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PAVEMENT STABILIZATION IN BANGLADESH: A REVIEW OF CONVENTIONAL AND EMERGING TECHNIQUES

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ABSTRACT

This study reviews the effectiveness of various pavement stabilization techniques used in Bangladesh. The road network in Bangladesh faces severe challenges in maintaining durability due to weak subgrade soil and heavy monsoon pattern. To address these issues, various conventional and emerging stabilization techniques have been applied to the base and subbase soils. This review analyses methods to improve the performance and lifespan of pavements based on local soil characteristics. Among different methods, chemical stabilization has been the most widely used. Using 8-10% cement as a stabilizer typically significantly increases unconfined compressive strength (UCS) and improves soaked durability. Partial replacement of cement with industrial by-products such as fly ash, sugarcane bagasse ash, or rice husk ash has also increased the California Bearing Ratio (CBR) from less than 2 to above 25 and reduced swelling by up to 47%. Mechanical stabilization methods using locally available, recycled materials have also demonstrated significant improvements in soil strength. Reclaimed asphalt pavement (RAP) blended with 5% cement or 1% bitumen increased CBR up to 50. Similarly, jute geotextile reinforcement improved field CBR values by 1.5 to 7 times on weak soils. Biological stabilization methods, particularly Microbially Induced Calcite Precipitation (MICP) and Enzyme Induced Carbonate Precipitation (EICP), have shown promising results. MICP-treated expansive soils have achieved up to 186% higher UCS and 85-90% lower swell strain. On the other hand, EICP using soybean urease and eggshell-derived calcium sources achieved UCS values of around 370 kPa, which is 8.5% higher than conventional methods. Overall, the review shows a transition from traditional to hybrid and bio-based stabilization techniques that combine industrial by-products and microbial processes to improve the pavement soil condition.

Keywords: *Pavement stabilization, Soil improvement, MICP, EICP, RAP*

1. INTRODUCTION

Transportation infrastructure plays a significant role in the economic and social development of any nation (Chanda et al., 2023). A well-developed transportation infrastructure improves a nation's economic potential by ensuring the effective utilization of available resources (Magazzino & Mele, 2021). Roadways serve as a critical backbone for facilitating such economic growth (Abadin & Hayano, 2022). The road network in Bangladesh has expanded significantly over the past five decades. It increased from only about 462 km of paved roads in 1947 to nearly 22,500 km in 2021 under the Roads and Highways Department (RHD) (RHD, 2021). This rapid growth shows the increasing reliance on the pavement network for accessibility. According to the Road Master Plan (2009), approximately 70% of the country’s road traffic is carried by the RHD network, and 59% of that traffic is concentrated on the national highways. The plan further states that overall traffic volume will increase by a factor of 4 by 2030, highlighting the growing pressure on pavement infrastructure (Abadin & Hayano, 2022). Therefore, ensuring the sustainability of the road network remains a major challenge for Bangladesh (Abadin & Hayano, 2022).

Road pavements in Bangladesh predominantly consist of unbound base layers with thin bituminous surfacing. Locally available brick aggregates and sand are commonly used for the foundation. However, improper grading and the rapid degradation of brick aggregates under traffic significantly weaken these layers. Prolonged monsoon rainfall and high groundwater levels further damage these unbound bases, which leads to early pavement failure (Alam, 2005). Effective stabilization of base and subbase layers can increase pavement durability. The purpose of a stabilized base or subbase layer is to act as a load-bearing transition zone between the pavement surface and the underlying subgrade soil. These layers can be incorporated into both flexible and rigid pavements (Mamun et al., 2016). Various stabilization methods are used to enhance the load-bearing capacity of pavement layers, and their effectiveness depends on the selection of suitable techniques and optimal stabilizer contents.

