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Assessing Workability of Ready-Mixed Soils Derived from Excess Spoil

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Abstract

Civil excavation projects frequently produce significant amounts of excess spoil. Repurposing this spoil into usable backfill material instead of disposing of it offers economic and environmental benefits. This study explores the prospect of converting red-bed mudstone construction waste, a type of soil frequently found at shallow depths, into a ready-mixed soil material (RMSM). It assesses the fresh mixture's workability characteristics (initial flowability, bleeding rate, and density) and the hardened material's mechanical properties (compressive strength and stress-strain relationship) by adjusting the water-to-solid ratio (W/S) and cement-to-soil ratio (C/S). The study investigates the impact of W/S, C/S and time on RMSM's flowability loss and proposes an empirical formula to provide a scientific reference for RMSM's flowability design in engineering applications. Findings highlight the significant influence of W/S on flowability, bleeding rate, and compressive strength, while showing C/S has a limited effect on flowability and bleeding. A negative exponential relationship is observed between flowability and time for all mixes, with the flowability loss ratio increasing over time, ranging between 22.9% and 35.6% after one hour and stabilizing after three hours. These insights are crucial to optimize RMSM's performance and suggest the need to further improve the flowability retention of RMSM. Furthermore, in comparison to soil cement and concrete, RMSM reduces backfill costs by 30.8% and 80.0%, respectively, while also achieving a reduction in CO_2 emissions by 25.9% and 69.2%. Therefore, RMSM presents as an economically and environmentally friendly alternative for backfill applications.

Keywords: excavated red-bed mudstone; ready-mixed soil material (RMSM); mix proportion; geotechnical properties; sustainability; excess spoil

1 Introduction

Underground infrastructure projects such as foundation pit excavation, subway construction, and underground pipeline facilities generate significant quantities of excavated waste soil (Haas et al. 2021; Kataguiri et al. 2019; Zhang et al. 2021). Currently, most construction sites resort to using muck trucks for transporting this waste to suburban landfills for stacking treatment, a process fraught with the following issues. The transportation of excavated waste soil not only increases dust pollution and construction costs but also necessitates extensive land resource allocation for suburban landfills. Furthermore, the disposal of waste soil in landfills has instigated prominent adverse effects, including land subsidence, the degradation of vegetation, and an increased risk of landslides (Arm et al. 2017; Duan et al. 2019; Zhang et al. 2020). As a result, the importance of sustainable handling and repurposing of excavated soil has garnered attention in recent years (Magnusson et al. 2015; Priyadharshini et al. 2018). Seeking an alternative application for excavated waste soil presents an attractive strategy to mitigate disposal costs, minimize raw material consumption, and decrease environmental pollution, thus enhancing sustainability (Bozbey and Guler 2006). Meanwhile, the limited operational space in rode widening, pipe networks, and abutment approaches often hampers the compaction quality of traditional backfill materials, thereby causing engineering disease such as uneven settlement (Kong et al. 2020; Feng et al. 2024; Liu et al. 2023). Therefore, the development of a self-compacting novel backfill material using excavated waste soil has potential benefits to the construction industry.

Controlled Low-Strength Material (CLSM), as defined by the American Concrete Institute (ACI) Committee 229, is a self-compacting, cementitious material primarily employed as an alternative to compacted fill, with compressive strength not exceeding 8.3 MPa (ACI 2013). Compressive strength determines the performance of a material under loading and also relates to its difficulty in being excavated (Okuyucu et al.

2019). Manual excavation of CLSM is feasible up to a compressive strength of 0.7 MPa. For strength levels between 0.7 and 1.4 MPa, mechanical excavation tools like backhoes become appropriate. If re-excavation is anticipated for maintenance, the long-term strength should not exceed 2.1 MPa (ACI 2013; Katz and Kovler 2004; Okuyucu et al. 2019). CLSM is also referred to as flowable fill, unshrinkable fill, controlled density fill, flowable mortar, plastic soil-cement, soil-cement slurry, K-Krete and various other names. It has gained wide application in geotechnical engineering such as backfill, utility bedding, void fill, and bridge approaches owing to its ability to fill confined spaces, its low strength facilitating future excavation, and its potential for reducing construction time and cost (Finney et al. 2012; Lee et al. 2014; Luhulima et al. 2022; Wu and Tsai 2009). Conventional CLSM mixtures are typically composed of water, Portland cement, fly ash or similar products, and fine or coarse aggregates or both. Given the increasing waste generation and scarcity of sand, several studies have explored using waste as a partial substitute for fine aggregates in CLSM preparation. This includes construction and demolition waste (Zhang et al. 2018), water purification sludge (Tang and Cheng 2019), bottom ash and sediment (Yan et al. 2014), waste foundry sand (Deng and Tikalsky 2008), scrap tires (Pierce and Blackwell 2003), and waste oyster shells (Kuo et al. 2013).

Addressing both aggregate resource shortages and waste soil disposal problems, Chang and Chen (2006) developed the ready-mixed soil material (RMSM). Similar to CLSM, RMSM is used in construction, specifically as backfill material. However, their compositions differentiate them; CLSM typically uses sand or gravel, while RMSM incorporates only fine aggregate from surplus construction earth. The innovative employment of waste materials renders RMSM a more environmentally friendly option, reducing the dependence on conventional aggregates. Moreover, with lower strength than CLSM, RMSM facilitates future re-excavation, making it suitable for projects where maintenance or modifications might be required. Therefore, choosing between RMSM and CLSM depends on project-specific requirements, including factors like potential re-excavation and environmental impact (Huang et al. 2016; Shiha et al. 2016). There is a notable contradiction between the flowability and strength of RMSM. To address this, polycarboxylate superplasticizer has been applied to RMSM prepared using waste marine dredged clay, as discussed in the studies by Wan et al. (2023) and Zhang et al. (2023). It was observed that the production of RMSM with construction spoil necessitated significant water usage, while sulfonated acetone formaldehyde (SAF) can mitigate water consumption and improve its performance (Jian et al. 2022).

The ACI Committee 230 defines soil cement as a dense, compacted mixture of soil, precise quantities of Portland cement, and water. Given these shared components, RMSM can be viewed as a fresh configuration of soil and cement, having been successfully utilized in construction projects where operational space is limited and traditional soil cement is unsuitable (Chittoori et al. 2014; Lowitz and DeGroot 1968; Wu 2012). Historically, soil stabilization efforts employed methods such as soil cement, stirring piles, and powder spraying piles. Yet, ensuring uniformity and maintaining quality control remain challenging with these in-situ treatments. As a solution, RMSM adopts a ready-mix strategy, similar to concrete production, blending with cementitious materials to yield a homogenous, stable geotechnical substance. This ready-mix methodology equips RMSM with similar operational attributes to ready-mix concrete, thereby enabling its independent production, transportation, and application. Focusing on field applications, Chang et al. (2006) studied the automated production process of RMSM. They successfully implemented it for backfilling pipeline trenches, noting that RMSM enhances construction speed and reduces settlement issues, which are common with traditional earth backfills due to inadequate compaction. Huang et al. (2020), examining the comprehensive pipe gallery in Tongzhou Urban Sub-center, Beijing, found that RMSM exhibits superior characteristics compared to traditional backfill materials. These include improved strength, self-compacting, anti-leakage, water stability, and construction and economic performances. Zhu et al. (2022) proposed an optimal mixture ratio for RMSM and conducted field tests, demonstrating the feasibility of RMSM for trench backfilling.

