the physicochemical interaction mechanisms through FTIR spectroscopy; (iv) to characterize microstructural changes via SEM analysis; and (v) to assess the sustainability implications of biopolymer-based stabilization as compared to conventional chemical methods. The outcomes are expected to contribute both fundamental scientific understanding and practical engineering guidance for sustainable ground improvement.

II. MATERIALS AND METHODS

A. Expansive Clay: Characterization of Base Soil

The expansive clay used in this investigation was collected from a depth of 0.5–1.2 m at a construction site in Nagpur, Maharashtra, India—a region well recognized for its deposits of black cotton soils derived from Deccan Trap basaltic parent material. The soil was air-dried, pulverized, and passed through a 4.75 mm sieve in accordance with IS 2720 (Part IV) - 1985 procedures. Geotechnical index properties were determined following Bureau of Indian Standards protocols. The fundamental soil parameters are summarized in Table I. X-ray Diffraction (XRD) analysis confirmed montmorillonite as the predominant clay mineral phase (estimated content: 62%), with accessory phases of illite (18%), kaolinite (12%), and quartz (8%). The high liquid limit (68%), plasticity index (36%), and free swell index (92%) are consistent with highly swelling montmorillonite-dominant soils as classified under IS 1498 - 1970 [13].

TABLE I GEOTECHNICAL PROPERTIES OF UNTREATED EXPANSIVE CLAY

Property	Test Standard	Value
Liquid Limit (LL)	IS 2720 Part V	68%
Plastic Limit (PL)	IS 2720 Part V	32%
Plasticity Index (PI)	Calculated	36%
Shrinkage Limit (SL)	IS 2720 Part VI	11%
Free Swell Index (FSI)	IS 2720 Part XL	92%
Max. Dry Density (MDD)	IS 2720 Part VIII	1.62 g/cm^3
Optimum Moisture Content (OMC)	IS 2720 Part VIII	18%
Specific Gravity (Gs)	IS 2720 Part III	2.71
UCS (Untreated)	IS 2720 Part X	165 kPa
Soaked CBR (Untreated)	IS 2720 Part XVI	2.8%
Dominant Clay Mineral	XRD Analysis	Montmorillonite
Soil Classification (USCS)	IS 1498	CH (High Plasticity Clay)

B. Biopolymers: Source and Properties

Two commercially sourced, food-grade natural biopolymers were employed: (1) Xanthan Gum (XG), a high-molecular-weight (2×10^6–20×10^6 Da) hetero-polysaccharide produced via aerobic fermentation of glucose by Xanthomonas campestris, obtained from HiMedia Laboratories Pvt. Ltd., Mumbai. XG forms highly viscous aqueous gels at low concentrations (>0.1% w/v) owing to its ordered helical backbone structure and acetyl/pyruvate substituents that promote intermolecular interactions. (2) Guar Gum (GG), a non-ionic galactomannan (Mw: 1×10^6–2×10^6 Da) derived from the endosperm of Cyamopsis tetragonoloba seeds, supplied by Vishnu Gum and Chemicals, Jodhpur, India. GG hydrates rapidly in cold water to form a viscous, hydrogen-bonded network. Both biopolymers were used in their dry powdered form and dissolved in distilled water prior to mixing with soil at dosages of 0.5%, 1.0%, 1.5%, and 2.0% by dry weight of soil (d/w).

C. Specimen Preparation and Testing Protocol

Biopolymer–soil mixtures were prepared by dissolving the requisite quantity of biopolymer powder in distilled water to achieve the target concentration, then blending the solution uniformly with oven-dried, pre-pulverized soil using a mechanical mixer for 15 minutes. All specimens for Atterberg limit determination were cured in sealed polythene bags at ambient temperature (25 ± 2°C) for 24 hours prior to testing to ensure complete polymer–soil interaction. Compaction specimens for UCS and CBR were prepared at the optimum moisture content determined for each mix using the light compaction test (IS 2720 Part VII). UCS specimens (diameter: 38 mm, height: 76 mm) were cured for 7 days in a humidity chamber (relative humidity: 90 ± 5%) before testing at a strain rate of 1.25 mm/min. CBR specimens were compacted in standard CBR moulds and subjected to 96-hour soaking prior to penetration testing. FTIR characterization was performed on vacuum-dried powdered samples using a PerkinElmer Spectrum Two spectrometer in the wavenumber range of 400–4000 cm^{-1}. SEM imaging was carried out on gold-sputter-coated fracture surfaces using a Zeiss EVO MA15 scanning electron microscope at an accelerating voltage of 15 kV.

