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Influence mechanism of supersulfated cement on the rheological behavior and mechanical properties of flowable solidified soil with construction waste soil

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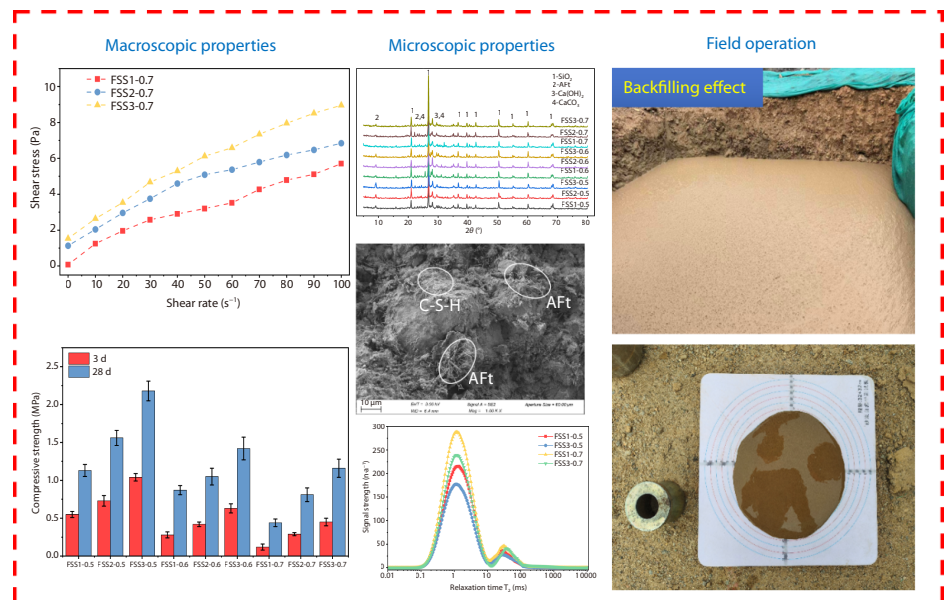
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Abstract: To improve the resource utilization of construction waste soil, supersulfated cement (SSC) was used as the main curing agent to prepare flowable solidified soil with construction waste soil. The effect of the water-solid ratio (W/S) and alkaline component (AC) content on the rheological behavior and mechanical properties of the solidified soil was investigated. In addition, its engineering applicability was further verified. The results showed that an increase in the W/S caused a certain shear-thinning phenomenon in the solidified soil. The increase in the AC content could improve the yield stress and plastic viscosity, optimizing the rheological characteristics of the fresh solidified soil. During hardening, higher W/S had a negative effect on the formation of hydration products, resulting in a loose microstructure, weakening the compressive strength and deformation resistance of solidified soil. In comparison, the increase in the AC content improved the alkaline environment of the SSC system, which promoted the formation of hydration products, enhancing the compactness of the solidified soil structure and refining the pore structure. When the W/S was 0.5 and the AC content was 7%, the solidified soil showed favorable rheological and mechanical properties. Its yield stress and plastic viscosity were 3.75 Pa and 0.088 Pa·s, respectively. After 28 d, its strength was 2.18 MPa, and the shrinkage degree only changed by 0.604%. Field operation further demonstrated that the solidified soil could reach a self-leveling effect, and it had favorable strength and slight shrinkage.



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Keywords: construction waste soil, supersulfated cement, flowable solidified soil, rheological behavior, mechanical properties

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1. Introduction

In recent years, with the rapid advancement of urbanization and the large-scale development of underground space worldwide, the generation of construction waste soil has increased sharply^[1,2]. According to statistics, the average annual growth rate of construction waste soil can reach 10%, with approximately 1.62 billion tons produced, making it the largest component of urban construction waste^[3,4]. Currently, construction waste is mainly disposed of through open-air stockpiling or simple landfilling, which occupies substantial land resources. In addition, it also leads to dust emissions, which can deteriorate air quality and cause continuous pollution to the environment^[5,6]. Therefore, developing efficient technologies for the resource utilization of construction waste has become essential for promoting the green development of civil engineering and protecting the ecological environment^[7].

Directly using construction waste soil in civil engineering applications such as roadbeds and foundations, followed by repeated compaction to achieve densification, is the simplest disposal method. However, this approach was mainly applicable to sandy gravel construction waste soil^[8,9]. The physicochemical properties of construction waste soil from different regions have significant differences. Hence, treating cohesive construction waste soil by direct compaction might result in poor compaction efficiency, leading to structural instability and insufficient bearing capacity^[10,11]. Therefore, solidification technology has been proposed to treat construction waste soil for the preparation of controlled low-strength materials (CLSM)^[12]. In the CLSM system, flowable solidified soil has attracted increasing attention due to its adjustable fluidity and controllable strength. On the one hand, it can consume a large amount of construction waste soil; on the other hand, it is used for backfilling in narrow spaces, including excavations and pipeline trenches^[13–15].

Flowable solidified soil is mainly composed of a curing agent, soil, and water. The cementitious performance of the curing agent is the key factor affecting the engineering performance of the solidified soil^[16]. Ordinary Portland cement (OPC) is commonly used as the conventional curing agent. Although this material is based on mature technology and provides a stable curing effect, its production is associated with high energy consumption and substantial carbon emissions, posing certain threats to the environment^[17,18]. Moreover, the use of OPC is inconsistent with China's strategic goals of "carbon peaking and carbon neutrality"^[19]. Therefore, replacing conventional curing agents with green and low-carbon alternatives is an important development direction.

Granulated blast furnace slag (GBFS) and desulfurized gypsum (DG) are industrial solid wastes, which are generated as by-products of steelmaking and coal-fired power generation, respectively^[20]. The resource utilization of these solid wastes can not only reduce the dependence on OPC but also mitigate the negative impact on the environment. The cementitious system composed of GBFS, DG, and alkaline components (AC) is generally referred to as supersulfated cement (SSC)^[21]. As a low-clinker and low-carbon cementitious mate-

rial, SSC has several advantages, including low hydration heat, high later strength, low carbon emissions, and resistance to salt erosion^[22–24].

Ju et al.^[25] prepared SSC using steel slag, GBFS, and DG, and found that ettringite (AFt) crystals were interspersed within the calcium silicate hydrate (C-S-H) gel network, thus making the microstructures denser and improving mechanical properties. This indicated that this SSC had the potential to replace the OPC. Subsequently, Ren et al.^[26] developed an SSC-based grouting material by optimizing the proportions of steel slag and DG. The resulting material formed denser microstructures, which exhibited a low permeability coefficient and achieved compressive strength exceeding 2.5 MPa. Based on this, Hao et al.^[27] further applied SSC to low liquid limit silt soil. The flowable solidified soil showed a spread diameter exceeding 370 mm and a 28-d compressive strength of up to 1.2 MPa. However, current research on the applicability and compatibility of SSC with construction waste soil (especially silty clay) is still relatively limited. The effect mechanism of SSC on the key engineering properties of flowable solidified soil containing construction waste soil has not yet been systematically investigated.

Therefore, in this study, SSC was used as the main curing agent to prepare the flowable solidified soil combined with construction waste soil. The rheological parameters of the solidified soil during the fresh mixing stage, as well as its strength and volume stability during the hardening stage, were systematically characterized. Subsequently, the phase composition, microstructure, and pore structure were determined, revealing the effect mechanisms of SSC on solidified soil. In addition, a field backfilling operation was conducted to verify the feasibility of solidified soil in engineering applications. The findings could provide a theoretical basis and experimental evidence for the low-carbon resource utilization of construction waste soil, which might promote its large-scale application in engineering.

2. Materials and methods

2.1. Raw materials and concrete preparation

The construction waste soil was from the Jinan East Station area in Jinan City, Shandong Province, China. The main type of the construction waste soil was silty clay, with a high moisture content (ω) of 30.8%. Its liquid limit (W_L) could reach 42.2%. In addition, the related soil parameters, including relative density (G_s), plastic limit (W_p), and plasticity index (I_p) of the soil, were provided, as shown in Table 1.

The particle size distribution and phase composition of the construction waste soil raw materials were measured, as shown in Fig. 1. The specific surface area and average particle size of the construction waste soil particles were $0.454 \text{ m}^2 \text{ g}^{-1}$ and $75.29 \text{ }\mu\text{m}$, respectively. In addition, the main mineral component of the construction waste soil was quartz,

Table 1. The basic physical properties of construction waste soil.

