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(Research Article)

Sustainable ground improvement using lime-stabilized soils and recycled construction materials: A performance-based evaluation for urban development

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Abstract

Most urban infrastructure constructions are carried out on soils with low bearing capacity, as well as compressibility, which might result in settlement. Ground improvement techniques are therefore necessary to improve soil performance before construction. This study investigates a sustainable ground improvement approach that combines lime stabilization with recycled construction materials for infrastructure foundations and pavement subgrades. The research evaluates the engineering performance of stabilized soil mixtures prepared with different proportions of lime and recycled materials. Laboratory testing includes soil characterization, compaction testing, curing, and unconfined compressive strength evaluation. The performance of stabilized mixtures is compared with untreated soil using strength improvement ratios and conceptual settlement analysis. The findings show that the addition of lime to the soil alters its structure as a result of a chemical reaction with clay particles, which increases the stiffness of the soil. The inclusion of recycled construction materials introduces granular particles that improve load transfer and reduce deformation. Soil mixes incorporating both lime and recycled materials exhibit improved strength and reduced settlement compared to untreated soil as well as lime stabilized soil. The findings show that this method of soil stabilization is a viable solution to addressing poor soil conditions while at the same time helping to conserve natural resources, thus promoting sustainable urban infrastructure development.

Keywords: Lime Soil Stabilization; Recycled Construction Materials; Sustainable Ground Improvement; Soil Strength and Settlement Behavior; Urban Infrastructure Development

1. Introduction

Urban infrastructure projects are frequently constructed on soils with low bearing capacity, high compressibility, and unstable mechanical properties. Such soil conditions create major difficulties for foundations, pavements, transportation systems, and underground utility networks. Weak soils often cause excessive settlement, deformation, and long-term structural damage under loading conditions. Ground improvement methods therefore remain an important topic in geotechnical engineering. Rapid urban expansion also increases demand for construction materials and contributes to environmental concerns associated with resource depletion and construction waste generation. Recent studies focus on sustainable construction practices and alternative engineering materials that reduce environmental impact while maintaining acceptable engineering performance. Research on sustainable dredging and sediment management reports that environmentally responsible material practices support infrastructure development with lower ecological impact [4]. Studies on sustainable construction materials for rural infrastructure projects indicate that recycled and locally available materials reduce construction costs and material consumption [8]. Structural durability also depends on material composition. Investigations on crack prevention in mass concrete structures report that suitable mixture selection and material design reduce structural deterioration and extend service life [5]. Research on reinforced concrete containing waste foundry sand and glass powder demonstrates the engineering

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potential of recycled materials in structural applications [10]. Similar findings appear in studies on bio-healable interlocking compressed earth bricks, where sustainable materials show satisfactory mechanical performance in construction systems [11].

Ground conditions strongly influence infrastructure performance. Weak soil layers contribute to foundation instability, slope failure, and excessive settlement. Infrastructure systems constructed on unstable soils may experience differential settlement and reduced structural reliability during operational loading. Research on seismic- and climate-resilient infrastructure design demonstrates that environmental hazards significantly affect foundation response and structural performance under dynamic loading conditions [9]. Flooding and climate-related stresses introduce additional concerns for infrastructure systems located in vulnerable regions. Studies on transportation infrastructure assessment discuss environmental considerations during project planning and development stages [7]. These findings indicate the importance of reliable ground treatment methods for modern infrastructure systems.

Soil stabilization remains one of the most common methods used to improve poor-quality soils. Lime stabilization is widely applied in clay-rich soils because chemical reactions between lime and clay minerals modify soil composition, reduce plasticity, and increase stability [1]. Research on cement-admixed soft clays explains that stabilization forms cementitious bonding structures within the soil matrix. These bonding structures increase soil stiffness and reduce deformation under applied stress [2]. Researchers have also investigated recycled construction materials for geotechnical applications. Studies on recycled crushed brick aggregates report acceptable compaction characteristics and mechanical performance in pavement sub-base systems [3]. The use of recycled materials reduces construction waste disposal and lowers dependence on natural aggregate resources, which supports sustainable construction practices in civil engineering projects.

