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Study on the Effects of Soft Soil curing agent on the Properties of Different Soils

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Abstract: This study systematically evaluates the engineering performance improvement of Soft Soil curing agent on four typical special soils: demolition waste, marine mud, shielded soil, and nuclear power station soil. Results indicate that without the addition of stabilizer, these soils exhibit poor workability, low strength, or setting difficulties; specifically, demolition waste remains unsetting with extremely low strength (0.11 MPa at 7d), marine mud suffers severe bleeding and fails to set even after 28 days, while shielded soil and nuclear power station soil demonstrate slow setting and insufficient early strength. With increased stabilizer dosage (10%–30%), significant improvements in flowability are observed, along with markedly shortened initial and final setting times, and linear growth in unconfined compressive strength. Notably, bleeding is completely inhibited in marine mud when the dosage reaches ≥20%. Although shielded soil contains foam agents that delay hydration, high dosages can still accelerate the reaction. For nuclear power station soil, the strength peaks around a dosage of 20%. This technology not only solves the difficult problem of special soil solidification but also achieves resource conservation and environmental emission reduction, demonstrating significant economic and environmental benefits.

1. Introduction

Since the mid-20th century, significant progress has been made in the research and application of Soft Soil curing agents worldwide. They are generally classified into inorganic, organic, ionic, and bio-enzyme soil stabilizers[1], each enhancing soil strength, bearing capacity, and durability through distinct mechanisms. Foreign scholars have conducted studies based on the curing mechanisms of different soil stabilizers. POONIJ[2] argued that inorganic soil stabilizers release a large amount of high-valent cations such as calcium and aluminum after reacting with water, which exchange with sodium, potassium, and aluminum ions on the surface of soil colloid particles. This greatly reduces the thickness of the electric double layer of soil colloid particles, destroys the bound water film on the particle surface, and promotes the flocculation and agglomeration of soil particles into larger aggregates. Electrostatic interaction is a major mechanism for the stabilization of soil by organic stabilizers, especially cationic organic stabilizers for clay. The surface of clay minerals is usually negatively charged, so polycations are easily adsorbed on the surface and edges of clay minerals, changing the water absorption near the clay mineral surface and forming large, stable flocculent particles[3]. This reduces the hydrophilicity of soil particles, forms a waterproof soil layer, and after compaction, the soil loses its ability to reabsorb water. Even when exposed to water again after compaction, the mechanical properties of the soil are not affected[4].

In recent years, domestic research on Soft Soil curing agents has focused on material innovation, mechanism deepening, and engineering application expansion, forming three core directions: resource utilization of industrial waste, development of bio-based materials, and optimization of composite functions. Soil stabilizers have broad application prospects in engineering construction, but differences in their mechanisms lead to variations in the effectiveness of improving soil properties and the degree of strength enhancement[5]. Inorganic soil stabilizers can be used to treat various soil types, and current research mainly focuses on the effects of different stabilizer dosages and curing times on the mechanical properties of stabilized soil. Shu Ben'an et al[6]. studied the influence of cement and steel slag dosages on the compressive strength of stabilized soil, and further explored the effects of different activators and their composites on the strength of steel slag-stabilized soil. Organic soil stabilizers can improve the unconfined compressive strength, shear strength, and water stability of soil. The stabilizers themselves do not cause negative impacts or damage to the environment, can reduce soil erosion, facilitate vegetation growth, and effectively enhance the erosion resistance of road embankments and slopes[7]. Ionic soil stabilizers can reduce the plasticity index and porosity of soil, improve soil structure and stability, decrease soil swelling potential and water absorption, and enhance soil mechanical and engineering properties. Ma Min et al[8]. used cement combined with ionic stabilizers and found that an appropriate amount of cement can further improve soil improvement effects. The

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*Corresponding author's e-mail: miner_885@163.com main reason is that ionic stabilizers can promote the cementation of cement and soil particles into an integrated structure, changing the physical structure of the soil. Current research on bio-enzyme soil stabilizers mainly focuses on the mechanical properties of stabilized soil. However, there is controversy regarding the effectiveness of bio-enzyme soil stabilizer technology, and most studies have shown that the curing effect of bio-enzymes can significantly improve soil strength and bearing capacity[9].

This study selected four types of special soils and used Soft Soil curing agent to replace traditional road construction materials, exploring its impact on different soil types. This approach can save resources and energy, protect land vegetation, reduce greenhouse gas emissions, and deliver both economic and environmental benefits, making it an innovative technology for the sustainable development of highway engineering. The research findings provide important reference value for related studies on Soft Soil curing agent.

