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Influence of composition of curing agent and sand ratio of engineering excavated soil on mechanical properties of fluidized solidified soil

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With the continuous expansion of the urban scale, the development of engineering construction has been accelerated. In this process, excavated engineered soils produced in the construction process are facing the problem of difficult treatment. In this work, the influence of the composition ratio of different curing agents on the strength of fluidized solidified soil was studied. It was found that when the proportion of fly ash and quicklime in the curing agent was 1:1, and the percentage of the curing agent in the soil was 15%, the 28 days unconfined compressive strength of fluidized solidified soil reached the maximum value. When the composition and content of the curing agent and the slump of the fluidized solidified soil remained unchanged, the strength and water stability of the fluidized solidified soil increased with the increase of the sand ratio of the excavated engineered soil. X-ray powder diffraction (XRD) and scanning electron microscopy (SEM) showed that with the increase of sand in the soil ratio, more needle-like ettringite crystals were produced in the fluidized solidified soil, which were more compact, had fewer voids, and had higher overall compactness. The carbon emissions of the prepared fluidized solidified soil and the common backfill materials were calculated, and it proved that the carbon emissions of the fluidized solidified soil were the lowest. Therefore, this work offers a new method for resource utilization of excavated soil and provides a carbon emission reference for green low-carbon building materials. Finally, it was recommended to choose engineered excavation soil with high sand content to obtain higher performance from fluidized solidified soil.

Keywords: *engineered excavated soil, fluidized solidified soil, composition ratio, mechanical properties, carbon emission*

1. Introduction

With the acceleration of urbanization, the construction of expressways, large bridges, super high-rise buildings, high-rise buildings, and other projects, a peak period of rapid development has begun. However, in the process of foundation construction, a large amount of engineered excavated soil is often generated, much of which is discarded as construction waste, resulting in waste of land resources as well as traffic accidents, landslides, and environmental pollution, created in the process of transportation and landfill [1–3]. Therefore, with the continuous development of urban and rural construction, the resource utilization of this excavated soil has become an urgent problem in construction projects.

To promote the resource utilization of engineering excavated soil, scholars have mainly focused on the front-end research on engineering of excavated soil in the past two years, such as recycling systems, classification, and disposal strategy analysis [4–7]. However, there is less research on how to convert it into new materials. Currently, the main resource utilization developed by engineering excavated soil includes calcining it into building materials [8–10] and pozzolanic materials [11–13] in the cementitious matrix and preparing fine aggregate [14–16] and solidified soil materials [17, 18]. The first two methods require transportation and calcination of the soil, which increases transport costs and energy consumption and is not conducive for the development of a green low-carbon economy. While the excavated soil is used as fine aggregate or instead of some traditional river sand in concrete, and although it can be used as the nucle-

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Table 1. Physical characteristics of engineering excavated soil

Type	Water content (%)	Density (g/cm^3)	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)
A	28.8	1.94	39.9	21.7	18.2
B	23.2	1.98	38.9	20.9	18.0
C	26.6	1.95	35.3	20.6	14.7



(A) (B) (C)

Fig. 1. Appearance of different excavated soils

ating agent of calcium silicate hydrate gel (C-S-H gel) to promote cement hydration, the performance of concrete can deteriorate with the increase of excavated soil content. *Solidified soil material* refers to using a curing agent to harden this excavated soil into blocks and unburned bricks with particular strength [19, 20], which can be used as temporary materials for on-site construction, but the amount produced is small, making it difficult to consume this excavated soil on a large scale.

In order to solve the above problems, researchers have developed a controllable low-strength material with high fluidity and self-compaction [21–23]. It is mainly composed of excavated soil, curing agent, and water. Scholars have carried out research on the influence of the composition of curing agents and excavated soil on the performance of low-strength materials [24, 25] and found that there are many kinds of curing agents, and it is difficult to unify the curing agents for different soil properties, which leads to the need to choose different curing agents when meeting different types of excavated soil in engineering practice. In addition, in the composition of excavated soil, clay accounts for a high proportion and has strong plasticity, leading to the need to add fine aggregate to ensure that low-strength materials have high strength [26]. Therefore, how to carry out unified and simple solidification treatment for different types of excavated soil to improve its consumption is still facing challenges.