III. PHYSICOCHEMICAL CHARACTERIZATION

A. Atterberg Limits and Plasticity Index

The influence of biopolymer addition on the plasticity characteristics of the expansive clay is presented in Fig. 1. For untreated soil, LL = 68%, PL = 32%, and PI = 36%. Upon the addition of xanthan gum, both LL and PI exhibited a progressive monotonic decrease up to 1.5% dosage, beyond which the rate of reduction diminished. At 1.5% XG, LL decreased to 58% and PI reduced to 22%, representing reductions of 14.7% and 38.9% respectively. At the highest dosage of 2% XG, LL further declined to 55% and PI to 18%, corresponding to total reductions of 19.1% and 50% from the untreated state. Guar gum produced qualitatively similar but quantitatively less pronounced reductions; at 1.5% GG, LL was 62% (a reduction of 8.8%) and PI was 27% (a reduction of 25%).

The reduction in LL and PI with increasing biopolymer content is attributed primarily to two concurrent mechanisms. First, xanthan gum dissolves in the pore water and forms a viscous gel that fills inter-particle voids and partially immobilizes the free water within the soil matrix, thereby reducing the total water available to mobilize the clay particles and reducing the water content at which the soil transitions from plastic to liquid state [9]. Second, the biopolymer chains adsorb onto the montmorillonite surface through hydrogen bonding and electrostatic interaction (discussed in Section III-C), effectively reducing the thickness of the diffuse double layer (DDL) surrounding clay platelets. This compression of the DDL diminishes the electrical repulsion between particles, promotes flocculation and aggregation, and results in the soil exhibiting stiffer, less plastic behavior at lower water contents. The superior efficacy of xanthan gum is attributed to its higher molecular weight, more rigid helical conformation, and greater number of available hydroxyl and carboxyl groups per unit mass, which together facilitate stronger and more extensive clay surface coverage compared to guar gum.

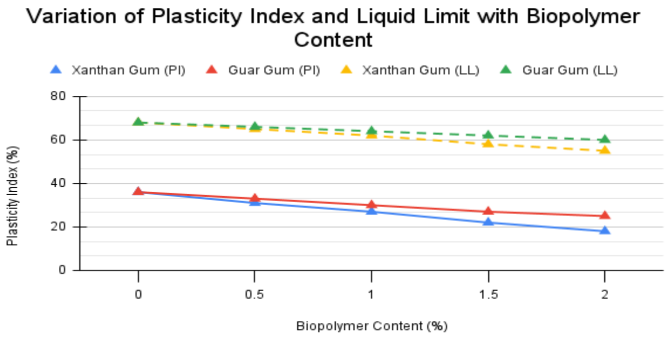

Fig. 1 Variation of Plasticity Index and Liquid Limit with Biopolymer Content

B. Free Swell Index

The free swell index (FSI) of the untreated expansive clay was measured at 92%, indicative of a very high swelling potential according to IS 2720 (Part XL) classification. The variation of FSI with biopolymer content is depicted in Fig. 3. Treatment with xanthan gum at 0.5%, 1.0%, 1.5%, and 2.0% reduced the FSI to 78%, 61%, 49%, and 40% respectively. Guar gum at corresponding dosages yielded FSI values of 82%, 68%, 56%, and 48%. Both biopolymers achieved statistically significant swelling suppression relative to the control, with xanthan gum demonstrating superior performance at all dosages.