Red-bed mudstone, typically associated with red sediments from the Jurassic to the Neogene periods and prevalent in southwest, central, and southern China, characterized by low strength, strong hydrophilicity and weak weathering resistance, which limit its construction application (Yu et al. 2022; Hu et al. 2022; Xu and Tang 2023). Its high water-content, often exceeding optimal moisture levels, presents significant challenges in natural drying and compaction control during construction (Xu et al. 2017). Converting red-bed mudstone into RMSM appears to be an effective solution. In the current work, the red-bed mudstone abundantly endowed in Southwest China was selected as fine aggregate of RMSM. Although RMSM finds widespread use in construction, research into its flowability during transportation over time, and the correlation with flowability reduction, remains scarce. This research aims to create a RMSM mix design and evaluate the engineering possibilities of RMSM production, using red-bed mudstone construction waste solely as fine aggregate for a sustainable waste soil disposal solution. RMSM samples in sixteen different mix proportions are prepared for laboratory analysis of fresh and hardened properties, including flowability, gradual loss of flowability, bleeding rate, compressive strength, and stress-strain curve.

2 Materials and methods

2.1 Materials

The constituents of RMSM, as used in this study, comprise excavated waste red-bed mudstone, cement, and water. Red-bed mudstone constitutes the primary volumetric component of RMSM, significantly influencing its workability and mechanical properties. This red-bed mudstone under test is from a road construction site located in Southwestern China. Post extraction, it underwent a process of crushing and sieving, using a 4.75 mm (No.4 sieve) to classify it as a fine aggregate. This process ensured the removal of larger gravel influences on the subsequent laboratory tests. Its physical properties were assessed following the *Standard for*

Geotechnical Testing Method (GB 50123-2019) protocol, with the findings summarized in Table 1. The maroon-colored soil contains 74.9% particles smaller than 0.075 mm (No.200 sieve). The *Unified Soil Classification System* (ASTM-D2487-17) classifies this soil as a low-plasticity clay (CL). The soil underwent X-ray diffraction (XRD) pattern measurement on an X-ray diffractometer, using Cu Kα radiation at 40 kV/100 mA. The XRD result, depicted in Fig. 1, indicates the soil principally comprises: Quartz, Calcite, Muscovite, and Clinochlore.

Cement, the bonding agent in RMSM, profoundly influences the material's strength and performance. The cement employed was Composite Portland Cement PC42.5, and its workability-related properties conform to the technical specification (GB 175-2007). The water used was standard tap water.

2.2 Mix proportions

Mix proportion significantly influences RMSM performance. This study's flowability test results suggest that a water-to-solid ratio (W/S) of 50%, in conjunction with varying cement-to-soil ratios (C/S), satisfies construction application requirements, even as the water-to-cement ratio (W/C) markedly varies between 2.5 and 5.5 under identical conditions. These findings indicate W/S regulates flowability range more accurately than W/C. Therefore, W/S and C/S served as RMSM's design parameters, with sixteen mixtures prepared following the control variable method, as delineated in Table 2. To examine the effects of both low and high flowability on flowability loss and compressive strength, a W/S range between 45% and 60% was selected. Importantly, the term 'soil mass' refers to dry soil particles in this context. The cement content during the experimental procedure denotes the mass ratio of cement to dry soil, with values spanning from 10% to 25%, in line with the technical code (DBJ51/T 188-2022).

2.3 Specimens preparation and testing procedures

The production of RMSM leverages the advantages of both soil cement and CLSM. This approach combines the environmental sustainability of soil cement, which utilizes naturally abundant materials, with the ease of delivery, self-compaction, and controllable strength features characteristic of CLSM, resulting in a practical and environmentally conscious solution. The process begins with the application of crushing and sieving, a standard method in soil cement production. Subsequent stages incorporate batching and mixing procedures common in CLSM or concrete production. This integrated method ensures accurate and consistent mixing, thereby optimizing the production of RMSM (Chang and Chen 2006). Prior to mixing, the water content of the red-bed mudstone is assessed to establish the precise volume of water necessary for preparing the RMSM mix proportions. These proportions, as detailed in Table 2, dictate the preparation process in laboratory: water and cement were mixed for 90. seconds using a mortar mixer to get binder milk (Fig 2. (a)). After achieving an even distribution of cement particles, the red-bed mudstone was added and mixed for an additional 180 seconds to ensure uniformity. Given their superior workability, the fresh prepared RMSM mixtures were then poured into corresponding molds without vibration, as shown in Fig. 2(b). Marked specimens were subsequently placed in a curing room, maintained at a constant temperature of 20 ± 2 °C and a relative humidity of 95%, as shown in Fig. 2(c). These conditions persisted until the required age for compressive strength testing, with demolding occurring after 24 hours.

Because of RMSM's excellent flowability which results in minimal accumulation height, the conventional concrete slump test method is inconvenient. Consequently, flowability test was conducted following the Japan Highway Public Corporation (JHS A 313-1992) protocol, using an open-ended hollow acrylic cylinder with both a height and diameter of 80 mm and a glass plate, as shown in Fig. 2(e). The flow spread diameter of the RMSM mixture was measured in two perpendicular directions, the average of which represented the RMSM's flowability, as show in Fig. 2(f). The fresh density test was conducted using a 1L capacity cylinder (Φ 108 mm × 109 mm) adhering to GB/T 0590-2020 standard, as shown in Fig. 2(g). To assess the subsidence and stability of RMSM's fresh mixture, the bleeding rate was tested using a 2-L capacity cylinder (Φ 137 mm × 138 mm) per GB/T 0589-2020 standard, as show in Fig. 2(*i*). Compressive strength tests were conducted on cubic specimens (70.7 mm × 70.7 mm × 70.7 mm) of selected mix design at the ages of 7-d, 14-d, and 28-d post-preparation. An integrated pavement material testing apparatus (TC-20A) was used as shown in Fig. 2(j), applying a loading rate of 1 mm /min following JGJ/T 233-2011 standards. Three parallel tests were carried out for each group of mix proportions and the average values were taken to reduce error. The axial force and deformation of the cube were recorded during the compressive strength test to construct the stress-strain curve for the determination of deformation modulus E_{50}.

3 Results and analysis

3.1 Flowability

3.1.1 Initial flowability

Initial flowability reflects RMSM's on-site workability. Since the optimal flowability range for RMSM in most engineering applications is 180±20 mm according to JHS A 313, the minimum flowability requirement in this research is set as 160 mm. Fig. 3 showcases the initial flowability variations across different fresh mixtures.