Environmental management and infrastructure planning also affect sustainable development practices. Studies on waste and water management strategies discuss methods that reduce environmental impacts associated with urban infrastructure systems [6]. Research on project management frameworks identifies approaches that reduce cost overruns and improve infrastructure project performance [12]. Engineering management applications also appear in studies on Industry 4.0 technologies and smart agricultural systems, where digital tools support operational efficiency and resource management [15]. Artificial intelligence applications in transportation engineering demonstrate the growing role of digital systems in traffic optimization and infrastructure operation [13]. Sustainable manufacturing and waste recovery practices contribute to resource conservation efforts. Research on bio-based and compostable packaging materials presents alternatives that reduce plastic waste generation [14]. Similar observations appear in studies on circular textile manufacturing systems, where waste recovery methods support sustainable industrial production and resource reuse [16]. Existing studies examine sustainable materials, infrastructure resilience, environmental management, transportation systems, and soil stabilization as separate research areas. Previous work explains chemical mechanisms associated with lime stabilization and evaluates recycled construction materials for structural and pavement applications. Other studies focus on project management, environmental planning, transportation optimization, and sustainable manufacturing systems. Limited research examines integrated approaches that combine lime stabilization with recycled construction materials for sustainable ground improvement in urban infrastructure projects.

This study investigates sustainable ground improvement methods that combine lime stabilization with recycled construction materials for urban infrastructure applications. The research evaluates the engineering behavior of lime stabilized soils blended with recycled materials under different soil conditions. Environmental considerations associated with recycled construction materials are included in the analysis. A performance based evaluation framework is applied to examine stabilization effectiveness for infrastructure foundations and pavement subgrades. The findings provide engineering insight into soil stabilization systems that combine chemical treatment with recycled construction materials for sustainable urban development.

2. Related Work

2.1. Sustainable Construction Materials in Civil Infrastructure

Research on sustainable construction materials examines methods that reduce environmental impact while maintaining acceptable engineering performance. Conventional construction materials contribute heavily to carbon emissions and resource depletion. Recent studies therefore investigate low-carbon materials and alternative construction resources for environmentally responsible infrastructure development. Bormon [4] studied sustainable dredging and sediment management techniques for coastal and riverine infrastructure. The study reported that environmentally responsible material practices reduce ecological impact and support infrastructure durability. Ria [8] investigated sustainable construction materials used in rural infrastructure projects and found that recycled and locally available materials reduce construction costs and material demand. Structural durability also depends on material composition. Shoag [5] examined sustainable construction materials and crack prevention techniques in mass concrete structures. The study reported lower structural deterioration and longer service life with appropriate material selection and mixture composition. Environmental assessment has also become part of infrastructure planning. Ria [7] evaluated environmental impacts associated with transportation infrastructure projects and discussed the importance of sustainable design considerations during project planning stages. These studies show the growing role of sustainable materials in infrastructure systems. However, most previous work concentrates on structural materials instead of geotechnical applications such as soil stabilization and ground improvement.

2.2. Soil Stabilization and Ground Improvement Methods

Ground improvement techniques address problems associated with weak soils in infrastructure construction. Stabilization methods increase soil strength, reduce compressibility, and improve load-bearing capacity. Lime stabilization remains one of the most common methods used for clay-rich soils. Bell [1] examined stabilization of clay minerals through lime treatment and reported that chemical reactions between lime and clay particles reduce soil plasticity while improving long-term stability. Horpibulsuk et al. [2] investigated cement-admixed soft clays and explained that stabilization forms cementitious bonding structures within the soil matrix. These bonding structures increase soil stiffness and reduce deformation under loading conditions. Researchers have also examined recycled construction materials in geotechnical applications. Arulrajah et al. [3] evaluated recycled crushed brick materials used in pavement sub-base systems and reported acceptable compaction behavior together with satisfactory engineering performance. The use of recycled aggregates also reduces dependence on natural aggregate resources. These findings indicate that lime stabilization and recycled materials both support sustainable infrastructure construction. Most existing studies, however, evaluate these methods separately, while integrated applications remain limited.