Stabilization techniques can be classified into three broad categories: mechanical, chemical, and biological methods. Mechanical stabilization increases soil strength through physical modifications, such as compaction, blending with well-graded materials, adding granular fillers, and incorporating soil reinforcement, such as geotextile or geogrid (Afrin, 2017). Chemical stabilization involves using additives like lime, cement, fly ash, or geopolymer binders to increase strength and water resistance by forming cementitious bonds within the soil matrix (Fondjo et al., 2021). In recent years, biological stabilization has gained increasing attention as a sustainable and eco-friendly approach through techniques such as Microbially Induced Calcite Precipitation (MICP) and Enzyme Induced Carbonate Precipitation (EICP). These methods increase soil stiffness and reduce permeability by forming calcium carbonate within the pore spaces (Hang et al., 2022; EZZAT, 2023). These stabilization approaches differ in their mechanisms, cost, and environmental implications. The selection of the most suitable technique depends on local soil type and climatic conditions.

This review focuses on pavement stabilization practices in Bangladesh from a sustainability perspective. Unlike global reviews, this study synthesizes Bangladesh-specific evidence by considering local soil conditions, climatic challenges, material availability, and environmental constraints. The paper evaluates conventional, recycled, and bio-based stabilization techniques in terms of strength improvement, durability, resource efficiency, and potential environmental benefits, including reduced cement consumption and waste reuse. By consolidating fragmented experimental findings into a unified framework, this review aims to support sustainable pavement design decisions and inform future research and policy development in Bangladesh.

2. METHODOLOGY

This study provides an in-depth analysis of pavement stabilization techniques implemented in Bangladesh. The primary sources for identifying relevant peer-reviewed journal articles, conference papers, and technical reports on this subject include Google Scholar, Scopus, and the Web of Science. Search keywords such as "pavement stabilization in Bangladesh," "soil stabilization," "cement or lime stabilized soil," "fly ash stabilization," "recycled materials in pavement," "MICP and EICP in soil improvement" were used.

Publications were selected based on their relevance and applicability to Bangladeshi soil and climatic conditions. The scope of this review is limited to laboratory and field studies conducted in Bangladesh between 2000 and 2025. Approximately 40 journal articles and conference papers on mechanical, chemical, and biological stabilization techniques were reviewed and formed the basis for this study.

3. RESULTS AND DISCUSSIONS

3.1 Chemical Stabilization

3.1.1 Mechanism of Chemical Stabilization

Chemical stabilization modifies the engineering behaviour of weak soils by introducing chemical additives that interact with soil minerals and pore water to improve strength, durability, and moisture resistance. (Little & Nair, 2009) reported stabilizers such as lime, Portland cement, fly ash, bitumen, and industrial by-products initiate a series of physicochemical reactions that fundamentally alter the soil structure. Traditional calcium-based stabilizers work primarily through cation exchange, flocculation-agglomeration, and pozzolanic reactions. In the initial stage, calcium ions from lime or cement replace sodium and hydrogen ions on clay surfaces, neutralizing negative surface charges and promoting particle flocculation, thereby reducing plasticity and improving workability. This is followed by pozzolanic reactions, where soluble silica and alumina from the soil react with calcium hydroxide to form calcium silicate hydrates (C-S-H) and calcium aluminate hydrates (C-A-H), cementitious compounds that bind soil particles together and significantly enhance long-term strength and stiffness. Portland cement stabilization involves rapid hydration of calcium silicates and aluminates, producing immediate strength gain through cementitious bonding. In contrast, residual lime generated during hydration continues to participate in slower pozzolanic reactions. Similarly, fly ash stabilization relies on the combination of hydration and pozzolanic processes. Class C fly ash contains self-cementing properties due to its high calcium content, whereas Class F fly ash requires an activator like lime or cement to initiate the reaction. These chemical processes collectively transform loose, moisture-sensitive soils into dense, durable, and load-bearing layers suitable for pavement applications (Little & Nair, 2009). Recently, geopolymer binders synthesized from industrial by-products such as slag or fly ash, activated with alkaline solutions, have gained attention for their potential to reduce CO_2 emissions while achieving comparable or superior strength to cement stabilization (Nanda & Priya, 2024).