In fact, the composition of the curing agent is closely related to the nature of the excavated soil, and the strength of controllable low-strength materials is mainly affected by the plastic clay. How to effectively treat the plastic clay will be the key to preparing controllable low-strength materials with high strength additives. Therefore, in this paper, a calcium-containing stabilizer, which could strengthen clay particles, was added to the curing agent, and the influence of the composition ratio of the curing agent and the sand ratio of the engineering excavated soil on the strength of the fluidized solidified soil was studied. The strengthening mechanism was studied using SEM and XRD, and the carbon emissions of the prepared fluidized solidified soil and the commonly used backfill materials were compared. The results of this experiment will provide a feasible scheme for the on-site self-consumption of excavated soil and a reference for carbon emissions of green low-carbon building materials. Therefore, the research in this work will be of great significance in improving the resource utilization rate of excavated soil and promoting low-carbon and green development of buildings.

Table 2. Chemical composition of cement (wt%)

Materials	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Alkali content	Loss
Cement	59.09	22.82	6.98	2.25	2.33	2.27	0.70	3.08

Table 3. Basic properties of fly ash

Fineness (%)	Chloride ion content (%)	Water demand ratio (%)	Loss on ignition (%)	Sulfur trioxide (%)	Water content (%)
19.8	0.014	102	2.38	0.79	0.11

Table 4. Mixing ratio of the fluidized solidified soil

Number	Type of soil	Soil (kg)	Cement (kg)	Fly ash (kg)	Quicklime (kg)	Water (kg)	Slump (kg)
A-1	A	800	60	60	0	736	240
A-2	A	800	60	45	15	736	235
A-3	A	800	60	30	30	736	220
A-4	A	800	60	15	45	736	190
A-5	A	800	60	0	60	736	180
B-1	B	800	60	20	30	400	220
C-1	C	800	60	30	30	294	220

2. Materials and methods

2.1. Materials

The three kinds of excavated soil studied here are all from the project construction site. Type A soil is plastic clay with a sand ratio of about 2%; Type B soil is mainly composed of plastic clay, containing a small amount of building slag, with a sand ratio of about 15%; Type C soil is mainly composed of completely weathered mudstone, containing a small amount of clay, with a sand ratio of about 68%. Physical characteristics and appearance of different soils were shown in Table 1 and Figure 1, respectively.

The cement is ordinary Portland cement produced by Sichuan Jinding (group) Emei Cement Plant Co., Ltd. Both fly ash and quicklime are commercially available materials. The performance parameters of cement and fly ash are shown in Tables 2 and 3.

2.2. Sample preparation

The amount of curing agent in this paper was 15% of the dry soil mass. By changing the type of soil and the composition ratio of the curing agent, one can control the water and solids ratio or slump, respectively, to mix the premixed fluidized solidified soil. Before mixing, all raw materials shall be dried, and the excavated soil be crushed into particles smaller than 10mm. The detailed sample preparation steps were as follows.

2.2.1. Mixing

According to the designed mix proportion, we weighed the soil and quicklime of corresponding quality and added them to the mixer for mixing for 5 min, then added cement and fly ash for mixing for 5 min, and finally added water for mixing for 5 min to obtain ready mixed fluidized solidified soil. We then tested its slump. The results are shown in Table 4.

2.2.2. Pouring

We applied a thin layer of release agent on the inner surface of 100×100×100mm cube test mold before pouring, and then poured the mixture into the test mold. After the pouring was completed, the excess mixture at the upper opening of the test

mold shall be scraped off and leveled with a spatula when the initial setting was near.

2.2.3. Curing

After the test piece was formed, we covered the surface with impermeable plastic film immediately and left it in the environment of 20 ± 2°C for 24 h, then marked and removed the mold. Finally, we put the test piece into a standard curing room with a temperature of 20 ± 2°C and relative humidity of more than 95% to cure for 7 days and 28 days.

2.3. Characterization

2.3.1. Slump test

Wetting the slump cone (100 × 200 × 300 mm) and the bottom plate, a small shovel was used to inject the mixture into the cone, to scrape off the excess mix after filling, and to smooth it. Then, we steadily lifted the slump cone vertically. The height difference between the height of the measuring cylinder and the highest point of the mixture after the spread was regarded as the slump value of the ready mixed fluidized solidified soil.

2.3.2. Unconfined Compression Strength (UCS) test

The strength of the test block was tested by an electro-hydraulic pressure testing machine (DYE-2000) at a loading rate of 5 kN/min until the test piece failed, and the load was recorded at the time of failure. Then, we calculated the unconfined compressive strength (Fcu) of the test piece according to the formula Fcu=P/A, where P is the failure load and A is the bottom area of the test piece. Three pieces were tested for each type of fluidized solidified soil, and then the average value was taken.