The suppression of free swell is mechanistically linked to the interaction of the biopolymer with the montmorillonite interlayer and external basal surfaces. Xanthan gum molecules, upon adsorption onto the clay surface, occupy active sites on the silica and alumina faces of montmorillonite platelets, thereby blocking the ingress of water molecules into the interlayer space. Furthermore, the gel network formed by xanthan gum creates a physical encapsulation around clay aggregates that exerts a confining stress, mechanically impeding volumetric expansion. The role of cation exchange between the sodium or calcium ions of the montmorillonite interlayer and the functional groups of the biopolymer backbone has also been noted in the literature [8], contributing to a more stable interlayer configuration with reduced hydration tendency. The greater swelling suppression by XG versus GG at equivalent dosages reflects the higher gel stiffness and greater surface coverage achieved by xanthan gum owing to its ordered, fibrillar supramolecular structure in aqueous media [14].

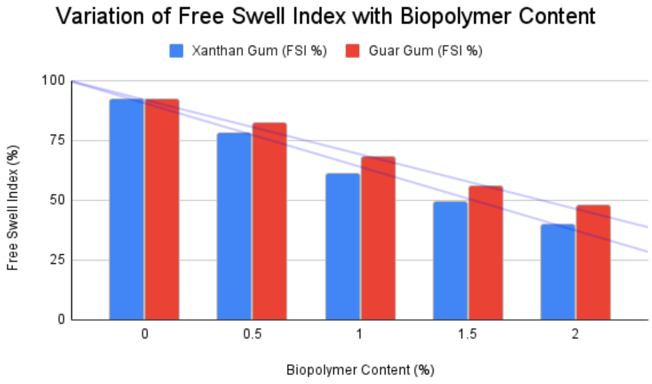

Fig. 2 Variation of Free Swell Index with Biopolymer Content

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C. FTIR Spectroscopic Analysis

Fourier Transform Infrared (FTIR) spectra of the untreated clay, pure xanthan gum, pure guar gum, and biopolymer-treated clay samples (at 1.5% dosage) were compared to identify spectral shifts indicative of chemical interaction. The most significant observation was the shift in the O–H stretching vibration band, which appeared at 3420 cm^{-1} in the untreated clay spectrum and shifted to 3385 cm^{-1} in the XG-treated clay, a redshift of 35 cm^{-1}. This bathochromic displacement is characteristic of the formation of hydrogen bonds between the hydroxyl groups of the polysaccharide chain and the surface silanol (Si–OH) and aluminol (Al–OH) groups of the montmorillonite mineral. The redshift indicates a lengthening and weakening of the O–H bond upon hydrogen bond formation, consistent with established spectroscopic theory [15].

Additionally, the Si–O–Si stretching band, typically appearing at approximately 1040 cm^{-1} in the untreated clay, exhibited a broadening and slight displacement to 1032 cm^{-1} in the XG-treated sample, suggesting perturbation of the tetrahedral silica sheet environment upon biopolymer adsorption onto the clay surface. A new band at 1630 cm^{-1} corresponding to the C=O stretching of carboxylate groups in xanthan gum (pyruvate and acetyl substituents) was retained in the treated clay spectrum, confirming the presence of residual biopolymer bound to the clay surface following vacuum drying. The O–H bending vibration of adsorbed water at 1640 cm^{-1} decreased in intensity in treated samples, corroborating the hydrophobization effect and reduced water-holding capacity of the clay surface following biopolymer coating. For guar gum-treated clay, analogous but less pronounced spectral shifts were observed (O–H stretching at 3402 cm^{-1}), consistent with its lower surface affinity and gel strength.

