Influence of Solidifying Agent on the Setting Time of Fluidized Soil

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Abstract. Flowable soil cement has high fluidity and is a self-leveling, low-cost material that can be used under various complex working conditions. The experiment used loess from the Qilihe District, Lanzhou City, Gansu Province as the base soil, cement and sandstone as auxiliary materials, soil stabilizer as an additive, and water as a mixing agent to conduct a series of tests on the mixtures with different cement content and stabilizer addition amounts. The research results indicate that the setting time of fluidized stabilized soil is significantly affected by the addition of cement; the more cement used, the shorter the setting time. The setting time of fluidized soil with soil solidifier increases first and then decreases with the increase in the concentration of the additive, with the most significant effect at a concentration of 0.02%.

Keywords: flowable solidified soil, soil solidifying agent, setting time

1 Research Background

With the accelerated development of modern infrastructure systems, conventional small-scale compaction equipment in traditional backfill engineering has gradually revealed technical limitations. Practical evidence demonstrates that standard construction methods exhibit significant variability in backfill compaction density and challenges in ensuring construction quality homogeneity. Furthermore, dimensional constraints of equipment frequently create operational blind spots when performing backfill operations in irregularly shaped foundation trenches or confined spaces. In this context, novel premixed flowable stabilized soil materials have emerged as an effective solution due to their inherent self-leveling properties and vibration-free self-compacting advantages.

In recent years, pre-mixed fluidized solidified soil, as a novel green engineering material, has demonstrated significant technical advantages in the field of geotechnical engineering backfilling. This material, through the composite action of curing agents and soil, exhibits both fluidity and rapid hardening characteristics, effectively addressing issues such as insufficient compaction and low construction efficiency associated with traditional backfill materials.[1]~[2] Scholars both domestically and internationally have conducted a series of studies on its engineering properties and

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application scenarios: in the field of transportation infrastructure, Le et al.[3] validated the feasibility of using fluidized soil as a backfill material for railway bridge abutment transition zones through experiments and numerical simulations; for special geological conditions, Zhang Xu et al.[4] developed a fluidized solidified soil formula with crushed stone aggregate suitable for collapsible loess; in the treatment of abandoned mines, Bertolini et al.[5] confirmed the stabilizing backfill effect of cement-based fluidized mixtures on gypsum mines. Additionally, Wang Jie[6] explored the environmental benefits of cement-based solidified fluidized soil from the perspective of solid waste resource utilization, further expanding the application dimensions of this technology.

Fluidized solidified soil, owing to its excellent fluidity and anti-scour properties, is widely applied in the treatment of karst foundations and the modification of expansive soils[7]~[8]. The use of entirely waste materials as curing agents offers significant economic and environmental benefits, and the fluidity and compressive strength of the solidified soil can be optimized by adjusting the mixing ratios[9]. Through testing methods such as XRD and SEM, researchers have unveiled the microstructural changes in solidified soil and elucidated the synergistic mechanisms of different curing agents[10]~[11]. For special soil types such as soft soil and sludge, the use of ionic curing agents can significantly enhance soil strength and improve drainage consolidation properties[12]~[13]. Jiang Mingye et al[14]. noted that both inorganic and organic curing agents significantly improve soil properties, with ionic curing agents showing advantages in treating expansive soils, while the environmental friendliness of bio-enzyme curing agents provides broad prospects for their application in ecological engineering. Wang Jing[15] investigated the solidification characteristics of fluidized loess using cement-based waste curing agents, exploring the effects of different raw material ratios on mechanical properties and water stability. Xu Riqing et al[16]. summarized the research progress on soft soil solidification materials, analyzing the mechanical properties and stability of inorganic, organic, bio-enzyme, and ionic curing materials, and pointed out the advantages, disadvantages, and applicable scopes of each type of material. Su Wenxuan et al[17]. studied the mechanism of cement and alkali-activated materials synergistically solidifying chloride saline soil, finding that the blending ratio and curing age significantly affect mechanical properties, and that synergistic reactions effectively improve material durability.