2.3. Infrastructure Resilience and Foundation Behavior

Infrastructure systems operate under environmental hazards such as earthquakes, flooding, and soil instability. Research in this area therefore focuses on foundation behavior and infrastructure resilience under different loading conditions. Bormon [4] investigated foundation settlement behavior in high-rise structures subjected to seismic loading. The study showed that soil–structure interaction significantly affects foundation stability during seismic events. Saikat et al. [9] discussed infrastructure design strategies suitable for coastal and urban regions exposed to climate and seismic hazards. The study examined environmental risk considerations in engineering design processes. Structural performance of sustainable construction materials has also received attention in recent research. Umar [10] investigated reinforced concrete containing waste foundry sand and glass powder and reported acceptable structural performance together with reduced material waste. Khalid [11] evaluated bio-healable interlocking compressed earth bricks for sustainable construction applications and reported favorable engineering properties for environmentally responsible building systems. These studies contribute to current knowledge on infrastructure resilience and sustainable material performance. Nevertheless, most investigations focus on structural systems and foundation response rather than integrated ground improvement methods for weak soils.

2.4. Sustainable Infrastructure Management and Environmental Practices

Infrastructure development also involves project management, environmental planning, and resource management practices. Islam [12] examined project management frameworks designed to reduce cost overruns in infrastructure projects. The study reported improved resource allocation and project efficiency through structured management approaches. Rahmatullah [15] investigated Industry 4.0 applications in sustainable agricultural infrastructure and discussed the role of digital engineering tools in infrastructure management systems. Ahmed [16] studied circular textile manufacturing and waste recovery systems and reported that sustainable resource management practices support environmentally responsible industrial production. Ali [14] examined bio-based and compostable packaging alternatives developed to reduce plastic waste generation. The study discussed the importance of sustainable waste management practices in industrial systems. These investigations address sustainability, environmental management, and resource efficiency. Geotechnical sustainability issues such as soil stabilization and sustainable ground improvement, however, receive limited attention within these studies.

2.5. Research Gap

Existing research addresses sustainable construction materials, soil stabilization, infrastructure resilience, environmental management, and project planning as separate subjects. Previous studies explain chemical mechanisms associated with lime stabilization and evaluate recycled construction materials in pavement and structural applications. Other investigations focus on environmental assessment, resource management, transportation systems, and infrastructure performance under hazard conditions. Limited research examines integrated approaches that combine lime stabilization with recycled construction materials for sustainable ground improvement in urban infrastructure systems. Studies that evaluate geotechnical performance together with environmental sustainability considerations remain limited. This research gap indicates the need for further investigation into sustainable ground improvement systems that combine lime-stabilized soils with recycled construction materials under a performance-based evaluation framework.

3. Methodology

This study evaluates a sustainable ground improvement method that combines lime stabilization with recycled construction materials for infrastructure foundations and pavement subgrades. The methodology used includes characterization of the soil, preparation of the stabilized mixture, laboratory testing, and assessment of the performance. This methodology compares the untreated soil with the stabilized mixture, comparing the changes in the soil's strength, compressibility, and capacity to carry loads.

3.1. Soil Sampling and Material Characterization

Soil samples are chosen based on the area where clayey or silty soils are normally found in urban construction works. These types of soil are known to display high plasticity and low capacity to carry loads, which might affect the stability of structures built on top of such soil. Characterization of the soil includes particle size distribution, Atterberg limits, moisture content, compaction, and so on. These tests define the physical properties of the soil and provide baseline data for performance comparison. Lime is selected as the stabilizing agent because lime reacts with clay minerals and alters soil plasticity and strength characteristics [4]. Recycled construction materials such as crushed brick or recycled aggregates are included in the mixture to reduce the use of natural aggregates and support sustainable construction practices. Previous studies report that recycled crushed brick materials show acceptable compaction and strength properties in pavement sub-base applications [10].

The stabilized mixture consists of three components: natural soil, lime, and recycled material. The general mixture formulation is represented as

$$M = S + L + R$$

where
M= stabilized soil mixture
S = natural soil
L = lime content
R = recycled construction material content

Different mixture ratios are prepared to evaluate the influence of lime and recycled materials on soil performance.