3.1.2 Summary of Previous Research in Bangladesh

(Mamun et al., 2016) evaluated sand-cement for sub-base construction using fine medium sands from Mymensingh, Fajilpur, Munshiganj, and Sunamganj. They found that 8-10% cement generally met the sub-base strength criteria at 14 days. Notably, 8% cement with Fajilpur/Sunamganj sands satisfied the low-traffic specifications, while 10% was recommended for heavier traffic. (Ashraf et al., 2018) investigated optimum cement content for soft soils around Chattogram (three sites), testing 0-10% cement with 7/14/28-day curing and wet-dry durability per ASTM D559. Unconfined Compressive Strength (UCS) increased with cement up to ~8% (plateauing afterwards), and specimens with ≥8% cement showed little mass/volume change under durability cycles, indicating both strength and durability benefits near the 8% level. (Haque et al., 2024) assessed Sugarcane Bagasse Ash (SBA) as a solo stabilizer for subgrade soil from the Hatikumrul-Bonpara highway, testing 5-20% SBA. SBA reduced PI, slightly increased Maximum Dry Density (MDD) up to ~15% SBA, and maximized UCS at ~204.5 kPa with 15% SBA, indicating a feasible, low-cost, lower-carbon alternative to lime/cement in Bangladeshi contexts. (Islam et al., 2024) explored fly ash (FA) and Crushed Waste Glass (CWG) as partial fine-aggregate replacements in sandy subgrade. With 0-35% FA or CWG, 25% FA yielded the best gains (~55.7% shear-strength increase and 44% CBR boost), highlighting synergy between industrial by-products and granular soils in Bangladesh. (Rahman et al., 2024) studied cement-stabilized highly organic soil from Khulna under staged preloading. They tested 10-20% cement with 3/7/28-day curing and added 10 kPa preloading during/after curing. Results showed substantial UCS improvement over untreated organic soil and beneficial effects of preloading on strength development. (Ashiq et al., 2024) performed a finite-element analysis (FEA) of road-embankment settlement using cement-stabilized soil (CSS) beneath the Chittagong Port Access Road, Teknaf. Field data and soil properties were used to model embankment performance in PLAXIS 2D with CSS layers containing 4 %, 8 %, and 12 % ordinary portland cement. Simulation results showed that CSS markedly reduced long-term settlement and increased the factor of safety compared with untreated soil. The optimum balance between cost and performance was achieved at 4 % cement, with additional CSS layers yielding only marginal improvements. The study also evaluated the inclusion of geotextile reinforcement, which slightly increased slope stability at 18° and 26°. Overall, the authors concluded that cement stabilization effectively mitigates settlement and improves embankment safety in soft-soil regions of Bangladesh.

Table 1 summarizes key chemical stabilization studies conducted in Bangladesh, highlighting stabilizer type, tests performed, and optimal content.

Table 1: Summary of chemical stabilization methods used for pavement

Study (year)	**Soil / Location**	**Stabilizing Agent (%)**	**Tests Performed**	**Key Findings / Improvements**	**Optimal Content/ Remarks**
Mamun et al. (2016)	Fine-medium sands (Mymensingh, Fajilpur, Munshiganj, Sunamganj)	Cement 0-10 %	UCS, CBR (sub-base assessment)	8 % cement met low-traffic criteria; 10 % for heavier traffic	8-10 % cement, depending on traffic load
Ashraf et al. (2018)	Soft silty/clayey soils around Chattogram	Cement 0-10 %	Compaction, UCS, durability loss	Strength increased up to ≈ 8 %; ≥ 8 % showed minimal mass loss	~8 % cement optimum
Haque et al. (2024)	Hatikumrul-Bonpara subgrade	Sugarcane Bagasse Ash (SBA) 5-20 %	Atterberg limits, Proctor, UCS	PI decreased; MDD ↑ to 15 %; UCS ≈ 204 kPa at 15 % SBA	15 % SBA optimum
Islam et al. (2024)	Sandy soil (Bangladesh)	Fly Ash 0-35 %; Crushed Waste Glass 0-35 %	Shear strength, CBR	25 % FA → 55.7 % ↑ shear strength and 44 % ↑ CBR	25 % FA best performance
Rahman et al. (2024)	Highly organic soil (Khulna)	Cement 10-20 % + 10 kPa preload	UCS, XRD/SEM	UCS significantly ↑, preloading further improved strength	≥ 15-20 % cement with preload
Hossain et al. (1991)	Alluvial silty soils (Bangladesh floodplains)	Cement 2-10 %; RHA 0-50 % as partial replacement	UCS, Atterberg limits, wet-dry loss tests	9 % cement met durability criteria; 25 % RHA replacement-maintained	9 % cement or 7.5 % cement + 2.5 % RHA

