Application of Fluidised Solidified Soil in Backfilling Narrow Foundation Pits and Trench Excavations

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Abstract: Addressing the challenges of backfilling deep, narrow trenches around new basement structures in urban renewal projects—where complex road layouts and environments, proximity to residential areas and municipal parks, and difficulties in ensuring adequate compaction with traditional backfill materials are prevalent—this paper systematically investigates the application of fluidised solidified soil in confined space backfilling. Taking the North Garden Renovation Project of Hefei DXL Hotel as a case study, the research focuses on: Through mix design and testing, a material ratio meeting strength and flowability requirements was established. A layered pumping construction technique and comprehensive quality control measures were proposed. Field practice demonstrated that fluidised solidified soil exhibits excellent self-compaction and workability, adapting to confined working environments less than 0.5m wide. Backfill compaction exceeded 98%, effectively mitigating settlement and leakage risks. Compared to conventional lime-soil backfilling, this technology reduces construction duration by approximately two-thirds and lowers overall costs by 18.2%. It minimises environmental impact while offering advantages in environmental protection, noise reduction, and safety, providing a reliable, efficient, and green solution for similar confined space backfilling projects.

Keywords: Fluidised Stabilised Soil; Confined Spaces; Manure Pit Backfilling; Pumped Construction

1. Introduction

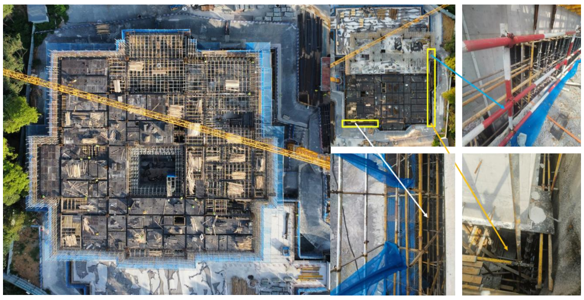
With the advancement of urban renewal and functional upgrades to existing buildings, renovation and expansion projects for high-end public structures are increasingly prevalent. Demolition-and-rebuild projects often feature complex surrounding roads and environments, situated adjacent to residential areas and municipal parks. To accommodate additional basement levels for parking or civil defence functions, underground structures frequently extend to depths of one to three storeys. This necessitates deep excavation, resulting in confined backfill spaces that pose significant construction challenges, heightened safety risks, and quality assurance difficulties. Addressing the challenges of deep backfill trenches and restricted operational space in such excavations, traditional backfill materials like plain soil or lime-stabilised soil rely on mechanical compaction. This approach struggles to ensure adequate compaction quality within confined areas, potentially leading to hazards such as uneven foundation settlement and external wall water ingress. Furthermore, conventional backfilling methods for such deep, narrow pits suffer from low efficiency, significant dust pollution, and noise disturbance, substantially impacting overall project timelines, costs, and safety objectives [1,2].

Fluidised stabilised soil represents an innovative green engineering material formed by mixing excavated spoil, construction debris, stabilising agents, and water. Its excellent fluidity and self-compacting properties render it suitable for backfilling confined, irregularly shaped spaces. However, successful application cases remain limited, particularly in addressing deep, narrow trench backfilling. Further research is required concerning its universal mix design, long-term performance, and safety benefits.This paper systematically examines the material properties, construction techniques, and comprehensive benefits of fluidised solidified soil based on engineering practice, providing solutions for backfilling projects in narrow foundation trenches [3].

2. Project Overview

This study is based on the North Garden Renovation Project of Hefei DXL Hotel. The

North Garden building has a total floor area of 10,520.26 m², comprising one basement level with a depth of 6 metres and an area of 4,010.75 m², and three above-ground levels. The first floor has a height of 6 metres, while the second and third floors are 4.5 metres high, with a total above-ground floor area of 6,509.51 m² and a building height of 20.3 metres. The construction drawings for this project specified the application of a waterproof protective layer and brickwork protective walls for the external walls of the underground structure. The original design required backfilling with 2:8 lime-soil mix beyond the protective layer. Due to the narrow width of the foundation trench and the presence of retaining structures within the trench space, the actual construction area is limited (see Figure 1). Backfilling with lime-soil presents significant challenges and fails to meet the design compaction requirements. Following a drawing review meeting, the backfill below the crown beam has been changed from 2:8 lime-soil to fluidised solidified soil.