Preparation of Stabilized Soil Specimens

Stabilized soil mixtures are prepared in laboratory conditions using controlled procedures. Natural soil samples are first air-dried and pulverized to remove large aggregates. Lime and recycled materials are then added according to predetermined proportions. Water is introduced into the mixture until the material reaches the optimum moisture content obtained from compaction testing. The mixture is blended thoroughly to obtain uniform distribution of lime and recycled materials within the soil matrix. Compaction tests determine the maximum dry density and optimum moisture content of each mixture. Cylindrical specimens are then prepared using standard Proctor compaction procedures. The samples remain in curing conditions for periods ranging from 7 to 28 days. During this period, chemical reactions between lime and soil minerals produce cementitious compounds that modify the internal soil structure. Mechanical performance of stabilized samples is measured through unconfined compressive strength tests. Strength improvement reflects the effectiveness of the stabilization process. The strength improvement ratio is expressed as

$$ISR = \frac{q_s}{q_u}$$

where
ISR = strength improvement ratio
q_s = compressive strength of stabilized soil

q_u = compressive strength of untreated soil

This ratio provides a quantitative comparison between stabilized and untreated soils.

3.2. Performance Evaluation Criteria

The performance of stabilized soil mixtures is evaluated using three main criteria: strength development, settlement behavior, and material sustainability. Strength development is determined from compressive strength values obtained from laboratory tests. Higher compressive strength indicates improved load-bearing capacity of the soil. Settlement behavior is examined using simplified foundation loading analysis. The stabilized soil layer is compared with untreated soil to identify differences in deformation under applied loads. Material sustainability is also considered during evaluation. The use of recycled construction materials reduces demand for natural aggregates and limits construction waste. The contribution of recycled materials is represented using a sustainability ratio

$$SR = \frac{w_r}{w_t}$$

where
SR = sustainability ratio
w_r = recycled material content
w_t = total stabilization material

This ratio indicates the proportion of recycled materials within the stabilization mixture.

3.3. Experimental Workflow

The research follows a structured sequence of experimental steps. Each stage supports the evaluation of stabilized soil performance.