				strength; RHA alone ineffective	
Ashiq et al. (2024)	Teknaf (Chittagong Port Access Road) soft soil	Cement-Stabilized Soil (CSS) 4-12 %	Finite-element analysis (Plaxis 2D), settlement & safety factor (Msf)	CSS reduced long-term settlement & increased safety factor; adding layers gave a minor extra benefit; geotextile further ↑ Msf by ≈ 0.07 for gentle slopes	4 % cement optimum for cost vs performance

3.2 Mechanical Stabilization

3.2.1 Mechanism of Mechanical Stabilization

Mechanical stabilization enhances the load-bearing capacity of pavement layers primarily by physically modifying the soil or base material rather than relying on chemical reactions. Techniques include intensive compaction to increase density, blending weak fine-grained subgrade soils with well-graded granular materials to improve gradation and drainage, or incorporating engineered reinforcements such as geotextiles, geogrids, and cellular confinement systems (geocells) to introduce tensile resistance and lateral confinement (Christopher et al., 2013). Reclaimed asphalt pavement (RAP) is now also widely used by incorporating processed RAP into the base or subbase. Existing pavement material can be reused, reducing resource consumption.

3.2.2 Summary of Previous Research in Bangladesh

(Alam, 2002) investigated local brick aggregates as alternatives to stone in road base construction and found that although brick aggregates degrade faster under load, appropriate gradation and compaction can make them viable for low-volume roads. (Islam et al., 2018) evaluated reclaimed asphalt pavement (RAP) as a base course material and reported that processed RAP provided adequate structural strength while reducing aggregate scarcity and construction cost. (Hoque & Islam, 2023) investigated geopolymer-based stabilization of expansive soil using Saw Dust Ash (SDA) as a sustainable aluminosilicate precursor in Compressed Stabilized Earth Blocks (CSEBs). Soil-SDA mixtures (0-20%) were activated with $NaOH\text{-}Na_2SiO_3$ at varying alkaline solution-binder ratios (A: B = 0.3-0.5). The optimum composition, 20% SDA with A: B = 0.5, achieved a compressive strength of 1.78 MPa after 28 days, meeting code requirements. Strength improvements up to 400% over untreated soil and reduced efflorescence under moist curing confirmed SDA-geopolymer's viability as a low-carbon alternative for expansive soil stabilization. Podder et al. (2025) rejuvenated aged RAP binders using recycled rice-bran oil, restoring penetration grade, reducing viscosity by 83 %, and markedly improving fatigue and rutting resistance, showing how waste bio-oils can extend the life of 100 % RAP mixtures. (Khan et al., 2014) field trialed on 5 km of rural roads showed CBR improvement from 1.5 to 7 times using Jute geotextile reinforcement through membrane action, moisture absorption, and subgrade consolidation, proving its cost-effective reinforcement value for weak soils in Bangladesh.

Table 2 summarizes key mechanical stabilization studies conducted in Bangladesh, highlighting stabilizer type, tests performed, and optimal content.

Table 2: Summary of mechanical stabilization methods used for pavement

Study (year)	**Soil / Location**	**Stabilizing Agent (%) / Material**	**Tests Performed**	**Key Findings / Improvements**	**Optimal Content / Remarks**

