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Mechanism analysis of alkali activated slag for soil improvement

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ABSTRACT: Inlight of the current global trend toward low carbon, environmental protection, and sustainable development, the environmental impact of CO_2 emissions from cement production and use has drawn significant attention. As a result, the technology of alkali-activated soil improvement, which aims to replace or reduce the use of cement, has become a focal point in recent research on new green cementitious materials both domestically and internationally. This paper analyzes and introduces the current research status from the perspectives of the improvement mechanism and chemical reactions of alkali-activated soil, the enhancement of related mechanical properties, and the environmental impact and ecological benefits. The findings reveal that the improved soil has the following characteristics: (1) The alkali activator triggers the active components in slag, producing cementitious products such as calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H), forming high-strength, durable cementitious materials that effectively enhance soil properties. (2) It significantly improves the soil's compressive strength, shear strength, and erosion resistance, while also offering good environmental adaptability and durability. (3) The production process utilizes industrial waste, reducing the consumption of natural resources and carbon emissions, aligning with the principles of green building and circular economy. These research findings provide a reference for new soil improvement methods.

KEYWORDS: Improved soil, Mechanical properties, Alkali-activated slag, Reaction mechanism, Environmental friendliness

I. INTRODUCTION

In civil engineering, the physical and mechanical properties of soil are crucial to the safety and stability of infrastructure. However, natural soils often exhibit heterogeneity and performance degradation, leading to foundation settlement, cracking, and other issues, which pose significant potential risks to engineering projects. This is particularly true in poor foundation conditions such as soft soils, expansive soils, and soils with high water content, where these soils exhibit unfavorable characteristics such as low bearing capacity, high compressibility, and susceptibility to deformation. These issues directly threaten the durability and service life of engineering structures. Therefore, improving soil performance has become a critical issue that needs to be addressed in civil engineering.

Traditional soil improvement methods, such as lime and cement stabilization, enhance the mechanical properties of soil by adding cementitious materials. However, these methods often come with high energy consumption and significant CO_2 emissions, which contradict the current global trend toward low-carbon and sustainable development. Additionally, the durability of cement-stabilized soils is often poor in certain extreme environments, such as acidic or high-salinity conditions, limiting their application. Therefore, it is crucial to find a new soil improvement technology that can effectively enhance soil performance while reducing environmental impact.

The technology of alkali-activated soil improvement has emerged as an innovative solution, showing great potential. This technology involves combining industrial by-products (such as blast furnace slag) with alkaline activators (such as sodium hydroxide and sodium silicate) to form high-strength, durable cementitious materials. Alkali-activated materials not only significantly enhance the compressive strength and shear strength of soils but also improve their durability and environmental adaptability. This is especially evident in their resistance to freeze-thaw cycles, wet-dry cycles, and chemical erosion. Moreover, the production process of alkali-activated materials can utilize industrial waste, effectively reducing the consumption of natural resources and carbon emissions, aligning with the principles of green building and circular economy.

The alkali-activated soil improvement technology not only enhances soil performance and extends the lifespan of engineering projects but also offers significant environmental benefits, providing a new approach to soil improvement that meets the requirements of sustainable development. As research and application of this technology deepen, it will bring safer, more economical, and more eco-friendly solutions to the field of civil engineering. Therefore, a brief analysis of alkali-activated soil improvement is conducted.

II. IMPROVEMENT MECHANISM AND CHEMICAL REACTIONS

The improvement mechanism and chemical reactions of alkali-activated slag-modified soil primarily rely on the activation of active components in slag by the alkali activator, resulting in the formation of reaction products with cementitious properties. The core of this process involves the dissolution, reorganization, and precipitation of silicates and aluminates in slag within an alkaline environment, forming cementitious materials similar to those produced in cement hydration. Through this mechanism, alkali-activated slag significantly enhances the mechanical properties and durability of the soil.

The process begins with the dissociation of the alkali activators (such as sodium hydroxide and sodium silicate) in water, creating a high pH alkaline environment. In this environment, the primary components of slag, such as silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3), gradually dissolve. The dissolved species, including silicate ions (SiO_4^{2-}) and aluminate ions (AlO_4^{4-}), further react with sodium ions (Na^+) or calcium ions (Ca^{2+}) in the solution to form new reaction products, mainly calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H).

These products fill the pores between soil particles and gradually solidify, forming a cementitious structure similar to that found in cement-based materials, significantly enhancing the overall strength of the soil. The C-S-H and C-A-H cementitious products generated during the reaction possess excellent bonding ability and durability. These cementitious products not only form tight connections between soil particles, reducing soil porosity, but also maintain relatively stable structures under different environmental conditions, significantly improving the soil's compressive strength, shear strength, and erosion resistance.

Additionally, the calcium hydroxide ($Ca(OH)_2$) produced during the reaction is alkaline, which can neutralize acidic substances in the soil to some extent, improving the soil's chemical environment and further enhancing its stability.

Of course, the effectiveness of alkali-activated slag-modified soil is influenced by various factors, including the chemical composition of the slag, the type and concentration of the alkali activator, the type of soil, and the initial moisture content. These factors collectively determine the rate of the alkali activation reaction, the types and quantities of reaction products, and the final performance of the improved soil. Therefore, in practical applications, it is necessary to optimize the mixture proportions and construction techniques according to specific soil conditions and engineering requirements to achieve the best improvement results.