Type	Ω (%)	G_s	W_L (%)	W_p (%)	I_p
Silty clay	30.8	2.74	42.2	24.8	17.4

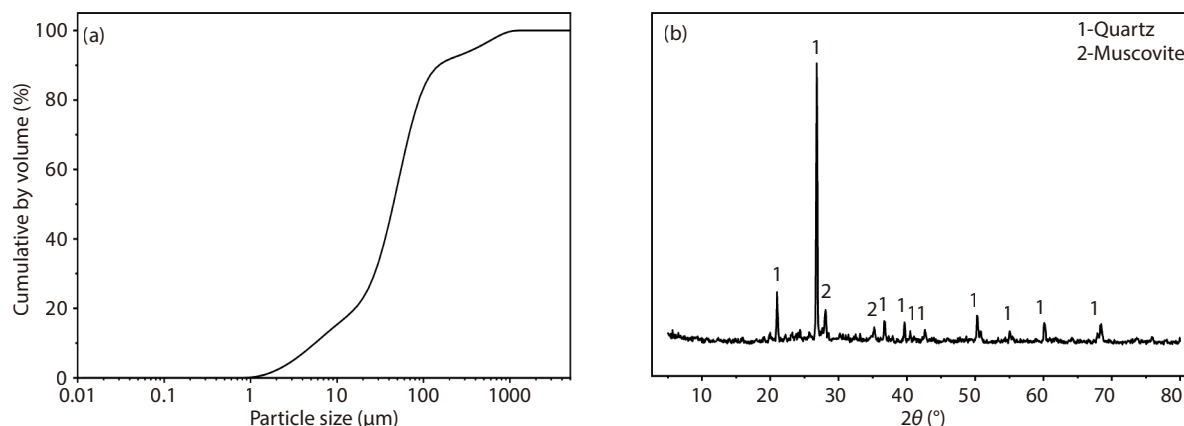


Fig. 1. The (a) particle size distribution and (b) phase composition of construction waste soil.

and a small amount of muscovite existed within it.

The main raw materials of the SSC curing agent were GBFS with the a 28-d activity index of 105%, DG with a crystalline water content of approximately 19%, and AC (mainly composed of cement clinker). The main chemical components of SSC are shown in Table 2.

The mix proportions of the flowable solidified soil are shown in Table 3. The mass proportion of GBFS in the SSC was fixed at 80%, while the AC content was set at 3%, 5%, and 7%, respectively, with the DG content adjusted accordingly. Meanwhile, the cementitious material-soil ratio (C/S) was maintained at 0.15, and the water-solid ratio (W/S) was set at 0.5, 0.6, and 0.7, respectively.

The preparation procedure of the flowable solidified soil was as follows. Firstly, the dried construction waste soil was crushed and passed through a 0.6 mm sieve. Subsequently, the construction waste soil, SSC, and water were added into a cement mortar mixer and thoroughly mixed for 3 min to obtain the fresh flowable solidified soil. The well-mixed slurry was then poured into molds and placed on a vibrating table for 60 s. Finally, the specimens were cured in a standard curing room at a temperature of 20 ± 2 °C and a relative humidity of $95\% \pm 5\%$ for the specified periods.

Table 2. The chemical composition of raw materials in SSC (%).

Raw materials	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	SO ₃	MgO
GBFS	36.41	34.10	17.61	1.01	1.62	6.22
DG	43.18	0.77	0.7	0.11	45.75	0.54
AC	45.29	22.63	6.96	10.43	1.12	5.39

Table 3. The mix proportions of flowable solidified soil.

NO.	GBFS	DG	AC	C/S	W/S
FSS1-0.5	80%	17%	3%	0.15	0.5
FSS1-0.6	80%	17%	3%	0.15	0.6
FSS1-0.7	80%	17%	3%	0.15	0.7
FSS2-0.5	80%	15%	5%	0.15	0.5
FSS2-0.6	80%	15%	5%	0.15	0.6
FSS2-0.7	80%	15%	5%	0.15	0.7
FSS3-0.5	80%	13%	7%	0.15	0.5
FSS3-0.6	80%	13%	7%	0.15	0.6
FSS3-0.7	80%	13%	7%	0.15	0.7

2.2. Fluidity and rheological behavior characterization

A coaxial cylindrical rheometer was used to investigate the rheological properties of flowable solidified soil. The testing procedure was as follows: Firstly, a pre-shear step was applied at a shear rate of 100 s^{-1} for 30 s; subsequently, the shear rate was increased from 1 s^{-1} to 100 s^{-1} and then decreased back to 1 s^{-1} , with a holding period of 10 s at each shear rate. Based on the test results, the rheological parameters, including yield stress and plastic viscosity, were determined and calculated. Each group sample was tested three times under the same conditions, and the average results were calculated as the rheological parameters.

According to the Chinese standard (DB37/T 5345-2025)[28], the self-leveling flow spread diameter of fresh flowable solidified soil was measured. The uniformly mixed slurry was poured into a mold with a height of 150 mm and upper and lower diameters of 75 mm each, and the surface was leveled using a scraper. Then, the mold was lifted, and a steel ruler with a range of 500 mm and an accuracy of 1 mm was used to measure the diameters of the slurry in the maximum direction and its perpendicular direction. Each group sample was tested three times under the same conditions, and the average results were calculated as the test results.

2.3. Mechanical properties and volume stability characterization

According to the Chinese standard (JTG 3441-2024)[29], the unconfined compressive strength of flowable solidified soil with $\Phi 50 \text{ mm} \times 50 \text{ mm}$ dimensions was determined at different curing periods using a compression testing machine at a loading rate of 1 mm min^{-1} . Each group sample was tested three times under the same conditions, and the average results were calculated as the test strength.

According to the Chinese standard (JTG 3420-2020)[30], the drying shrinkage volume change rate (SVR) of flowable solidified soil with $25 \text{ mm} \times 25 \text{ mm} \times 280 \text{ mm}$ dimensions was measured. Before measurement, the specimens were cured under standard conditions for 1 d, and then immersed in water at 20 °C for further curing for 2 d. Subsequently, the specimens were placed in a drying shrinkage chamber at 20 °C and 50% humidity to continue curing for different periods. At each period, the length change of the specimens was measured. Each group sample was tested three times under

the same conditions, and the average values were calculated as the test results. The test specimens are shown in Fig. 2.



Fig. 2. The specimens of flowable solidified soil after drying shrinkage curing.

2.4. Microscopic properties measurement

X-ray diffraction (XRD) was used to analyze the phase evolution characteristics of flowable solidified soil with 2θ ranging from 5° to 80° at a scanning rate of 5° min^{-1} . Before testing, the specimens were ground into powder.

Scanning electron microscopy (SEM) was used to characterize the micromorphology of flowable solidified soil at room temperature under an accelerating voltage of 15 kV. To enhance electrical conductivity and ensure reliable signal quality, the specimens were subjected to vacuum drying and gold-sputter coating before observation and were subsequently affixed to the specimen stub using conductive adhesive. To eliminate potential interference from moisture, all specimens were pre-dried for 24 h in a vacuum drying oven at 40°C before XRD and SEM testing.

Low-field nuclear magnetic resonance (NMR) was used to determine the pore structure characteristics of flowable solidified soil with $\Phi 50 \text{ mm} \times 50 \text{ mm}$ dimensions under a constant magnetic field of 0.3 T. Each group sample was tested three times under the same conditions, and the average results were selected. Before measurement, the specimens were saturated with water under vacuum conditions for 24 h. Following saturation, the specimens were tightly wrapped with cling film to maintain their water retention state.

2.5. Field backfilling operation

To verify the feasibility of applying flowable solidified soil prepared using SSC in practical engineering, the field backfilling operation was carried out based on the laboratory test results using the mixture with the best performance. The physicochemical properties of the construction waste soil used in the field operation were consistent with those of the soil used in the laboratory. In addition, the field backfilling area was an excavation with $5 \text{ m} \times 5 \text{ m} \times 1.5 \text{ m}$ dimensions.

3. Results and discussion

3.1. Fluidity and rheological behavior

The rheological curves of the flowable solidified soil are

shown in Fig. 3. With the increase in AC content, the shear stress of the solidified soil exhibited a consistent upward tendency under the same shear rate conditions. This indicated that a higher AC content could promote the formation of internal flocculation structures, thereby having a positive effect on the yield stress of solidified soil.

With the increase in W/S , at the same AC content, the shear stress of the solidified soil significantly decreased, and the rheological curves became gentler, indicating that the increase in the W/S weakened the interaction between particles, enhancing the flowability of the solidified soil. When the W/S was 0.5 and 0.6, the rheological curve of fresh solidified soil was approximately a straight line, indicating that its rheological characteristics in a stable state essentially conformed to the Bingham model. However, when the W/S was increased to 0.7, the rheological curves exhibited certain non-linear characteristics, suggesting that the solidified soil might undergo shear-thickening or shear-thinning effects during shearing. Hence, the Bingham model might not accurately describe the rheological behavior, while the Herschel-Bulkley (H-B) model might be more appropriate for characterizing this process^[31].

The rheological curves of flowable solidified soil under different W/S and AC content were fitted using the Bingham model and the H-B model, respectively. When the W/S was 0.5 and 0.6, the R^2 obtained from the two models exceeded 0.99, as shown in Table 4. In the H-B model, the parameter n is a critical indicator for distinguishing shear-thinning from shear-thickening behavior. At this W/S , the rheological index of solidified soil was basically close to 1, indicating that during the mixing, only a slight thickening or thinning phenomenon occurred, and the rheological behavior closely approximated the Bingham fluid. Therefore, the Bingham model could better describe the rheological characteristics of the solidified soil under this condition.