2.3.3. Microstructure test

The central fragment of the sample damaged by the strength test was selected for freeze-drying for 24 h, then the flat section was selected for gold spraying treatment, and the microscopic morphology of the sample was tested by field emission scanning microscope (SEM, JSM-5900LV JEOL). In addition, the dried fragments were crushed into particles with a diameter less than 100 μm powder, and XRD (XRD, Ultima IV, Rigaku Corporation, Japan) was used to test the composition of the sample. The scanning range and scanning rate of the instrument were 5–85° and 10°/min, respectively.

2.3.4. Softening coefficient test

After standard curing for 7 days, 14 days, and 28 days, we put the test blocks into the curing pool filled with tap water for soaking curing, and placed them into the standard curing room together with the non-soaked test blocks for further curing for 14 days, and then the unconfined compressive strength of the test blocks was tested. The softening coefficient was the ratio of the strength of the soaked and non-soaked test blocks.

3. Results and discussions

3.1. Effect of composition ratio of curing agent on strength of fluidized solidified soil

The solidifying effect of the curing agent on the soil was closely related to the composition of the curing agent. Figure 2 showed the influence of different composition ratios of curing agents on the strength of fluidized solidified soil under the same dosage of curing agent. The results showed that the 28 day unconfined compressive strength of the fluidized solidified soil increased first and then decreased with the increase of the ratio of quicklime in the curing agent. This was mainly because the plastic clay had a poor engineering property. Quicklime is a calcium-containing stabilizer, which could exchange calcium ions with clay to produce flocculation, which reduced the thickness of bound water film in clay minerals, thus reducing adsorption and plasticity of clay, improving the engineering properties [27]. In addition, quicklime reacted with water to generate $Ca(OH)_2$, increasing the alkalinity of the mixture, which was conducive to stimulating the activity of fly ash, generating pozzolanic reaction to generate hydrated calcium silicate C-S-H gel, and further improving the strength of fluidized solidified soil. However, if the proportion of quicklime was too high, the excess $Ca(OH)_2$ could absorb carbon dioxide to produce calcium carbonate, which has no direct contribution to strength. If the fly ash is too low, the growth

rate of the late strength and the negative effects of early strength could be weakened, resulting in a decrease in the 28 day strength and a slowed growth rate in the 7 day strength. For example, in the A-4 and A-5 samples, the content of fly ash was lower, the late strength increased slowly, and the overall strength was low due to the reduction of the secondary hydration reaction and the micro-aggregate reaction of fly ash. Therefore, after a comprehensive comparison, the ratio of cement: fly ash: quicklime in the curing agent was 2:1:1, which was more appropriate.

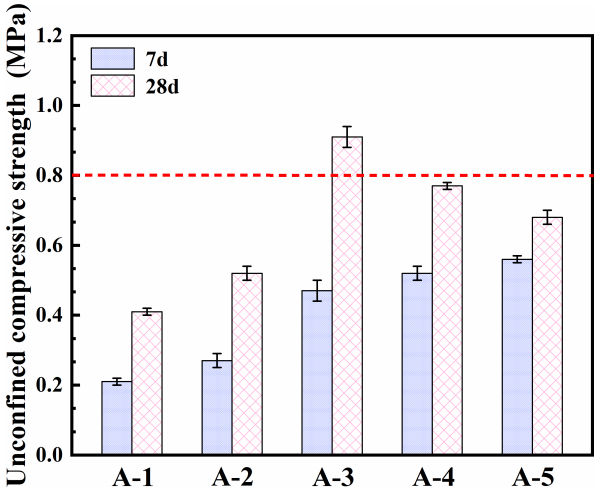


Fig. 2. Variation diagram of strength of fluidized solidified soil with composition ratio of curing agent

3.2. Influence of sand ratio of engineering excavated soil on strength of fluidized solidified soil

In order to study the influence of sand ratio of excavated soil on the strength of fluidized solidified soil, the above-preferred composition ratio of curing agent and its dosage was selected to prepare fluidized solidified soil with the same slump. Its unconfined compressive strength was tested, and the results are shown in Figure 3. The results show that the strength of the prepared fluidized solidified soil increased in turn with the increase of sand ratio in the excavated soil. This was because the increase of sand ratio reduced the content of clay particles, so that the engineering plasticity of the soil mixed with quicklime was enhanced. At the same time, the amount of water used to mix the fluidized solidified soil to the same fluidity was reduced, which indirectly increased the amount of the curing agent in the fluidized solidified soil, so that the final strength was significantly improved. In general, the excavated soil contains sand or hard materials, which can play the role of fine aggregate in the fluidized solidified soil and help to improve its strength.