(a) Aerial View of the Project **(b) Narrow Manure Trench**

Figure 1. Project Foundation Pit Trench

3. Fluidised Stabilised Soil Properties, Mix Design and Preparation Method

3.1 Raw Materials and Mix Design

During fluidised solidified soil preparation, in-situ excavated soil was utilised, thereby avoiding unsuitable materials such as those containing high organic matter, domestic waste, expansive soils, or silty soils. The cement employed was P·O 42.5 Conch Cement, with specific parameters detailed in Table 1. The powdered stabiliser utilised was a weakly alkaline, non-corrosive composite stabilising material, produced through physicochemical activation of natural and artificial inorganic mineral raw materials. Material characteristics are outlined in Table 2.

Table 1. Cement Performance Parameters

Setting Time/min		Flexural strength/MPa		Compressive strength/MPa	
Initial setting	Final setting	3 days	28 days	3 days	28 days
150	210	4.9	7.0	26.0	46.0

Table 2. Curing Agent Performance Parameters

Colour	Odour	Density	Specific Surface Area	pH
Greyish white	None	2600 kg/m³	≥ 400 m²/kg	8–10

The mix design of fluidised solidified soil is the core element in ensuring its final performance [4]. It must satisfy the fundamental principles of meeting design strength, workability, and setting time requirements while also considering economic viability. The design process begins by establishing several preliminary proposals for solidifying agent dosage and admixture schemes, expressed as percentages of the original soil's dry mass, based on the basic properties of the native soil, such as moisture content and particle size distribution. Subsequently, systematic laboratory mix design tests are conducted to evaluate key process parameters including slump spread, wet density, and setting time for each formulation. Test specimens are prepared, standard-cured, and tested for 7-day and 28-day unconfined compressive strength. Where necessary, durability indicators such as bleeding rate and frost resistance are also verified [5].Through comprehensive analysis of test data, the optimal construction mix design was optimised and determined, with the core key parameters being the curing agent dosage, target water-to-solid ratio, cement content, and native soil content. See Table 3.

Table 3. Mix Proportion of Fluidized Solidified Soil

Native Soil/kg	Water/kg	Solidifier/kg	Cement/kg
900	700	2	150

3.2. Properties of Fluidised Stabilised Soil

Fluidised stabilised soil constitutes a soil material system fundamentally characterised by synergistic physicochemical modification. Its physical modification arises from the pore-filling effect of stabiliser particles, optimising the original soil particle gradation. Chemical modification occurs through pozzolanic reactions between active components (e.g., Ca^{2+}) in the stabiliser and the soil's silicoaluminates, forming a hydrated calcium silicate (C-S-H) gel network structure.This dual action confers exceptional filling properties: firstly, controllable fluidity with flowability typically maintained within 180±20mm to accommodate pipeline pumping; secondly, designable strength with 28-day compressive strength flexibly adjustable between 0.4 and 10MPa.Furthermore, compared to conventional lime-soil backfilling methods, fluidised solidified soil backfilling achieves a breakthrough by reducing the minimum working width to 0.5m, completely resolving the issue of mechanical compaction failure when trench widths are less than 1m. Additionally, compared to traditional lime-soil mixtures, fluidised solidified soil offers superior water stability, reduced shrinkage, and higher compaction density [6], as detailed in Table 4.