2 Test

2.1 Raw Materials

The experimental materials primarily consist of base soil, Portland cement, and soil stabilizer. The base soil originates from discarded soil from a project in Qilihe District, Lanzhou City, Gansu Province, sourced from a depth of 1 to 3 meters and exhibiting good workability. The soil specimens were dried, sieved through a 5 mm standard sieve, and purified to eliminate impurities, ensuring uniformity and consistency. The soil exhibits weakly acidic characteristics with a pH value of 5.8, along with moderate viscosity, making it suitable for soil stabilization experiments.

The Portland cement utilized is P.O 42.5 ordinary Portland cement produced by Gansu Qilian Mountain Cement Group, characterized by high strength and excellent stability, conforming to the specifications of GB175-2009 "General Portland Cement." The selected soil stabilizer is type 2-2 product from a Shandong-based manufacturer, representing an innovative green construction material. This stabilizer is noted for its effective consolidation properties and environmental compatibility, offering a stable performance and capacity to enhance the geotechnical properties of the base soil.

Chemical composition analysis of the base soil and sandstone reveals the presence of bicarbonate (HCO_3^-), chloride (Cl^-), calcium (Ca^{2+}), magnesium (Mg^{2+}), and sulfate (SO_4^{2-}) ions. Notably, the sandstone exhibits a strong alkaline nature with a pH of 9, while the base soil maintains weak acidity with a pH of 5.8. This significant pH discrepancy necessitates rigorous proportioning trials to optimize the mixture ratio and mitigate potential chemical interactions. Table 1 provides a detailed account of the chemical constituents, serving as an essential reference for subsequent mixture design and performance evaluations.

Table 1. Content of Trace Elements in Raw Materials (Unit:mol/1).

Ingredients	HCO_3	CL^-	Ca^{2+}	Ma^{2+}	SO_4^{2-}
Soil	1.0	2.1	16.9	0.9	23.8
Gravel	0.5	9.2	5.5	6.8	36.5

The test results indicate that the loess has a plasticity index of 9.8, with a plastic limit of 30.1% and a liquid limit of 20.3%, classifying it as a low-plasticity silt. The natural water content of the soil is 6.7%, with a maximum dry density of 1.91 g/cm³ and an optimum water content of 12.8%. The curvature coefficient (Cc) of the loess is 2.05, and the uniformity coefficient (Cu) is 24.38. For the sandy soil, the curvature coefficient (Cc) is 1.20, and the uniformity coefficient (Cu) is 15.08. These results demonstrate that both the loess and sandy soil are well-graded.

By referring to the specification "Soil Stabilizing Admixtures" (CJT486-2015), for mixtures using soil stabilizers, cement should be chosen as P.O 42.5 Ordinary silicate cement, cement in accordance with the specification "Technical Standard for Ready-Mixed Fluidized Soil Construction" (T/CECS 1037-2022) The performance was tested as required, and the results are shown in Table 2.

The cement exhibited a specific surface area of 336 cm²/g, with its setting time, flexural strength, and compressive strength demonstrating full compliance with the specifications governing the use of cementitious materials in flowable filler applications. All tested parameters satisfied the stringent criteria outlined in standardized protocols for rheology-controlled filling material systems, confirming the material's suitability as a performance-guaranteed binder in engineered flowable composites.

Table 2. Table of Cement Physical and Mechanical Properties.

Specific surface area /(cm^2·g^{-1})	Setting time/ min		Bending strength / MPa		Compressive strength/ MPa	
	Initial setting	Final setting	3d	28d	3d	28d
336	170	227	4.9	6.9	26.8	53.8

As shown in Figure 1, The determination of cement setting time was conducted in accordance with standard test methods, utilizing a Vicat apparatus to measure both initial and final setting times. Operational parameters were strictly controlled in compliance with specification requirements throughout the testing process. The optimal water content determined through the standard consistency test was 27.6%, which served as the reference water condition for setting time determination. As shown in Figure 2, For mechanical performance testing, a fully automated digitally controlled flexural-compressive testing machine was employed for strength evaluation.

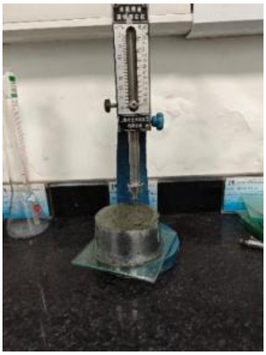

Fig. 1. Setting Time Test.