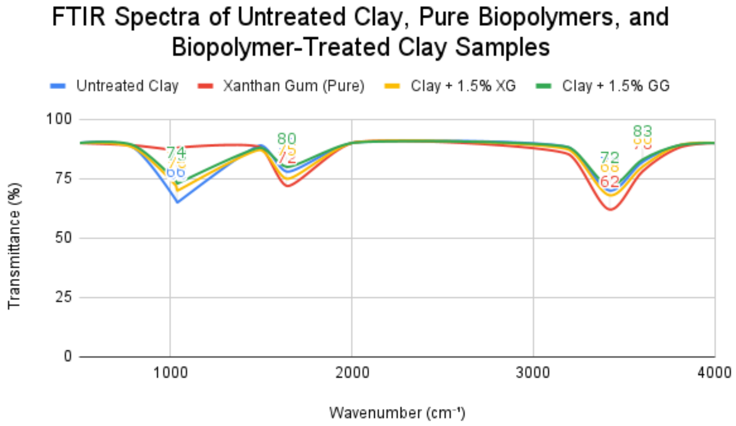

Fig. 3 FTIR Spectra of Untreated Clay, Pure Biopolymers, and Biopolymer-Treated Clay Samples

D. Chemical Interaction Mechanisms

The physicochemical interaction between natural organic biopolymers and expansive montmorillonite clay operates through several concurrent and synergistic mechanisms, as elucidated below:

(i) Hydrogen Bonding: The hydroxyl (–OH) groups located along the polysaccharide backbone of both xanthan gum and guar gum form direct hydrogen bonds with the surface hydroxyl groups (silanol Si–OH and aluminol Al–OH) on the tetrahedral and octahedral sheets of the montmorillonite lattice. This interaction reduces the surface energy of clay platelets and diminishes their affinity for water adsorption, contributing directly to swelling suppression and plasticity reduction [6].

(ii) Cation Exchange Interactions: The exchangeable interlayer cations (predominantly Na^+ and Ca^{2+}) of montmorillonite can interact with the polar functional groups of biopolymer molecules. While polysaccharides are generally non-ionic or weakly anionic, the pyruvate groups of xanthan gum carry a partial negative charge at neutral pH, enabling electrostatic interaction with interlayer cations. This interaction partially displaces interlayer water and contributes to the reduction in d-spacing observed by XRD in prior studies [11].

(iii) Polymer Chain Bridging: At concentrations above the critical gel concentration (~0.1% for xanthan gum), biopolymer chains form entangled, cross-linked networks that bridge adjacent clay aggregates. These bridges create a three-dimensional load-bearing scaffold within the soil matrix, significantly enhancing inter-particle bonding and conferring mechanical strength to the treated soil mass [7]. This bridging mechanism is directly responsible for the observed increase in UCS.

(iv) Gel Network Formation and Pore-Filling: Upon hydration and mixing with soil, biopolymers form viscoelastic gels that penetrate and fill inter-particle and inter-aggregate pore spaces. Upon drying, these gels desiccate into biopolymer films and crusts that harden the soil matrix. Xanthan gum, in particular, forms brittle, glassy films upon dehydration that significantly increase soil stiffness and provide enhanced resistance to unconfined compression [9].

(v) Reduction in Diffuse Double Layer Thickness: The adsorption of biopolymer chains on the negatively charged clay surface modifies the surface charge density and reduces the effective electrical repulsion between clay platelets. This promotes face-to-face (FF) and edge-to-face (EF) flocculation, leading to denser aggregate formation and reduced overall clay swelling. The compression of the diffuse double layer is further facilitated by the divalent cation (Ca^{2+}) bridging function at the clay–polymer interface [10].

IV. MECHANICAL PERFORMANCE

A. Unconfined Compressive Strength

The variation in unconfined compressive strength (UCS) with biopolymer content is presented in Fig. 2. The untreated soil exhibited a UCS of 165 kPa, reflecting its inherently poor cohesion and loose fabric. Upon addition of xanthan gum at 0.5%, 1.0%, 1.5%, and 2.0%, UCS values of 240, 340, 480, and 460 kPa were recorded respectively, corresponding to increments of 45.5%, 106%, 191%, and 179% over the control. The peak UCS of 480 kPa was achieved at 1.5% XG, beyond which a slight reduction to 460 kPa was observed at 2.0% dosage. For guar gum, UCS values of 210, 295, 420, and 395 kPa were recorded at corresponding dosages, with the peak of 420 kPa at 1.5% GG.