However, when the W/S was increased to 0.7, compared with the Bingham model, the fitting effect of the H-B model was significantly better, with R^2 exceeding 0.99. Under this condition, the rheological indices for FSS1-0.7, FSS2-0.7, and FSS3-0.7 were determined to be 0.729, 0.641, and 0.754, respectively. This indicated that at this W/S , the solidified soil exhibited shear-thinning behavior. With the increase in shear rate, the apparent viscosity of the fresh solidified soil gradually decreased. This thinning characteristic was beneficial for reducing the pipeline transportation resistance during the pumping stage, improving the flow-filling ability and self-leveling effect.

The rheological parameters mainly included the yield stress and plastic viscosity. The effect of AC content and W/S on the yield stress of the flowable solidified soil is shown in Fig. 4a. The yield stress can characterize the static flow resistance of the freshly mixed solidified soil and reflect the ability of the internal flocculation structures to resist initial flow, which is negatively correlated with the dispersion distance of the flocculation structures^[32]. The yield stress of FSS1-0.5 was 2.29 Pa. With the increase in AC content, the yield stress of FSS2-0.5 and FSS3-0.5 increased to 3.02 Pa and 3.75 Pa, respec-

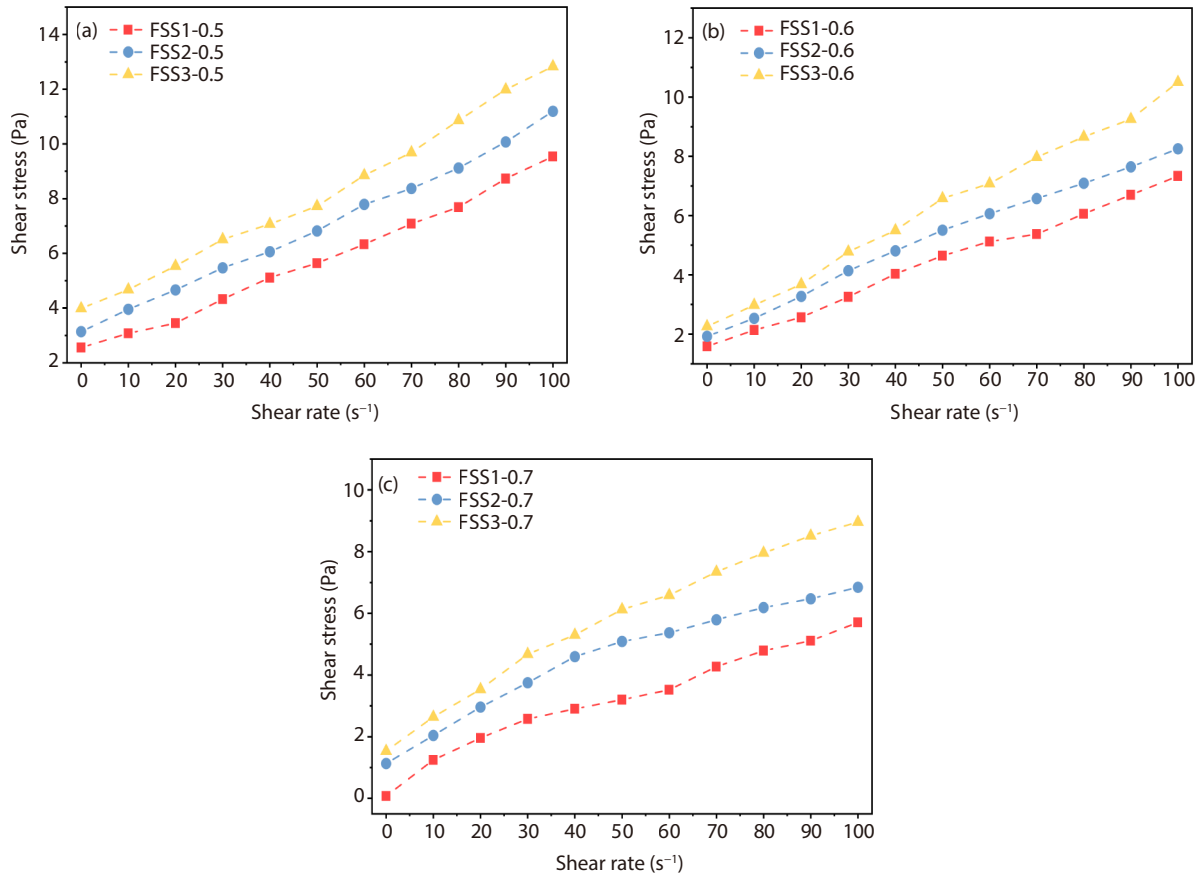


Fig. 3. The rheological curves of flowable solidified soil with (a) 0.5, (b) 0.6, and (c) 0.7 W/S.

Table 4. The rheological equations and correlation coefficients of flowable solidified soil.

NO.	Rheological model (Bingham/H-B)	R^2 (Bingham/H-B)
FSS1-0.5	$\tau=2.29+0.070\dot{\gamma}/\tau=2.59+0.031\dot{\gamma}^{1.175}$	0.99/0.99
FSS2-0.5	$\tau=3.02+0.078\dot{\gamma}/\tau=3.26+0.045\dot{\gamma}^{1.119}$	0.99/0.99
FSS3-0.5	$\tau=3.75+0.088\dot{\gamma}/\tau=4.03+0.049\dot{\gamma}^{1.124}$	0.99/0.99
FSS1-0.6	$\tau=1.58+0.057\dot{\gamma}/\tau=1.53+0.065\dot{\gamma}^{0.972}$	0.99/0.99
FSS2-0.6	$\tau=2.09+0.063\dot{\gamma}/\tau=1.81+0.012\dot{\gamma}^{0.863}$	0.99/0.99
FSS3-0.6	$\tau=2.24+0.081\dot{\gamma}/\tau=2.18+0.091\dot{\gamma}^{0.976}$	0.99/0.99
FSS1-0.7	$\tau=0.66+0.051\dot{\gamma}/\tau=0.16+0.186\dot{\gamma}^{0.729}$	0.97/0.99
FSS2-0.7	$\tau=1.80+0.055\dot{\gamma}/\tau=0.99+0.313\dot{\gamma}^{0.641}$	0.95/0.99
FSS3-0.7	$\tau=2.08+0.073\dot{\gamma}/\tau=1.44+0.237\dot{\gamma}^{0.754}$	0.98/0.99

tively. In comparison, an increase in W/S led to a reduction in yield stress to some extent, with the yield stress for FSS1-0.6 and FSS1-0.7 decreasing to 1.58 Pa and 0.66 Pa, respectively.

The plastic viscosity of the flowable solidified soil is shown in Fig. 4b. Unlike the yield stress, the plastic viscosity can reflect the resistance of fresh solidified soil to shear flow, which is closely associated with the concentration and morphology of solid particles, as well as interparticle interactions within the slurry^[33]. The plastic viscosity of FSS1-0.5, FSS2-0.5, and FSS3-0.5 was 0.070, 0.078, and 0.088 Pa·s, respectively. When the W/S was 0.7, the plastic viscosity of FSS1-0.7, FSS2-0.7, and FSS3-0.7 decreased to 0.051, 0.055, and 0.073 Pa·s, respectively.

The increase in AC content could provide more alkaline components and active ions to the fresh flowable solidified

soil. These alkaline components rapidly dissolved and altered the ionic environment of the slurry, which could accelerate the dissolution rate of GBFS in an alkaline environment to some extent. This process facilitated the dissociation of Si-O bonds, which activated the cementitious reactivity of GBFS and accelerated its hydration reaction in the sulfate environment. Meanwhile, reactive ions could also directly participate in the nucleation and growth of hydration products^[34].

Therefore, compared with the SSC system with lower AC content, the system with higher AC content could generate more hydration products. These hydration products enhanced the interparticle bonding and flocculation structures in the fresh solidified soil, increasing the yield stress. In addition, they increased the specific surface area and volume fraction of solid particles in the slurry, resulting in greater internal friction resistance during flow and increasing plastic viscosity correspondingly.

In contrast, with the increase in the W/S, the free water content in the fresh flowable solidified soil increased, which could dilute the concentration of solid particles per unit volume of slurry. This weakened the physical contact and chemical bonding between the particles, increasing the average interparticle distance and reducing the strength of the flocculation structures, leading to a decrease in yield stress. Meanwhile, the increased W/S thickened the water film on particle surfaces, which lubricated the relative sliding between particles and reduced the internal friction resistance during flow, thereby decreasing the plastic viscosity of the solidified

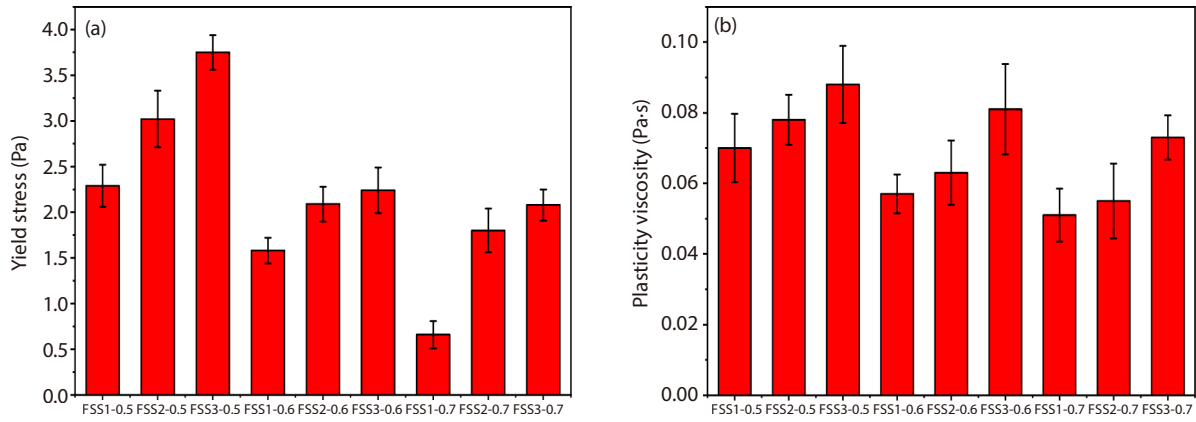


Fig. 4. The (a) yield stress and (b) plastic viscosity of flowable solidified soil.

soil[35].