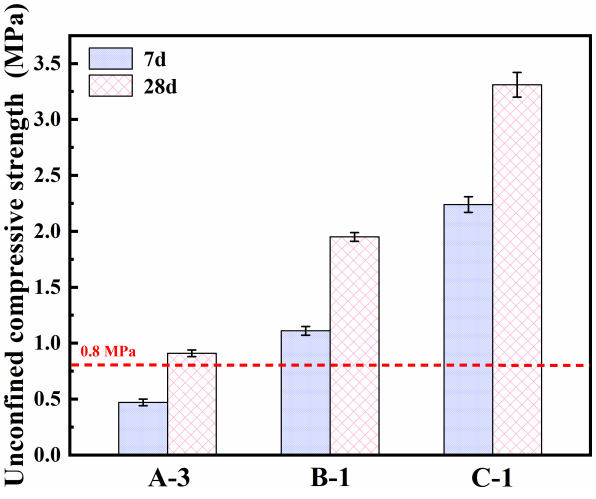


Fig. 3. Unconfined compressive strength of fluidized solidified soil with different sand ratio

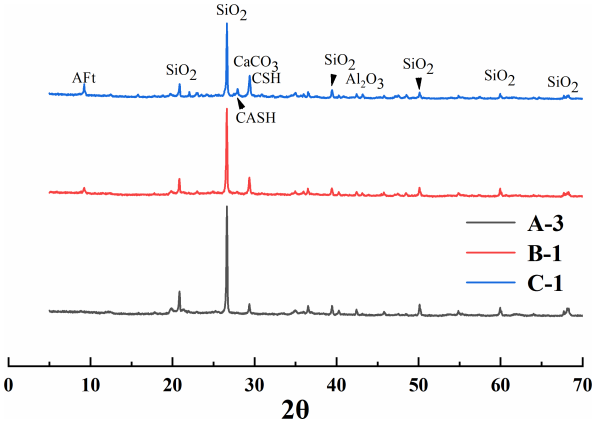


Fig. 4. X-ray diffraction patterns of fluidized solidified soil with different sand ratio after 28 days of curing. (AFt: ettringite ($3CaO{\cdot}Al_2O_3{\cdot}3CaSO_4{\cdot}32H_2O$); CSH: calcium silicate hydrate ($Ca_5Si_6O_{16}(OH)*4H_2O$); CASH: calcium silicoaluminate hydrate ($Ca_2Al_2\ SiO_7(OH)*4nH_2O$))

