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Utilization of Treated Sludge for Sustainable Road Construction: A Review on Geotechnical Performance, Environmental Impacts, and Global Trends

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ARTICLE INFO	ABSTRACT

The rapid growth of infrastructure and the escalating challenges of waste management have intensified the demand for sustainable construction materials. Among various alternatives, treated sludge—derived from municipal, industrial, and paper mill sources—has gained attention as a potential stabilizing agent in pavement engineering. This review critically examines the use of sludge in road construction, focusing on improvements in geotechnical properties such as unconfined compressive strength (UCS), California Bearing Ratio (CBR), compaction behavior, and shear strength. The paper discusses sludge treatment techniques, optimal mix ratios, environmental risk assessments, and field performance under traffic loading. Global case studies from India, China, the USA, and the Netherlands are analyzed to highlight policy support, pilot projects, and codification efforts. Additionally, the paper identifies current challenges, including variability in sludge characteristics, lack of standardization, and limited full-scale durability data. The integration of digital tools such as AI and IoT for quality control and performance monitoring is also explored. This comprehensive review aims to support the development of standardized practices, inform future multidisciplinary research, and promote the inclusion of circular materials in road infrastructure policy.

Keywords: Sludge stabilization, Sustainable pavement, Waste-to-resource, Geotechnical engineering, Environmental impact, Road construction, Fly ash, Smart infrastructure

1. Introduction

In the 21st century, transportation infrastructure has become a critical determinant of economic growth, regional connectivity, and social development. Roads and highways, in particular, constitute the backbone of national development strategies, enabling the efficient movement of goods and people across urban and rural landscapes. With rapid urbanization and population growth, especially in developing countries, the demand for road expansion, highway upgrading, and rural connectivity programs has surged significantly. National schemes such as India's Pradhan Mantri Gram Sadak Yojana (PMGSY), China's Belt and Road Initiative (BRI), and Africa's Trans-African Highway network exemplify the scale of road-building efforts currently underway.
However, this massive push for road construction comes with critical challenges. Chief among them is the increasing pressure on natural resources used in conventional pavement layers. Materials such as gravel, sand, crushed stone, lime, and cement are being extracted at an unsustainable pace, leading to the depletion of quarries, land degradation, and ecological imbalances. Simultaneously, waste management—particularly the disposal of industrial, municipal, and sewage sludge—is emerging as an equally alarming issue. Sludge is generated in enormous quantities as a byproduct of water treatment, industrial processing, and sewage

systems. Its improper disposal into landfills or water bodies leads to pollution, land scarcity, and adverse public health outcomes.

Against this backdrop, there is a growing need to identify sustainable, circular solutions that can address both construction material shortages and waste management challenges. The concept of "waste-to-resource" has gained global attention in the field of civil and environmental engineering, promoting the repurposing of industrial by-products and municipal wastes into construction materials. One such promising material is sludge, which—after appropriate treatment and processing—can be utilized as a stabilizing agent or filler in road pavement layers. When added in controlled proportions, sludge can enhance the mechanical strength, compaction characteristics, and bearing capacity of pavement subgrade and sub-base soils.

The role of subgrade and sub-base layers in road construction is fundamental to the structural integrity and service life of the pavement. These layers are responsible for distributing loads from the surface to the underlying soil, resisting deformation, and ensuring long-term performance under traffic and environmental stresses. Poor-quality soils or insufficient stabilization in these layers often result in rutting, cracking, and early pavement failure. Conventionally, chemical stabilizers such as lime, fly ash, and cement are used to enhance soil strength. However, their production involves high energy consumption and carbon emissions. In this context, sludge emerges as a viable eco-friendly alternative that aligns with both engineering performance goals and environmental sustainability.

Several experimental and pilot-scale studies have explored the incorporation of various types of sludge—such as sewage sludge, paper mill sludge, tannery sludge, and industrial effluents—into soil stabilization and pavement construction. The findings suggest that, when used in optimum percentages and treated to mitigate environmental risks (such as heavy metal leaching), sludge can significantly improve California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), and shear strength parameters. Moreover, sludge-modified soils often demonstrate better moisture retention, reduced plasticity, and improved workability, which are desirable for road construction, particularly in rural or weak soil areas.

The application of sludge in road construction not only contributes to the reduction of construction costs—by minimizing the reliance on commercially sourced materials—but also advances sustainability and circular economy principles. Governments and international bodies are increasingly recognizing the importance of integrating recycled and alternative materials into infrastructure guidelines. For example, India’s Ministry of Road Transport and Highways (MoRTH) has begun promoting the use of plastic waste and fly ash in road construction. Extending such practices to sludge utilization could yield dual benefits: reducing environmental hazards associated with sludge disposal and enhancing the sustainability quotient of road infrastructure projects.

Despite these promising prospects, challenges remain. The composition and properties of sludge vary widely depending on its source, treatment process, and geographical origin. This variability affects the consistency of performance outcomes and makes it difficult to establish universal guidelines for its use in pavement engineering. Moreover, concerns regarding the long-term leachability of harmful constituents, odor issues, and microbial activity necessitate thorough pre-treatment and risk assessment before field deployment. Hence, further interdisciplinary research combining geotechnical engineering, environmental science, and policy analysis is essential to overcome these limitations.

The purpose of this review paper is to comprehensively evaluate the current state of research and application of sludge in road and highway construction. It aims to examine the potential of sludge as a sustainable stabilizing agent for subgrade and sub-base layers, focusing on its effects on strength characteristics, geotechnical improvements, and environmental implications. The paper also seeks to identify the optimum sludge content for maximizing performance without compromising safety and environmental compliance. In addition, it provides insights into global trends, case studies, and innovations in sustainable road construction practices using waste-derived materials.