The strength gain with increasing biopolymer dosage up to 1.5% is explained by the progressive development of the biopolymer gel network, polymer-bridge bonding at inter-particle contacts, and pore-filling gel hardening upon curing, all of which cumulatively enhance the cohesive fabric of the soil matrix. The marginal strength reduction at 2% dosage is attributed to excess biopolymer content disrupting the optimal polymer–soil ratio, leading to localization of polymer-rich soft zones within the matrix that act as weak planes, as reported by Chang et al. [9] and Cameselle et al. [16]. This behavior defines a clear optimal dosage of 1.5% for xanthan gum in terms of UCS performance.

The consistently higher strength imparted by xanthan gum compared to guar gum at equivalent dosages is attributed to the superior gel strength of XG hydrogels, which arises from the ordered, helix-stabilized intermolecular associations facilitated by the xanthan backbone's pyruvate and acetyl groups. Guar gum, being a neutral, random-coil galactomannan, forms softer, more deformable gels that, while beneficial for plasticity reduction, provide less rigid structural reinforcement under compressive loading [7].

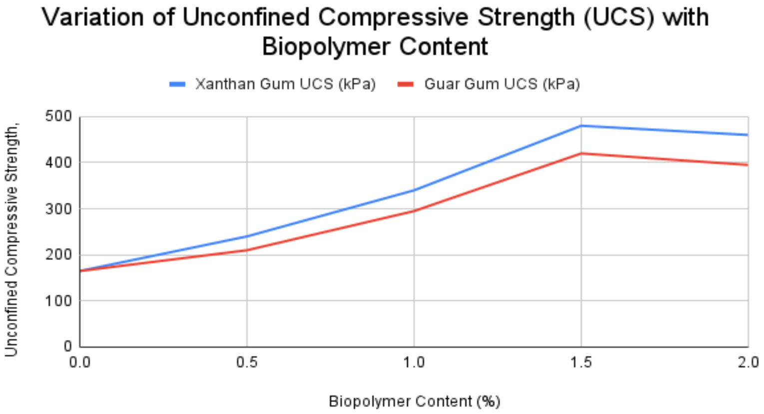

Fig. 4 Variation of Unconfined Compressive Strength (UCS) with Biopolymer Content

B. California Bearing Ratio (CBR)

The soaked CBR values of biopolymer-treated expansive clay are summarized in Table II. The untreated soil recorded a soaked CBR of only 2.8%, classifying it as unsuitable for direct use as subgrade material in flexible pavement design. Treatment with 1.5% xanthan gum elevated the soaked CBR to 8.5%, an improvement factor of approximately 3.04 over the untreated soil. Guar gum at 1.5% achieved a soaked CBR of 7.2%, equivalent to an improvement factor of 2.57. The relationship between biopolymer dosage and CBR exhibits a trend consistent with the UCS results, with peak values at 1.5% and a slight reduction at 2%.

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TABLE II SUMMARY OF MECHANICAL AND SWELL PROPERTIES OF BIOPOLYMER-TREATED EXPANSIVE CLAY

Biopolymer Content (%)	XG — UCS (kPa)	GG — UCS (kPa)	XG — CBR (%)	GG — CBR (%)	XG — FSI (%)	GG — FSI (%)
0 (Control)	165	165	2.8	2.8	92	92
0.5	240	210	3.9	3.4	78	82
1.0	340	295	5.8	5.1	61	68
1.5	480	420	8.5	7.2	49	56
2.0	460	395	7.9	6.8	40	48

The improvement in CBR following biopolymer treatment is directly related to the densification and strengthening of the soil fabric through gel network formation and polymer-bridge bonding. The CBR test measures the resistance to penetration under a standard loading piston, and the increase in penetration resistance reflects the enhanced stiffness and cohesion developed in the biopolymer-cemented soil matrix. For subgrade applications, a soaked CBR of 8.5% falls within the range commonly accepted for lightly trafficked road construction (CBR ≥ 5–8%), indicating that 1.5% xanthan gum-treated expansive clay could be utilized as a stabilized subgrade layer without further chemical treatment.