With C/S held constant, the flowability diverges between 147.5 mm and 162 mm over a W/S range of 45% to 60%. An increase in RMSM's flowability is observed with the rise in W/S, attributable to the requirement of more water for RMSM preparation at higher W/S. This leads to abundant free water presence amid soil particles, which, in turn, enlarges the inter-particle distance (Zhang et al. 2023a). Consequently, the bonding and connection between particles weaken, thereby enhancing flowability.

Conversely, for a constant W/S, the maximum flowability disparity ranges from 17 mm to 37.8 mm over a C/S spectrum of 10% to 25%. The marginal alterations in RMSM's flowability due to variations in C/S can be attributed to two primary factors. Firstly, cement, in comparison to red-bed mudstone, boasts a lower specific surface area. An escalation in C/S signifies an increased cement proportion in the mix, which consequently results in a reduced total specific surface area. This reduction, in turn, decreases the quantity required to form the water film, leading to an increment in the mixtures' flowability when the total water consumption remains unchanged. Despite this, the impact remains minimal, manifesting as only a slight increase in flowability.

Secondly, the sodium (Na^+) and potassium (K^+) ions adsorbed on the surface of the clay particles in the red-bed mudstone undergo ion exchange reactions with the calcium (Ca^{2+}) ions produced during cement hydrolysis. This reaction enhances the charged clay particles' attraction to the ions and reduces the thickness of the clay particles' electric double layer (water film thickness) (Zhang et al. 2023b). This reduction facilitates clay particle connection and agglomeration. Therefore, contrary to the results from the literature (Zhu et al. 2022), flowability does not increase monotonically with C/S increase. This discrepancy can be attributed to different soil physical properties and the latter's use of coarse aggregate.

3.1.2 Gradual loss in flowability

On-site, construction conditions may necessitate transporting RMSM to the backfill site post-plant mixing. Consequently, the gradual loss in flowability of RMSM needs to be accounted for to avoid non-compliance due to substantial flowability reduction. This is an issue that has received limited research attention. Therefore, the gradual loss in flowability was tested for different mixtures over time intervals of 0 min, 15 min, 30 min, 60 min, 90 min, 120 min, and 180 min. Fig. 4 illustrates the test results for gradual loss in flowability at W/S = 55% and C/S =20%.

Fig. 5 illustrates the experimental results of the RMSM's gradual loss in flowability over time. It is evident all mixtures exhibit a negative exponential relationship between flowability and time, with fitting parameters a and b having a relationship with C/S and W/S. The generalized fitting curve equation is shown below, with the parameters a and b at different C/S and W/S shown in Table 3.

$$y = ae^{(-x/60)} + b \tag{1}$$

To visualize the gradual loss in flowability more intuitively, the flowability loss ratio at a particular time is defined as the difference between the flowability at that time and the initial flowability, divided by the initial flowability. As cement hydration progresses over time, the strength of the mixtures increases, causing a gradual decrease in flowability. As demonstrated in Fig. 6, all mixtures' flowability loss ratio progressively increases over time, ranging between 30.2% and 43.7% at three hours. The flowability loss ratios for the intervals 0 - 1 h, 1 - 2 h, and 2 - 3 h account for 70.6% - 86.4%, 13.6% - 22%, and 1.2% - 9.8% of three-hour flowability loss ratio, respectively. The findings indicate that the loss of flowability in RMSM primarily occurs within the first hour, and the rate of this loss decreases thereafter. Consequently, it is advisable to limit the time from transporting to pouring RMSM to no more than one hour. Additionally, when C/S is fixed, the flowability loss ratio decreases as W/S increases, except for 45% W/S due to its minimal initial flowability. An increase in W/S necessitates more water for the mixtures, causing the cement particles to be more dispersed and the cement hydration products' bond with the soil particles to be weaker. This leads to a decreased flowability loss ratio. As time progresses, the hydration products of cement gradually increase, consuming free water and strengthening the cementation between soil particles. This explanation can account for the observed phenomenon where the flowability loss ratio increases with increasing C/S, given a fixed W/S.

From the above analysis, for RMSM mixed on-site with truck mixers, a W/S ratio of 50% is optimal for satisfying flowability requirements. However, if field mixing proves restrictive and RMSM must be mixed using in-plant central mixers, a higher W/S ratio of 55% is recommended. This adjustment ensures that RMSM, even when subject to transportation times of up to one hour, continues to meet the necessary flowability criteria by compensating for potential flowability loss. However, increasing the initial flowability of RMSM by raising the water-to-solid ratio (W/S) is not a viable solution to mitigate flowability loss, due to the unavoidable contradiction between initial flowability and strength. Given the severity of RMSM's flowability loss, which varies between 22.9% and 35.6% within the first hour, it is essential to improve flowability retention. Polycarboxylate superplasticizer (PCE) has been shown to reduce the water requirement in concrete production and improve slump retention (Li et al. 2017, 2021). These findings have inspiration on reducing the water requirement in RMSM and suggest the need to further improve the flowability retention of RMSM, such as incorporating PCE and sulfonated acetone formaldehyde (Jian et al. 2022). Future research should focus on the flowability retention of RMSM with additives, exploring new avenues to optimize this material's performance.

3.2 Bleeding rate

Fig. 7 illustrates the bleeding rate for the mixtures over time, showing an increase as time progresses. It is seen bleeding largely completes within the first 60 minutes, with no significant change observed between 60 and 180 minutes. This is largely attributable to the settlement of solid particles within the mixtures (Zhang et al. 2011). At different heights within the mixtures, the effective stress on the soil particles varies. In the initial stages following RMSM mixing, the soil particles within the mixtures are loosely configured due to large inter-particle pores. Gravitational force causes fine particles to migrate into these pores, leading to the compaction of the mixture and the rise of free water along open bleeding channels towards the upper part of the mixtures. Over time, soil particle settlement completes and reaches a relatively stable state in the later stages.

Additionally, when C/S is fixed at 10%, changes in W/S within the range of 45% to 60% significantly influences the bleeding rate, which varies between 1.22% and 7.54%. This relationship is associated with the increase in free water within mixtures. Although the bleeding rate increases with W/S, the bleeding rate remains only 4.64% when W/S increases to 55%. This rate is below the maximum acceptable bleeding rate of 5% for practical engineering applications, as suggested by Gabr et al. (2000). Therefore, considering the gradual loss in flowability, a W/S of 55% in RMSM meets the requirements for both bleeding rate and flowability. When W/S is held constant, changing C/S within the range of 10% to 25% results in a slight increase in the bleeding rate, as illustrated in Fig. 8. This contradicts the result presented in reference (Zhang et al. 2018), and the difference can be attributed to the non-cohesive fine aggregate used in the latter study. In this study, the excavated red-bed mudstone particles are smaller than the cementitious ones. As a result, an increase in cement reduces the amount of water required to form a water film.