2. Experiment

2.1. Raw Materials

Five typical special soils were selected for this study, with their basic properties as follows:

(1)Construction waste soil is derived from building demolition projects, with complex and uneven composition, including bricks, concrete fragments, mortar, and other components. It has poor particle gradation and a moisture content of 15%-25%.

(2)Sludge is taken from coastal sedimentary sludge, with a natural moisture content as high as 65%-85%, a void ratio of 1.5-2.0, and an organic matter content of 3%-8%. It is a material with high moisture content, high compressibility, and low strength.

(3)Shield tunneling soil is the waste soil generated during subway tunnel shield construction, with a moisture content of 20%-30%, containing a certain amount of additives such as foaming agents and polymers.

Nuclear power plant-contaminated soil is soil that may be contaminated during the operation of nuclear power plants. Representative nuclides (Cs-137, Sr-90, Co-60) were added, and the initial contamination concentration was controlled at 1000-5000 Bq/kg

2.2. Preparation of Stabilizer

Ordinary Portland Cement (OPC): Grade 42.5R, specific surface area 350 m²/kg; Mineral powder: S95 grade, activity index ≥95%; Gypsum: Fineness 5.0%; Quicklime: Industrial grade, effective CaO content ≥88%; Sodium silicate pentahydrate: Sodium oxide content 8.0%, silica content 28.0%. The stabilizer formula was: 200~230 g cement, 670~700 g mineral powder, 100~120 g gypsum, 0~10 g quicklime, and 0~20 g sodium silicate pentahydrate.

2.3. Experimental Design

A single-factor experimental design was adopted to investigate the effects of different stabilizer dosages on the fluidity, bulk density, and unconfined compressive strength of different soil types. Specimens of 70.7 mm × 70.7 mm were prepared according to standard sampling methods. After curing to the specified ages (7d, 14d, 28d) under standard conditions (temperature 20±2°C, humidity ≥95%), tests were conducted.

2.4. Test Methods

(1)The setting time test of soft soil-stabilized soil was carried out in accordance with the national standard GB/T 1346 "Test Methods for Water Requirement of Normal Consistency, Setting Time and Soundness of Cement".

(2)The fluidity test of soft soil-stabilized soil was performed in accordance with the industry standard CJ/T 526-2018 "Soft Soil curing agent".

(3)The bulk density test of soft soil-stabilized soil was conducted in accordance with the industry standard CJ/T 526-2018 "Soft Soil curing agent".

(4)The unconfined compressive strength test of soft soil-stabilized soil was implemented in accordance with the industry standard CJ/T 526-2018 "Soft Soil curing agent".

3. Experimental Results and Analysis

3.1. Study on the Effect of Soft Soil curing agent on the Properties of Construction Waste Soil

Construction waste soil from building demolition was selected for testing. Different dosages of the Soft Soil curing agent were added to explore its effects on the properties of construction waste soil. The test data are shown in Table 1.

According to Table 1, When no Soft Soil curing agent was added, the flowability loss of slurry is small, resulting in a non-setting condition. It takes 28 days to reach a strength of 0.11 MPa. Increasing the dosage of the solidifying agent improves the flowability to 225 mm, while the bulk density increases linearly, making the soil more compact. The initial and final setting times are shortened, and the compressive strength rises linearly. A dosage range of 10% - 20% can improve flowability, density, and strength. The 28-day strength exceeds 2.0 MPa, meeting most engineering requirements. If high flowability was required, it can be increased to 20%, but attention should be paid to the effect of the shortened final setting time.

Table 1. Effects of different dosages of Soft Soil curing agent on the properties of construction waste soil

Sample Number	Soft soil curing agent Dosage/%	Muck/g	Water/g	Mobility/mm		Bulk density/ (kg/m^3)	Unconfined compressive strength /MPa			Setting time/min	
				0min	60min		7d	14d	28d	Initial setting	Final setting
P1	0	615	591	211	207	1440	0	0	0.11	Non-condensing	
P2	10		617	212	181	1452	0.85	0.99	1.44	790	1390
P3	13		629	217	182	1455	0.92	1.15	1.56	730	1330
P4	16		640	221	186	1458	1.23	1.53	1.99	690	1290
P5	20		670	225	192	1459	1.53	1.98	2.47	650	1230

3.2. Study on the Effect of Soft Soil curing agent on the Properties of Sludge

Sedimentary sludge from coastal areas was selected for testing. Different dosages of the Soft Soil curing agent were added to explore its effects on the properties of sludge. The test data are shown in Table 2.