When the W/S was 0.7, the increase in free water significantly reduced the concentration of solid particles in the solidified soil. Under a lower shear rate, certain flocculation structures could still form between the particles. However, with the increase in the shear rate, the weak flocculation structures were gradually disrupted, and the particles rearranged along the flow direction, reducing the flow resistance and exhibiting shear-thinning behavior.

The self-leveling flow spread diameter of the fresh flowable solidified soil was measured, as shown in Fig. 5. The spread diameter of FSS1-0.5 was 215 mm. With the AC content increased from 3% to 7%, the spread diameter of FSS2-0.5 and FSS3-0.5 decreased by 6 mm and 10 mm, respectively, indicating a negative correlation between AC content and the fluidity of the solidified soil. When the W/S increased from 0.5 to 0.7, the spread diameters of FSS1-0.6 and FSS1-0.7 increased by 36 mm and 55 mm, respectively, compared with that of FSS1-0.5. This indicated that the W/S had a more significant influence on the spread diameter of the solidified soil.

It could be seen that under different AC content and W/S conditions, the evolution tendency of the spread diameter of solidified soil was consistent with its rheological behavior during shear. An increase in AC content had an enhancing effect on the flocculation structures within the slurry, reducing the

fluidity of the solidified soil correspondingly. In contrast, the increase in W/S significantly improved the fluidity of the solidified soil through dilution and lubrication, achieving a better self-leveling effect. Overall, the self-leveling flow spread diameters of the flowable solidified soil under different AC content and W/S were all larger than 200 mm, which satisfied the relevant standard requirement (DB37/T 5345-2025).

3.2. Mechanical properties

The compressive strength of the flowable solidified soil after curing for 3 d and 28 d is shown in Fig. 6. The strength of FSS1-0.5 at the two curing periods was 0.55 MPa and 1.03 MPa, respectively. In comparison, the strength of FSS2-0.5 and FSS3-0.5 increased to 0.73 MPa and 1.04 MPa at 3 d, and 1.56 MPa and 2.18 MPa at 28 d, respectively. With the increase in AC content, the strength of the solidified soil showed an upward tendency. For FSS3-0.5, when the W/S increased to 0.6, the strength of FSS3-0.6 at 3 d and 28 d decreased by 0.41 MPa and 0.76 MPa, respectively. When the W/S was 0.7, the strength of FSS3-0.7 at the corresponding curing periods further decreased by 0.59 MPa and 1.02 MPa, respectively.

The Ca(OH)_2 generated during AC hydration increased the alkalinity of the alkaline component system. This promoted the hydrolysis of GBFS and induced the formation of calcium aluminate hydrate (C-A-H). The C-A-H further reacted with SO_4^{2-} supplied by DG to form Aft. The combination of

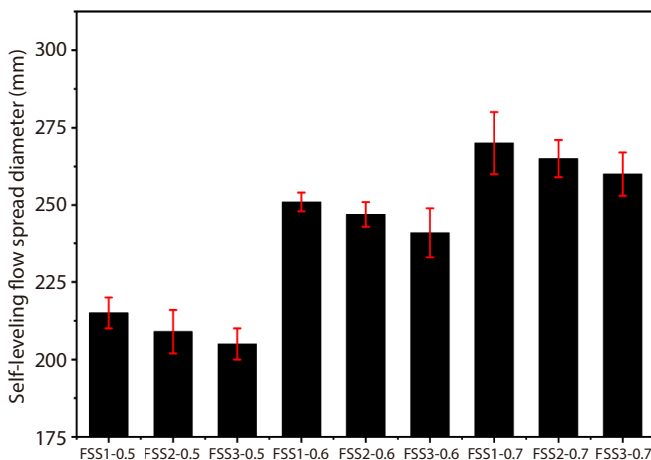


Fig. 5. The fluidity of flowable solidified soil.

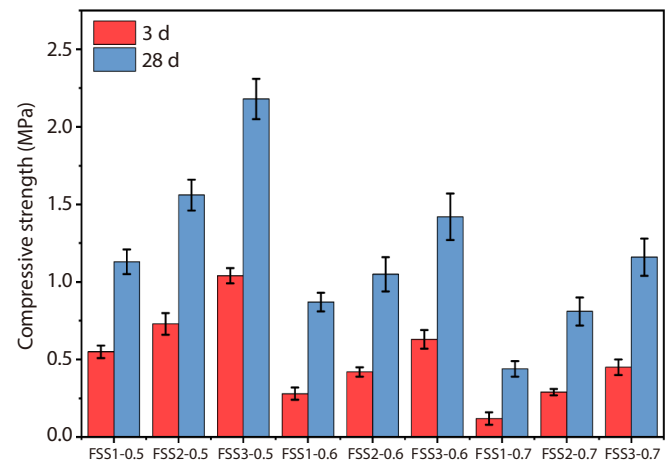


Fig. 6. The mechanical properties of flowable solidified soil.

Aft and C-S-H gel provided framework support for the solidified soil, thereby improving its compressive strength^[36]. Meanwhile, a higher AC content could consume the free water adsorbed on soil particles. The resulting hydration products could fill the pore structures of soil particles, which bonded the loose particles together to form a denser structure, further enhancing the strength of the solidified soil.

During mixing and early curing, the negative charges inside the silty clay particles could adsorb free water and form a water film around the particles. This increased the inter-particle spacing and weakened the frictional resistance and bonding effect between particles. This adverse effect became more pronounced with increasing *W/S*.

As the water film gradually disappeared during curing, more pores were left within the clay particle, resulting in a decrease in compactness and a reduction in the strength of the solidified soil. In addition, the increase in the *W/S* reduced the amount of hydration products. As a result, fewer hydration products were available to fill pores and bond soil particles. Meanwhile, the nucleation sites of hydration products became relatively dispersed, making it difficult to form a continuous and dense skeleton network within the solidified soil, thereby further decreasing its strength^[27,37].

Overall, when the *W/S* was 0.5 and 0.6, the strength of the flowable solidified soil with different AC contents all satisfied the relevant standard requirement (DB37/T 5345-2025). However, when the *W/S* increased to 0.7, only the solidified soil with an AC content of 7% could satisfy the standard requirement. This indicated that the *W/S* had a more significant effect on the strength of the solidified soil than the change in AC content. Therefore, reasonable control of the *W/S* was essential to ensure the mechanical properties of solidified soil.

3.3. Volume stability

The length of the specimens after demolding and maintenance in water for 2 d was defined as the initial length. The dimensional changes of the specimens were measured using a length comparator to determine the change in SVR of solidified soil at different curing periods, as shown in Fig. 7. The SVR could be calculated by Equation (1):

$$SVR = \frac{L_T - L_0}{L_0} \times 100 \quad (1)$$

where L_0 is the initial length before drying, mm; and L_T is the length after drying for different periods, mm. Due to the reduction in the length of the solidified soil during drying, the SVR all showed negative values, indicating the occurrence of volumetric shrinkage. Under the negative value condition, the smaller SVR of solidified soil indicated more significant drying shrinkage deformation.

During the dry curing for 1 d and 3 d, the difference in SVR among the solidified soil with different AC content and *W/S* was relatively small, indicating that the early drying shrinkage deformation had not yet significantly differentiated. After the curing time increased to 7 d, the SVR of solidified soil under different conditions showed an evident difference. When the *W/S* was 0.5, the SVR of FSS1-0.5 was -0.544% , whereas that of FSS3-0.5 was alleviated to -0.472% , corresponding to a 13.24% decrease in shrinkage degree. When the *W/S* increased to 0.7, the SVR of FSS1-0.7 and FSS3-0.7 were -0.924% and -0.832% , respectively; compared with FSS1-0.5, the corresponding shrinkage degree increased by 69.85% and 52.94%. At this curing period, the drying shrinkage of the solidified soil was effectively mitigated as the AC content increased from 3% to 7%.

When the curing age reached 14 d, the drying shrinkage of the flowable solidified soil continued to increase. The SVR of FSS1-0.5 and FSS3-0.5 were -0.672% and -0.580% , respectively. Under the *W/S* of 0.7, the corresponding SVR of the solidified soil were -1.172% and -1.072% , respectively. This indicated that drying shrinkage deformation of solidified soil was more significant under a higher *W/S*, whereas increasing the AC content could inhibit the development of volume instability to some extent. As a further increase in curing periods, the increment in SVR gradually decreased and tended to stabilize, while the overall variation tendency among different mixtures remained basically consistent.