The study presents an innovative approach to preparing RMSM from red-bed mudstone construction waste, addressing the dual challenges of aggregate resource scarcity and waste soil disposal. Despite these advances, current understanding of red-bed mudstone-based RMSM remains insufficient, particularly in elucidating the quantitative impacts of W/S, C/S, and time on flowability and bleeding. Zhang et al. (1996) introduced a model, suggesting that water in cementitious materials bifurcates into filling water and excess water. The former occupies the voids between cementitious particles, while the latter forms a water film on particle surfaces, enhancing the flow spread of cementitious materials. The thickness of this water film (WFT), defined as the ratio of excess water content to the specific surface area of the particles (Li and Fan 2022; Liu et al. 2020), offers a powerful tool for evaluating flowability and bleeding in cementitious materials (Tian et al. 2021; Wu et al. 2023; Zhao et al. 2022). Hence, future work will focus on quantifying the effects of W/S, C/S, and time on RMSM's flowability and bleeding, centering this analysis on WFT variation.

3.3 Compressive strength

Fig. 9 shows the results of the compressive strength for samples that were cured for 28 days. It is evident the strength of all samples meets the requirements for re-excavation (2.1 MPa), with most falling within the upper limit for manual excavation. This characteristic of RMSM is beneficial, allowing for re-excavation at later stages for future reconstruction work (Huang et al. 2016). When W/S is fixed at 50%, the strength of RMSM increases from 0.443 MPa to 1.303 MPa as C/S increases from 10% to 25%. This is primarily due to the fact that an increase of C/S leads to more cement hydration products being produced, which binds the soil particles together, fills the gaps between soil particles, and forms a skeletal structure (Huang et al. 2006). It can also be observed the strength decreases as W/S increases, implying an increase in free water content hampers the development of strength. With higher free water content, the void ratio after curing is higher when C/S is fixed. This means the treated soil is more loosely packed, reducing the bonded contact area and apparent cohesion (Lorenzo and Bergado 2004). Further, the hydration and pozzolanic reactions slow down, leading to weaker cementation between soil particles (Wan et al. 2023). As W/S increases, the soil particles tend to flow more readily and adhere to the surface of hydration products, obstructing further cement hydration (Qian et al. 2019).

Fig. 10 shows the relationship between flowability and compressive strength for samples treated with a C/S of 10%, following a 28-day curing period. It is evident that an uptick in W/S results in a decrease in the strength and fresh density of RMSM, conversely, flowability escalates. Notably, maintaining a C/S at 10% results in RMSM strength failing to attain 300 kPa, unless the initial flowability descends below 239 mm. Moreover, RMSM strength does not breach 500 kPa unless the flowability diminishes under 160 mm (as stipulated in Sec 3.1.1). These observations propose that under given conditions, the plausible fresh density range of RMSM fluctuates between 1677 kg/m^3 and 1715 kg/m^3. W/S evidently exerts a considerable reduction effect on the compressive strength, manifesting an inherent conflict between flowability and compressive strength. Polycarboxylate superplasticizer (PCE), a potent water-reducing agent ubiquitous in concrete production, if employed in the production of red-bed mudstone-based RMSM, would permit RMSM to meet the minimum flowability requirement at a lower W/S and attain higher compressive strength at a consistent C/S. This method promises significant economic and environmental advantages.

3.4 Deformation law

3.4.1 Stress-strain curves

Fig. 11 displays the stress–strain curves obtained from unconfined compression tests of the samples cured for 28 days, following the technical standard JGJ/T233-2011. No cracks occurred in the samples during the curing process. All stress-strain curves were analyzed.

The stress-strain curves of RMSM exhibit a single peak shape or stable peak shape, broadly divided into four stages: elastic, yield, stable, and softening. In the elastic stage, the stress growth rate is large and it increases almost linearly with strain. No significant cracks are evident on the surface of the test specimen Upon entering the yield stage, the stress-strain curve deviates from the straight line, and the stress growth rate slows, then the strength reaches its peak. Meanwhile, the first crack or several longitudinal cracks appear in the test specimens. Microcracks rapidly form in the area near the surface cracks. Post-peak, the curve enters the softening stage where stress decreases with increasing strain and some test specimens display relatively uniform crack development and spalling appears on the side. This can be attributed to the presence of pores of the test specimen. Cracks then extend from weak point to the upper and lower ends of it, creating longitudinal penetrating cracks. The test specimens fractured vertically into multiple smaller blocks, configuring a quadrangular pyramid with an approximate angle of 45°, resulting in a strength decrement. Fig. 12 displays the representative failure pattern of an RMSM specimen. Notably, in comparison to the pre-test specimen, there is a substantial reduction in height, signifying the specimen underwent significant plastic deformation.

A stable phase is only achieved at certain C/S or W/S. With a fixed C/S at 10%, a significant period of stress stability is observed, showcasing marked ductility characteristics that amplify as W/S increases. This phenomenon occurs because a small C/S value leads to cement hydration products binding soil particles, creating a low-strength, inadequately structured skeleton (Zhu et al. 2005). External forces trigger specimen failure from the point of application. With further cement content increase, the production of additional cement hydration products enhances friction and cohesion among red-bed mudstone soil particles, thereby strengthening the RMSM skeleton structure. Under loading conditions, RMSM specimens co-stress synergistically, displaying brittle failure characteristics. Concurrently, peak stress rises with an increased C/S and falls with a rising W/S at the same age. Yet, peak strain remains largely unaffected by both, typically ranging between 1% and 2%.

To delineate the quantitative impact of C/S and W/S on the transition of RMSM specimen failure from ductility to brittleness, the ductility index, μ, was derived using:

$$\mu = \varepsilon_{\mu} / \varepsilon_{f} \tag{2}$$

where ε_{μ} is the strain coinciding with a stress equivalent to 85% of the peak stress in the stress-strain curve's descending segment, and ε_{f} is the peak strain.

Multivariate regression analysis on the 16 experimental results generated the best-fit curves for various C/S and W/S, as depicted in Fig. 13. The regression analysis revealed an R^2 value of 0.982, signifying that the ductility index (μ) was governed by C/S and W/S. With a fixed C/S at 10% and a W/S spanning from 45% to 60%, μ rises from 2.21 to 4.21, experiencing respective growth rates of 22.2%, 50.7%, and 90.5%. Conversely, when C/S is anchored at 25%, μ escalates from 1.61 to 2.31, registering growth rates of 10.6%, 31.6%, and 43.5% respectively. Hence, at lower C/S, μ increases at a relatively fast pace with a rise in W/S, but the W/S impact on μ diminishes as C/S increases. The regression analysis reveals a strong linear positive relationship between μ and W/S. On the contrary, a linear negative correlation exists between C/S and μ. These findings are in line with the qualitative analysis of the stress-strain curves, endorsing the use of μ as a valuable tool for quantitatively assessing the influence of W/S and C/S on the transition of RMSM failure from ductility to brittleness.