Alam (2002)	Roadbase materials across Bangladesh	Local brick & sand aggregates	Los Angeles Abrasion, gradation analysis	Brick aggregates degrade ≈ 4.5× faster than stone; proper gradation mitigates weakness	Suitable for low-volume roads with controlled gradation
Islam et al. (2018)	Tongi-Ashulia-Zerabo-EPZ Road (N302)	RAP (50-100%) + 5 % cement / 1 % bitumen	Soaked CBR, gradation	100 % RAP → CBR 15; CBR 47 @ 50 % RAP + 5 % cement; CBR 52 @ 100 % RAP + 1 % bitumen	50 % RAP + 5 % cement optimum
Hoque & Islam (2023)	Expansive soil (Bangladesh)	Sawdust Ash (0-20%) + NaOH & Na_2SiO_3 (geopolymer)	Compressive, flexural, tensile strength; SEM, EDXA, FTIR	Max strength 1.78 MPa @ 20 % SDA, A: B = 0.5; flexural 0.35 MPa; tensile 0.31 MPa; moist curing ↓ efflorescence	20 % SDA & A: B = 0.5 optimum; eco-friendly geopolymer for expansive soil blocks
Podder et al. (2025)	Recycled RAP binder (Bangladesh)	Rice Bran Oil (RBO 3-6%) as bio-rejuvenator	Penetration, viscosity, DSR, MSCR, FTIR	5.5 % RBO restored binder to 60/70 grade; viscosity ↓ 83%; fatigue resistance ↑	5.5 % RBO optimal for binder rejuvenation
Khan et al. (2014)	Weak subgrades (< 3 % CBR), rural roads (Bangladesh)	Jute Geotextile (JGT) reinforcement	Field CBR monitoring	CBR ↑ 1.5-7×; load-carrying capacity ↑ via membrane action and moisture absorption	Effective low-cost reinforcement for rural roads

3.3 Biological Stabilization

3.3.1 Mechanism of Biological Stabilization

Biological stabilization improves soil by inducing mineral precipitation or biomass-driven bonding within the pore space, prominently through microbially induced calcite precipitation (MICP) and enzyme-induced carbonate precipitation (EICP). In MICP, ureolytic bacteria hydrolyse urea to produce carbonate ions that, in the presence of Ca^{2+}, precipitate $CaCO_3$, which bridges particles, increasing stiffness, strength, and reducing hydraulic conductivity. Performance depends on cell delivery, cementation solution chemistry, injection strategy, and curing (DeJong et al., 2010). In EICP, a purified urease enzyme (typically plant-derived) catalyzes urea hydrolysis without live microbes, offering simpler logistics and potentially fewer biosafety constraints. EICP has shown substantial gains in stiffness and favourable life-cycle impacts relative to Portland cement in treated soils (Ahenkorah et al., 2021). Beyond urea-$CaCO_3$ systems, bio-based ground improvement may include bio-plugging or bio-grouting for cracks and voids and dust control on unpaved roads, as demonstrated in transportation applications (Chu & Wen, 2015)

3.3.2 Summary of Previous Research in Bangladesh

(Imran et al., 2022) evaluated the durability of MICP-treated sand reinforced with jute fibres under distilled and artificial seawater for coastal protection. Jute fibres enhanced durability by over 50%, though wet-dry cycles reduced strength due to partial breakdown of calcium carbonate. The study emphasized fibre reinforcement as an effective means of improving the long-term performance of

MICP-treated soils under coastal conditions. (Paul et al., 2025) examined MICP with jute fibre reinforcement for stabilizing expansive soil in Bangladesh. The hybrid method increased UCS by 186% and reduced swell strain and pressure by 85-90%, with 1.5% jute fibre giving the best results. The study confirmed improved cohesion and reduced deformability, indicating a practical and eco-friendly stabilization approach. (Paul & Islam, 2025) proposed a sustainable method for stabilizing expansive subgrade soils using MICP via bio-stimulation combined with waste sugarcane bagasse and recycled polyester fibres. The hybrid process improved UCS, STS, and CBR while reducing shrink-swell behaviour. Microstructural and microbial analyses confirmed enhanced calcite bonding and fibre-matrix interaction, with 0.5% fibre and a 4-day mellowing period giving optimal performance for durable subgrade stabilization. (Hoque & Islam, 2023) implemented EICP using soybean urease and a sustainable calcium source derived from waste eggshells ($Ca(CH_3COO)_2$) to reduce the environmental impact of conventional $CaCl_2$-based bio-cementation in Bangladesh. The study optimized the solution composition at a 1:1 molar ratio of calcium acetate to urea with 50 g/L soybean extract, achieving a 7-day UCS of 371 kPa and 0.40 % $CaCO_3$ content. The eggshell-soybean EICP yielded 8.5 % higher UCS than the traditional $CaCl_2$ system, confirming its superior efficiency and eco-friendliness for sandy soil stabilization.