Table 4. Performance Comparison between Fluidised Stabilised Soil and Lime Soil

Property Material	Traditional lime soil	Fluid-Stabilised Soil
Water Stability	Prone to softening upon water exposure (softening coefficient ≤0.7), leading to settlement of backfill structures.	High water resistance, with strength retention rate >85% after immersion, demonstrating excellent water stability.
Shrinkage settlement	Dry shrinkage rate as high as 1.5%–2.5%, prone to settlement cracks after manure pit backfilling due to moisture loss, causing uneven stress distribution on side walls.	Hardened volume shrinkage rate <0.1%, virtually negligible, preventing settlement-induced tearing of waterproofing layers and lateral wall structures.
Lateral pressure equilibrium	Manual compaction yields significant density variations (85%–90%), causing substantial lateral soil pressure disparities in localised areas that may induce minor wall deformations.	Compaction density exceeds 95%, ensuring uniform lateral pressure distribution that meets support requirements while preventing lateral wall compression.
Long-term structural safety	Ongoing settlement threatens the integrity of the waterproofing layer and the stability of the main structure.	Unconfined compressive strength ≥ 0.5 MPa at 28 days, with sustained long-term strength development.

3.3 Preparation Process

Fluidised solidified soil is produced by mixing excavated spoil, solidifying agent, water, and admixtures according to a specific mix ratio. To ensure material uniformity, the native soil undergoes preliminary processing including crushing and screening to remove impurities and control particle size. Subsequently, based on the mix ratio determined by testing, the pre-treated soil, specialised solidifying agent, mixing water, and admixtures are precisely measured using automated mixing equipment. Continuous mixing is recommended during the mixing process. Most of the water is pre-mixed with the soil, followed by the addition of the solidifying agent and the remaining water. The total mixing time should be no less than 3 minutes to ensure the formation of a highly fluid, uniform, and stable slurry. The prepared fluidised solidified soil is pumped to the work site for pouring. Immediately after pouring, measures such as covering and watering should be implemented for moisture retention curing for no less than 7 days, ultimately forming a novel engineering material with the designed strength[7]. The preparation process is shown in Figure 2.

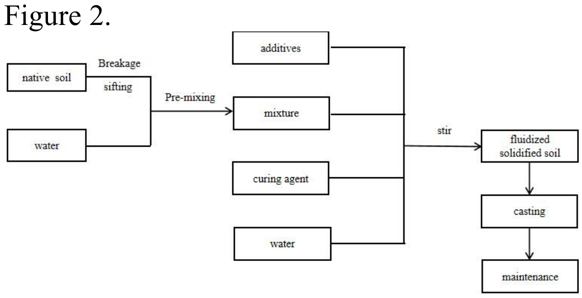


Figure 2. Preparation Process for Fluidised Stabilised Soil

4. Construction Process Flow

4.1 Trench Preparation and Survey Layout

Clear construction debris from the base pit bottom and drain accumulated water, ensuring the waterproofing layer and protective layer of the basement exterior walls pass inspection. Subsequently, mark out layer-by-layer elevation control lines along the pit side walls. The first layer's pouring thickness shall not exceed 0.5m, with subsequent layers not exceeding 1m each.

Simultaneously calculate the theoretical backfill volume to dynamically guide on-site construction.

4.2 Raw Materials and Mix Proportion Control

Prioritise use of native soil excavated on-site. Curing agents and water must possess valid certification. The benchmark mix design parameters are 28-day strength $\geq$ 0.7 MPa and flow value 180 $\pm$ 20 mm. Initial mixes must undergo trial batching verification, with strength test reports retained.

4.3 Preparation and Transportation of Fluidised Stabilised Soil

The preparation of fluidised solidified soil employs on-site mixing when sufficient space is available, utilising specialised equipment for a two-minute mixing process before transportation via concrete mixer trucks. Where site constraints exist, off-site prefabrication is adopted, with slurry transported to the site by tanker and subsequently blended with the solidifying agent according to the specified ratio via automated metering equipment. Based on practical conditions, this project employs on-site mixing for fluidised solidified soil preparation (see Figure 3).It is crucial to note that the solidifying agent must not be added in advance. This is because solidifying agents are typically alkali-reactive materials, such as cement or slag powder, which undergo hydration reactions upon contact with water and the active components in soil, such as silicoaluminates. This reaction commences immediately upon mixing and exhibits irreversible time-dependent characteristics. Premixed materials would undergo continuous reaction during transportation, leading to reduced workability, pumping difficulties, and uneven early strength development. Furthermore, transport delays could cause partial initial setting of the soil within the tanker.

