Review of chemical methods for road pavement stabilization: prospects for application in Uzbekistan

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Abstract. This article provides an overview of methods for stabilizing the subgrade soils of road pavements using nanomaterials and polymer additives. A theoretical-comparative analysis is performed on both traditional stabilization methods and modern approaches that employ nanosilica, nanoclays, carbon nanotubes, and various polymers. The mechanisms of action of the stabilizers and their influence on the physico mechanical properties of soils are examined, along with the advantages and disadvantages of each method. Particular attention is devoted to the specific climatic and geological conditions of Uzbekistan. Based on an analysis of the literature and modeling results reported by both domestic and international researchers, recommendations are made for selecting optimal stabilization methods for different soil types and climatic zones in Uzbekistan. It should be noted that this study is a review and does not present the results of original experiments.

Keywords: soil stabilization, road pavement, nanomaterials, polymers, nanosilica, strength, water resistance, frost resistance, sharply continental climate, loess soils.

1. Introduction

The state of Uzbekistan's road infrastructure is characterized by a diversity of pavement types, as well as variations in road density and extent across different regions [1]. With increasing traffic intensity and challenging climatic conditions [2], there has been a rise in the proportion of asphalt concrete roads, reflecting a commitment to improving road quality and durability [3]. The sharply continental climate, with hot summers and cold winters, coupled with seismic activity in certain regions, imposes heightened requirements on the strength and longevity of road pavements [4]. Moreover, the prevalent loess and silty clay soils in Uzbekistan exhibit low load-bearing capacities and are prone to settlement, heaving, and erosion, leading to premature pavement failure [5]. These issues, in turn, adversely affect the national economy by increasing transportation costs, reducing road safety, and limiting regional accessibility.

Traditional chemical stabilization methods for subgrade soils, such as the use of enzymes, liming [6], silicate treatment, cementation, resin treatment, and the application of bituminous emulsions [7], have several limitations. Although cementation can achieve high strength, it may result in crack formation due to shrinkage and temperature-induced deformations [8]. Liming is relatively ineffective for clayey soils [9], and resins and bituminous emulsions are susceptible to aging and degradation under ultraviolet radiation and temperature fluctuations [6]. Additionally, these conventional methods are often associated with high costs and adverse environmental impacts.

In recent years, increased attention has been directed toward the application of nanomaterials [10-12] and polymer additives [13] for soil stabilization. Nanomaterials, such as colloidal silica, nanoclays (montmorillonite, kaolinite), nano bentonite, and carbon nanotubes (CNTs), possess unique properties that can significantly enhance the physico mechanical characteristics of soils [14, 15]. Polymer additives, on the other hand, improve soil strength, water resistance, and frost resistance while also reducing permeability [16, 17].

The aim of this study is to conduct a theoretical comparative analysis of the effectiveness of various stabilization methods for road pavement subgrade soils using nanomaterials and polymer additives, taking into account the specific climatic and geological conditions of Uzbekistan, and to develop recommendations for optimizing the choice of stabilization methods.

To achieve this objective, the following tasks were addressed:

1) Systematically reviewing and synthesizing the existing literature on the influence of various types of nanomaterials and polymer additives on the physico mechanical properties of soils.

2) Conducting a comparative analysis of the effectiveness of different stabilization methods (traditional, nanomaterial based, polymer based, and combined approaches) based on published laboratory and field study results.

3) Summarizing the outcomes of modeling the behavior of stabilized soils (using nanomaterials and polymers) under conditions characteristic of Uzbekistan.

4) Developing recommendations for the selection of optimal stabilization methods for road pavement subgrade soils using nanomaterials and polymers for various soil types and climatic zones in Uzbekistan.

It should be noted that this study is a review based on the analysis and synthesis of data presented in scientific literature and technical documentation.

2. Materials and method

This study is based on a theoretical comparative analysis of data obtained from scientific articles, monographs, dissertations, research reports, patents, standards (GOST, ASTM, ISO), and technical specifications. Sources were selected based on their relevance to the research topic, the reliability of the presented information, and the novelty of the results. The methods employed in the data analysis included systematization, synthesis, comparison, classification, and analysis. In assessing the impact of various stabilizers on soil properties, parameters such as compressive strength, modulus of elasticity, water resistance, frost resistance, durability, cost, technological feasibility, and environmental friendliness were compared. To evaluate the behavior of stabilized soils under conditions characteristic of Uzbekistan, modeling results reported in previous studies were utilized [18-20].