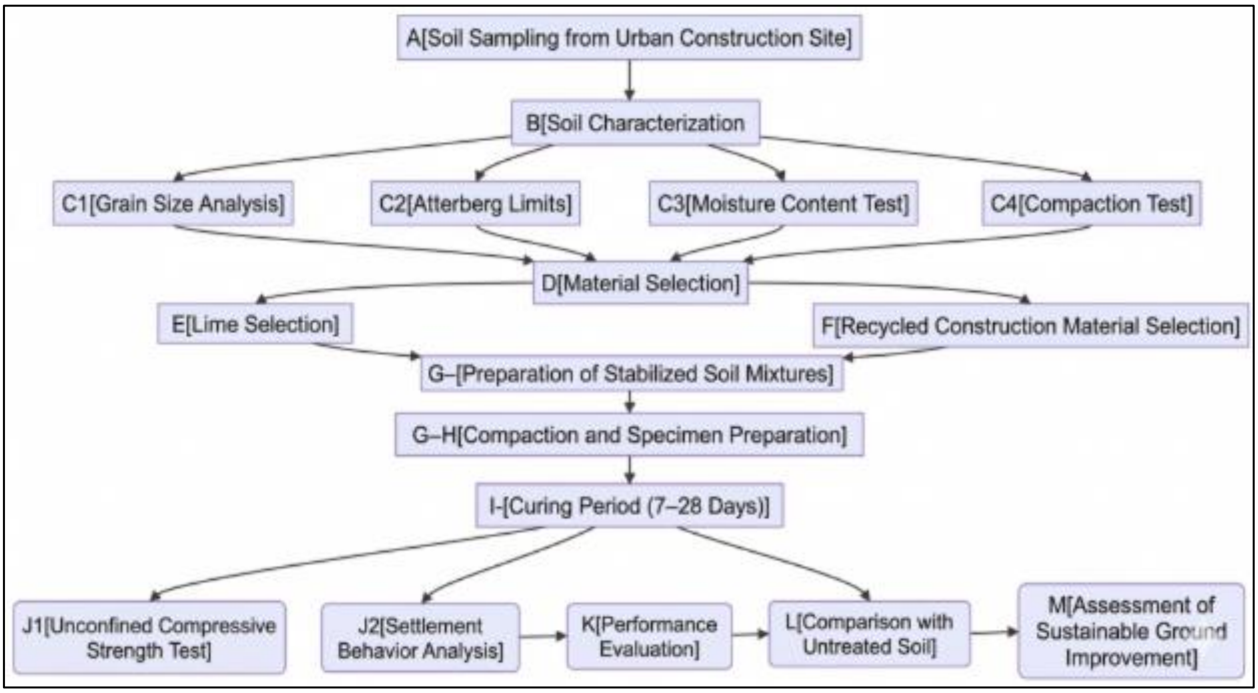

Figure 1 Research workflow used for evaluating sustainable ground improvement using lime-stabilized soils and recycled construction materials

The workflow includes the following stages:

- Soil sampling and geotechnical characterization
- Selection of lime and recycled construction materials
- Preparation of stabilized soil mixtures

- Compaction and curing of soil specimens
- Laboratory testing of mechanical properties
- Performance evaluation and comparison with untreated soil

This process allows systematic evaluation of soil stabilization performance under controlled laboratory conditions.

3.4. Conceptual Ground Improvement Model

The stabilized ground system is represented as a layered structure beneath infrastructure elements such as pavements or foundations.

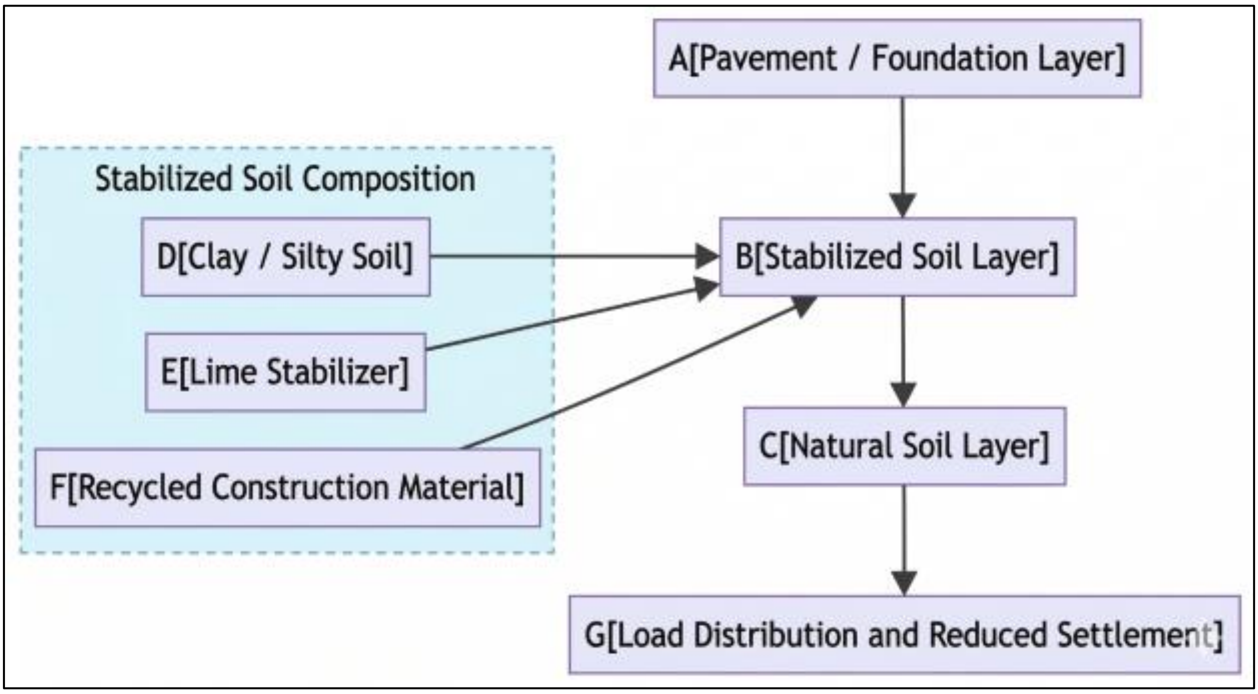

Figure 2 Conceptual structure of stabilized soil used for ground improvement consisting of natural soil, lime stabilizer, and recycled construction materials

