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Assessing Workability of Ready-Mixed Soils Derived from Excess Spoil

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1 **Abstract**

2 Civil excavation projects frequently produce significant amounts of excess spoil. Repurposing this spoil into
3 usable backfill material instead of disposing of it offers economic and environmental benefits. This study
4 explores the prospect of converting red-bed mudstone construction waste, a type of soil frequently found at
5 shallow depths, into a ready-mixed soil material (RMSM). It assesses the fresh mixture's workability
6 characteristics (initial flowability, bleeding rate, and density) and the hardened material's mechanical
7 properties (compressive strength and stress-strain relationship) by adjusting the water-to-solid ratio (W/S) and
8 cement-to-soil ratio (C/S). The study investigates the impact of W/S, C/S and time on RMSM's flowability
9 loss and proposes an empirical formula to provide a scientific reference for RMSM's flowability design in
10 engineering applications. Findings highlight the significant influence of W/S on flowability, bleeding rate, and
11 compressive strength, while showing C/S has a limited effect on flowability and bleeding. A negative
12 exponential relationship is observed between flowability and time for all mixes, with the flowability loss ratio
13 increasing over time, ranging between 22.9% and 35.6% after one hour and stabilizing after three hours. These
14 insights are crucial to optimize RMSM's performance and suggest the need to further improve the flowability
15 retention of RMSM. Furthermore, in comparison to soil cement and concrete, RMSM reduces backfill costs
16 by 30.8% and 80.0%, respectively, while also achieving a reduction in CO₂ emissions by 25.9% and 69.2%.
17 Therefore, RMSM presents as an economically and environmentally friendly alternative for backfill
18 applications.

19 **Keywords:** excavated red-bed mudstone; ready-mixed soil material (RMSM); mix proportion; geotechnical
20 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; Katagiri 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 road 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

65 like potential re-excavation and environmental impact (Huang et al. 2016; Shiha et al. 2016). There is a notable
66 contradiction between the flowability and strength of RMSM. To address this, polycarboxylate
67 superplasticizer has been applied to RMSM prepared using waste marine dredged clay, as discussed in the
68 studies by Wan et al. (2023) and Zhang et al. (2023). It was observed that the production of RMSM with
69 construction spoil necessitated significant water usage, while sulfonated acetone formaldehyde (SAF) can
70 mitigate water consumption and improve its performance (Jian et al. 2022).

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

87 ratio for RMSM and conducted field tests, demonstrating the feasibility of RMSM for trench backfilling.

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

101 **2 Materials and methods**

102 **2.1 Materials**

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

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

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

118 **2.2 Mix proportions**

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

129 **2.3 Specimens preparation and testing procedures**

130 The production of RMSM leverages the advantages of both soil cement and CLSM. This approach

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

146 Because of RMSM's excellent flowability which results in minimal accumulation height, the
147 conventional concrete slump test method is inconvenient. Consequently, flowability test was conducted
148 following the Japan Highway Public Corporation (JHS A 313-1992) protocol, using an open-ended hollow
149 acrylic cylinder with both a height and diameter of 80 mm and a glass plate, as shown in Fig. 2(e). The flow
150 spread diameter of the RMSM mixture was measured in two perpendicular directions, the average of which
151 represented the RMSM's flowability, as show in Fig. 2(f). The fresh density test was conducted using a 1L
152 capacity cylinder (Φ 108 mm \times 109 mm) adhering to GB/T 0590-2020 standard, as shown in Fig. 2(g). To

153 assess the subsidence and stability of RMSM's fresh mixture, the bleeding rate was tested using a 2-L capacity
154 cylinder (Φ 137 mm \times 138 mm) per GB/T 0589-2020 standard, as show in Fig. 2(i). Compressive strength
155 tests were conducted on cubic specimens (70.7 mm \times 70.7 mm \times 70.7 mm) of selected mix design at the ages
156 of 7-d, 14-d, and 28-d post-preparation. An integrated pavement material testing apparatus (TC-20A) was used
157 as shown in Fig. 2(j), applying a loading rate of 1 mm /min following JGJ/T 233-2011 standards. Three parallel
158 tests were carried out for each group of mix proportions and the average values were taken to reduce error.
159 The axial force and deformation of the cube were recorded during the compressive strength test to construct
160 the stress-strain curve for the determination of deformation modulus E_{50} .

161 **3 Results and analysis**

162 **3.1 Flowability**

163 *3.1.1 Initial flowability*

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

167 With C/S held constant, the flowability diverges between 147.5 mm and 162 mm over a W/S range of
168 45% to 60%. An increase in RMSM's flowability is observed with the rise in W/S, attributable to the
169 requirement of more water for RMSM preparation at higher W/S. This leads to abundant free water presence
170 amid soil particles, which, in turn, enlarges the inter-particle distance (Zhang et al. 2023a). Consequently, the
171 bonding and connection between particles weaken, thereby enhancing flowability.

172 Conversely, for a constant W/S, the maximum flowability disparity ranges from 17 mm to 37.8 mm over
173 a C/S spectrum of 10% to 25%. The marginal alterations in RMSM's flowability due to variations in C/S can
174 be attributed to two primary factors. Firstly, cement, in comparison to red-bed mudstone, boasts a lower

175 specific surface area. An escalation in C/S signifies an increased cement proportion in the mix, which
176 consequently results in a reduced total specific surface area. This reduction, in turn, decreases the quantity
177 required to form the water film, leading to an increment in the mixtures' flowability when the total water
178 consumption remains unchanged. Despite this, the impact remains minimal, manifesting as only a slight
179 increase in flowability.