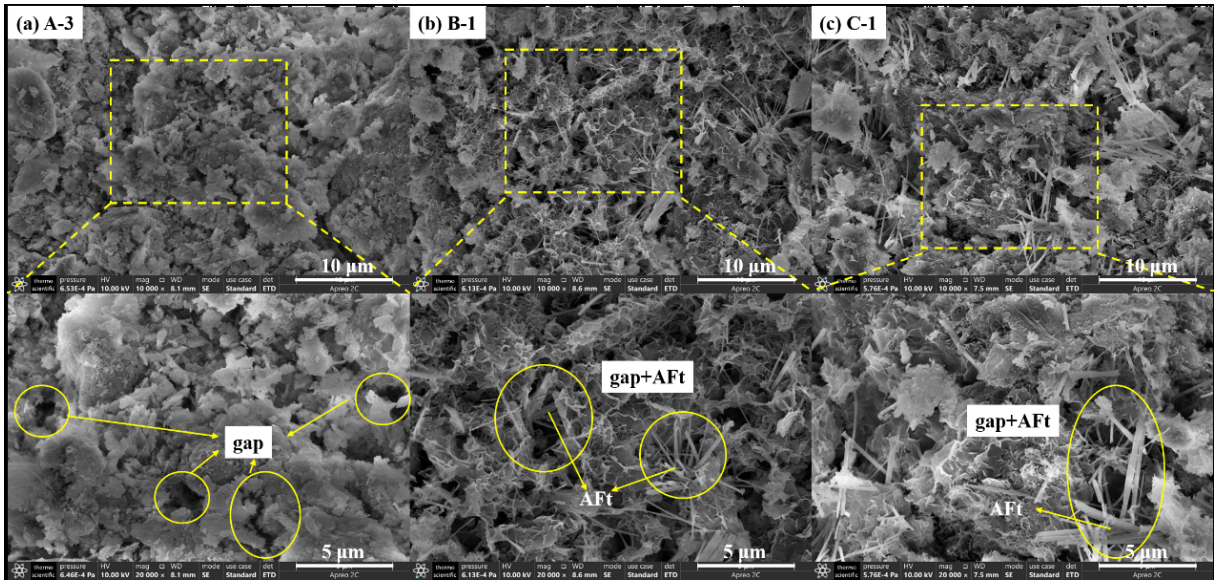


Fig. 5. Micrograph of fluidized solidified soil with different sand ratio after 28 days of curing (AFt: ettringite ($3CaO{\cdot}Al_2O_3{\cdot}3CaSO_4{\cdot}32H_2O$))

3.3. X-ray Diffraction (XRD) analysis

To study the micro mechanism of the strength change of fluidized solidified soil, the XRD of fluidized solidified soil with different sand ratio after 28 days of curing was tested, and its spectrum is shown in Figure 4. Cement will generate calcium hydroxide ($Ca(OH)_2$) and calcium silicate (CSH) during hydration, but there was almost no diffraction peak of $Ca(OH)_2$ in Figure 4. This was because it has a secondary hydration reaction with silicon dioxide (SiO_2), and continuously generates hydrated calcium silicate (CSH). In addition, with the increase of sand ratio in excavated soil, the diffraction peaks of ettringite (AFt), hydrated calcium silicate (CSH), and calcium silicoaluminate hydrate (CASH) were enhanced. This showed that the reaction products with strengthening effect in the fluidized solidified soil could increase with the increase of sand ratio. This showed that the reaction products with strengthening effect in the fluidized solidified soil could increase with the increase of sand ratio.

3.4. Scanning Electron Microscope (SEM) analysis

The micromorphology of fluidized solidified soil with different sand ratio was tested by SEM, and the results are shown in Figure 5. The gaps between soil particles in Figure 5a were obvious, while there were also gaps that basically filled with needle-like ettringite (AFt) in Figure 5b and c. Ettringite is a crystal formed by the combination of cement hydration product C-A-H (calcium aluminate hydrate) and sulfate ions. The higher content of the curing agent can strengthen the cation exchange on the surface of soil particles and generate more hydration products (AFt: ettringite ($3CaO{\cdot}Al_2O_3{\cdot}3CaSO_4{\cdot}32H_2O$); CSH: calcium silicate hydrate ($Ca_5Si_6O_{16}(OH)*4H_2O$); CASH: calcium silicoaluminate hydrate ($Ca_2Al_2SiO_7(OH)*4nH_2O$)) which can compact soil particles, and improve the strength of fluidized solidified soil. In addition, it can be seen in Figure 5b and c that the generated hydration products that could fill gaps were mainly needle-like AFt. Comparing Figure 5b with 5c, it can be found that the AFt crystals in Figure 5b were loosely packed, while the AFt crystals in Figure 5c were larger and more tightly packed, which was consistent with the high-

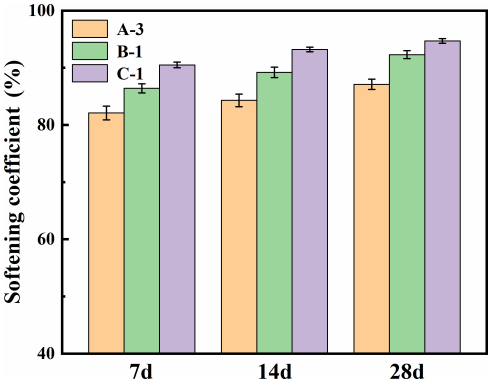


Fig. 6. Variation of softening coefficient of fluidized solidified soil with different sand ratio with curing age before soaking

intensity AFt diffraction peak of the liquid solidified soil prepared by Type C soil in the XRD analysis.