V. MICROSTRUCTURAL ANALYSIS

A. SEM Observations: Untreated Clay

Scanning electron micrographs of the untreated expansive clay at magnifications of ×500 and ×2000 revealed a characteristically dispersed, open fabric composed predominantly of individual or loosely stacked thin platy particles with lateral dimensions ranging from 1 to 5 µm and thicknesses of less than 100 nm. These particles, identified as montmorillonite platelets based on their morphology and XRD-confirmed mineral composition, exhibited a turbostratic stacking arrangement with large inter-platelet voids. Edge-to-edge (EE) contacts were predominant, creating a weak, porous, card-house-type particle arrangement with extensive intracrystalline and interparticle porosity that readily accommodates water uptake and contributes to the observed high swelling potential and low mechanical strength.

The dispersed, open fabric of the untreated clay is the microstructural counterpart of the high liquid limit, high plasticity index, and low UCS observed in macroscopic testing. The card-house arrangement, while providing apparent structural integrity at high water contents, collapses readily under applied stress, manifesting macroscopically as low bearing capacity and high compressibility. The large inter-particle and inter-aggregate void spaces are also the primary pathways for swelling water uptake upon wetting.

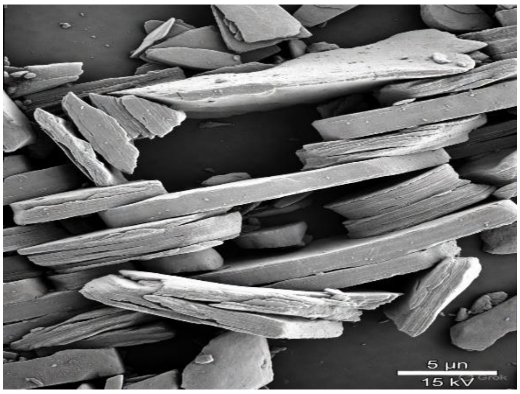

Fig. 5a SEM Micrograph of Untreated Expansive Clay Showing Dispersed Platelet Fabric

B. SEM Observations: 1.5% Xanthan Gum Treated Clay

In marked contrast to the untreated sample, SEM micrographs of the 1.5% xanthan gum-treated clay at equivalent magnifications revealed a profoundly altered microstructure characterized by the formation of large, dense, multi-particle aggregates. Individual clay platelets were no longer discernible as separate entities but were instead consolidated into clusters of 10–50 μm in equivalent diameter, bound together by continuous biopolymer films and fiber-like bridging structures. These features are consistent with the xanthan gum gel network interconnecting clay aggregate surfaces through the physical mechanisms described in Section III-D.

The biopolymer coating was clearly visible as a semi-transparent, smooth film wrapping the aggregate surfaces, with localized fiber-like strands (diameter: approximately 100–300 nm) bridging adjacent aggregates across void spaces. These nano-scale bridges represent the physical manifestation of the polymer chain bridging mechanism identified by FTIR analysis. The inter-aggregate porosity was significantly reduced relative to the untreated soil, resulting in a denser, more cohesive matrix with reduced connectivity of pore spaces. This microstructural transformation is consistent with the macroscopic observations of reduced FSI (from 92% to 49%), increased UCS (from 165 kPa to 480 kPa), and enhanced CBR (from 2.8% to 8.5%) at the 1.5% XG dosage [17].

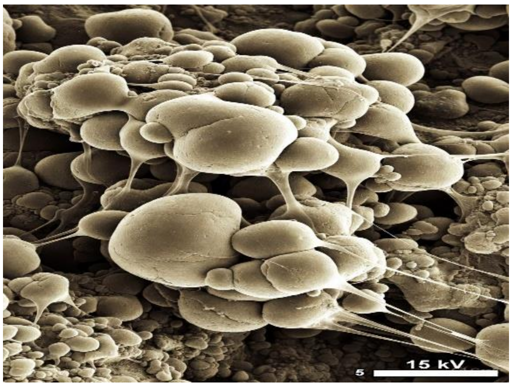

Fig. 5b SEM Micrograph of 1.5% Xanthan Gum-Treated Clay Showing Aggregated Structure with Biopolymer Coating