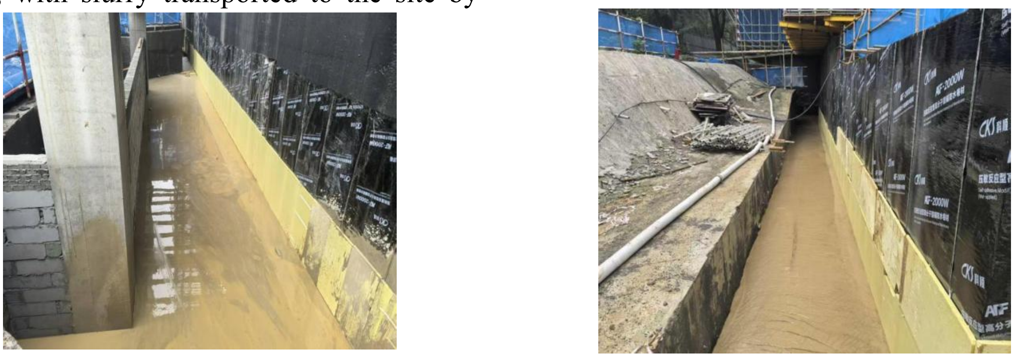


Figure 3. Fluidised Stabilised soil Backfilling Construction

4.4 Layered Pouring Operations

Where site conditions permit, pumped placement shall prioritise use of tower cranes. Placing pipes shall discharge towards the bottom of the trench, strictly avoiding impact on retaining structures, basement external walls, or other critical elements. Fluidised stabilised soil shall be placed from lower to higher elevations. Subsequent layers shall only be placed after the preceding layer has reached final setting. Liquid levels within each layer shall be maintained horizontally, with pumping velocity and pipe diameter adjusted in real-time according to backfill volume [8].

4.5 Moisture Retention Curing and Product Protection

Each layer shall be immediately covered with plastic sheeting for moisture retention after placement. Continuous curing shall be maintained for at least seven days after final setting of the top layer, with regular watering during the curing period. Warning lines and signage shall be installed, and personnel shall be strictly prohibited from treading on the surface until strength requirements are met.

5. Key Construction Techniques and Full-Process Quality Control

5.1 Key Construction Techniques

The pumping and placement technique for flowable stabilised soil within narrow trenches demonstrated significant effectiveness. A layered, stepped placement scheme was adopted: the initial layer was limited to 0.5m thickness to control lateral pressure, with subsequent layers increased to 1.0m. High-powered specialised machinery and wide-diameter pipelines were selected for pumping equipment, with flow velocity rationally controlled to minimise head loss. Placement followed the principle of deep sections before shallow ones to prevent cold joints.Furthermore, to accommodate confined working conditions, compact high-precision mixing equipment and conduit pumping methods were employed, substantially reducing the required on-site working area. Optimised material flow routes and layered construction techniques effectively managed lateral pressure accumulation. In locally restricted areas such as waist beams and excavation corners, supplementary manual fine-grading and flexible conduit filling techniques were utilised to eliminate quality blind spots entirely, ensuring both forming precision and structural integrity [9].

5.2 Full-Process Quality Control

Quality control for flowable stabilised soil construction relies on comprehensive monitoring measures and systematic inspection protocols. This project implemented stringent dual-control elevation management: horizontal control lines were marked on side walls prior to pouring, with real-time verification during pouring using total stations, maintaining layer thickness deviations within ±1% of design values. Bleeding was addressed through secondary mixing or adding 2%–5% silica fume. During the curing phase, full-coverage moisture retention was implemented. Geotextile fabric was laid to maintain humidity ≥90% for over seven days, with strict prohibition of mechanical disturbance. Upon material arrival, random samples were taken at the pouring site to verify flowability and strength. Flow tests shall be conducted at least once per 200m³ of placement and at least once per layer. Strength control is achieved through systematic specimen retention: standard-cured specimens (100mm × 100mm × 100mm cube moulds) shall be retained for each placement for strength testing. For continuously placed flowable solidified soil of the same mix design, when placement volume is less than 400m³,one set of specimens shall be prepared per 200 m³; when the placement volume exceeds 400 m³, one set of specimens shall be prepared per 400 m³. Compressive strength testing shall be conducted after 28 days of standard curing. The results of on-site specimen performance testing are presented in Table 5.