Characteristics of the Materials Considered:

– Soils: The basic soils considered were those typical for Uzbekistan – loess, silty clays, and sandy loams [5]. Their characteristics, including particle size distribution, mineralogical composition, and physico mechanical properties, were adopted from literature sources [21-23].

– Nanomaterials: The nanomaterials examined include nanosilica (SiO_2), nanoclays (montmorillonite, kaolinite), carbon nanotubes (CNTs), and metal nano oxides (TiO_2, Al_2O_3, Fe_2O_3). Their characteristics (particle size, specific surface area, chemical composition, and particle shape) were derived from published studies [11, 12, 14, 15, 24-28].

– Polymer Additives: The polymer additives considered include polyacrylamide (PAM), polyvinyl acetate (PVA), styrene acrylic copolymers, polyurethanes, and epoxy resins. Their characteristics (chemical composition, molecular weight, and properties) were presented based on literature data [13, 16, 17, 29-34].

– Traditional Stabilizers: For comparison, traditional stabilizers such as cement, lime, and bituminous emulsions were also examined. Their characteristics were based on GOST standards and published research data [9, 35-37].

3. Results

The primary objective of soil stabilization in road construction is to improve the physico mechanical properties of soils, such as compressive strength, modulus of elasticity, water resistance, and frost resistance. The literature provides extensive data on the effectiveness of various stabilizers, both traditional (cement, lime, bituminous emulsions) and innovative (nanomaterials and polymers).

Tables 1, 2, and 3 summarize the impact of different types of nanomaterials (Table 1), polymer additives (Table 2), and traditional stabilizers (Table 3) on the physico mechanical properties of soils. These data were derived from an analysis and synthesis of numerous studies published in the scientific literature. It should be noted that the ranges of values presented reflect variability due to differences in soil types, testing methodologies, and experimental conditions.

Table 1. Effect of nanomaterials on soil properties

Nanomaterial	Concentration (%)	Effect on compressive strength	Effect on modulus of elasticity	Effect on water resistance	Effect on frost resistance
Nanosilica (SiO_2)	0.5-5	Increase by 20-150 %	Increase by 10-100 %	Increase	Increase
Nanoclays (montmorillonite)	1-7	Increase by 10-80 %	Increase by 5-60 %	Increase	Increase
Carbon Nanotubes (CNTs)	0.1-1	Increase by 30-200 %	Increase by 20-150 %	Increase	Increase
Metal Nano-oxides (TiO_2, Al_2O_3, Fe_2O_3)	1-5	Increase by 10-50 %	Increase by 5-40 %	Increase	Insignificant increase/no effect

Table 2. Effect of polymer additives on soil properties

Polymer additive	Concentration (%)	Effect on compressive strength	Effect on modulus of elasticity	Effect on water resistance	Effect on frost resistance
Polyacrylamide (PAM)	0.1-1	Increase by 10-60 %	Increase by 5-40 %	Increase	Increase
Polyvinyl Acetate (PVA)	1-5	Increase by 20-80 %	Increase by 10-50 %	Increase	Increase
Styrene-Acrylic Copolymers	1-5	Increase by 30-100 %	Increase by 15-70 %	Increase	Increase
Polyurethanes	1-5	Increase up to 200 %	Increase up to 150 %	Significant increase	Significant increase

Table 3. Effect of cement, lime, and bituminous emulsions on soil properties

Stabilizer	Concentration (%)	Effect on compressive strength	Effect on modulus of elasticity	Effect on water resistance	Effect on frost resistance
Cement	0.1-1	Increase by 10-60 %	Increase by 5-40 %	Increase	Increase
Lime	1-5	Increase by 20-80 %	Increase by 10-50 %	Increase	Increase
Bituminous Emulsions	1-5	Increase by 30-100 %	Increase by 15-70 %	Increase	Increase

As can be seen from Tables 1-3, different stabilizers exert varying effects on soil properties.

Based on a review of the literature, a comparative analysis was conducted to evaluate the effectiveness of various soil stabilization methods according to the following criteria:

– Strength: Carbon nanotubes and polyurethanes yield the greatest increase in compressive strength. Nanosilica and styrene–acrylic copolymers also demonstrate significant strength enhancements, although cementation, while providing high strength, may lead to crack formation.

– Modulus of Elasticity: Carbon nanotubes and polyurethanes considerably increase the modulus of elasticity, whereas nanosilica and styrene-acrylic copolymers show moderate improvements.

– Water Resistance: All the nanomaterials and polymers considered enhance the water resistance of soils, with polyurethanes being the most effective.

– Frost Resistance: Nanomaterials and polymers, except for some metal nano oxides, improve the frost resistance of soils.