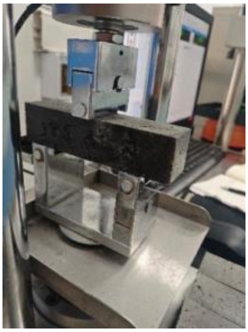

Fig. 2. Mechanical Property Testing of Cement.

The determination of the flowability of the paste, with its value and the requirements of the specifications as shown in Table 3.

Table 3. Cement paste fluidity value.

Determine the time	Initial		30min		60min	
Net slurry fluidity (mm)	value	requirement	value	requirement	value	requirement
	181.8	≥100	167.9	≥90	154.5	≥80

The fundamental properties of soil and cement in raw materials exert synergistic control effects on the key performance indicators of novel flowable filling materials. Under engineering application conditions, component optimization and performance compatibility of raw materials can effectively ensure that the flow characteristics of the filling material satisfy construction process requirements. The mineral composition and natural gradation characteristics of soil significantly influence the rheological behavior of the slurry and the structural compactness of the hardened matrix, with the physicochemical activity of fine particles potentially impacting the material's long-term stability. Conversely, the cementitious activity and particle morphology of cement dominantly regulate the early-stage hydration reaction kinetics and strength development patterns of the system. Under the premise of reasonably controlling the quality of raw materials, by adjusting the granular composition and interfacial interactions of the soil-cement composite system, can achieve a synergy between the material's workability and its mechanical durability.

2.2 Experimental Plan

The setting time test was conducted in accordance with the Standard for Test Methods of Basic Properties of Construction Mortar (JGJ/T 70-2009). This comparative study focuses on evaluating the synergistic effects and individual performance of these two stabilizers under varying dosage conditions, with particular emphasis on their temporal impact on the hardening process of fluidized soil mixtures.

Based on the specifications outlined in the standard 《Soil Stabilizing Admixtures》 CJ/T 486-2015, Portland Ordinary (P.O) 42.5 grade ordinary Portland cement was selected. Considering the engineering geological characteristics of typical loess in the Longzhong region, including its particle size distribution and hydro-sensitivity, Type II-2 stabilizer was chosen as the soil stabilizing agent for this study through a comprehensive review of relevant literature.

Analysis of the effect of cement dosage on setting time, In the flowable stabilized soil mixture, the proportions of other components were fixed as follows: 34% aggregate content, 30% water content, and 0.025% soil stabilizer. The experimental cement dosages and corresponding setting time results are detailed in Table 4.

Table 4. Cement Consumption and Test Results.

Cement dosage	4%		6%		8%		10%	
Amount of soil stabilizer /‰	0	0.25	0	0.25	0	0.25	0	0.25

Setting time (min)	495	536	383	471	351	442	323	419

Analysis of the effect of soil stabilizer dosage on setting time, In the flowable stabilized soil mixture, the proportions of other components were fixed as follows: 34% aggregate content, 30% water content, and 8% cement content. The experimental dosages of soil stabilizer and corresponding setting time results are presented in Table 5.

Table 5. Amount of soil stabilizer and test results.

Amount of soil stabilizer /‰	0	0.05	0.1	0.15	0.2	0.25	0.3
Setting time (min)	351	392	403	422	443	427	413

2.3 Experimental Method

The setting time test was conducted in accordance with the Standard for Test Methods of Basic Properties of Construction Mortar (JGJ/T 70-2009). A digital mortar penetrometer was employed, utilizing a container with an internal diameter of 140 mm and height of 75 mm for slurry containment. The penetration needle featured a cross-sectional area of 30 mm². The prepared mortar mixture was placed into the container and stored in a test chamber maintained at 20 ± 2°C. Bring the penetration needle into contact with the surface of the mixture, then slowly and uniformly press it vertically into the mixture to a depth of 25 mm within 10 seconds. Record the instrument reading during each penetration. The penetration resistance value is calculated using Equation 1, and the test is ceased when the resistance reaches 0.7 MPa. A plot is then created to illustrate the relationship between the penetration resistance and time, from which the time corresponding to a penetration resistance of 0.5 MPa is determined as the setting time value.

$$f_P = \frac{N_P}{A_P} \tag{1}$$

In the equation ——Penetration Resistance Value (MPa), Accurate to 0.01MPa;
——Static pressure at a penetration depth of 25 mm (N);
——The cross-sectional area of the penetration test needle, and so 30mm².