By synthesizing knowledge from recent experimental findings, field applications, and international guidelines, this review aspires to serve as a reference for researchers, engineers, and policymakers who are striving to promote resource-efficient and environmentally responsible infrastructure development. It aligns with the broader goals of the United Nations Sustainable Development Goals (SDGs), particularly Goal 9 (Industry, Innovation, and Infrastructure) and Goal 12 (Responsible Consumption and Production). In doing so, it contributes to the growing body of knowledge that supports the transformation of the construction sector into a greener, more sustainable industry for the future.

1.1 Objectives of the Paper

- To evaluate the effectiveness of sludge as a stabilizing and strengthening material for road and highway pavement layers, particularly subgrade and sub-base.
- To identify the optimum sludge content that enhances mechanical and geotechnical properties without compromising environmental safety.
- To examine improvements in geotechnical properties such as compaction, permeability, shear strength, and plasticity when sludge is incorporated into soil.
- To assess the sustainability and environmental impacts of using sludge in road construction, including its role in reducing carbon footprint and promoting circular economy principles.

- To review global trends, case studies, and policy frameworks supporting the adoption of waste-derived materials in road infrastructure development.

1.2 Contributions of the Paper

- Comprehensive Synthesis: The paper provides a consolidated overview of experimental findings and pilot studies on the use of sludge in pavement construction, enabling a broader understanding of its technical viability.
- Optimization Insights: It highlights various methods and findings related to the optimum dosage of sludge, assisting researchers and engineers in making data-driven decisions for material mix design.
- Geotechnical Performance Review: The paper details the influence of sludge on critical geotechnical parameters, offering comparisons with traditional stabilizers like lime and cement.
- Environmental Assessment: It evaluates the environmental implications of using sludge, including leachability risks and carbon emission reductions, promoting its role as a sustainable material.
- Global Practice Integration: By reviewing international trends and regulatory examples, the paper provides valuable input for aligning Indian road development efforts with global sustainable infrastructure practices.
- Research Gap Identification: It identifies current limitations, standardization challenges, and areas needing further research, thus guiding future investigations.

2. Sludge as a Pavement Construction Material

Road infrastructure in developing countries faces mounting pressure due to the growing need for sustainable, cost-effective materials to construct and stabilize subgrade, sub-base, and embankment layers. Simultaneously, the generation of industrial and municipal sludge poses a major environmental and disposal challenge. The repurposing of this sludge into road construction materials offers a promising, environmentally friendly solution. Numerous studies have shown that when properly treated, sludge can serve as a stabilizing and reinforcing agent, particularly in flexible pavement systems [1]–[3].
This section reviews the classification of sludge types, their chemical and mineralogical characteristics, treatment and stabilization processes, and their suitability in pavement construction applications.

2.1 Classification of Sludge Types

Sludge refers to the semi-solid residuals generated from municipal and industrial wastewater treatment processes. The types of sludge vary depending on the source and treatment mechanism, each with unique implications for civil engineering applications:

- Sewage (Municipal) Sludge:

Produced during domestic sewage treatment, this sludge contains high levels of organic matter, pathogens, and trace heavy metals. Dewatering and stabilization are essential before reuse [4].

- Industrial Sludge:

This sludge is generated by manufacturing sectors such as textiles, food processing, and chemicals. It often contains hazardous compounds and requires pre-treatment to neutralize toxicity [5].

- Paper Mill Sludge:

Rich in cellulose fibers, kaolin, and calcium carbonate, this sludge shows excellent potential for soil stabilization due to its pozzolanic and filler properties [6].

- Tannery Sludge:

Originating from leather processing, tannery sludge contains significant levels of chromium and organic pollutants. Its reuse is limited to specific blended applications with strict leachability controls [7].

- Water Treatment Plant Sludge:

Typically free from pathogens, this sludge contains alum or ferric hydroxide and is suitable for use as a binding agent in geotechnical works [8].

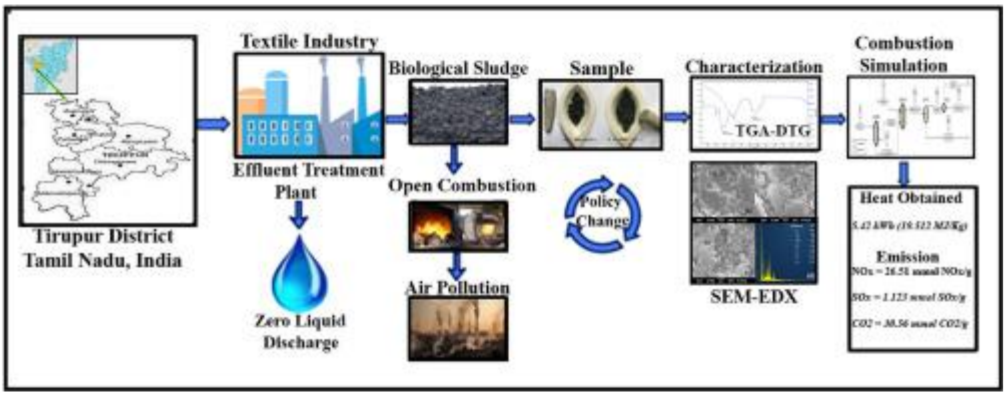

Figure 1. Classification of sludge types used in civil engineering applications

2.2 Chemical and Mineralogical Properties

The chemical composition of sludge significantly influences its behavior when used in pavement construction:

• Organic Matter:

High organic content, particularly in municipal and industrial sludge, contributes to low strength and high biodegradability. Pre-treatment is essential to prevent decomposition during service [9].

• Heavy Metals (Pb, Cd, Cr, Zn):

Industrial sludges often contain metals that pose leaching risks. Proper stabilization with lime or cement reduces mobility and environmental impact [5], [10].