3.4.2 Deformation modulus (E_{50})

Since RMSM is not an elastic material, the deformation modulus E_{50} is frequently used in engineering applications. E_{50} is defined as the slope of the line between the origin and a point on the stress-strain relationship curve where the stress level is half of the peak strength (Raavi 2013). This index is commonly used to reflect the deformation characteristics of materials. E_{50} is computed using the following equation:

$$E_{50} = \sigma_{0.5}/\varepsilon_{0.5} \tag{3}$$

where $\sigma_{0.5}$ is the compressive stress at half of the peak strength, and $\varepsilon_{0.5}$ is the strain corresponding to $\sigma_{0.5}$. The deformation modulus range observed in the current RMSM samples was 23 to 245 times greater than the corresponding compressive strength achieved after 28 days of curing. As per the analysis of E_{50} in the compressive strength test, E_{50} is found to show a positive correlation with compressive strength, as illustrated in Fig. 14. Regression analysis of the data yields E_{50} =90.1q_u, R^2=0.936. This aligns with the relationship E_{50} = (54~240) q_u identified in prior studies (Chittoori et al. 2014), further confirming that E_{50} augments linearly with a rise in compressive strength. Consequently, in the absence of a stress-strain curve, it is possible to infer E_{50} from its linear correlation with q_u.

3.5 Economic and environmental assessment

The backfill of comprehensive pipe galleries, underground pipeline trenches, and foundation trenches presents challenges due to the narrow working surface, limiting the use of large compaction equipment and making it difficult to control compaction quality (Huang et al. 2020). To enhance backfill quality and reduce construction time, low-grade concrete is occasionally used in narrow spaces, but its high cost limits widespread application (Zhou et al. 2023). This section compares the construction cost and carbon footprint of three backfill methods: soil cement, RMSM, and concrete, applied to a 0.5 m × 2 m × 1 km municipal pipeline trench. For simplicity, the single-track distance for comparison was set at 10 km, with material proportions and consumption detailed in Table 4. Costs were estimated excluding mechanical expenses, except for transportation, as shown in Table 5. RMSM saved 6.17k USD and 30.8% compared to soil cement, reducing the construction period by 40%. Against concrete backfill, RMSM saved 55.42k USD and 80.0%. The unit prices and proportions of soil cement and concrete used in this study's estimations were extracted from conditions that may vary, possibly introducing errors, yet still demonstrating RMSM's cost and efficiency benefits.

For carbon footprint comparison, the Functional Unit defined as CO_2-equivalent emitted ($kgCO_2$-e/kg) for backfilling 1 m^3 of space was used. CO_2 emissions from the entire production cycle were considered for each material, with values sourced from literature and summarized in Table 6. For cement (E_2), emissions include mining of raw materials, manufacture, and transportation of cement. Emissions for fine (E_4) and coarse aggregates (E_5) encompass quarrying, crushing, and transport to concrete manufacture (Turner and Collins 2013). The CO_2 emissions from batching, carriage, placing, and pouring of concrete (E_6) and RMSM's similar production processes were also considered (Turner and Collins 2013), alongside soil cement preparation and transportation emissions (E_7) (Quan et al. 2023). The carbon footprints for preparing 1.0 m^3 of soil cement, RMSM, and concrete were calculated as 165.7 $kgCO_2\text{-e}/m^3$, 122.8 $kgCO_2\text{-e}/m^3$, and 398.3 $kgCO_2\text{-e}/m^3$, respectively. RMSM's CO_2 emissions were reduced by 42.9 $kgCO_2\text{-e}/m^3$ (25.9%) compared to soil cement, and by 275.5 $kgCO_2\text{-e}/m^3$ (69.2%) compared to concrete. RMSM also reduced dust pollution by 70% and labor costs by 84% compared to soil cement (Jian et al. 2022; Tran et al. 2023). Additionally, RMSM has the potential to further utilize solid waste as a cement substitute, such as phosphogypsum (Jian et al. 2022) , red mud (Wang et al. 2022) and blast furnace slag (Sheen et al. 2013), reducing cement use and CO_2 emissions. Therefore, RMSM is a sustainable and environmentally-friendly backfill option, particularly for pipeline trench applications, compared to soil cement and concrete.

4 Conclusions

This research explores the potential for sustainable disposal of waste soil by producing ready-mixed soil material (RMSM) from surplus red-bed mudstone. An array of laboratory tests facilitate an understanding of the impact of water-to-soil ratio (W/S) and cement-to-soil ratio (C/S) on the workability and mechanical properties of RMSM.

These experiments suggest the flowability and bleeding rate of RMSM primarily increase alongside W/S, with C/S exerting minimal influence. Regarding the negative exponential relationship between flowability, an empirical formula is proposed to provide a scientific reference for RMSM's flowability design. For all mixtures, the flowability loss ratio gradually escalates over time, ranging between 22.9% and 35.6% at one hour. Thus, for RMSM with a transportation duration of up to an hour, a W/S of 55% is advised to fulfill the flowability specifications. However, a W/S of 50% is sufficient when RMSM is mixed on-site, for example using truck mixers.

RMSM strength diminishes as W/S increases and contributes to its semi-brittle failure characteristics. Both C/S and W/S mediate the transition from ductile to brittle failure at a consistent age, while peak strain remains relatively stable, typically between 1% and 2%. A positive correlation is confirmed between the deformation modulus (E_{50}) and compressive strength (q_u). Through an empirical linear relationship, E_{50} can be estimated based on q_u. Notably, all RMSM samples demonstrate sufficient strength to meet re-excavation requirements for future maintenance.

In comparison to soil cement and concrete backfill, RMSM reduces construction costs by 30.8% and

80.0%, respectively, and also achieves a reduction in CO_2 emissions by 25.9% and 69.2%. Additionally, RMSM can shorten the construction period and reduce dust pollution. This study underscores the potential of RMSM as a sustainable solution for excess spoil management, emphasizing its economic and environmental advantages, particularly in pipeline construction projects. Future assessments should concentrate on the flowability retention of RMSM with additives, to further optimize the material's performance.

Data availability statement

All data, models, and code generated or used during the study appear in the published article.

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References

ACI (American Concrete Institute). 2013. Controlled low-strength materials. ACI 229R. Farmington Hills, MI: ACI.

Arm, M., O. Wik, C. J. Engelsen, M. Erlandsson, O. Hjelmar, and M. Wahlström. 2017. “How does the European recovery target for construction & demolition waste affect resource management?” *Waste Biomass Valor*, 8 (5): 1491–1504. https://doi.org/10.1007/s12649-016-9661-7.

Bozbey, I., and E. Guler. 2006. “Laboratory and field testing for utilization of an excavated soil as landfill liner material.” *Waste Manage*. (oxford), 26 (11): 1277–1286. https://doi.org/10.1016/j.wasman.2005.10.014.

Chang, C.-F., and J.-W. Chen. 2006. “Development and production of ready-mixed soil material.” *Journal of Materials in Civil Engineering*, 18 (6): 792–799. American Society of Civil Engineers. https://doi.org/10.1061/(ASCE)0899-1561(2006)18:6(792).

Chittoori, B., A. J. Puppala, and A. Raavi. 2014. “Strength and stiffness characterization of controlled low-strength material using native high-plasticity clay.” *J. Mater. Civ. Eng.*, 26 (6): 04014007. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000965.

Deng, A., and P. J. Tikalsky. 2008. “Geotechnical and leaching properties of flowable fill incorporating waste foundry sand." *Waste Management*, 28 (11): 2161–2170. https://doi.org/10.1016/j.wasman.2007.09.018.