The configuration includes three layers:

- Surface structural layer (pavement or foundation)
- Stabilized soil layer composed of soil, lime, and recycled materials
- Natural soil layer located below the improved ground layer

The stabilized layer distributes structural loads across a wider area and reduces settlement in weak soil conditions.

Table 1 Experimental Design of Stabilized Soil Mixtures

Sample ID	Soil (%)	Lime (%)	Recycled Material (%)	Description
S1	100	0	0	Natural soil (control sample)
S2	95	5	0	Lime-stabilized soil
S3	90	5	5	Lime with recycled material
S4	85	5	10	Increased recycled material content
S5	80	10	10	High stabilization mixture

The experimental matrix allows for the comparison between untreated soil, lime-treated soil, and mixtures with recycled construction materials. The results obtained in the laboratory are the basis for assessing the effectiveness of sustainable ground improvement methods in the construction of infrastructure.

4. Discussion and Results

This section presents the observations obtained from the stabilized soil mixtures and compares their performance with untreated soil. The analysis focuses on compressive strength development, settlement response, and the contribution of recycled construction materials in the stabilization process. Laboratory results are interpreted in relation to the stabilization procedures described in the methodology.

4.1. Strength Behavior of Stabilized Soil Mixtures

Unconfined compressive strength tests were carried out on untreated soil and stabilized soil mixtures prepared with different proportions of lime and recycled construction materials. The untreated soil sample (S1) represents the natural soil condition without stabilization. Stabilized mixtures S2–S5 contain increasing proportions of lime and recycled materials. The untreated soil exhibits the lowest compressive strength because of weak bonding between soil particles and high plasticity. There is a noticeable increase in the strength of the soil during the process of lime treatment. Chemical reactions take place between the clay content of the soil and the lime. This reaction causes the formation of compounds that bind the soil together. Mixtures containing recycled construction materials show further strength improvement. Recycled crushed particles function as granular inclusions within the soil matrix. These particles increase frictional resistance and improve load transfer within the stabilized soil layer. The results indicate that mixtures S3 and S4 show higher compressive strength than the lime-only mixture.

Figure 3 presents the relative compressive strength levels for the different soil mixtures.