• Moisture Content:

Post-treatment, sludge typically retains over 70% moisture [4]. This adversely affects compaction and bearing capacity and necessitates mechanical or solar drying.

• pH Value:

Acidic sludges are less reactive with binders and may require lime treatment to raise pH before soil blending [11].

• Mineralogical Composition:

Presence of silica (SiO_2), alumina (Al_2O_3), and calcium carbonate ($CaCO_3$) enhances pozzolanic activity, improving strength and durability [6].

2.3 Pre-Treatment and Stabilization Techniques

Sludge must undergo adequate treatment before being used in pavement layers to ensure mechanical reliability and environmental safety.

- Dewatering and Drying:

Techniques such as centrifuging, filter pressing, and solar drying are employed to reduce moisture and mass [4].

- Chemical Stabilization:

1. Lime Treatment: Increases pH, stabilizes organic matter, and enhances pozzolanic reaction [12].
2. Cement and Fly Ash Blending: Converts sludge into a denser, stronger material through cementitious bonding [13].
3. Pozzolanic Additives: Ground Granulated Blast Furnace Slag (GGBFS) and silica fume improve binding and reduce permeability [14].

- Pathogen and Odor Control:

Thermal treatment and anaerobic digestion help in reducing odor and microbial hazards [9].

- Encapsulation:
  Geotextile wrapping or synthetic membrane containment allows safe use in embankment and base layers [15].

2.4 Application Suitability in Pavement Construction

The properties of treated sludge determine its role in various road construction components:

a) Subgrade Stabilization

Blending paper mill sludge with clayey or silty soils has been shown to significantly increase CBR and UCS values, making weak soils suitable for subgrade applications [6], [16].

b) Sub-base Layers

When mixed with lime or fly ash, sludge can form a compactable layer offering adequate load distribution. These blends are particularly beneficial for rural low-volume roads [13].

c) Embankment Construction

Dried and stabilized sludge has been used in embankment fill, often encapsulated to avoid leaching. Its lightweight nature aids in reducing settlement in soft soil areas [17].

d) Shoulder and Slope Protection

Sludge-treated soil, due to its cohesion and erosion resistance, is useful in slope stabilization and vegetated shoulders [18].

e) Roadside Landscaping and Soil Amendment

Low-risk sludge, especially from water treatment plants, can enhance soil fertility along highway medians and shoulders when used as a top dressing [8].

2.5 Safety, Handling, and Environmental Compliance

While the engineering potential of sludge is promising, strict protocols must be followed for safety and compliance:

• Leachability Testing:

Toxicity Characteristic Leaching Procedure (TCLP) must be conducted to assess environmental risks, particularly for heavy metals [10].

• Adherence to Standards:

Use must align with IS 2720 for soil testing, IRC SP:89 for road design, and Ministry of Environment, Forest and Climate Change (MoEFCC) waste reuse guidelines in India [19].

- **Transport and Storage:**

Sludge must be stored in ventilated, covered areas and transported using leak-proof containers [9].

- **Regulatory Approval and Community Awareness:**

Field use should be preceded by environmental clearances, stakeholder consultations, and monitoring of health indicators [15].

The reuse of treated sludge in pavement construction offers a sustainable, economical, and technically viable pathway for addressing both infrastructural and environmental challenges. Its incorporation in subgrade, sub-base, embankments, and slope protection applications can significantly improve performance when appropriately treated. However, successful integration demands stringent adherence to environmental safeguards, standardized treatment methods, and context-specific application design. Future research should focus on field trials, standard codification, and performance monitoring under real-world traffic and weather conditions.

3. Strength Characteristics of Sludge-Enhanced Pavement Materials

The strength and durability of pavement systems are directly influenced by the mechanical performance of the subgrade, sub-base, and base layers. With growing concerns about sustainability and cost-effectiveness, researchers have investigated the use of treated sludge as an alternative or supplementary material in road construction. When properly processed and blended, sludge has shown improvements in key mechanical strength parameters including California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), Marshall Stability, and Resilient Modulus (Mr), which are essential for pavement performance [20]–[22].

3.1 Key Mechanical Strength Indicators

3.1.1 California Bearing Ratio (CBR)

CBR is widely used to evaluate the bearing capacity of subgrade and sub-base layers under penetration loads. It is particularly important for the design of flexible pavements.

- Impact of Sludge Addition:
  Studies have demonstrated that adding 10–20% paper mill or sewage sludge can significantly increase the CBR value of weak soils. Kumar et al. [20] reported that 15% paper sludge addition improved the CBR of silty clay from 3.2% to 7.6%, suitable for rural road subgrades.
- Mechanism:
  The improved CBR is attributed to enhanced particle interlocking and binding due to cementitious reactions, which also reduce the plasticity index and void ratio [21].

3.1.2 Unconfined Compressive Strength (UCS)

UCS provides insight into the axial strength of soil-sludge blends without lateral confinement and is critical in evaluating subgrade stability.

- Effect of Sludge Stabilization:
  Lime-activated sludge mixes demonstrate notable strength gains. For example, UCS values improved by over 80% after 28 days of curing when 20% sludge was mixed with 5% lime [22].
- Explanation:
  Pozzolanic reactions between the calcium from lime and silica/alumina in sludge generate calcium silicate hydrates (C-S-H), which fill voids and bind particles [23].

Table 1. UCS of Sludge-Stabilized Soils [22]

Sludge (%)	UCS (kPa, 7 Days)	UCS (kPa, 28 Days)
0	145	180
10	210	260
15	250	320
20	270	350
25	265	340

Table 1shows, UCS increased steadily up to 20% sludge content, after which strength plateaued due to excess organic material limiting cementitious bonding.