III. IMPROVEMENT OF MECHANICAL PROPERTIES

The improvement of the mechanical properties of alkali-activated slag-modified soil is primarily achieved through the chemical reactions between the alkali activator and slag. The activation process dissolves the active components of the slag in a high-pH environment, generating cementitious products such as calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H). These products form strong bonding structures between soil particles, significantly enhancing the mechanical properties of the modified soil, including compressive strength, shear strength, and erosion resistance.

3.1 Compressive Strength

During the alkali activation process, the silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3) in the slag dissolve in the alkaline solution, generating silicate and aluminate ions. These ions further react with sodium or calcium ions to form the primary cementitious products, C-S-H and C-A-H. These products not only possess excellent bonding capabilities but also gradually fill and seal the pores in the soil during the hardening process, significantly reducing the soil's porosity, thereby increasing its overall density and strength. Studies have shown that the compressive strength of alkali-activated slag-modified soil can reach or even exceed that of traditional cement-stabilized soil, especially after long-term curing, where the strength improvement is more pronounced.

3.2 Shear Strength

The shear strength of alkali-activated slag-modified soil has also been significantly improved. The C-S-H and C-A-H cementitious products form a network structure between soil particles, effectively increasing friction and cohesion between the particles, thereby enhancing the soil's shear resistance. This improvement is particularly important for engineering structures that must withstand shear forces, such as slopes and foundations.

3.3 Erosion Resistance

Alkali-activated slag-modified soil also exhibits excellent erosion resistance. In corrosive environments, such as acidic or high-salinity soils, the alkali-activated products effectively resist the intrusion of external corrosive substances, maintaining the stability of the soil structure. This resistance is due to the high chemical stability of C-S-H and C-A-H products, which are not easily decomposed or dissolved in harsh conditions, thus providing long-term durability protection.

In summary, alkali-activated slag-modified soil significantly improves the mechanical properties of soil by generating high-strength and stable cementitious products. The improvements in compressive strength, shear strength, and erosion resistance are particularly notable, making this technique more effective than traditional soil improvement methods. As a result, alkali-activated slag-modified soil shows great potential for various engineering applications.

IV. ENVIRONMENTAL IMPACT AND ECOLOGICAL BENEFITS

Alkali-activated slag-modified soil not only excels in mechanical performance but also offers significant environmental impact and ecological benefits, particularly in resource utilization, carbon emission reduction, and soil remediation.

(1) Alkali-activated slag-modified soil effectively utilizes industrial by-products, such as blast furnace slag. These by-products, typically waste from steel production, are converted into cementitious materials through alkali activation technology. This process not only mitigates environmental issues related to waste accumulation but also facilitates waste resource recovery, aligning with the principles of circular economy and sustainable development. Compared to traditional cement production, the alkali activation process of slag consumes less energy and reduces the depletion of natural resources, helping to alleviate resource scarcity.

(2) The production process of alkali-activated slag-modified soil significantly reduces the carbon footprint. Cement manufacturing is one of the most energy-intensive and carbon-emitting industries, accounting for approximately 8% of global CO_2 emissions. In contrast, the production of alkali-activated slag materials does not require high-temperature calcination, resulting in a substantial reduction in CO_2 emissions. Therefore, the use of alkali-activated slag-modified soil not only enhances soil performance but also effectively reduces carbon emissions, offering significant environmental benefits.

(3) Alkali-activated slag-modified soil also shows potential in the remediation of contaminated soils. Many industrial sites, due to prolonged industrial activities, contain heavy metals and other harmful substances in the soil. The alkaline components in alkali-activated slag can neutralize acidic pollutants in the soil, while the resulting cementitious products can immobilize heavy metals, reducing their mobility and bioavailability, thereby lowering the threat to the environment and human health. This characteristic makes alkali-activated slag-modified soil valuable for applications in mine reclamation and industrial site remediation.

(4) Alkali-activated slag-modified soil also demonstrates strong durability and erosion resistance, maintaining long-term stability under harsh environmental conditions. This durability not only extends the service life of engineering structures, reducing the need for maintenance and reconstruction, but also further minimizes environmental impact, in line with the principles of ecological engineering.

In summary, while improving the mechanical properties of soil, alkali-activated slag-modified soil also offers significant environmental impact and ecological benefits. Through reduced carbon emissions, efficient resource utilization, and contaminated soil remediation, this technology provides a sustainable solution for the civil engineering field with vast application potential.

V. CONCLUSION

(1) The alkali-activated soil improvement technology combines industrial by-products (such as blast furnace slag) with alkaline activators, relying on the activation of reactive components in the slag to produce calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) as cementitious products. This process forms high-strength, durable cementitious materials that effectively improve soil properties.

(2) This technology significantly enhances the soil's compressive strength, shear strength, and erosion resistance. It also exhibits excellent environmental adaptability and durability, particularly in resisting freeze-thaw cycles, wet-dry cycles, and chemical erosion.
(3) The production process utilizes industrial waste, reducing the consumption of natural resources and carbon emissions, which aligns with the principles of green construction and circular economy.

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