From Table 2, it can be analyzed that without adding the Soft Soil curing agent, the flowability loss of sludge is relatively small, and it remains un-set even after 28 days. As the dosage of the solidifying agent increases, the initial flowability changes slightly, but the flowability after 60 minutes shows a slight upward trend with increasing dosage. This indicates that increasing the dosage helps maintain the stability of the fluidity. The change in bulk density is not significant; however, the initial and final setting times are notably shortened, demonstrating that higher dosages result in faster setting rates. The strength at all ages significantly increases with dosage. The 7-day strength rises from 0.23 MPa (13%) to 1.74 MPa (30%), while the 28-day strength increases from 0.79 MPa to 2.64 MPa, an increase exceeding three times. This suggests that increasing the dosage effectively enhances the mechanical properties of the sludge. When the dosage reaches 13%, severe bleeding occurs; at 16%, bleeding turns mild; and when the dosage reaches 20% or higher, there is no bleeding. This indicates that sufficient dosage effectively inhibits water separation, improving the homogeneity and stability of the solidified body. In summary, when the dosage of the Soft Soil curing agent falls within the range of 20% – 30%, the sludge exhibits good workability, high strength, and complete inhibition of bleeding, making it an optimal dosage range.

Table 2. Effects of different dosages of Soft Soil curing agent on the properties of sludge

Sample Number	Soft soil curing agent Dosage/%	Sludge/g	Water/g	Mobility /mm		Bulk density/(kg/m^3)	Unconfined compressive strength/MPa			Setting time/min		bleeding degree
				0min	60min		7d	14d	28d	Initial setting	Final setting	
P6	0	625	421	220	218	1732	0	0	0	Non-condensing		Severe
P7	13		459	223	184	1754	0.23	0.46	0.79	3140	3610	Severe
P8	16		470	219	190	1757	0.7	0.89	0.98	3000	3520	Slight
P9	20		483	216	192	1760	1.2	1.5	1.61	2950	3440	None
P10	30		502	225	193	1760	1.74	2.18	2.64	2880	3340	None

3.3. Study on the Effect of Soft Soil curing agent on Shield Tunneling Soil

Shield tunneling soil contains additives such as foaming agents and polymers introduced during the shield construction process. These substances can interfere with the hydration process of the stabilizer. Studies have shown that the chemical additives in shield soil retard the cement hydration rate, leading to slower development of early-age strength, though they have little effect on the ultimate strength. Waste soil generated from metro tunnel shield construction was selected for testing. Different dosages of Soft Soil curing agent were added to investigate its influence on the properties of the shield soil. The resulting data are presented in Table 3.

From Table 3, it can be seen that without adding the Soft Soil curing agent, the flowability loss of shield soil is not significant. It remains un-set even after 14 days, with a strength of only 0.21 MPa at 28 days. As the dosage of the solidifying agent increases, the initial flowability increases by approximately 5.7%, indicating that increasing the dosage slightly improves the initial workability of the shield soil. However, the change in flowability after 60 minutes is relatively small (about 3.3%), suggesting that the dosage has limited effect on maintaining fluidity, possibly due to interference from residual additives (such as foam agents) in the shield soil. The impact of the solidifying agent dosage on the overall performance of the shield soil is not significant (maximum difference < 0.4%), indicating that the dosage has little effect on material density, and the structural stability of the solidified body does not change significantly with increased dosage. The initial setting time is shortened by approximately 18.2%, and the final setting time is shortened by approximately 21.6%. This indicates that the setting time of the shield soil significantly decreases with increasing dosage. Increasing the dosage may accelerate the hydration reaction, offsetting the retarding effect of the additives and thereby speeding up the solidification process. The compressive strength at all ages steadily increases with the dosage of the solidifying agent.