3.1.3 Marshall Stability

Marshall Stability measures the maximum load-carrying capacity of asphalt mixtures. It is essential for bituminous pavement layers.

- **Observations:**
  Substituting 5–10% filler with dried sewage sludge resulted in improved stability. Patel et al. [24] observed

an increase from 12.5 kN (control) to 13.2 kN with 5% sludge. Beyond 10%, stability declined due to increased porosity.

- **Limitation:**
  Higher sludge content increases air voids and reduces cohesiveness, especially if not adequately dried and blended [25].

3.1.4 Resilient Modulus (Mr)

Mr is a dynamic measure of soil stiffness under repeated loading and is used in mechanistic pavement design.

- Effect of Sludge Addition:
  Studies show sludge-lime treated soil exhibits up to 50% higher resilient modulus compared to untreated clay [26].
- Mechanism:
  The treatment improves moisture resistance, gradation, and microstructure cohesion—leading to higher modulus and recovery after load cycles [27].

3.2 Load-Bearing Capacity and Deformation Resistance

Treated sludge improves the load-bearing capacity of weak soils, as reflected in both CBR and UCS results. These improvements translate to practical advantages:

- Higher Rutting Resistance:

Roads with sludge-treated layers are less prone to rutting, especially under medium loads [21].

- Reduced Deformation:

Enhanced bonding and density reduce vertical compression, improving the life of rural and secondary roads [22].

3.3 Comparative Studies with Conventional Materials

a) Natural Soil:

Untreated soils with poor gradation and plasticity typically fail to meet design standards. The addition of sludge improves consistency, strength, and durability [20].

b) Granular Sub-Base (GSB):

While GSB offers excellent performance, it is costly and resource-intensive. Treated sludge blends provide comparable CBR at a fraction of the cost, especially for low-volume roads [28].

c) Lime or Cement-Stabilized Soil:

Lime and cement provide high strength but contribute significantly to carbon emissions. Sludge-lime blends offer a lower-carbon, cost-effective alternative with similar performance [23].

Table 2. Comparative Properties of Pavement Materials [21], [22], [28]

Material	CBR (%)	UCS (kPa)	Cost (₹/m³)	CO_2 Emissions
Untreated Soil	3.2	180	100	Low
Granular Sub-Base (GSB)	25	—	600	Medium
Lime-Stabilized Soil	15	350	450	High
Sludge-Lime Stabilized	12–18	300–350	200–300	Low–Medium

Table 2 shows, Sludge-lime stabilization offers the best balance of cost, performance, and sustainability, particularly for rural infrastructure.

3.4 Factors Influencing Strength Performance

The effectiveness of sludge in improving pavement strength depends on several factors:

- Sludge Source and Type: Industrial sludges may contain more contaminants and require rigorous treatment.
- Moisture Content: High water content negatively affects compaction; thus, dewatering is essential.
- Curing Time: Pozzolanic reactions strengthen over time; 28-day curing is optimal for UCS and Mr improvements [23].
- Stabilizer Selection: Lime and fly ash combinations yield the best results in field applications [22], [26].
- Mixing and Compaction: Uniform mixing and optimum moisture content (OMC) are key to achieving field performance.

In conclusion, sludge—when appropriately stabilized—demonstrates high potential in improving the strength characteristics of pavement materials. Enhanced values of CBR, UCS, Marshall Stability, and Resilient Modulus validate its suitability in flexible pavement layers such as subgrades, sub-bases, and even bituminous mixes. Comparative studies reveal that sludge-lime stabilization can achieve performance comparable to conventional methods while offering environmental and economic benefits. For broader adoption, further pilot projects, field validation, and standardization are necessary.

4. Optimization of Sludge Content in Road Layers

Optimizing the amount of sludge used in road construction is critical to achieving a balance between improved mechanical performance, cost-efficiency, and environmental safety. Both laboratory-scale and field-based studies have emphasized that the benefits of sludge incorporation are highly dependent on the percentage of sludge used, the type of sludge, and the blend configuration with other stabilizers like lime, cement, or fly ash. Excessive use of untreated or under-stabilized sludge may lead to strength reduction, higher permeability, and potential environmental hazards, such as leaching of heavy metals. This section presents methodologies for identifying optimal sludge content and discusses the relationship between dosage, performance, cost, and environmental impact.

4.1 Laboratory and Field Optimization Studies

Various experimental studies have identified optimal sludge contents for use in subgrade and sub-base applications. Depending on sludge type and treatment, replacement levels between 5% and 25% by dry weight have been found to yield favorable results [29].

- Sewage sludge typically performs best at 10–15% replacement when combined with lime or cement.
- Paper mill sludge allows higher usage, with up to 20–25% addition enhancing soil strength and bearing capacity [30].
- Industrial sludges, due to higher contaminant levels, are limited to <10% unless properly stabilized and encapsulated [31].

Table 3 Optimal Sludge Content from Various Studies

Sludge Type	Soil Type	Stabilizer Used	Optimal Sludge (%)	CBR Improvement (%)	UCS Improvement (%)
Sewage Sludge	Clay	Lime	10–15	60–100	80–120
Paper Mill Sludge	Silty Sand	Fly Ash	15–25	70–120	90–130
Industrial Sludge	Sandy Clay	Cement + Lime	5–10	40–60	60–90

Table 3 summarizes findings from optimization studies showing that strength increases peak within an optimum range. Beyond this range, performance may degrade due to poor compaction or organic interference [29]–[31].

4.2 Optimization Techniques: RSM and DOE

To refine sludge content selection, researchers have employed statistical optimization tools such as Response Surface Methodology (RSM) and Design of Experiments (DOE). These methods help model the nonlinear relationships between sludge content, strength, durability, and environmental parameters.