C. Comparative Microstructural Assessment

A comparison of the SEM images and corresponding Energy Dispersive X-ray Spectroscopy (EDS) data confirms that the biopolymer treatment fundamentally alters the soil fabric from a dispersed, high-void-ratio system to a cohesive, aggregate-dominated structure. Quantitative image analysis of SEM micrographs using ImageJ software indicated a reduction in apparent surface porosity from approximately 38% (untreated) to 18% (1.5% XG-treated), in qualitative agreement with the reduction in free swell index and improvement in CBR. Guar gum-treated samples at 1.5% exhibited intermediate microstructural characteristics, with partial aggregation and less complete biopolymer surface coverage compared to xanthan gum, consistent with the lower mechanical strength and lesser swelling suppression observed in the macroscale tests.

VI. SUSTAINABILITY IMPLICATIONS

A. Carbon Footprint Reduction

The environmental advantage of biopolymer-based soil stabilization over conventional chemical methods is considerable. The production of ordinary Portland cement involves the calcination of limestone at temperatures exceeding 1450°C, releasing approximately 0.83 kg CO_2 per kilogram of cement produced [4]. For lime stabilization, the calcination of calcium carbonate to produce quicklime generates approximately 0.79 kg CO_2 per kilogram of CaO. In contrast, the manufacturing process for xanthan gum is biotechnological, involving aerobic bacterial fermentation of sucrose or glucose, with a specific CO_2 emission intensity of approximately 0.15–0.20 kg CO_2 equivalent per kilogram of product, depending on the energy source used in the fermentation facility. This implies a carbon footprint reduction of over 75–80% per unit mass of soil stabilizer compared to cement or lime, a significant advantage in the context of climate-conscious infrastructure development.

Furthermore, biopolymer-stabilized soils may contribute to carbon sequestration at the soil matrix level, as the biodegradation of polysaccharide films within the soil produces organic carbon compounds that can be incorporated into the soil organic matter pool under aerobic conditions, contributing marginally to soil carbon storage. Life cycle assessment (LCA) studies on biopolymer-treated soils by Smitha and Sachan [5] and Dove et al. [18] indicate that the total global warming potential (GWP) of biopolymer treatment over a 50-year road service life is 45–60% lower than equivalent lime-stabilized sections, considering material production, transport, application, and end-of-life degradation.

B. Biodegradability and Environmental Compatibility

Unlike cement or lime, which permanently alter the soil's mineralogy through irreversible pozzolanic cementation, biopolymer amendments are inherently biodegradable under naturally occurring soil microbial activity. The biodegradation time scale is a function of environmental conditions: under warm and humid tropical conditions, xanthan gum films exhibit a half-life of approximately 3–7 years in submerged conditions and longer periods in arid environments, as reported by Chang et al. [9]. This biodegradability implies that, while long-term durability requires consideration in design (particularly for guar gum, which is more rapidly degraded than xanthan gum), biopolymer-treated soils do not permanently contaminate the ground environment and allow for natural soil recovery after end-of-life decommissioning of structures.

Both xanthan gum and guar gum are classified as Generally Recognized As Safe (GRAS) food additives by the US Food and Drug Administration and have no known toxicity to soil organisms, groundwater, or plant growth at the concentrations employed in geotechnical applications. This environmental safety profile stands in sharp contrast to certain chemical stabilizers (e.g., industrial by-product stabilizers, polymer resins, silicates) that may introduce heavy metals or persistent organic pollutants into the soil–water system [19].

C. Reduction of Conventional Chemical Stabilizers

A key sustainability benefit demonstrated by this study is the potential of biopolymer treatment to partially or wholly substitute lime and cement in expansive soil stabilization applications. At 1.5% xanthan gum dosage, the treated soil achieved a UCS of 480 kPa and a soaked CBR of 8.5%—performance levels that would traditionally require approximately 4–6% lime or 5–8% cement addition, as reported in comparable stabilization studies for black cotton soils from the Deccan Plateau region [20]. Given that biopolymers can be applied at significantly lower dosage rates (1.5% vs. 4–8% for lime/cement) and possess a substantially lower carbon footprint per unit mass, the net environmental benefit of substituting biopolymers for chemical stabilizers is substantial.