An increase in the *W/S* increased the initial free water content in the flowable solidified soil system. During subsequent drying and curing, the migration and evaporation of a large amount of water more readily generated capillary negative pressure within the solidified soil, thereby inducing more significant drying shrinkage deformation. Meanwhile, the higher initial water content weakened the compactness of the internal structure and resulted in a looser microstructure, which further aggravated shrinkage deformation.

In comparison, increasing the AC content could provide more alkaline components to the solidified soil, promoting the hydration reaction of the SSC system and generating more hydration products. These hydration products could reduce capillary tension and enhance the bonding effect between soil particles by forming a denser spatial structure, thereby effectively inhibiting the drying shrinkage deformation of the solidified soil^[38].

3.4. Microscopic properties analysis

3.4.1. XRD pattern

The microscopic properties of flowable solidified soil are

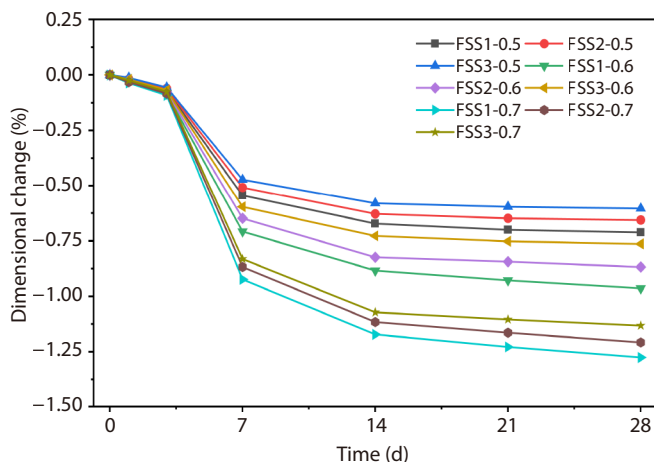


Fig. 7. The volume stability of flowable solidified soil.

strongly correlated with its mechanical properties and volume stability. The XRD pattern can reveal the chemical evolution of solidified soil using SSC as the curing agent during hardening through its crystalline phase characteristics. The phase composition of the flowable solidified soil after curing for 28 d under different AC content and W/S was characterized to evaluate the hydration degree of SSC, as shown in Fig. 8.

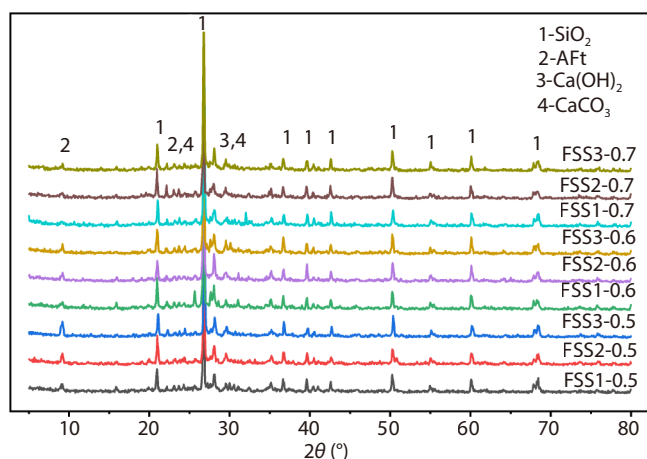


Fig. 8. The phase composition of flowable solidified soil after curing for 28 d.

In the XRD pattern, the presence of the SiO_2 characteristic peaks was mainly related to the quartz in the construction waste soil, but no obvious muscovite mineral phase was observed. Distinct Aft crystal characteristic peaks appeared,

indicating that Aft was the main hydration product of the SSC system. This product played an important role in the early strength development and volume stability of solidified soil. With the increase in W/S, the intensity of the Aft characteristic peak gradually decreased, indicating that higher W/S diluted the reaction system and reduced the effective concentrations of Ca^{2+} , AlO_4^{5-} , and SO_4^{2-} , thereby inhibiting sufficient crystallization and growth of Aft. In comparison, the Aft characteristic peaks gradually strengthened with increasing AC content, indicating that an appropriate alkaline environment facilitated the dissolution of reactive components in GBFS and promoted the hydration reaction of the system to accelerate the formation of Aft^[39].

In addition, characteristic peaks of Ca(OH)_2 were also present in the pattern. The Ca(OH)_2 was generated during the hydration of calcium silicate minerals in cement clinker contained in AC. The presence of Ca(OH)_2 provided a favorable alkaline environment for the SSC system and promoted the formation of Aft^[40]. Moreover, the presence of CaCO_3 characteristic peaks indicated that SSC came into contact with a certain amount of CO_2 and underwent carbonation reactions.

3.4.2. SEM microstructure

The microstructure evolution of the flowable solidified soil after curing for 28 d was observed using SEM. The effect of the W/S and AC content on the microstructure was comparatively analyzed, as shown in Fig. 9. In the microstructure of all solidified soil specimens, needle-rod-shaped Aft crystals and flocculent C-S-H gel structures could be observed. These hydration products adhered to the surfaces of soil particles to grow and accumulate within the interparticle pores, forming

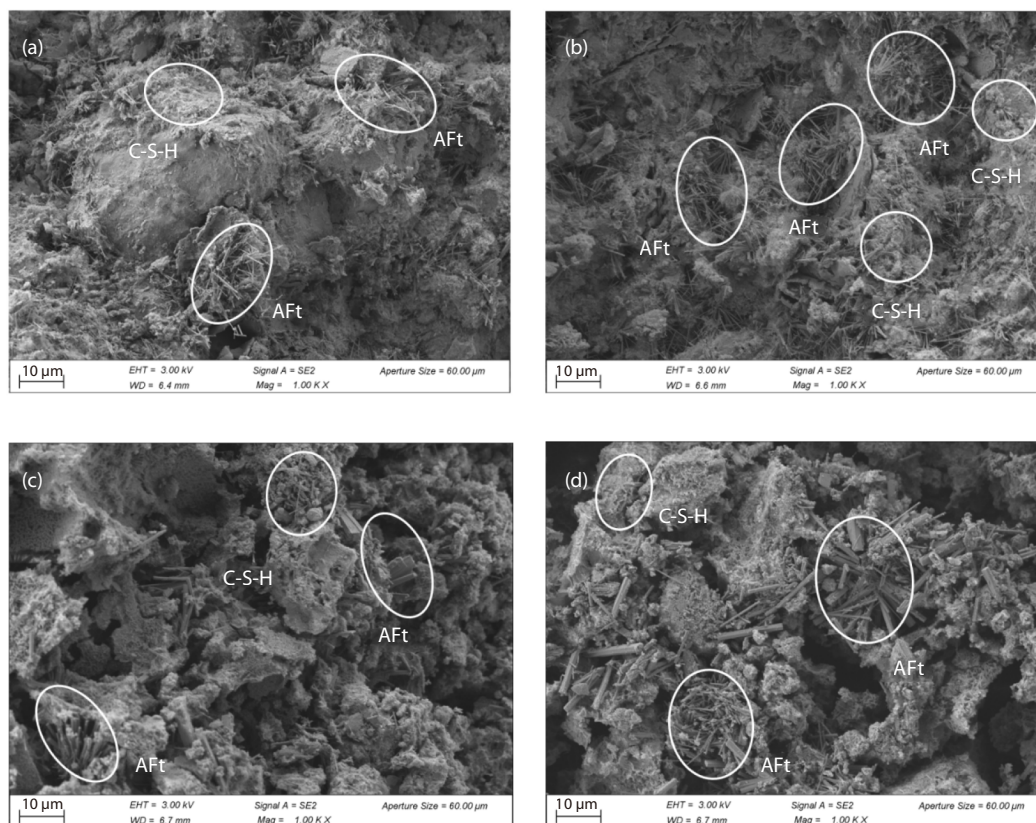


Fig. 9. The microstructure of (a) FSS1-0.5, (b) FSS3-0.5, (c) FSS1-0.7, and (d) FSS3-0.7 after curing for 28 d.

filling, encapsulating, and bonding effects with the soil particles. This provided the microstructural basis for the strength development and volume stability of the solidified soil^[41].

At a W/S of 0.5, the microstructure of the solidified soil was optimized when the AC content increased from 3% to 7%, as shown in Fig. 9a and b. The increase in AC content could enhance the alkaline environment of the SSC system, which promoted the dissolution of reactive components in GBFS and accelerated the release of active ions (Ca^{2+} , AlO_4^{5-} , and SiO_4^{4-}). This could provide more reactant sources for the formation of hydration products, increasing the amount of hydration products generated correspondingly.

In comparison, more Aft crystals were formed in FSS3-0.5. These crystals grew between soil particles, which could fill the interparticle pores and act as a framework to some extent. Meanwhile, the abundant C-S-H gel adhered to the surface of soil particles and provided a bonding effect on the particles, thereby effectively improving the compactness of the solidified soil microstructures. This further enhanced the integrity and deformation resistance of the overall structure, ultimately contributing to the improvement in compressive strength and volume stability^[13].