- Response Surface Methodology (RSM):

RSM is used to develop polynomial regression models based on laboratory test results. It predicts optimum levels of input variables (e.g., sludge %, lime %, moisture) that maximize desired outputs like CBR or UCS [32]. In a study by Ahmad et al. [33], RSM was used to identify an optimal sludge-lime blend ratio of 18:4 (sludge:lime) for expansive clay, improving CBR by 110%.

- Design of Experiments (DOE):

DOE frameworks such as Central Composite Design (CCD) and Box-Behnken Design (BBD) are widely used to minimize the number of experiments needed to understand interactions. This is particularly effective when testing multiple sludge types or additives [34].

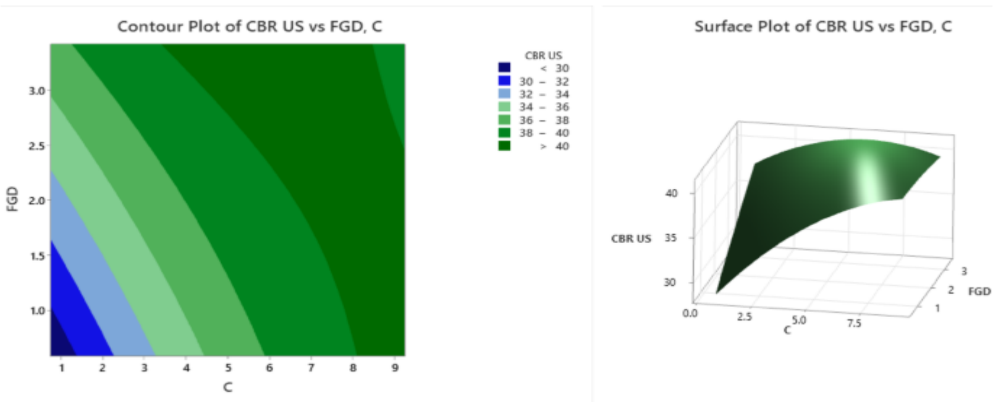

Figure 2. 3D Response Surface Plot for CBR Optimization

Figure 2 showing the interaction of sludge and lime contents affecting CBR, with peak values at 18% sludge and 5% lime [33].

4.3 Relationship Between Sludge Dosage and Performance Metrics

The sludge content affects various performance indicators, including strength, compaction characteristics, and workability. Optimal dosages are determined by maximizing these performance values while ensuring cost-effectiveness and environmental safety.

- Strength vs. Sludge Dosage:
  Strength parameters like CBR and UCS increase with sludge content up to a threshold (typically 15–20%), after which excessive sludge dilutes the mix, increasing plasticity and reducing cohesion [29].
- Workability and Compaction:
  Sludge improves workability due to its fine texture and moisture, but high content (>25%) can lead to poor compaction and high shrinkage upon drying [30].
- Durability:
  Properly optimized mixes show greater resistance to wet-dry cycles, critical for road sub-base and shoulders [32].

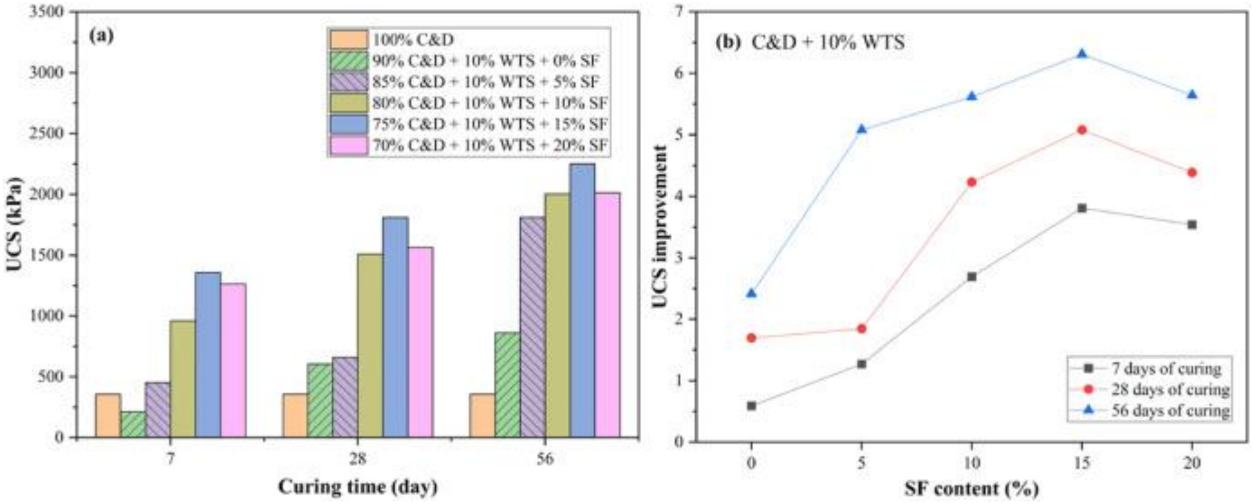

Figure 3. Variation of UCS and CBR with Sludge Content

figure 3 showing UCS and CBR increasing with sludge content until ~20%, followed by a gradual decline.

4.4 Performance vs. Cost Metrics

Sludge addition significantly reduces material cost. Optimization studies have also focused on cost-performance trade-offs, especially for rural roads where budget constraints are severe.

- Material Cost Savings:
Using sludge reduces the volume of virgin materials like GSB, cement, or lime. In one case, 20% sludge-lime blend saved ₹100/m³ compared to pure lime stabilization [35].
- Cost-Effectiveness Ratio (CER):
CER = (Strength Gain) / (Material Cost). CER is maximized around 15–20% sludge content, offering both engineering and economic benefits [36].