Table 3. Effects of different dosages of Soft Soil curing agent on the properties of shield tunneling soil

Sample Number	Soft soil curing agent Dosage/%	shield muck/g	Water/g	Mobility/mm		Bulk density/ (kg/m³)	Unconfined compressive strength /MPa			Setting time/min	
				0min	60min		7d	14d	28d	Initial setting	Final setting
P11	0	660	620	208	199	1838	0	0	0.21	Non-condensing	
P12	10		640	210	183	1850	1.93	2.86	3.75	770	1340
P13	13		630	213	181	1849	2.35	3.21	4.23	740	1260
P14	16		642	220	186	1855	3.08	4.16	51.6	700	1190
P15	20		670	222	189	1857	4.21	5.55	6.74	630	1050

3.4. Study on the Effect of Soft Soil curing agent on the Properties of Nuclear Power Plant-Contaminated Soil

Soil that may be contaminated during the operation of nuclear power plants was selected for testing. Different dosages of the Soft Soil curing agent were added to explore its effects on the properties of nuclear power plant-contaminated soil. The test data are shown in Table 4.

As shown in Table 4, without the addition of the soft soil stabilizer, the flowability loss of nuclear power station soil is minimal. It has not yet reached initial setting after 14 days, and only achieves a strength of 0.18 MPa at 28 days. with the increase in Soft Soil curing agent dosage, the initial fluidity increases by 11%. However, when the dosage reaches 20%, the fluidity shows a decreasing trend, indicating that at higher dosages, the growth in fluidity slows down or slightly declines. The 60-minute fluidity increases continuously from 153 mm (at 10% dosage) to 175 mm (at 20% dosage), suggesting that a higher dosage helps reduce the loss of fluidity over time and improves the construction and workability of the soil. The effect of Soft Soil curing agent dosage on the bulk density of the nuclear power plant soil is minimal, indicating that the dosage has a limited impact on soil compactness. The initial setting time of the nuclear power plant soil is shortened by approximately 25%, and the final setting time by about 24%. The increase in Soft Soil curing agent dosage significantly accelerates the setting process of the soil, which may be beneficial for rapid strength development in engineering applications. Moreover, at all curing ages, the compressive strength increases significantly with higher dosages, particularly in the early stages (7 days and 14 days), where the increase is more pronounced.

Table 4. Effects of different dosages of Soft Soil curing agent on the properties of nuclear power plant-contaminated soil

Sample Number	Soft soil curing agent Dosage/%	nuclear power plant-contaminated soil/g	Water/g	Mobility/mm		Bulk density (kg/m³)	Unconfined compressive strength /MPa			Setting time/min	
				0min	60min		7d	14d	28d	Initial setting	Final setting
P16	0	700	459	195	189	1768	0	0	0.18	Non-condensing	
P17	10		482	196	153	1777	0.32	0.59	0.88	680	1010
P18	13		475	211	166	1780	0.69	0.95	1.09	640	940
P19	16		493	221	170	1785	0.81	1.51	1.60	570	840
P20	20		520	220	175	1786	0.99	1.79	1.92	510	770

4. Conclusion

(1) Without adding soft soil stabilizer, the four types of soil have no engineering application value: Under the condition without stabilizer, shield soil, slurry, shield soil, and nuclear power station soil all suffer from abnormal setting (extremely long initial/final setting time or non-setting), poor mechanical properties. The unconfined compressive strength at 28 days is as high as only 0.21 MPa, and slurry suffers severe bleeding, failing to meet the basic requirements for material strength and stability in highway engineering construction.

(2) Adding soft soil stabilizer significantly improves the setting characteristics and mechanical properties of the four soils: With the increase in stabilizer dosage, the initial and final setting times of the four soils are significantly shortened (e.g., for shield soil, the initial setting time was reduced from 23040 min to 650 min at a dosage of 20%). This solves the problem of non-setting without curing; the unconfined compressive strength at various ages shows a regular growth pattern. Among them, when the dosage is 20%, the 28-day strength of shield soil reaches 6.74 MPa, and when the dosage is 30%, the 28-day strength of slurry reaches 2.64 MPa, which can all meet the strength requirements of corresponding engineering scenarios.

(3) The effect of stabilizer dosage on the performance of different soils has a differentiated optimal range: When the dosage is 10% ‑ 20%, shield soil achieves engineering applicable standards for fluidity, density, and strength;

slurry requires a controlled dosage of 20% ‑ 30% to balance workability and strength while completely inhibiting bleeding; shield soil and nuclear power station soil achieve a better balance between strength growth and setting efficiency at dosages of 16% ‑ 20%, with excessive dosage resulting in weakened marginal effects on performance improvement.

(4) Soft soil stabilizer can optimize soil properties: For high water content slurry, a dosage ⩾20% eliminates bleeding and improves uniformity; for shield soil, it counteracts the retarding effect and accelerates hydration. The unit weight of the four soils rises slightly with dosage, indicating that it promotes compaction and enhances stability.

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