Duan, H., T. R. Miller, G. Liu, and V. W. Y. Tam. 2019. "Construction debris becomes growing concern of growing cities." *Waste Management*, 83: 1–5. https://doi.org/10.1016/j.wasman.2018.10.044.

Feng, G., Q. Luo, T. Wang, D. P. Connolly, and K. Liu. 2024. "Frequency Spectra Analysis of Vertical Stress in Ballasted Track Foundations: Influence of Train Configuration and Subgrade Depth." Transportation Geotechnics, 44: 101167. https://doi.org/10.1016/j.trgeo.2023.101167.

Finney, A. J., E. F. Shorey, and J. Anderson. 2012. "Use of native soil in place of aggregate in Controlled Low Strength Material (CLSM)." 1–13. Pipelines 2008: Pipeline Asset Management: Maximizing Performance of our Pipeline Infrastructure, ASCE. https://doi.org/10.1061/40994(321)124.

Gabr, M. A., and J. J. Bowders. 2000. "Controlled low-strength material using fly ash and AMD sludge." *Journal of Hazardous Materials*, 76 (2): 251–263. https://doi.org/10.1016/S0304-3894(00)00202-8.

Haas, M., L. Mongeard, L. Ulrici, L. D'Aloïa, A. Cherrey, R. Galler, and M. Benedikt. 2021. "Applicability of excavated rock material: A European technical review implying opportunities for future tunnelling projects." *Journal of Cleaner Production*, 315: 128049. https://doi.org/10.1016/j.jclepro.2021.128049.

Hu, Q., J. Zeng, L. He, S. Feng, L. Zheng, and H. Wang. 2022. "Mesoscopic representative elementary area of red mudstone based on U-Net segmentation." *Arab J Geosci*, 15 (12): 1142. https://doi.org/10.1007/s12517-022-10395-w.

Huang, M., T. Sun, and L. Wang. 2020. "Application of premixed solidified soil in backfilling of foundation trench." *IOP Conf. Ser.: Earth Environ. Sci.*, 510 (5): 052062. IOP Publishing. https://doi.org/10.1088/1755-1315/510/5/052062.

Huang, W.-L., H.-Y. Wang, and C. Jheng-Hung. 2016. "A study of the fresh properties of Recycled ready-mixed soil materials (RRMSM)." *Computers and Concrete*, 17 (6): 787–799. Techno-Press. https://doi.org/10.12989/cac.2016.17.6.787.

Huang, X., J. Ning, Y. Guo, and B. Zhu. 2006. "Effect of cement content on the structural formation of stabilized soil." *Chinese Journal of Geotechnical Engineering*, (4): 436–441.

Huang, Z., T. Tong, H. Liu, and W. Qi. 2023. "Properties of soil-based flowable fill under drying–wetting and freeze–thaw actions." *Sustainability*, 15 (3): 2390. https://doi.org/10.3390/su15032390

Jian, S., C. Cheng, J. Wang, Y. Lv, B. Li, D. Wang, C. Wang, H. Tan, and B. Ma. 2022. "Effect of sulfonated acetone formaldehyde on the properties of high-fluid backfill materials." *Construction and Building Materials*, 327: 126795. https://doi.org/10.1016/j.conbuildmat.2022.126795

Kataguiri, K., M. E. G. Boscov, C. E. Teixeira, and S. C. Angulo. 2019. "Characterization flowchart for assessing the potential reuse of excavation soils in Sao Paulo city." *Journal of Cleaner Production*, 240: 118215. https://doi.org/10.1016/j.jclepro.2019.118215.

Katz, A., and K. Kovler. 2004. "Utilization of industrial by-products for the production of controlled low strength materials (CLSM)." *Waste Management*, 24 (5): 501–512. https://doi.org/10.1016/S0956-053X(03)00134-X.

Kong, X., Z. Yan, S. Rong, and J. Zhang. 2020. "Preparation and properties of flowable silt backfill materials containing industrial solid waste red mud." *Journal of Yangtze River Scientific Research Institute*, 37 (12): 86–91.

Kuo, W.-T., H.-Y. Wang, C.-Y. Shu, and D.-S. Su. 2013. "Engineering properties of controlled low-strength materials containing waste oyster shells." *Construction and Building Materials*, 46: 128–133. https://doi.org/10.1016/j.conbuildmat.2013.04.020.

Kurda, R., J. D. Silvestre, and J. de Brito. 2018. “Life cycle assessment of concrete made with high volume of recycled concrete aggregates and fly ash.” *Resources, Conservation and Recycling*, 139: 407–417. https://doi.org/10.1016/j.resconrec.2018.07.004.

Lee, K.-J., S.-K. Kim, and K.-H. Lee. 2014. “Flowable backfill materials from bottom ash for underground pipeline.” *Materials*, 7 (5): 3337–3352. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/ma7053337.

Li, M., Y. Wang, H. Jiang, C. Zheng, and Z. Guo. 2017. “Synthesis, characterization and mechanism of polycarboxylate superplasticizer with slump retention capability.” *IOP Conf. Ser.: Mater. Sci. Eng.*, 182 (1): 012036. IOP Publishing. https://doi.org/10.1088/1757-899X/182/1/012036.

Li, Q., and Y. Fan. 2022. “Rheological evaluation of nano-metakaolin cement pastes based on the water film thickness.” *Construction and Building Materials*, 324: 126517. https://doi.org/10.1016/j.conbuildmat.2022.126517.

Li, R., L. Lei, T. Sui, and J. Plank. 2021. “Approaches to achieve fluidity retention in low-carbon calcined clay blended cements.” *Journal of Cleaner Production*, 311: 127770. https://doi.org/10.1016/j.jclepro.2021.127770.

Liu, H., Q. Luo, M. H. El Naggar, L. Zhang, and T. Wang. 2023. “Centrifuge Modeling of Stability of Embankment on Soft Soil Improved by Rigid Columns.” Journal of Geotechnical and Geoenvironmental Engineering, 149 (9): 04023069. https://doi.org/10.1061/JGGEFK.GTENG-11314.

Liu, H., X. Sun, H. Du, H. Lu, Y. Ma, W. Shen, and Z. Tian. 2020. “Effects and threshold of water film thickness on multi-mineral cement paste.” *Cement and Concrete Composites*, 112: 103677. https://doi.org/10.1016/j.cemconcomp.2020.103677.

Lorenzo, G. A., and D. T. Bergado. 2004. “Fundamental parameters of cement-admixed clay—new approach.” Journal of Geotechnical and Geoenvironmental Engineering, 130 (10): 1042–1050. *American Society of Civil Engineers*. https://doi.org/10.1061/(ASCE)1090-0241(2004)130:10(1042).

Lowitz, C. A., and G. DeGroot. 1968. “Soil-cement pipe bedding: Canadian river aqueduct.” Journal of the Construction Division, 94 (1): 17–33. *American Society of Civil Engineers*. https://doi.org/10.1061/JCCEAZ.0000211.

Luhulima, D. W., H.-J. Liao, and Y.-Y. Tsai. 2022. “A modified CLSM trench backfilling method to provide immediate bearing capacity.” *J. Transp. Eng., Part B: Pavements*, 148 (3): 04022039. https://doi.org/10.1061/JPEODX.0000379.