3 Test Results and Analysis

3.1 The Effect of Cement Dosage on Setting Time

With the increase in cement dosage, the setting time of fluidized soil is significantly reduced. The analysis indicates that during the hydration reaction process, cement generates hydration products, which can rapidly form a network structure, thereby accelerating the solidification of the soil mass. The greater the cement dosage, the faster the hydration reaction rate, resulting in more cementitious substances produced, making the soil structure denser and consequently shortening the setting time.

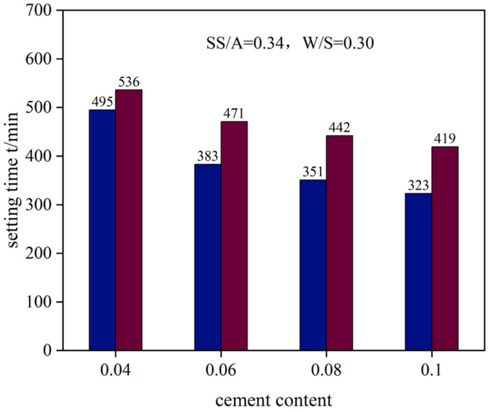

Fig. 3. Cement Consumption Impact Chart

As shown in Figure 3, The influence of cement on the setting of fluidized solidified soil is remarkably significant. For mixtures without any cement, the penetration resistance value only reaches 0.13 MPa after 72 hours of standard curing conditions, and the increase is very slow. In contrast, mixtures with 4% cement can achieve a penetration resistance value of 0.7 MPa in just 495 minutes. During the process of increasing the cement-to-aggregate ratio from 4% to 6%, the setting time is observed to decrease significantly from 495 minutes to 383 minutes, a reduction of up to 23%. When the cement content is further increased to 10%, the setting time is shortened to 323 minutes. Research indicates that the effect of cement dosage on adjusting the setting time exhibits a distinct phased variation pattern. It is evident that as the cement dosage continues to increase, its effect on the setting time of the mixture gradually diminishes.

The mechanism by which cement shortens the setting time of fluidized solidified soil stems from the rapid hydration reaction of its cementitious components: tricalcium silicate and tricalcium aluminate in cement quickly release Ca^{2+} and OH^- ions upon contact with water, forming a highly alkaline pore solution environment. This not only directly promotes the rapid nucleation and growth of ettringite and C-S-H gel but also activates the active components in the soil stabilizer to accelerate ion exchange. Meanwhile, the micro-aggregate filling effect of cement particles shortens the migration path of free water in the slurry, increases the contact area for hydration reactions, and its exothermic properties further raise the system temperature, accelerating molecular diffusion rates.

Given the significant impact of cement dosage on setting time, it is recommended to select an appropriate cement dosage in practical applications to achieve the desired setting speed. For instance, if a faster setting speed is required, the cement dosage can be increased to more than 4%. An 8% cement dosage can significantly shorten the setting time, but when the cement dosage is increased to 10%, the effect on shortening the setting time diminishes. Therefore, it is advisable to choose the cement dosage based on specific needs in practical applications, without exceeding 8%, to avoid resource waste and cost increases.

3.2 The Effect of Soil Stabilizer Concentration on Setting Time

The addition of soil stabilizers will delay the setting time of fluidized solidified soil, as the stabilizers react with cement, which may affect the rate of cement hydration and delay the formation of hydration products, thereby extending the setting time. From the experimental results, it is observed that the amount of the hardener added has different effects on the setting time. When the concentration of the hardener is low, its retarding effect on the cement hydration reaction is minimal. However, as the concentration of the hardener increases, the retarding effect becomes significant. Once the concentration reaches a certain level, further increasing the concentration of the hardener has a gradually diminishing effect on the setting time.