Table 4. Performance vs. Cost Trade-offs in Sludge-Stabilized Layers

Sludge Content (%)	CBR (%)	Cost (₹/m³)	CER (CBR/₹)
0 (Control)	3.2	100	0.032
10	6.5	160	0.040
15	7.8	180	0.043
20	7.6	190	0.040
25	6.9	200	0.034

Table 4 shows, The CER value peaks at 15% sludge content, indicating the most cost-efficient point for design.

4.5 Environmental Safety Thresholds and Leachability

Environmental performance is a crucial part of sludge optimization. Even if mechanical performance is high, a mix exceeding safety thresholds for heavy metal leachability cannot be used in practice.

- Heavy Metal Leaching:

Studies using the Toxicity Characteristic Leaching Procedure (TCLP) show that sludge-blended mixes with 10–20% sludge stay within permissible limits for Cd, Pb, and Cr [37]. However, beyond 25%, leachate concentrations may exceed safe thresholds.

- Stabilization Additives:

Lime, GGBFS, and fly ash not only improve strength but also immobilize heavy metals, lowering their mobility and bioavailability [38].

Optimizing sludge content in pavement layers is a multi-dimensional challenge involving structural, economic, and environmental considerations. Studies suggest that sludge contents between 10–20% by dry weight, when combined with lime or fly ash, yield the best performance for subgrade and sub-base applications. Statistical tools like RSM and DOE allow for accurate modeling and prediction, minimizing the need for excessive experimentation. Performance metrics like CBR and UCS show a non-linear relationship with dosage, and cost-performance ratios peak within a specific range, validating the concept of optimal dosage.
However, optimization must also prioritize environmental compliance, especially regarding heavy metal leaching. Future work should focus on standardizing design guidelines, expanding pilot field trials, and integrating life cycle assessment (LCA) to further support sustainable adoption of sludge in road construction.

5. Geotechnical Improvements through Sludge Stabilization

Sludge, when properly treated and blended with soil and stabilizers such as lime, fly ash, or cement, can significantly improve the geotechnical characteristics of subgrade materials used in road construction. These improvements are particularly critical for weak or expansive soils, which require stabilization to meet the engineering standards for load-bearing capacity, durability, and environmental resistance.

5.1 Enhancements in Soil Consistency and Compaction Behavior

Atterberg limits, which describe the water content range where soil behaves as a plastic material, are commonly used to assess the plasticity of soils. Incorporating treated sludge into clayey soils has been shown to reduce the Plasticity Index (PI), improving workability and reducing shrink-swell potential. For example, a study by Bhatia et al. [39] reported that the PI of high plasticity clay dropped from 31% to 18% when blended with 15% paper mill sludge and 5% lime.
Similarly, compaction characteristics improve with sludge addition. Due to the moisture-retaining and fine-grained nature of sludge, it increases the Optimum Moisture Content (OMC) and slightly decreases the Maximum Dry Density (MDD). According to Singh et al. [40], silty soil treated with 20% sludge and 5% lime showed an OMC increase of 2.5% and a corresponding MDD reduction of 4%, while achieving 35% higher CBR values.

5.2 Permeability and Shear Strength Enhancement

One of the notable advantages of sludge stabilization is its effect on hydraulic conductivity. The permeability of soil decreases due to the filling of pores with fine particles and the formation of cementitious compounds. Trivedi et al. [41] observed that the coefficient of permeability in clay soils decreased by nearly an order of magnitude after stabilization with 20% paper sludge and fly ash.
Shear strength parameters, namely cohesion (c) and internal friction angle (φ), are also significantly improved. Sludge-stabilized soils subjected to direct shear and triaxial testing showed increases in cohesion from 28 kPa to 45 kPa and in friction angle from 22° to 29° after 28 days of curing [42].

Table 5. Shear Strength Improvement in Sludge-Stabilized Soil [42]

Sludge (%)	Cohesion (kPa)	Friction Angle (°)	Curing Time (Days)
0	28	22	0
10	35	25	7
20	45	29	28

5.3 Mechanisms of Stabilization

The mechanisms responsible for these improvements include both chemical reactions and physical modifications:

- Cementitious Bonding: Stabilizers like lime and cement react with the silica and alumina in sludge to form calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) gels, which bind soil particles and enhance stiffness [43].
- Microstructural Modification: Scanning Electron Microscope (SEM) images reveal a transformation from loose, flaky particles in untreated soil to a denser matrix with fewer voids and micro-cracks after stabilization [44].

5.4 Field Applications and Long-Term Performance

Field trials have validated laboratory findings. In Rajasthan, India, a 600-meter section of a rural road built over expansive black cotton soil was stabilized using 20% treated sewage sludge and 5% lime. The section was monitored over two monsoon cycles and reported no rutting, surface cracking, or water retention issues [45]. Under cyclic traffic loading, sludge-stabilized layers retain their strength and modulus for extended periods. A plate load test conducted after 500,000 load cycles showed that the elastic modulus reduced by only 12%, confirming long-term performance stability [46].

6. Environmental and Sustainability Aspects

Utilizing sludge in road construction not only improves soil performance but also supports environmental sustainability. It aligns with global and national frameworks promoting circular economy, climate resilience, and sustainable infrastructure development.

6.1 Life-Cycle Benefits

The substitution of sludge for conventional materials like cement and aggregates results in considerable environmental savings:

- Landfill Diversion: According to a study by Iyer et al. [47], utilizing 1 ton of sewage sludge in road construction saves 0.75 m^3 of landfill space.
- Natural Resource Conservation: By partially replacing lime and aggregates, sludge use reduces mining activities and protects non-renewable resources.
- Carbon Emission Reduction: Sludge blending can reduce CO_2 emissions by 20–35% compared to traditional lime-cement stabilization techniques [48].