Table 5. Performance Test Results for Fluidised Stabilised Soil

No.		Density/(kg/m³)	Flow/mm	Compressive Strength/MPa
Layer 1	1-1	1790	170	1.04
	1-2	1782	174	0.95
	1-3	1787	173	0.98
Level 2	2-1	1778	176	0.98
	2-2	1810	167	1.10
	2-3	1798	169	1.05
Level 3	3-1	1802	173	1.07
	3-2	1791	170	1.01
	3-3	1805	165	1.04
Level 4	4-1	1790	172	1.02
	4-2	1785	175	0.97
	4-3	1813	165	1.09

6. Project Benefit Analysis

6.1 Technical and Economic Benefits

This project involved backfilling 2,100m³ of manure pits. The fluidised solidified soil technique reduced the construction period to 8 days, achieving a 10-day advance over the original lime-soil scheme. Cost savings were realised in two key areas: firstly, eliminating manual compaction reduced labour requirements from 180 man-days to 48 man-days; secondly, streamlining heavy machinery usage cut costs for rollers, bulldozers and similar equipment by over 50%.Calculations indicate that for each cubic metre of backfill, the total cost of the fluidised solidified soil scheme was merely 147.7 yuan, representing an 18.2% reduction compared to the traditional lime-soil scheme's 180.6 yuan. Detailed costs are presented in Table 6.

6.2 Environmental Protection and Quality Benefits

During the construction phase, this project utilised locally sourced materials, employing excavated soil from the foundation pit as the primary raw material. This significantly reduced the need for transporting external soil, thereby lowering energy consumption and carbon emissions while effectively mitigating the disruption caused by vehicle transport to surrounding traffic and the environment. Concurrently, the production and pouring of fluidised solidified soil generated no dust and minimal noise, eliminating the compaction vibrations and dust pollution associated with conventional backfilling. This markedly enhanced the environmental standards at the construction site, reducing disturbances to residents and complaints. In terms of quality and efficiency, fluidised solidified soil backfill demonstrates outstanding engineering performance. The backfill mass exhibits uniform density, with tested compaction averaging 98.2% – approximately 8% higher than traditional lime-soil backfill. This effectively inhibits groundwater infiltration, preventing potential post-construction settlement and structural leakage risks associated with inadequate compaction, thereby enhancing overall project durability and safety reserves.The fluidised stabilised soil's self-levelling and micro-expansion properties ensure close contact with retaining structures, minimising interface voids and enhancing lateral stability of the excavation [10].

Table 6. Cost Comparison of Fluid-Stabilised Soil and Lime-Soil Backfill

Cost/(CNY/m³)	Original lime-soil scheme	Fluid-Stabilised Soil Method
Materials and Transport Costs	130.2.	126.5
Labour costs	27.8	8.6
Machinery costs	15.2	7.1
Other	7.4	5.5
Total	180.6	147.7

7. Conclusion

This project systematically resolved the challenge of backfilling narrow trenches through material innovation and process reform.

(1)Establishing a dual-control mix design system for strength and flowability achieved coordinated regulation of 0.8 MPa strength and 180mm flowability, guaranteeing construction quality.

(2)The introduction of a layered pumping technique, employing a staged pouring strategy with a 0.5m initial layer and 1.0m subsequent layers, successfully accommodated the complex trench geometry while effectively preventing structural damage from excessive lateral pressure.

(3)A comprehensive quality chain control system was implemented, standardising management from raw material measurement precision to curing cycles. Engineering applications validated its integrated benefits: construction duration reduced by over two-thirds, costs lowered by 18.2%, while simultaneously achieving environmental and energy-saving green objectives.

The narrow trench flow-stabilised soil backfill technique not only offers distinct advantages in terms of cost and schedule, but also demonstrates significant comprehensive benefits in environmental protection and engineering quality. It provides a safe, reliable, and environmentally friendly construction solution for similar backfill projects in confined spaces.

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