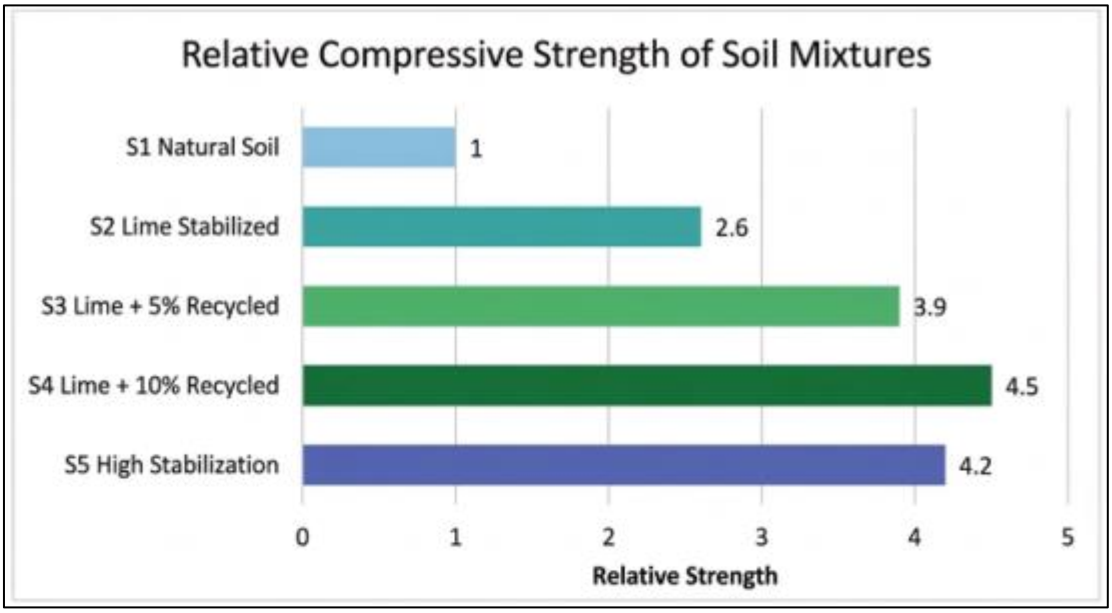

Figure 3 Relative compressive strength of untreated soil and stabilized soil mixtures containing lime and recycled construction materials

The figure shows a clear increase in strength after stabilization. Mixture S4 produces the highest strength level. This mixture contains balanced proportions of lime and recycled materials, which produces favorable particle interaction and granular reinforcement. Mixture S5 maintains high strength; however, larger recycled particle content slightly influences compaction characteristics. The strength improvement ratio introduced in the methodology confirms the increase in soil strength compared with untreated soil. These results indicate that the combined use of lime and recycled materials improves the mechanical behavior of weak soils used in infrastructure construction.

4.2. Settlement Response of Stabilized Soil Layers

Settlement behavior forms an important parameter in ground improvement evaluation. Weak soils often experience considerable deformation under structural loads. Stabilized soil layers modify stress distribution within the soil mass and reduce vertical deformation.

The conceptual behavior of load transfer within stabilized ground is illustrated in Figure 4.

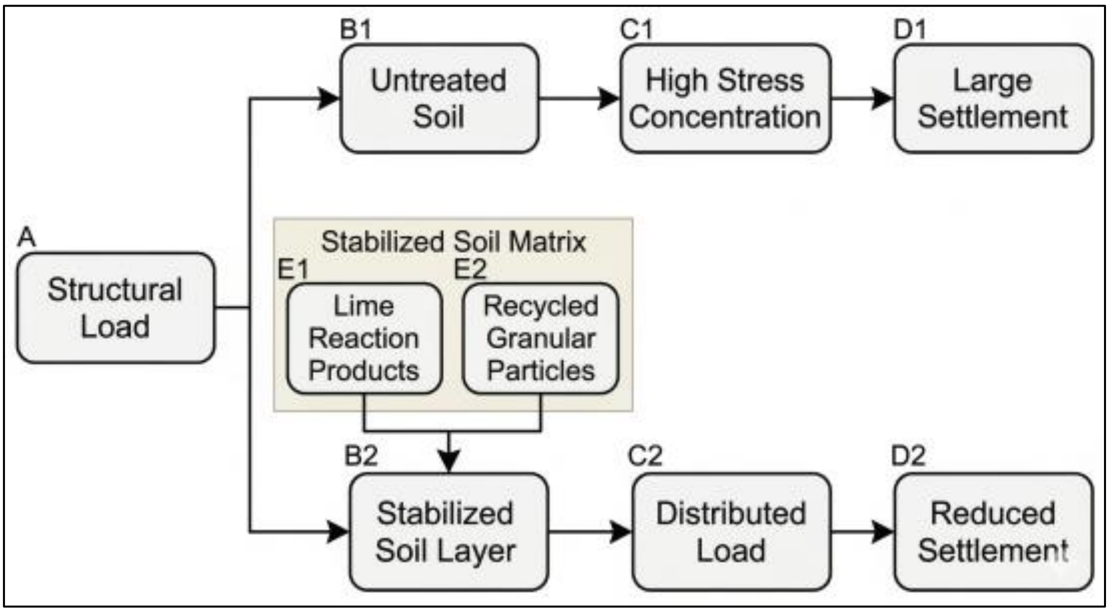

Figure 4 Conceptual comparison of load distribution and settlement behavior between untreated soil and lime-stabilized soil containing recycled construction materials

Untreated soil concentrates structural loads within a limited area of the foundation soil. High stress concentration produces significant vertical settlement. Stabilized soil layers behave differently. Cementitious compounds produced through lime reactions increase soil stiffness, while recycled particles create a granular skeleton within the mixture. The stabilized layer spreads structural loads across a wider region of the soil mass. Stress intensity in the natural soil decreases, which results in lower settlement. This mechanism improves foundation stability and supports infrastructure construction in weak soil environments.