When the W/S increased to 0.7, the microstructure of the solidified soil exhibited a more obvious porous and loose characteristic, as shown in Fig. 9c and d. Many pores and discontinuous soil particle structures could be observed in FSS1-0.7 and FSS3-0.7. Due to the evaporation and migration of the high content of free water during the solidified soil hardening, more capillary pores and interconnected pores were formed. Consequently, the number of pores and pore diameters increased, weakening the bonding effect between soil particles.

Meanwhile, the increase in W/S affected the hydration reaction of the SSC system and reduced the formation of hydration products. As a result, the Aft crystals and C-S-H gel could not easily form a continuous and dense bonding network, thereby weakening the filling effect of the hydration products on the pores between soil particles and the bonding effect on the particles^[42]. Although the amount of hydration products in FSS3-0.7 increased to some extent, the improvement effect on the porous and loose structure of the solidified soil was relatively limited. Therefore, at a higher W/S , the mechanical properties of the solidified soil decreased, accompanied by significant volume shrinkage.

3.4.3. NMR pore structure

The transverse relaxation time (T_2) spectra of pore water in the flowable solidified soil were obtained using NMR, which was used to characterize the internal pore structure and pore size distribution of the solidified soil, as shown in Fig. 10. The T_2 relaxation time was positively correlated with the pore size of the solidified soil. The T_2 spectra of the solidified soil generally exhibited an obvious bimodal distribution feature.

The first peak appeared within the short relaxation time range, which was mainly associated with gel pores and transition pores in the solidified soil. This peak showed the highest signal intensity, indicating that small pore structures dominated the total pore volume of the solidified soil. The second

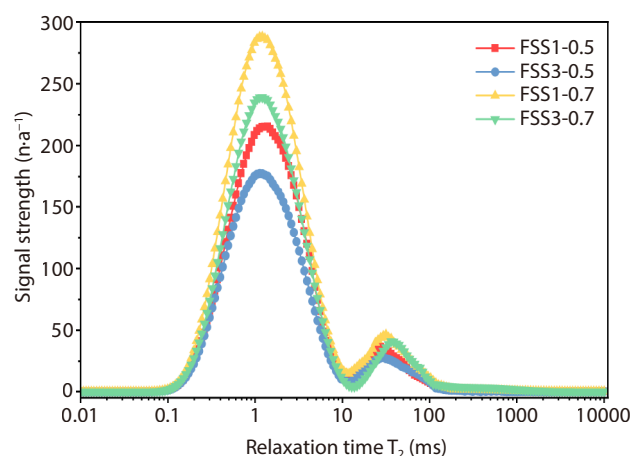


Fig. 10. The T_2 spectra curves of flowable solidified soil.

peak was basically located within the relaxation time range of 10–100 ms, which was primarily related to capillary pores.

With the increase in the W/S and the decrease in the AC content, the signal intensity of the relaxation peaks in the T_2 spectra increased, indicating an increase in the number of large pores and a gradual coarsening of the pore structure in the solidified soil. The area enclosed by the T_2 spectra curves and the horizontal axis can reflect the total signal intensity of pore water in the solidified soil and is closely related to the total pore volume^[43]. The calculated results are shown in Fig. 11a.

In comparison, FSS3-0.5 exhibited the smallest integrated area of 3004.79, corresponding to the lowest porosity of only 8.28%. When the W/S increased to 0.7, the integrated areas of FSS1-0.7 and FSS3-0.7 increased to 7654.73 and 5749.77, with corresponding porosities of 10.33% and 9.54%, respectively. This indicated that a higher W/S increased the internal pore volume of the solidified soil.

The solidified soil with a higher W/S contained more free water. During hardening, the evaporation of excess water readily led to the formation of more capillary pores and interconnected pores, resulting in an increase in total porosity. In comparison, increasing the AC content promoted the hydration reaction and generated more hydration products, which filled the pores between soil particles and enhanced interparticle bonding, thereby reducing the porosity of the solidified soil to some extent.

In general, according to different pore sizes, the pore structures of solidified soil can be classified into gel pores (< 10 nm), transition pores (10–50 nm), capillary pores (50–100 nm), and macropores (> 100 nm)^[7,44]. The changes in the proportion of different pore size structures in the solidified soil under different AC content and W/S are shown in Fig. 11b. The proportion of gel pores in FSS1-0.5 was 17.10%, which increased to 25.05% in FSS3-0.5 with increasing AC content. The gel pores in solidified soil are closely related to the formation and accumulation of hydration products. Therefore, the increase in the gel pore proportion indicated an increase in the amount of hydration products, which contributed to improving the compactness of the microstructures of the solidified soil.

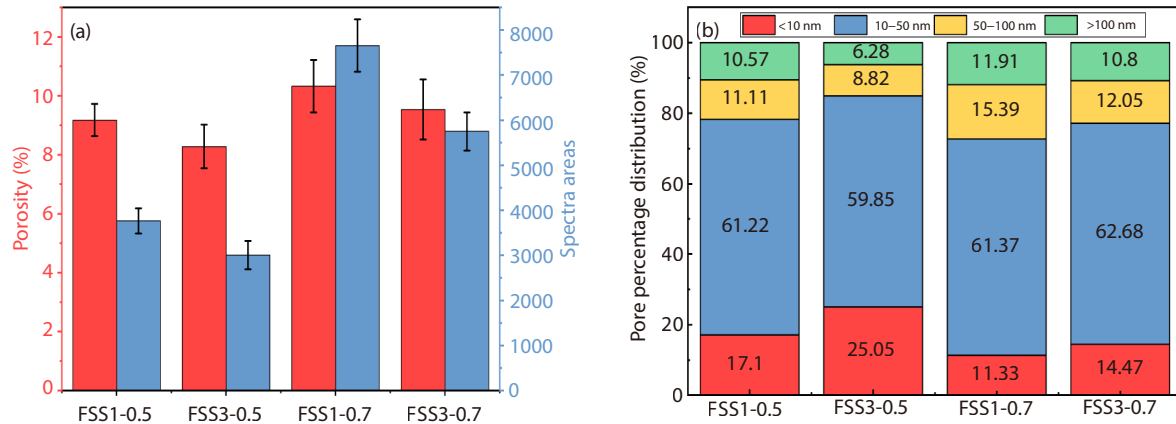


Fig. 11. The (a) porosity and spectra areas, and (b) pore percentage distribution of flowable solidified soil.

In comparison, the proportion of gel pores decreased with increasing W/S . The gel pore proportions in FSS1-0.7 and FSS3-0.7 were 11.33% and 14.47%, respectively. Under a high W/S , the higher water content in the solidified soil system increased the spacing between soil particles, making it difficult for hydration products to sufficiently fill the pores^[45]. For FSS3-0.5, the proportions of capillary pores and macropores were the smallest, at only 8.82% and 6.28%, respectively. In comparison, the proportions of capillary pores in FSS1-0.7 and FSS3-0.7 increased to 15.39% and 12.05%, while the corresponding proportions of macropores increased to 11.91% and 10.80%, respectively. For the solidified soil with a high W/S , excess water migrated or evaporated during hardening and drying, resulting in the formation of more capillary pores and macropores among soil particles. This weakened the pore-filling effect of hydration products.

3.5. Field backfilling operation analysis

Based on the laboratory test results, the FSS3-0.5 mixture with a W/S of 0.5 and an AC content of 7% was selected for the field backfilling operation. The ambient temperature and relative humidity on the backfilling day were 21 °C and 67%, respectively. The mixed solidified soil was transported by a ready-mix truck and directly poured into the backfilling area.

Due to its favorable flowability, the material achieved a self-leveling filling effect. To reduce water evaporation and prevent early shrinkage caused by moisture loss, the backfilling area was immediately covered with plastic film for curing after pouring.

Field backfilling observations showed that the solidified soil had developed a certain load-bearing capacity after 24 h of drying and hardening, which was sufficient to support personnel standing and subsequent construction operations. After hardening for 7 d, the interface between the solidified soil and the excavation wall exhibited a favorable contact state, and no obvious volume shrinkage deformation or surface cracking caused by water evaporation was observed, as shown in Fig. 12.

Meanwhile, the workability and mechanical properties of the in-situ flowable solidified soil were tested, and the results are shown in Fig. 13. The solidified soil exhibited favorable flowability, with a field-measured spread diameter of 212 mm, which was close to the laboratory test result. This indicated that the material could achieve a favorable self-leveling state during pouring. Subsequently, specimens were prepared simultaneously from the field mixture and covered with plastic film. They were then cured under the same natural environmental conditions as the solidified soil in the excava-

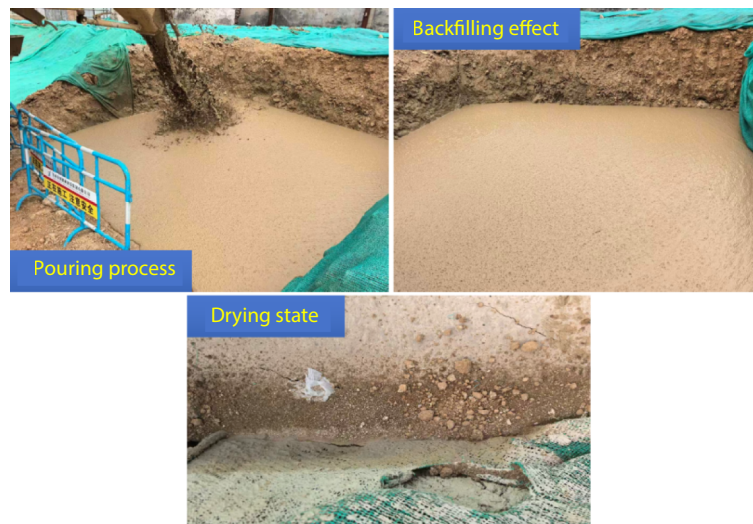


Fig. 12. The field backfilling process of flowable solidified soil.