3.5. Water stability of fluid stabilized soil

As a foundation backfill material, the fluidized solidified soil will inevitably be eroded by rainwater or groundwater during its service. The change of its performance after soaking in water is one of the key factors affecting the foundation settlement. In this paper, the water stability of fluidized solidified soil with different sand ratio was tested, and the results are shown in Figure 6. It could be found that the softening coefficient of fluidized solidified soil with the same sand ratio increased with the increase of curing age before soaking under the same soaking time. This was related to the curing age before soaking, that is, with the extension of the curing age, the more hydration products of the curing agent, the better the soil solidification effect. When soaking, it is difficult for water to soak into the solidified soil, so that the softening coefficient is higher. For the fluidized solidified soil with different sand ratio, under the same curing age before soaking, the internal voids caused by more hydration products were decreased and the compaction density between soil particles was increased with the increase of the sand ratio, making it more difficult for water to be absorbed during soaking, resulting in less impact on the performance of the fluidized solidified soil with higher sand ratio. In a word, according to the requirements of construction standards, it is required to cure for not less than 7 days after pouring and covering a membrane. Even if the membrane is removed and soaking occurs in the rainstorm weather, the softening coefficient of the fluidized solidified soil prepared in this paper can reach more than 80%, which is applicable to the backfilling of most projects.

3.6. Carbon emission calculation of different backfill materials

Green building is an important way to achieve energy conservation and emission reduction, and the research and application of green low-carbon building materials is one of the methods of green building. As the main component of fluidized solidified soil is excavated soil, it can reduce the emission of construction waste and environmental pollution after use and is a green low-carbon building material. In order to better understand the low carbon characteristics of fluidized solidified soil, carbon emissions of it and traditional backfill materials were calculated on raw materials. The composition, amount, and carbon emission factor of each backfill material were shown in Table 5.

The calculation formula for total carbon emissions generated by each raw material used in this paper was shown in Formula (1):

$$\mathrm{CSC} = \sum_{k=1}^{n} M_k \times F_k \tag{1}$$

Where, CSC is the total carbon emission of each raw material used in the production stage of building materials (kg CO_2e/m^3); M_k is the consumption of the kth main raw material; F_k is the carbon emission factor of k main raw materials ($kgCO_2e$). The calculation results are shown in Figure 7. Cementitious materials in different backfill materials had an important impact on carbon emissions, that was, their carbon emissions account for more than 90%. For example, in lime-soil and foamed concrete, the carbon emissions of cementitious materials reached 99.9%, which was mainly due to the high consumption of cementitious materials and the amplification of carbon emissions. Through comparison, it was found that the amount of cementitious material used for fluidized solidified soil

Table 5. Mass ratio (kg) and corresponding raw material carbon emission factor used in carbon emission calculation of different backfill materials [28–32]

Backfill materials	Clay	Quicklime	Cement	Fly ash	Sand	Aggregate	Water	Water reducer	Foaming agent	Excavated soil
Lime-soil	1120	360								
C15 plain concrete			168	82	840	1170	160	2.5		
Foamed concrete			332		812		358		0.23	
Fluidized solidified soil		48	72	24			598			958
Carbon emission factor (kg CO_2e/t)	2.69	1190	735	8	2.51	2.18	0.168	28	1950	1.0