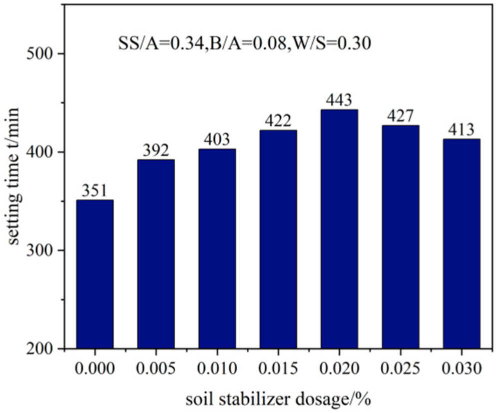

Fig. 4. Soil Stabilizer Impact Map

As shown in Figure 4, For mixtures without soil stabilizer, the setting time required to achieve the desired strength was 351 min. Upon the addition of soil stabilizer, the setting time progressively increased with higher stabilizer dosages. When the stabilizer dosage reached 0.02%, the setting time attained its peak value, extending by 92min compared to the stabilizer-free mixture, demonstrating a significant retarding effect.

The incorporation of soil stabilizing agents exhibits a prolonging effect on setting time; however, within a specific dosage range, their influence on setting duration remains adjustable. To achieve controlled extension of the setting period, it is advisable to moderately incorporate soil stabilizing agents under scenarios requiring delayed hardening. This approach ensures predictable workability while maintaining the structural integrity of the stabilized matrix through optimized dosage adjustment.

4 Conclusion

The functional additives and activators contained in soil stabilizers can improve the surface properties of soil particles, promote the bonding between cement and soil mass, and increase the compactness and strength of fluidized stabilized soil. However, this improvement effect may slow down the initial hydration reaction of cement to some extent, thereby extending the setting time.

The addition of cement to fluid solidified soil shortens the setting time, primarily because the silicate minerals in cement rapidly hydrate upon contact with water, generating C-S-H gel and ettringite. These products quickly form a rigid skeleton structure. Increasing cement content elevates system temperature, proliferates nucleation sites for hydration products, and enhances alkalinity in pore solution, thereby accelerating ion exchange and crystallization processes. In contrast, soil stabilizers prolong the setting time through the action of their functional components: anionic dispersants employ electrostatic repulsion to disperse cement particles, creating adsorption layers that hinder water contact with cement surfaces; organic retardants form complexes with calcium ions to inhibit initial hydrolysis reactions; hydrophilic polymers generate water-retaining films at interfaces, effectively reducing water-cement ratio and delaying hydration progression.

The mechanism behind the delayed setting and enhanced later-stage strength in cement-soil flowable fill materials with the addition of soil stabilizers can be attributed to three main aspects: 1) The organic polymers in the stabilizer adsorb onto the surface of cement particles, forming a temporary protective coating that inhibits rapid hydration reactions of early-stage minerals like C_3S and C_3A during the initial phase, thereby prolonging the induction period for setting regulation. 2) The reactive aluminosilicate components in the stabilizer gradually dissolve in the alkaline environment and undergo secondary pozzolanic reactions with $Ca(OH)_2$ generated from cement hydration. This produces cementitious C-S-H and C-A-S-H gels that continuously fill pores and bridge interfaces between soil particles and the cement matrix during later stages, optimizing microstructural compactness. 3) The retarding effect allows more complete hydration reactions, preventing premature hardening-induced accumulation of internal defects. Ultimately, this synergistic mechanism facilitates the formation of a high-density, highly cross-linked composite structure with improved long-term mechanical strength.

Overall, the content of cement admixture and the concentration of soil stabilizers are pivotal factors in regulating the setting time of fluidized stabilized soil, and their interaction significantly influences the performance of the fluidized stabilized soil. In practical applications, appropriate mix ratios should be selected based on specific engineering requirements and environmental conditions. Low-cement + hardener scheme: If a long setting time is required (such as for large-volume casting), a combination of 4% cement and 0.025% hardener can be used (536 minutes), which is more economical than simply increasing the amount of cement. High-cement + no hardener scheme: If rapid hardening is needed (such as for emergency repairs), a 10% cement without hardener combination (323 minutes) achieves the highest efficiency.

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