4.3. Sustainability Contribution of Recycled Construction Materials

Sustainable infrastructure development requires reduced use of natural aggregates and responsible use of construction waste. Recycled construction materials provide an alternative resource for ground improvement applications. The stabilization mixtures prepared in this study contain recycled crushed brick or aggregate particles. These materials replace a portion of natural aggregates used in conventional stabilization processes. Their use reduces construction waste disposal and promotes efficient material use.

The sustainability contribution of recycled materials is represented through the sustainability ratio

$$SR = \frac{w_r}{w_t}$$

Where
w_r represents recycled material content
w_t represents the total stabilization material.

Higher sustainability ratios correspond to greater recycled material participation within the stabilization mixture. Samples S3, S4, and S5 contain increasing proportions of recycled materials. These mixtures demonstrate improved resource efficiency while maintaining acceptable soil strength and stability.

4.4. Comparative Performance of Stabilized Soil Mixtures

A comparative assessment of the soil mixtures provides insight into the most effective stabilization configuration.

Table 2 Performance comparison of stabilized soil mixtures

Sample	Lime (%)	Recycled Material (%)	Strength Level	Settlement Behavior	Sustainability
S1	0	0	Low	Large settlement	Very low
S2	5	0	Moderate	Moderate reduction	Low
S3	5	5	High	Good reduction	Medium
S4	5	10	Very high	Strong reduction	High
S5	10	10	High	Strong reduction	High

The comparison indicates that mixtures containing both lime and recycled materials produce higher strength and lower settlement than untreated soil. Mixture S4 demonstrates balanced performance in terms of strength development and material sustainability. Larger recycled material content does not produce additional improvement beyond this proportion.

Limitations of the Study

This study evaluates sustainable ground improvement using lime stabilization and recycled construction materials through laboratory testing and conceptual performance evaluation. Several limitations remain. The experimental investigation uses controlled laboratory conditions, while natural field conditions may contain variable soil layers, groundwater effects, and environmental influences that affect soil behavior. The mixture proportions tested represent selected combinations of lime and recycled materials. Other combinations may produce different mechanical responses. Further studies have to be conducted on the long-term durability of the treated soil during cyclic loading, changes in moisture content during the seasons, and environmental factors. Field-scale testing has to be conducted to understand the settlement behavior of the treated soil during the process of infrastructure construction.

5. Conclusion

In this study, ground improvement using lime stabilized soils and recycled construction materials for infrastructure base course and pavement subgrade construction is discussed. From the observations in the laboratory, it is evident that lime treatment can improve the strength of the soils through chemical reactions with clay particles, which form cement-like compounds. Recycled construction materials introduce granular particles within the stabilized soil mixture. These particles contribute frictional resistance and improve load transfer in the soil matrix. The experimental evaluation indicates higher compressive strength and lower settlement for stabilized mixtures compared with untreated soil. The mixture of lime and recycled materials has shown enhanced performance compared to lime treatment alone. The mixture of moderate amounts of lime and recycled materials has shown balanced performance in terms of soil strength, settlement reduction, and material efficiency. The results of the study have shown that this type of stabilization can be used for infrastructure construction in soils with poor bearing capacity and can reduce the need for using natural resources in construction materials.

Future studies could involve field scale studies of stabilized soil layers under construction conditions. Long term studies could investigate durability under repeated loading, seasonal moisture changes, and environmental conditions. Further studies could investigate the performance of different types of recycled construction materials and their interactions with different types of soils. Large-scale tests of stabilized foundations could provide more information on the settlement behavior of the structures.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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