– Durability: Nanomaterials and polymers generally provide greater durability for stabilized soils compared to traditional methods, particularly under aggressive environments and cyclic loading.

– Cost: Although the cost of nanomaterials and polymers may exceed that of traditional stabilizers (cement, lime), the extended service life of the pavement can offset these expenses.

– Technological Feasibility: The application of nanomaterials and polymers may require more advanced equipment and mixing technologies than conventional methods.

– Environmental Impact: Some nanomaterials and polymers could pose potential environmental risks, necessitating further studies to assess their ecological safety.

Several studies have modeled the behavior of stabilized soils under conditions similar to those in Uzbekistan, characterized by sharp temperature fluctuations and seismic activity [10, 18, 25, 34, 38-42]. The modeling results indicate that using nanomaterials and polymers can significantly reduce pavement deformations and enhance resistance to dynamic loads.

Preliminary analysis suggests that the application of nanomaterials and polymers for soil stabilization in Uzbekistan's road construction is potentially cost effective, given the increased service life of the pavement and the reduced maintenance and repair expenses.

4. Discussions

The stabilization mechanisms provided by nanomaterials and polymers differ considerably. Nanosilica, owing to its high specific surface area and pozzolanic activity, reacts with cement hydration products (if present) or with calcium hydroxide (in the case of lime stabilization) to form additional cementitious compounds. Nanoclays, with their layered structures, intercalate between soil particles, thereby increasing density and reducing permeability. Carbon nanotubes, characterized by high strength and flexibility, reinforce the soil matrix and enhance its resistance to tensile and bending stresses.

Polymer additives form films on the surface of soil particles, binding them together and reducing water permeability. Some polymers, such as polyacrylamide, may also engage in chemical interactions with soil particles, forming strong bonds.

The analysis indicates that nanomaterials and polymers can be more effective than traditional stabilization methods, particularly under the challenging climatic and geological conditions of Uzbekistan. These innovative approaches not only enhance the strength and durability of road pavements but also reduce their sensitivity to moisture and temperature variations. Moreover, the combined use of nanomaterials and polymers may produce a synergistic effect, whereby their positive influences on soil properties mutually reinforce each other.

In the context of Uzbekistan's road construction, the prospects for using nanomaterials and polymers are significant. Nevertheless, for widespread implementation, further research, including field trials, is required to validate their effectiveness and safety under site specific conditions.

5. Conclusions

Nanomaterials (nanosilica, nanoclays, carbon nanotubes) and polymer additives (polyacrylamide, polyvinyl acetate, styrene–acrylic copolymers, polyurethanes) have considerable potential to enhance the compressive strength, water resistance, frost resistance, and durability of road pavement subgrade soils. The comparative analysis demonstrates that nanomaterials and polymers can be more effective than traditional stabilization methods (e.g., cementation, liming), particularly under the severe climatic and geological conditions of Uzbekistan. Furthermore, the combined application of nanomaterials and polymers may yield a synergistic effect, further enhancing soil properties. The use of these advanced materials is also potentially economically advantageous due to the extended lifespan of the pavement and the associated reductions in maintenance and repair costs.

For various soil types and climatic zones in Uzbekistan, the following stabilization methods are recommended:

– Loess Soils: Use nanosilica (2-4 %), styrene–acrylic copolymers (1-3 %), or a combination of nanosilica (1-2 %) and polyacrylamide (0.2-0.5 %).

– Silty Soils: Use nanosilica (1-3 %), polyvinyl acetate (2-4 %), and carbon nanotubes (0.2-0.5 %).

– Sandy Loams: Use nanosilica (1-3 %), polyvinyl acetate (2-4 %), and carbon nanotubes (0.2-0.5 %).

It is recommended that additional research, including laboratory and field experiments, be conducted to optimize the formulations of soil, nanocomposite and soil, polymer mixtures, taking into account the specific conditions of individual road construction projects in Uzbekistan. An assessment of the environmental safety of the employed nanomaterials and polymers is also necessary. Furthermore, technological guidelines should be developed for the application of nanomaterials and polymers in Uzbekistan's road construction, including quality requirements for materials, detailed mixing procedures, and methods for quality control of the stabilization processes.

This study contributes to the advancement of both the theory and practice of soil stabilization and has the potential to enhance the quality and durability of road construction in Uzbekistan. The research outcomes can be utilized in the preparation of design and cost estimate documentation for the construction and reconstruction of roads, as well as in the development of normative and technical standards.

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Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflict of interest

The authors declare that they have no conflict of interest.

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