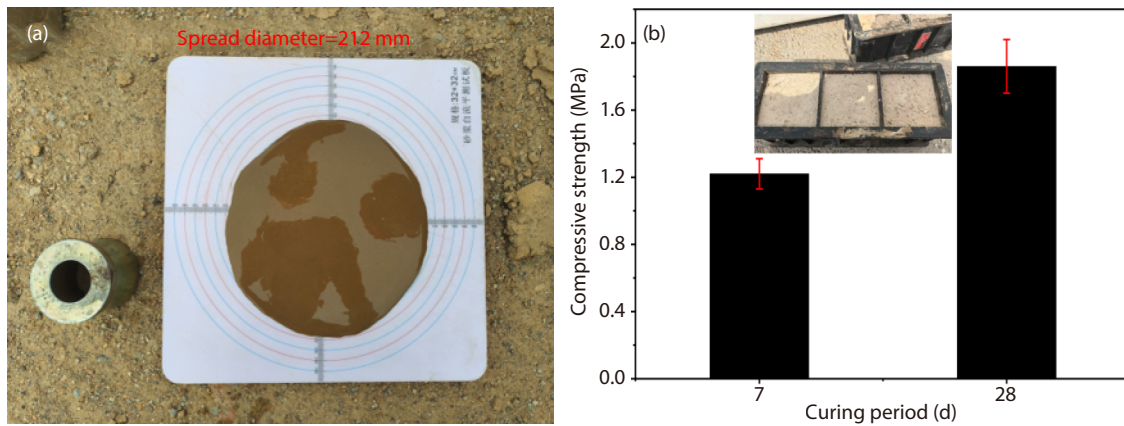


Fig. 13. The (a) spread diameter and (b) compressive strength of flowable solidified soil during field backfilling.

tion to reflect the actual field hardening process as closely as possible.

The compressive strengths of the field-prepared specimens after curing for 7 d and 28 d were measured to be 1.22 MPa and 1.86 MPa, respectively. These results indicated that the flowable solidified soil showed favorable mechanical properties and could satisfy the bearing capacity requirements of backfilling engineering applications to some extent.

4. Conclusions

This study focused on the rheological behavior, mechanical properties, and engineering applicability of the flowable solidified soil that could be applied to low-carbon backfilling in geotechnical and tunnel engineering. The following conclusions can be drawn:

(1) The increase in AC content optimized the rheological properties of the fresh solidified soil by strengthening its flocculation structure. Compared with FSS1-0.5, the yield stress and plastic viscosity of FSS1-0.7 decreased by 71.18% and 27.14%, whereas the corresponding rheological parameters of FSS3-0.5 increased by 63.76% and 25.71%, respectively.

(2) The increase in the *W/S* had a negative effect on the mechanical properties and volume stability of flowable solidified soil, while increasing the AC content could mitigate this effect. Compared with FSS1-0.5, the strength of FSS1-0.7 decreased by 57.28%, and its shrinkage degree increased by 69.85%. The strength of FSS3-0.5 increased by 111.65%, while its shrinkage degree decreased by 13.24%.

(3) An increase in *W/S* weakened the interaction between hydration products and soil particles, resulting in loose structures. However, increasing the AC content accelerated the formation of hydration products, strengthening the bonding effect of products on soil particles. Hence, the compactness of solidified soil was improved, and its pore structures were effectively optimized.

(4) An appropriate *W/S* and AC content could synergistically improve the rheological behavior and mechanical properties of flowable solidified soil. The field operation showed that the solidified soil had a favorable self-leveling effect. After curing for 7 d, the overall structure remained relatively stable, and the strength was 1.22 MPa, indicating its potential feasibility for engineering applications.

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Data availability

All data needed to support the conclusions in the paper are presented in the manuscript. Additional data related to this paper may be available from the corresponding authors upon request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contribution statement

Heping Qiu: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – Original draft. **Qingsong Zhang:** Resources, Project administration, Writing – review & editing. **Haotian Tang:** Methodology, Writing – review & editing. **Chunyang Li:** Writing – review & editing, Investigation. **Pengfei Song:** Methodology, Validation. **Zhenmin Wan:** Writing – review & editing, Data curation.

Use of AI statement

None.

References

- [1] Qi, Z., Li, J., Lang, L., et al. Development of ternary all-solid-waste cementitious materials and utilization in engineering sediment waste stabilization. *Journal of Rock Mechanics and Geotechnical Engineering*, **2026**, 18(3): 2288–2299. <https://doi.org/10.1016/j.jrmge.2025.05.024>.
- [2] Liu, J., Zhao, B., Zhang, S., et al. Experimental study on preparation of solidified soil from residue of construction waste. *Construction and Building Materials*, **2024**, 442: 137631. <https://doi.org/10.1016/j.conbuildmat.2024.137631>.