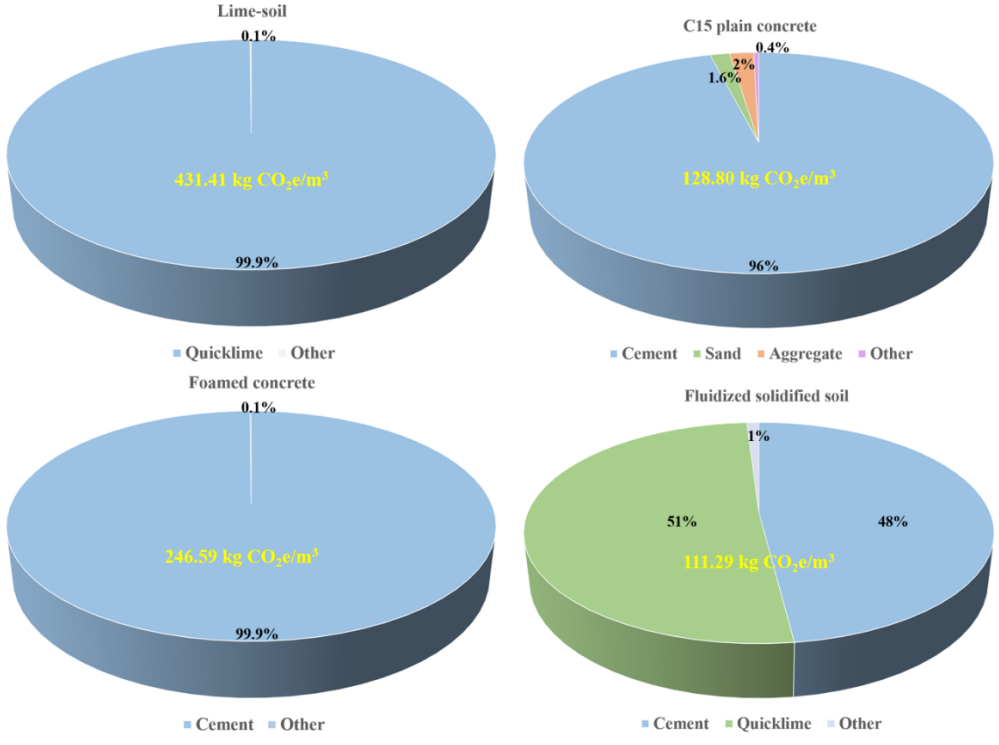


Fig. 7. Comparison diagram of carbon emissions of fluidized solidified soil and traditional backfill materials

was the lowest, so that it had the lowest carbon emission, which was only 111.29 kgCO_2e/m^3. At the same time, due to the high fluidity and self-compactness of the fluidized solidified soil, mechanical compaction or vibration was not required during the backfilling construction, which could further reduce the construction carbon emissions. Therefore, the fluidized solidified soil is an excellent green low-carbon building material, which can be widely used in the green construction process.

3.7. Engineering applications

The fluidized solidified soil prepared in this paper was used for engineering demonstration, and the demonstration effect is shown in Figure 8. By using the mix ratio of fluid solidified soil described in this article, and using excavated soil on the construction site, a self-compacting backfill material with high flow and controllable strength was prepared. This material was mainly used for backfilling projects such as foundation trenches, cavities, and roadbed. During the application process, it was also necessary to pay attention to curing the poured fluidized solidified soil for no less than seven days, otherwise, the surface of the solidified soil was prone to cracking. The results of curing and non-curing are shown in Figure 9. The application of fluidized solidified soil can save costs, reduce environmental damage and pollution, greatly alleviate the shortage of mineral resources, improve the utilization rate of solid waste resources, and reduce carbon emissions.



Fig. 8. Field application of the fluidized solidified soil prepared in this paper

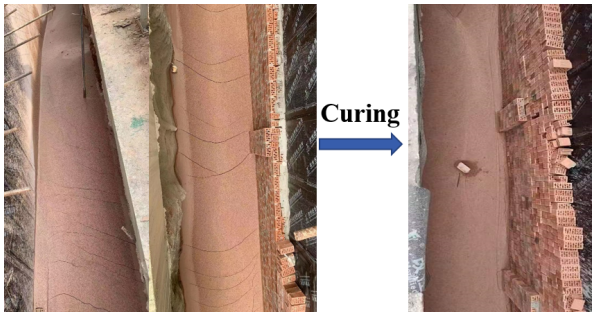


Fig. 9. Surface morphology of uncured and cured solidified soil

4. Conclusion

In this paper, the influence of the composition ratio of the curing agent and the sand ratio of the excavated soil on the strength of the fluidized solidified soil was studied. The micro-solidification mechanism of fluidized solidified soil was analyzed by micro-testing technology. Then the carbon emissions of different backfill materials were calculated. The results showed that there was an optimum ratio of quicklime to fly ash in the curing agent. In addition, the strength and water stability of fluidized solidified soil could increase with the increase of sand ratio in the soil. In the fluidized solidified soil with a high sand ratio, filling and compacting soil particles was better because of the high content, size, and compactness of ettringite, which made the soil body have higher strength. Finally, compared with the traditional backfill materials, the prepared fluidized solidified soil had the minimum carbon emissions. Therefore, this paper provided a feasible plan for preparing fluidized solidified soil for backfilling and could provide a basis for selecting materials for future green construction. Although this work proposes a material that can be used for foundation pit backfilling, its application scenarios are limited. Therefore, the next step will continue to focus on engineering excavation soil as the main material, and research new multifunctional composite materials to further improve the resource utilization rate of excavation soil and reduce mineral resource development.

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.

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