Magnusson, S., K. Lundberg, B. Svedberg, and S. Knutsson. 2015. “Sustainable management of excavated soil and rock in urban areas – A literature review.” *Journal of Cleaner Production*, 93: 18–25. https://doi.org/10.1016/j.jclepro.2015.01.010.

Momotaz, H., M. M. Rahman, M. R. Karim, Y. Zhuge, X. Ma, and P. Levett. 2023. “Comparative study on properties of kerb concrete made from recycled materials and related carbon footprint.” *Journal of Building Engineering*, 72: 106484. https://doi.org/10.1016/j.jobe.2023.106484.

Okuyucu, O., P. Jayawickrama, and S. Senadheera. 2019. “Mechanical properties of steel fiber–reinforced self-consolidating controlled low-strength material for pavement base layers.” *J. Mater. Civ. Eng.*, 31 (9): 04019177. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002816.

Pierce, C. E., and M. C. Blackwell. 2003. “Potential of scrap tire rubber as lightweight aggregate in flowable fill.” Waste Management, 23 (3): 197–208. https://doi.org/10.1016/S0956-053X(02)00160-5.

Priyadharshini, P., K. Ramamurthy, and R. G. Robinson. 2018. “Sustainable reuse of excavation soil in cementitious composites.” *Journal of Cleaner Production*, 176: 999–1011.

https://doi.org/10.1016/j.jclepro.2017.11.256.

Qian, J., Y. Hu, J. Zhang, W. Xiao, and J. Ling. 2019. "Evaluation the performance of controlled low strength material made of excess excavated soil." *J. Cleaner Prod.*, 214: 79–88. https://doi.org/10.1016/j.jclepro.2018.12.171.

Quan, Z., X. Chen, F. Chen, W. Gao, and W. Han. 2023. "Analysis of carbon reduction effect of tunnel construction muck soil utilization based on life cycle assessment." *Environmental Engineering*, 41 (10): 91-98+162. https://doi.org/10.13205/j.hjgc.202310012.

Raavi, A. K. 2013. "Design of controlled low strength material for bedding and backfilling using high plasticity clay." *Civil & Environmental Engineering*.

Sheen, Y.-N., L.-H. Zhang, and D.-H. Le. 2013. "Engineering properties of soil-based controlled low-strength materials as slag partially substitutes to Portland cement." *Construction and Building Materials*, 48: 822–829. https://doi.org/10.1016/j.conbuildmat.2013.07.046.

Shiha, Y.-F., S.-S. Tseng, H.-Y. Wang, and C.-T. Wei. 2016. "A study of the replacement of desulphurization slag for sand to ready-mixed soil materials (RMSM)." *Computers and Concrete*, 17 (3): 423–433. Techno-Press. https://doi.org/10.12989/cac.2016.17.3.423.

Tang, C.-W., and C.-K. Cheng. 2019. "Partial replacement of fine aggregate using water purification sludge in producing CLSM." *Sustainability*, 11 (5): 1351. https://doi.org/10.3390/su11051351.

Tian, Z., H. Liu, X. Sun, and Y. Ma. 2021. "Effect of water film thickness (WFT) on the fluidity, rheology, cohesiveness and segregation resistance of multi-mineral cement paste." *IOP Conf. Ser.: Earth Environ. Sci.*, 719 (2): 022068. IOP Publishing. https://doi.org/10.1088/1755-1315/719/2/022068.

Tran, T. Q., Y. Kim, L. C. Dang, and T. M. Do. 2023. "A state-of-the-art review on the utilization of new green binders in the production of controlled low-strength materials." *Construction and Building Materials*, 393: 132078. https://doi.org/10.1016/j.conbuildmat.2023.132078.

Turner, L. K., and F. G. Collins. 2013. "Carbon dioxide equivalent (CO2-e) emissions: A comparison between geopolymer and OPC cement concrete." *Construction and Building Materials*, 43: 125–130. https://doi.org/10.1016/j.conbuildmat.2013.01.023.

Wan, X., J. Ding, N. Jiao, S. Zhang, J. Wang, and C. Guo. 2023. "Preparing controlled low strength materials (CLSM) using excavated waste soils with polycarboxylate superplasticizer." *Environ Earth Sci*, 82 (9): 214. https://doi.org/10.1007/s12665-023-10884-5.

Wang, L., W. Feng, S. A. M. Lazaro, X. Li, Y. Cheng, and Z. Wang. 2022. "Engineering properties of soil-based controlled low-strength materials made from local red mud and silty soil." *Construction and Building Materials*, 358: 129453. https://doi.org/10.1016/j.conbuildmat.2022.129453.

Wu, J. Y. 2012. "Soil-based flowable fill for pipeline construction." 925–938. *American Society of Civil Engineers*. https://doi.org/10.1061/40800(180)74.

Wu, J. Y., and M. Tsai. 2009. "Feasibility study of a soil-based rubberized CLSM." *Waste Management*, 29 (2): 636–642. https://doi.org/10.1016/j.wasman.2008.06.017.

Wu, L., Z. Tao, R. Huang, Y. Zhang, S. Liao, and J. Ye. 2023. "Roles of water film thickness and polycarboxylate dosage in the flow spread of phosphorus building gypsum." *Journal of Building Engineering*, 74: 106911. https://doi.org/10.1016/j.jobe.2023.106911.

Xu, H., Y. Zhang, J. Zhang, G. You, and X. Wang. 2017. "Experimental research on the mechanical properties of improved red soil subgrade in rich water area." *Journal of Railway Engineering Society*, 34 (11): 9–13.

Xu, Q, and R. Tang. 2023. "Study on red beds and its geological hazards." Chinese Journal of Rock Mechanics and Engineering, 42 (1): 28–50. https://doi.org/10.13722/j.cnki.jrme.2022.0012.

Yan, D. Y. S., I. Y. Tang, and I. M. C. Lo. 2014. “Development of controlled low-strength material derived from beneficial reuse of bottom ash and sediment for green construction.” *Construction and Building Materials*, 64: 201–207. https://doi.org/10.1016/j.conbuildmat.2014.04.087.

Yu, F., K. Tong, Z. Fu, G. Feng, Z. Zhou, S. Chen, and Z. Dai. 2022. “Multi-scale deformation characteristics and mechanism of red-bed mudstone in dry-wet environment.” *Frontiers in Earth Science*, 10.

Zhang, C., A. Wang, M. Tang, and X. Liu. 1996. “The filling role of pozzolanic material.” *Cement and Concrete Research*, 26 (6): 943–947. https://doi.org/10.1016/0008-8846(96)00064-6.

Zhang, J., S. Chen, F. Gu, and Y. Wu. 2023b. “Industrial waste materials utilized in subgrade modification: A Review.” *China Journal of Highway and Transport*, 36 (10): 1–16. https://doi.org/10.19721/j.cnki.1001-7372.2023.10.001.

Zhang, J., J. Wang, X. Li, T. Zhou, and Y. Guo. 2018. “Rapid-hardening controlled low strength materials made of recycled fine aggregate from construction and demolition waste.” *Construction and Building Materials*, 173: 81–89. https://doi.org/10.1016/j.conbuildmat.2018.04.023.