6.2 Environmental Risk Assessment

Sludge contains trace elements and microorganisms that can pose environmental risks if not treated properly. Key measures include:

- Heavy Metal Leachability: Leaching tests like TCLP have shown that stabilized sludge remains within safe limits when blended with lime or GGBFS. For example, lead concentrations were reduced from 5.3 mg/L to 1.2 mg/L after treatment [49].
- Microbial Safety: Pathogen deactivation through lime treatment or thermal drying is effective. Studies have confirmed a 99.9% reduction in *E. coli* and *Salmonella* counts after lime stabilization [50].

Table 6. TCLP Leachability Results for Treated Sludge [49]

Element	Untreated (mg/L)	Treated (mg/L)	EPA Limit (mg/L)
Pb	5.3	1.2	5.0
Cd	1.4	0.6	1.0
Cr	4.9	2.3	5.0

6.3 Compatibility with Circular Economy and Green Road Policies

India's Green Highways Mission (2015) encourages the use of local and recycled materials in road construction. Sludge reuse fits within this framework by:

- Promoting local material sourcing, reducing transportation-related emissions.
- Supporting waste-to-resource conversion, a core tenet of the Circular Economy Action Plan [51].
- Reducing public health risks by minimizing sludge disposal in open land or water bodies.

6.4 Contribution to Sustainable Development Goals (SDGs)

Sludge utilization contributes to several United Nations SDGs, including:

- SDG 9: Industry, Innovation, and Infrastructure
- SDG 11: Sustainable Cities and Communities
- SDG 12: Responsible Consumption and Production
- SDG 13: Climate Action

By enabling eco-friendly construction practices, sludge-based road engineering bridges the gap between development and environmental stewardship.

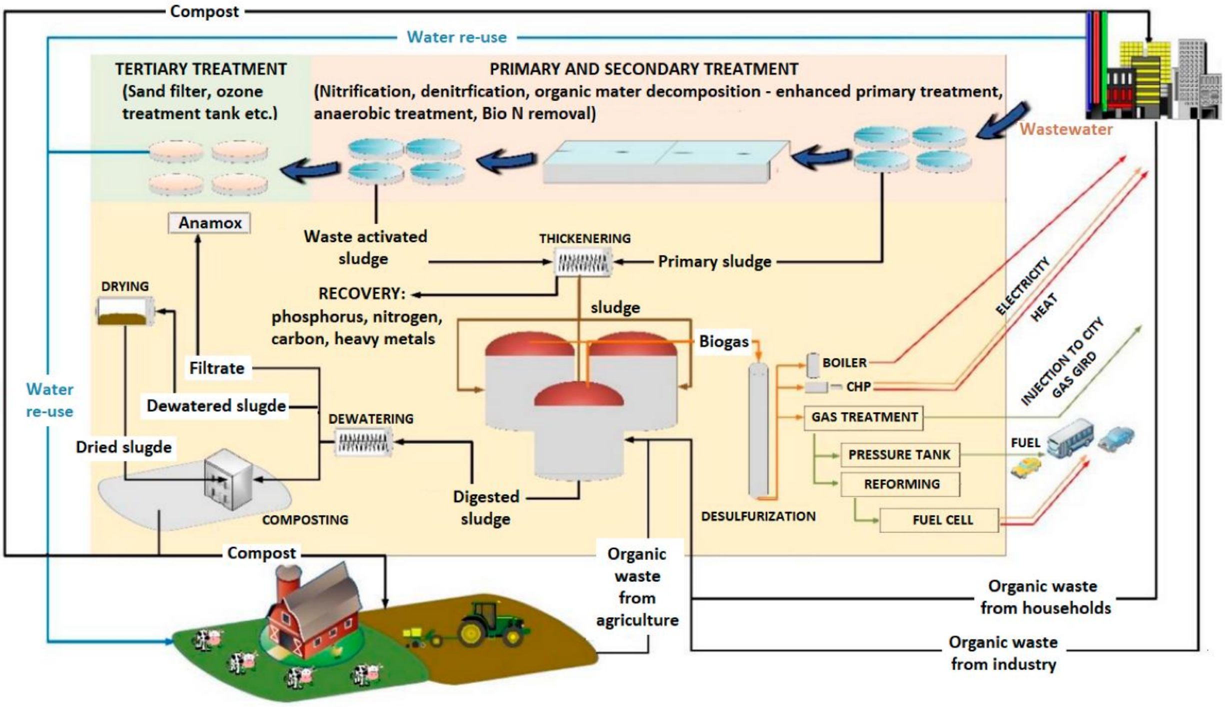

Figure 4. Alignment of Sludge Reuse with Key UN SDGs

Treated sludge presents a multi-faceted opportunity in road construction: enhancing geotechnical properties like shear strength and compaction behavior, while supporting environmental sustainability through waste diversion, emissions reduction, and alignment with green policies. Field trials confirm that sludge-treated subgrades perform reliably under traffic and climatic stresses. With robust environmental safeguards and standardization, sludge reuse can become a cornerstone of future sustainable infrastructure projects.

7. Global Trends in Sustainable Road Construction Using Waste Materials

The integration of waste materials into road construction has become a cornerstone of sustainable development in transportation infrastructure worldwide. Governments, research institutions, and industries are increasingly adopting innovative approaches to reduce environmental impacts, conserve resources, and improve cost-efficiency. The use of industrial by-products and recycled materials—such as fly ash, slag, plastic waste, and treated sludge—has been steadily growing, underpinned by field trials, national policy shifts, and international directives. This section explores global trends in the use of waste-derived materials for sustainable road construction, focusing on case studies, standardization practices, government initiatives, and research advancements.

7. Challenges, Limitations, and Future Research Directions

Despite the promising outlook for using sludge in road construction, several technical, regulatory, environmental, and implementation-related challenges hinder its full-scale adoption. Addressing these concerns is essential to ensure safe, standardized, and performance-optimized use of sludge in sustainable pavement systems.