- org/10.1016/j.conbuildmat.2024.137631.
- [3] Liu, Y., Lu, H., Liu, M., et al. Microanalytical characterizations, mechanical strength and water resistance performance of solidified dredged sludge with industrial solid waste and architecture residue soil. *Case Studies in Construction Materials*, **2022**, 17: e01492. <https://doi.org/10.1016/j.cscm.2022.e01492>.
 - [4] Wang, B., Xiao, J., Zheng, Z., et al. Assessment of construction spoil generation: A case study in China. *Journal of Cleaner Production*, **2025**, 532: 146879. <https://doi.org/10.1016/j.jclepro.2025.146879>.
 - [5] Lang, L., Zhu, M., Pu, S. Recycling engineering sediment waste as sustainable subgrade material using ground granulated blast-furnace slag, electrolytic manganese residue and cement. *Environmental Technology & Innovation*, **2025**, 37: 103969. <https://doi.org/10.1016/j.eti.2024.103969>.
 - [6] Jia, Z., Guo, X., Zhao, Q., et al. Mechanical and carbonation properties of construction waste soil solidified with cement, desulfurized gypsum, and silica fume. *Geotechnical and Geological Engineering*, **2025**, 43(5): 207. <https://doi.org/10.1007/s10706-025-03172-5>.
 - [7] Qi, Y., Wang, Q., Wang, S., et al. Reuse of improved shield muck as reinforcement material for bridge erosion protection. *Transportation Geotechnics*, **2026**, 60: 101999. <https://doi.org/10.1016/j.trgeo.2026.101999>.
 - [8] Zhang, J., Liu, K., Yang, H., et al. Investigation into the dynamic compaction reinforcement characteristics and particle crushing effects of construction and demolition waste. *Soils and Foundations*, **2026**, 66(2): 101757. <https://doi.org/10.1016/j.sandf.2026.101757>.
 - [9] Wang, Q., Kong, L., Tseng, M. L., et al. Solid waste material reuse analysis: Filling the road subgrade with riverway silt and sediment. *Environmental Science and Pollution Research*, **2022**, 29(23): 35096–35109. <https://doi.org/10.1007/s11356-022-18650-z>.
 - [10] Katsioti, M., Katsiotis, N., Rouni, G., et al. The effect of bentonite/cement mortar for the stabilization/solidification of sewage sludge containing heavy metals. *Cement and Concrete Composites*, **2008**, 30(10): 1013–1019. <https://doi.org/10.1016/j.cemconcomp.2008.03.001>.
 - [11] Huang, X., Zhang, R., Wu, Z., et al. Comparison between physicochemical combined method and conventional cement solidification method for treating heavy metal-contaminated slurry-like mud. *Journal of Cleaner Production*, **2025**, 523: 146460. <https://doi.org/10.1016/j.jclepro.2025.146460>.
 - [12] Teng, W., Liu, X., Xiao, G. Strength development and micro-mechanistic insights of calcium carbide residue-alkali-activated CLSM. *Results in Engineering*, **2026**, 31: 111338. <https://doi.org/10.1016/j.rineng.2026.111338>.
 - [13] Lei, B., Pang, S., Xie, F., et al. Optimization of ratios and strength formation mechanism of fluidized solidified soil from multi-source solid wastes. *Journal of Building Engineering*, **2025**, 108: 112958. <https://doi.org/10.1016/j.jobe.2025.112958>.
 - [14] Zhou, Y., Zhang, R., Yang, X., et al. The design methodology for proportioning fluidized solidified soil. *Journal of Building Engineering*, **2025**, 111: 113127. <https://doi.org/10.1016/j.jobe.2025.113127>.
 - [15] Tan, H., Ma, C., Li, S., et al. Experimental study on the influence of fiber characteristics on the working property of underwater flowable solidified soil: Flowability, anti-dispersion, strength and anti-scour resistance. *Ocean Engineering*, **2024**, 312: 119230. <https://doi.org/10.1016/j.oceaneng.2024.119230>.
 - [16] Yan, C., Wang, J., Wang, C. Study on the engineering properties and curing mechanisms of flowable solidified soil prepared from shield muck. *KSCE Journal of Civil Engineering*, **2026**, 30(7): 100568. <https://doi.org/10.1016/j.kscej.2026.100568>.
 - [17] Feng, T., Lin, K., Zhang, D., et al. Fluidized solidified soil using construction slurry improved by fly ash and slag: Preparation, mechanical property, and microstructure. *Materials Research Express*, **2024**, 11(11): 115301. <https://doi.org/10.1088/2053-1591/ad84a5>.
 - [18] Zhao, G., Guan, H., Yan, H., et al. Properties and underlying mechanism of flowable solidified shield tunnelling muck: A synergistic approach using slag powder, fly ash and activator. *Journal of Environmental Chemical Engineering*, **2025**, 13(6): 119990. <https://doi.org/10.1016/j.jece.2025.119990>.
 - [19] Huang, J., Zhao, D., Zhao, P. Review on technical pathways and assessment for carbon peaking and carbon neutrality in China's building materials industry. *Discover Sustainability*, **2025**, 6(1): 1188. <https://doi.org/10.1007/s43621-025-02006-x>.
 - [20] Hao, J., Zhou, Z., Chen, Z., et al. Synergistic mechanisms of steel slag, granulated blast furnace slag, and desulfurization gypsum in high-content steel slag-based cementitious backfill materials. *International Journal of Mining Science and Technology*, **2025**, 35(6): 1005–1018. <https://doi.org/10.1016/j.ijmst.2025.05.007>.
 - [21] Feng, S., Zheng, J., Nie, J., et al. Influence of alkaline activators and simulated seawater on the carbonation performance of industrial solid waste-based persulfate cement. *Journal of Materials in Civil Engineering*, **2026**, 38(8): 04026247. <https://doi.org/10.1061/jmce7.mteng-21990>.
 - [22] Ban, J., Lu, J. X., Ma, B., et al. Hydration and physicochemical immobilization mechanisms of pozzolanic-hazardous waste in supersulfated cement. *Cement and Concrete Composites*, **2025**, 158: 105970. <https://doi.org/10.1016/j.cemconcomp.2025.105970>.
 - [23] Lang, L., Wang, D., Chen, B., et al. Efficient stabilization of dredged sediment by combining nano-modification and low-carbon supersulfated cement. *Journal of Rock Mechanics and Geotechnical Engineering*, **2026**, 18(5): 4034–4049. <https://doi.org/10.1016/j.jrmge.2025.08.013>.
 - [24] Cui, S., Fan, K., Yao, Y. Effect of carbide slag dosage on hydration behavior and mechanical properties of supersulfated cement. *Construction and Building Materials*, **2025**, 491: 142823. <https://doi.org/10.1016/j.conbuildmat.2025.142823>.
 - [25] Ju, Y., Zhang, S., Jia, S., et al. Influence of calcium formate dosing on early mechanical properties and microstructure of SS-GBFS-DG cementitious materials. *Process Safety and Environmental Protection*, **2025**, 196: 106935. <https://doi.org/10.1016/j.psep.2025.106935>.
 - [26] Ren, C., Wang, D., Fang, K., et al. Properties and Hardening Mechanism of Solid Waste Based Grouting Materials. *Bulletin of the Chinese Ceramic Society*, **2025**, 44(4): 1328–1336. (in Chinese)
 - [27] Hao, W., Tang, L., Wu, R., et al. Performance Study and Application of Flowable Solidified Soil Using Low-Carbon Cementitious Materials Composed Entirely of Solid Waste. *Materials Reports*, **2025**, 39(S2): 499–504. (in Chinese)
 - [28] Housing and Urban-Rural Development Department of Shandong Provincial, Shandong Administration for Market Regulation. Technical Specifications for Building Engineering of Fluidized Solidified Soil Application. DB37/T 5345-2025: **2025**.
 - [29] Ministry of Transport of the People's Republic of China. Test Methods of Materials Stabilized with Inorganic Binders for Highway Engineering. JTG 3441-2024: **2024**.
 - [30] Ministry of Transport of the People's Republic of China. Testing Methods of Cement and Concrete for Highway Engineering. JTG 3420-2020: **2020**.
 - [31] Zhang, H., Zhang, Q., Tang, S., et al. Effects of fly ash and silica fume on the rheological properties of magnesium phosphate cement-emulsified asphalt (MPC-EA) composite repair materials.

- Construction and Building Materials*, **2024**, 433: 136708. <https://doi.org/10.1016/j.conbuildmat.2024.136708>.
- [32] Qiu, H., Song, P., Yu, J., et al. The rheological behavior characterization and prediction of cement concrete containing magnetite (Fe_3O_4) and/or carbon fiber. *Journal of Building Engineering*, **2024**, 89: 109329. <https://doi.org/10.1016/j.job.2024.109329>.
- [33] Song, P., Wang, X., Wang, Y., et al. Assess the interaction of water reducers and accelerators on the rheological and early hydration properties of cement-based materials. *Journal of Materials Research and Technology*, **2025**, 36: 806–822. <https://doi.org/10.1016/j.jmrt.2025.03.046>.
- [34] Gruskovnjak, A., Lothenbach, B., Winnefeld, F., et al. Quantification of hydration phases in supersulfated cements: Review and new approaches. *Advances in Cement Research*, **2011**, 23(6): 265–275. <https://doi.org/10.1680/adcr.2011.23.6.265>.
- [35] Wang, N., Bao, Y., Wang, W., et al. Research on the properties and microstructural evolution of ecological flowable solidified soil prepared from water treatment plant residual sludge. *Journal of Environmental Chemical Engineering*, **2026**, 14(1): 120901. <https://doi.org/10.1016/j.jece.2025.120901>.
- [36] Zhou, Y., Peng, Z., Chen, L., et al. The influence of two types of alkali activators on the microstructure and performance of supersulfated cement concrete: Mitigating the strength and carbonation resistance. *Cement and Concrete Composites*, **2021**, 118: 103947. <https://doi.org/10.1016/j.cemconcomp.2021.103947>.
- [37] Wang, Z., Chen, Y., Wang, D., et al. Performance and mix proportion of industrial residue-cement fluid solidified shield muck. *Rock and Soil Mechanics*, **2026**, 47(2): 595–606.
- [38] Wan, Z., He, T., Zheng, B., et al. Influence of fly ash and granulated blast furnace slag on autogenous shrinkage and drying shrinkage of cement-based materials mixed with alkali accelerator and alkali-free accelerator. *Drying Technology*, **2024**, 42(14): 2137–2154. <https://doi.org/10.1080/07373937.2024.2407520>.
- [39] Shao, C., Gong, Y. A., Zhang, Q. S., et al. Recycling waste gypsum and calcium carbide slag for the production of all-solid-waste supersulfated cement. *Physics of Fluids*, **2024**, 36(12): 127159. <https://doi.org/10.1063/5.0244454>.
- [40] Qiu, H., Wu, Y., Yu, J., et al. Effect of calcium-silicate-hydrate (C-S-H) nano-crystals on the hydration rate and early strength of microwave-absorbing cement mortar containing magnetite (Fe_3O_4) powder. *Ceramics International*, **2023**, 49(23): 39039–39048. <https://doi.org/10.1016/j.ceramint.2023.09.241>.
- [41] Shi, Y., Zhang, S., Gao, P., et al. Reaction mechanism regulation in high-phosphogypsum supersulfated cement: Nano-metakaolin-induced formation of a compact Aft/C-(A)-S-H network and immobilization of phosphorus and fluorine. *Construction and Building Materials*, **2026**, 512: 145347. <https://doi.org/10.1016/j.conbuildmat.2026.145347>.
- [42] Chen, S., Feng, C., Fu, T., et al. Performance and characterization of fluidized solidified soil prepared by synergistic cement and phosphogypsum with slag powder-fly ash. *Journal of Wuhan University of Technology-Mater. Sci. Ed.*, **2025**, 40(5): 1320–1329. <https://doi.org/10.1007/s11595-025-3170-0>.
- [43] Liu, L., He, Z., Cai, X., et al. Application of low-field NMR to the pore structure of concrete. *Applied Magnetic Resonance*, **2021**, 52(1): 15–31. <https://doi.org/10.1007/s00723-020-01229-7>.
- [44] Jiang, Z. L., Pan, Y. J., Lu, J. F., et al. Pore structure characterization of cement paste by different experimental methods and its influence on permeability evaluation. *Cement and Concrete Research*, **2022**, 159: 106892. <https://doi.org/10.1016/j.cemconres.2022.106892>.
- [45] Zeng, W., Zhang, M., et al. Laboratory evaluation of the engineering properties of fluidized solidified soil prepared with multi-source solid waste for municipal backfill engineering. *International Journal of Geomechanics*, **2026**, 26(2): 04025333. <https://doi.org/10.1061/ijgnai.gmeng-10604>.



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