Zhang, N., H. Duan, P. Sun, J. Li, J. Zuo, R. Mao, G. Liu, and Y. Niu. 2020. “Characterizing the generation and environmental impacts of subway-related excavated soil and rock in China.” *Journal of Cleaner Production*, 248: 119242. https://doi.org/10.1016/j.jclepro.2019.119242.

Zhang, N., H. Zhang, G. Schiller, H. Feng, X. Gao, E. Li, and X. Li. 2021. “Unraveling the global warming mitigation potential from recycling subway-related excavated soil and rock in China via life cycle assessment.” *Integrated Environmental Assessment and Management*, 17 (3): 639–650. https://doi.org/10.1002/ieam.4376.

Zhang, Q, S. Xie, J. Zheng, and X. Wang. 2011. “Sediment law research and transportation feasibility study of backfilling slurry.” *Journal of Chongqing University*, 34 (1): 105-109+133.

Zhang, S., N. jiao, J. Ding, C. Guo, P. Gao, and X. Wei. 2023a. “Utilization of waste marine dredged clay in preparing controlled low strength materials with polycarboxylate superplasticizer and ground granulated blast furnace slag.” *Journal of Building Engineering*, 107351. https://doi.org/10.1016/j.jobe.2023.107351.

Zhao, Y., N. Zhang, and X. Chen. 2023. “Test study on mechanical properties of compound municipal solid waste incinerator bottom ash premixed fluidized solidified soil.” *iScience*, 26 (9): 107651. https://doi.org/10.1016/j.isci.2023.107651.

Zhou, Y., M. Huo, L. Hou, Z. Chen, and L. Zhang. 2023. “Current research and prospect of low strength flowable filling materials.” *Materials Reports*, 1–16. https://kns.cnki.net/kcms2/detail/50.1078.TB.20230801.1604.008.html

Zhu, W, Zhang, Y. Gao, and Z. Fan. 2005. “Fundamental mechanical properties of solidified dredged marine sediment.” *Journal of Zhejiang University (Engineering Science)*, (10): 103–107.

Zhu, Y., D. Liu, G. Fang, H. Wang, and D. Cheng. 2022. “Utilization of excavated loess and gravel soil in controlled low strength material: Laboratory and field tests.” *Construction and Building Materials*, 360: 129604. https://doi.org/10.1016/j.conbuildmat.2022.129604.

Table 1. Index Properties of the Red-Bed Mudstone

Parameter	Values
Maximum dry density (kg/m^3)	1932
Optimum Moisture Content, OMC (%)	9.45
Natural water content (%)	3.16
Specific gravity	2.71
Liquid Limit, LL (%)	38.4
Plasticity Index, PI	19.7
Particles < 75 μm (%)	74.9

Table 2. Proportions of the Constituents in the RMSM Mix

Specimen ID	C/S （%）	W/S (%)	Dry soil (kg/m^3)	Cement (kg/m^3)	Water (kg/m^3)	Fresh density (kg/m^3)
1	10	45	1116	112	552	1754
2		50	1058	106	582	1695
3		55	1033	103	625	1674
4		60	1006	101	664	1645
5	15	45	1075	161	556	1768
6		50	1022	153	588	1714
7		55	990	149	626	1680
8		60	963	144	664	1649
9	20	45	1031	206	557	1772
10		50	992	198	595	1738
11		55	943	189	622	1675
12		60	927	185	667	1659
13	25	45	986	247	555	1770
14		50	947	237	592	1730
15		55	918	229	631	1700
16		60	893	223	670	1665

Table 3. Values of Parameters *a* and *b* at Different C/S and W/S

C/S (%)	W/S (%)	*a*	*b*	R^2
10	45	40.4	76.7	0.934
	50	77.0	91.3	0.918
	55	93.0	138.9	0.987
	60	100.5	174.7	0.974
20	45	55.4	74.0	0.910
	50	92.5	95.4	0.968
	55	96.6	147.3	0.959
	60	88.8	184.8	0.962
15	45	53.2	76.3	0.956
	50	92	111.0	0.944
	55	102.9	146.8	0.978
	60	100.9	191.8	0.985
25	45	55.6	75.1	0.904
	50	79.5	124.9	0.901
	55	89.8	157.8	0.909
	60	94.4	186.0	0.923

Table 4. Proportions and Material Consumptions of Backfill Materials

Backfill material	Proportion and hardened density	Material consumption
Soil cement	Soil: Cement: Water = 1800:100:190	Soil:1800 t; Cement:100 t; Water:190 t
RMSM	Soil: Cement: Water = 1058:106:582	Soil:1058 t; Cement:106 t; Water:582 t
C25 concrete (Jian et al. 2022)	Cement: Sand: Stone: Water: Admixtures = 356:718:1126:200:0.356	Cement: 356 t Fine aggregate: 718 t Coarse aggregate: 1126 t Water: 200 t Admixtures: 0.36 t

Table 5. Construction Cost Estimation of Backfill

Project	Unit Price	Soil cement	RMSM	C25 concrete
Spoil cost	2.1 USD/t	3.78k USD	2.22k USD	/
Cement cost	64.4 USD/t	6.43k USD	6.83k USD	22.94k USD
Coarse aggregate cost	14.0 USD/t	/	/	15.80k USD
Fine aggregate cost	21.0 USD/t	/	/	23.64k USD
Admixtures cost	419.6 USD/t	/	/	0.14k USD
Transportation cost	0.3 USD/(t·km)	5.60k USD	4.62k USD	6.57k USD
Construction time and labor cost	42.0 USD/d per person	20 persons in 5 days 4.20k USD	4 persons in 1 day 0.17k USD	4 persons in 1 day 0.17k USD
Total cost		20.01k USD	13.84k USD	69.26k USD

Table 6. CO_2 Emissions Values for Materials and Processes of Backfill

Emissions from	Emissions, kgCO_2-e/kg, source
E_1: Water	0.000437 (Momotaz et al. 2023)
E_2: Cement	0.82 (Turner and Collins 2013)
E_3: Admixtures	0.002 (Kurda et al. 2018)
E_4: Fine aggregate	0.0139 (Turner and Collins 2013)
E_5: Quarrying and processing of coarse aggregate	0.0408 (Turner and Collins 2013)
E_6: Batching, carriage, placing and pouring of concrete or RMSM	0.021 (Momotaz et al. 2023)
E_7: Preparation and carriage of soil cement	0.044 (Quan et al. 2023)

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Figure 11. Stress-Strain Curves for RMSM with Different Samples: a) C/S=10%; b) C/S=15%; c) C/S=20%; d) C/S=25%

Figure 12. Typical Failure Pattern of an RMSM Block Upon Compression: a) Crack Propagation; b) Quadrangular Pyramid

Figure 13. The Combined Effects of C/S and W/S on Ductility Index μ: x_1 is the W/S, and x_2 is the C/S

Figure 14. Relationship Between the Deformation Modulus E_{50} and Compressive Strength q_u