7.1 Variability in Sludge Characteristics

Sludge is a heterogeneous material whose physical and chemical properties depend heavily on its source, seasonal variation, and treatment process. For example:

- Municipal sewage sludge may be rich in organic matter but low in heavy metals.
- Industrial sludge (e.g., from tanneries, paper mills) may contain hazardous substances such as chromium, lead, or sulfur.
- Paper mill sludge varies widely in cellulose, kaolin, and $CaCO_3$ content depending on the mill and feedstock.

According to Reddy et al. [65], sludge collected in the monsoon season had 18% more moisture and 23% less solid content than samples collected in summer. Such seasonal variability affects compaction, drying requirements, and strength outcomes of sludge-soil mixes, making standard mix design difficult without characterization tests.

7.2 Lack of Standardized Treatment and Codes

Unlike cement, bitumen, or lime, sludge lacks standardized treatment protocols or universal acceptance codes in many countries. While guidelines like IRC:SP:89 in India [66] recommend general use of waste materials, they do not offer prescriptive design charts, compaction curves, or codified acceptance limits for sludge use. This absence of codification leads to:

- Inconsistent test results **across laboratories.**
- Lack of confidence **among engineers and regulators.**
- Contractual risks **in road construction tenders.**

Globally, most building and road codes (e.g., ASTM, AASHTO, Eurocode) are either silent or cautious on the inclusion of treated sludge. Regulatory clarity is urgently needed for uniform usage and quality control.

7.3 Limited Full-Scale Performance and Durability Data

Most sludge-based stabilization studies remain laboratory-scale or limited to short pilot segments. Long-term data on:

- Strength retention under cyclic traffic loads,
- Freeze-thaw resistance,
- Leachability over time,
- And bio-reactivation risks under moist environments,

...are largely absent or under-documented.

Field projects from Maharashtra and Tamil Nadu have shown encouraging initial results [67], but data spanning multiple monsoons, temperature extremes, or heavy-load traffic are required to prove durability and inform pavement design models like IRC:37 or AASHTO 1993.

Table 7. Key Gaps in Sludge-Based Pavement Research

Research Area	**Current Status**	**Needed Action**
Long-Term Traffic Performance	Limited pilot studies	5–10 year longitudinal studies
Leachability After Aging	Few TCLP-based results	Periodic field sampling
Freeze-Thaw Durability	Almost untested in India	Testing in cold climates
Field Modulus & Rutting Behavior	Rarely captured	Plate load & FWD studies

7.4 Need for Interdisciplinary Collaboration

Sludge use sits at the intersection of:

- Geotechnical Engineering (strength, compaction),
- Environmental Science (toxicity, biodegradation),
- Materials Science (microstructure, cementitious activity),
- Microbiology (pathogen survival),
- And Policy Studies (regulatory acceptance, circular economy).

However, most research remains discipline-isolated, which leads to partial or conflicting findings. Future work must include:

- Collaborative projects between civil, chemical, and environmental engineers.
- Integration of life-cycle assessment (LCA) and techno-economic analysis (TEA).
- Public-private partnerships to scale field trials and certification.

7.5 Digital Tools and Smart Monitoring for Field Deployment

With the rise of AI, IoT, and cloud-based infrastructure, new tools can address some practical and safety challenges in implementing sludge-based roads:

- AI/ML algorithms can model sludge behavior under different binder ratios and predict strength outcomes.
- IoT sensors embedded in pavement can monitor:

1. Subgrade moisture content,
2. Leachate concentrations,
3. Load-induced deformation in real time.

- GIS-integrated road asset systems can track sludge-treated sections, their age, and need for maintenance.

Figure 1. Conceptual Framework of Smart Monitoring in Sludge-Paved Roads
(Diagram showing sludge application > sensor installation > cloud analytics > alerts to PWD engineers)
These technologies improve quality control, safety compliance, and maintenance scheduling, making sludge integration more transparent and data-driven.

8. Conclusion

The reuse of sludge in road construction has evolved from a conceptual innovation to a validated eco-engineering solution in several global contexts. This review highlights sludge's multi-dimensional advantages—geotechnical, economic, and environmental—when properly treated and optimized.

Key Contributions of Sludge in Pavement Engineering

- Improves weak soil behavior by increasing UCS, CBR, and reducing permeability.
- Reduces construction costs by replacing lime, aggregates, and virgin fillers.
- Minimizes landfill dependency and CO_2 emissions from traditional materials.
- Supports circular economy and green infrastructure goals, including SDG 9, 11, and 13.

Strategic Recommendations for the Future

1. Codification and Standardization
- Include sludge-based soil blends in national road codes (e.g., IRC, ASTM).
- Develop regional mix design manuals with optimal content, compaction energy, and curing needs.
2. Pilot Projects and Field Trials
- Launch 5–10 multi-climatic zone test roads using sludge, with embedded sensors and periodic testing.
- Document performance over 3–5 years for rutting, cracking, and leachability.
3. Digital Integration
- Use BIM, AI, and IoT to manage sludge logistics, ensure treatment quality, and monitor long-term field data.
- Link road health to centralized dashboards for data-driven PWD operations.
4. Policy and Industry Engagement
- Incentivize sludge usage in public works through green rating systems.
- Align with missions like India's Green Highways Policy, Atal Mission for Rejuvenation and Urban Transformation (AMRUT), and Swachh Bharat.

Sludge represents more than just a waste problem—it is a resource opportunity. By converting environmental liabilities into infrastructure assets, engineers and policymakers can take a decisive step toward sustainable, circular construction. With appropriate treatment, performance validation, and smart monitoring, sludge can pave the way—literally—for greener, smarter, and more resilient roads.

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