Table 3 summarizes key biological stabilization studies conducted in Bangladesh, highlighting stabilizer type, tests performed, and optimal content.

Table 3: Summary of biological stabilization methods used for pavement

Study (year)	**Soil / Location**	**Stabilizing Agent (%) / Material**	**Tests Performed**	**Key Findings / Improvements**	**Optimal Content / Remarks**
Imran et al. (2022)	Coastal sand (laboratory study)	MICP + Jute fibre reinforcement	Durability, mechanical & microstructural tests	Jute fibres ↑ durability >50%; WD cycles caused partial $CaCO_3$ loss and strength reduction	Jute reinforcement improved MICP durability; promising for coastal and erosion control use
Paul et al. (2025)	Expansive soil (Bangladesh)	MICP via bio-stimulation + Jute fibre (0.5-2%)	UCS, 1D swell, linear shrinkage, SEM	Strength ↑186%; swell strain ↓85%; swell pressure ↓90%; $CaCO_3$ ↑176%; microstructure improved	1.5% jute fibre gave best performance; eco-friendly solution for expansive subgrades
Paul & Islam (2025)	Expansive subgrade soil	MICP (bio-stimulation) + Sugarcane bagasse & polyester fibres (0.25-1%)	UCS, STS, CBR, shrink-swell, SEM-EDS, FTIR, DSC-TGA	Strength ↑ (UCS, STS, CBR); shrink-swell ↓; improved calcite bonding & fibre reinforcement synergy	0.5% fibre + 4-day mellowing optimal; eco-friendly hybrid approach for subgrades

Hoque & Islam (2023)	Poorly graded sandy soil (Bangladesh)	EICP via soybean urease + Ca $(CH_3COO)_2$ from eggshells	Precipitation efficiency, UCS, $CaCO_3$ content	1:1 molar Ca $(CH_3COO)_2$: urea + 50 g/L soybean → UCS = 371 kPa; $CaCO_3$ = 0.40 %; 8.5 % higher UCS than $CaCl_2$-EICP	Demonstrated sustainable EICP using waste eggshell calcium; effective, low-impact soil reinforcement

4. CONCLUSIONS

The rapidly expanding road network in Bangladesh continues to face significant challenges due to weak subgrade soils, increasing traffic loads, and intense rainfall. Researchers have investigated various sustainable soil stabilization methods to improve the durability of pavement networks. The reviewed studies show that pavement stabilization methods have shifted from traditional cement and lime treatments to more sustainable approaches using industrial by-products, recycled materials, and bio-based techniques. Among chemical stabilizers, cement remains the most widely used. Partial substitution with fly ash, sugarcane bagasse ash, or rice-husk ash not only enhanced the strength and durability but also reduced carbon emissions and material costs. Mechanical stabilization using brick aggregates, RAP, and jute geotextiles also demonstrated strong potential, as it utilizes waste resources to increase the strength of pavement soil layers. Emerging biological techniques such as MICP and EICP also offered environmentally friendly alternatives to traditional binders. Studies indicated that these methods can significantly extend pavement life by increasing the unconfined compressive strength of underlying soil.

Overall, the review highlights that while chemical and mechanical stabilization methods are already proven, they should be progressively optimized using industrial by-products to reduce environmental impact. Recycled materials and bio-based techniques show strong potential for sustainable pavement applications under Bangladesh's soil and climatic conditions. Research should focus on developing hybrid stabilization frameworks that combine the rapid strength gain of cementitious materials with the long-term environmental benefits of biological and recycled alternatives. Continuous field monitoring and policy support will be essential to ensure durable, resilient pavement infrastructure in Bangladesh.

Declaration of Use of AI

The authors used AI tools for improving language clarity and grammatical accuracy, including minor paraphrasing and sentence restructuring. AI tools were not used to generate scientific content. The authors take full responsibility for the accuracy and integrity of the manuscript.

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