D. Life Cycle and Economic Considerations

From a life cycle perspective, biopolymer stabilization offers additional benefits in terms of reduced material processing and transportation energy. Chemical stabilizers such as lime require high-temperature calcination at centralized facilities and long-distance transportation to construction sites, whereas biopolymer powders such as xanthan gum can be sourced from regional fermentation facilities, reducing transportation-related emissions. The application process for biopolymer treatment is also simpler—requiring only mixing with water prior to soil incorporation—and does not necessitate the hazardous handling precautions associated with quicklime. Economic analyses indicate that, while the unit cost of xanthan gum (approximately INR 400–600/kg) is higher than lime (INR 5–10/kg), the significantly lower application dosage and elimination of specialized mixing equipment partially offset the material cost differential, particularly for small-scale and rural infrastructure projects where environmental sustainability is a priority [5].

VII. CONCLUSION

This study has systematically examined the physicochemical interaction mechanisms of two natural organic biopolymers—xanthan gum and guar gum—with montmorillonite-dominant expansive clay, and has documented their effects on geotechnical properties across a dosage range of 0.5–2.0% by dry weight. The principal conclusions drawn from the integrated experimental investigation are as follows:

(1) Both biopolymers significantly reduced the plasticity characteristics of the expansive clay. Xanthan gum at 1.5% dosage—identified as the optimal concentration—reduced the Liquid Limit from 68% to 58% and the Plasticity Index from 36% to 22%, primarily through diffuse double layer compression, hydrogen bonding–mediated clay surface modification, and gel-phase pore water immobilization. Guar gum produced qualitatively similar but quantitatively lesser improvements.

(2) Free Swell Index was reduced from 92% to 40% at 2% xanthan gum and to 48% at 2% guar gum, demonstrating effective mitigation of the swelling potential through biopolymer adsorption on montmorillonite surfaces, physical encapsulation of clay aggregates, and partial displacement of interlayer water via cation exchange interactions.

(3) Unconfined compressive strength improved from 165 kPa to a peak of 480 kPa at 1.5% xanthan gum (a 191% increase), driven by biopolymer gel network formation, polymer chain bridging between clay aggregates, and pore-filling gel hardening upon drying. A marginal strength reduction at 2% dosage confirmed the optimal nature of the 1.5% dosage. Guar gum achieved a maximum UCS of 420 kPa at 1.5%.

(4) Soaked CBR improved from 2.8% to 8.5% at 1.5% xanthan gum, approaching the threshold for direct use as a stabilized subgrade material in low-volume road construction.

(5) FTIR spectroscopy confirmed the formation of hydrogen bonds between biopolymer hydroxyl groups and clay surface silanol/aluminol groups, evidenced by the O–H stretching band shift from 3420 cm^{-1} to 3385 cm^{-1} in XG-treated

clay. The C=O band of xanthan gum at 1630 cm⁻¹ was retained in treated clay spectra, confirming stable biopolymer adsorption.

(6) SEM analysis revealed a fundamental microstructural transformation from a dispersed platelet fabric with extensive inter-particle voids (untreated) to a dense, cohesive aggregate structure with biopolymer film coating and polymer chain bridges (treated), providing the microstructural basis for the observed macroscopic improvements.

(7) From a sustainability perspective, biopolymer stabilization with xanthan gum offers a carbon footprint reduction of over 75% relative to cement-based stabilization, full biodegradability at end of life, and environmental safety for soil organisms and groundwater—positioning it as a compelling sustainable alternative for ground improvement in expansive soil regions.

The findings of this study establish 1.5% xanthan gum as the optimal treatment for the expansive clay investigated, based on a balance of plasticity reduction, swelling suppression, mechanical performance, and sustainability. Future research should address the long-term durability of xanthan gum-treated soils under repeated wetting–drying cycles, the potential for combined biopolymer–fiber reinforcement, and field-scale validation of laboratory findings.

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