180 Secondly, the sodium (Na^+) and potassium (K^+) ions adsorbed on the surface of the clay particles in the
181 red-bed mudstone undergo ion exchange reactions with the calcium (Ca^{2+}) ions produced during cement
182 hydrolysis. This reaction enhances the charged clay particles' attraction to the ions and reduces the thickness
183 of the clay particles' electric double layer (water film thickness) (Zhang et al. 2023b). This reduction facilitates
184 clay particle connection and agglomeration. Therefore, contrary to the results from the literature (Zhu et al.
185 2022), flowability does not increase monotonically with C/S increase. This discrepancy can be attributed to
186 different soil physical properties and the latter's use of coarse aggregate.

187 *3.1.2 Gradual loss in flowability*

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

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

197 the parameters a and b at different C/S and W/S shown in Table 3.

$$198 \quad y = ae^{(-x/60)} + b \quad (1)$$

199 To visualize the gradual loss in flowability more intuitively, the flowability loss ratio at a particular time
200 is defined as the difference between the flowability at that time and the initial flowability, divided by the initial
201 flowability. As cement hydration progresses over time, the strength of the mixtures increases, causing a
202 gradual decrease in flowability. As demonstrated in Fig. 6, all mixtures' flowability loss ratio progressively
203 increases over time, ranging between 30.2% and 43.7% at three hours. The flowability loss ratios for the
204 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
205 flowability loss ratio, respectively. The findings indicate that the loss of flowability in RMSM primarily occurs
206 within the first hour, and the rate of this loss decreases thereafter. Consequently, it is advisable to limit the
207 time from transporting to pouring RMSM to no more than one hour. Additionally, when C/S is fixed, the
208 flowability loss ratio decreases as W/S increases, except for 45% W/S due to its minimal initial flowability.
209 An increase in W/S necessitates more water for the mixtures, causing the cement particles to be more dispersed
210 and the cement hydration products' bond with the soil particles to be weaker. This leads to a decreased
211 flowability loss ratio. As time progresses, the hydration products of cement gradually increase, consuming
212 free water and strengthening the cementation between soil particles. This explanation can account for the
213 observed phenomenon where the flowability loss ratio increases with increasing C/S, given a fixed W/S.

214 From the above analysis, for RMSM mixed on-site with truck mixers, a W/S ratio of 50% is optimal for
215 satisfying flowability requirements. However, if field mixing proves restrictive and RMSM must be mixed
216 using in-plant central mixers, a higher W/S ratio of 55% is recommended. This adjustment ensures that RMSM,
217 even when subject to transportation times of up to one hour, continues to meet the necessary flowability criteria
218 by compensating for potential flowability loss. However, increasing the initial flowability of RMSM by raising

219 the water-to-solid ratio (W/S) is not a viable solution to mitigate flowability loss, due to the unavoidable
220 contradiction between initial flowability and strength. Given the severity of RMSM's flowability loss, which
221 varies between 22.9% and 35.6% within the first hour, it is essential to improve flowability retention.
222 Polycarboxylate superplasticizer (PCE) has been shown to reduce the water requirement in concrete
223 production and improve slump retention (Li et al. 2017, 2021). These findings have inspiration on reducing
224 the water requirement in RMSM and suggest the need to further improve the flowability retention of RMSM,
225 such as incorporating PCE and sulfonated acetone formaldehyde (Jian et al. 2022). Future research should
226 focus on the flowability retention of RMSM with additives, exploring new avenues to optimize this material's
227 performance.

228 **3.2 Bleeding rate**

229 Fig. 7 illustrates the bleeding rate for the mixtures over time, showing an increase as time progresses. It
230 is seen bleeding largely completes within the first 60 minutes, with no significant change observed between
231 60 and 180 minutes. This is largely attributable to the settlement of solid particles within the mixtures (Zhang
232 et al. 2011). At different heights within the mixtures, the effective stress on the soil particles varies. In the
233 initial stages following RMSM mixing, the soil particles within the mixtures are loosely configured due to
234 large inter-particle pores. Gravitational force causes fine particles to migrate into these pores, leading to the
235 compaction of the mixture and the rise of free water along open bleeding channels towards the upper part of
236 the mixtures. Over time, soil particle settlement completes and reaches a relatively stable state in the later
237 stages.

238 Additionally, when C/S is fixed at 10%, changes in W/S within the range of 45% to 60% significantly
239 influences the bleeding rate, which varies between 1.22% and 7.54%. This relationship is associated with the
240 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

263 upper limit for manual excavation. This characteristic of RMSM is beneficial, allowing for re-excavation at
264 later stages for future reconstruction work (Huang et al. 2016). When W/S is fixed at 50%, the strength of
265 RMSM increases from 0.443 MPa to 1.303 MPa as C/S increases from 10% to 25%. This is primarily due to
266 the fact that an increase of C/S leads to more cement hydration products being produced, which binds the soil
267 particles together, fills the gaps between soil particles, and forms a skeletal structure (Huang et al. 2006). It
268 can also be observed the strength decreases as W/S increases, implying an increase in free water content
269 hampers the development of strength. With higher free water content, the void ratio after curing is higher when
270 C/S is fixed. This means the treated soil is more loosely packed, reducing the bonded contact area and apparent
271 cohesion (Lorenzo and Bergado 2004). Further, the hydration and pozzolanic reactions slow down, leading to
272 weaker cementation between soil particles (Wan et al. 2023). As W/S increases, the soil particles tend to flow
273 more readily and adhere to the surface of hydration products, obstructing further cement hydration (Qian et al.
274 2019).

275 Fig. 10 shows the relationship between flowability and compressive strength for samples treated with a
276 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
277 strength and fresh density of RMSM, conversely, flowability escalates. Notably, maintaining a C/S at 10%
278 results in RMSM strength failing to attain 300 kPa, unless the initial flowability descends below 239 mm.
279 Moreover, RMSM strength does not breach 500 kPa unless the flowability diminishes under 160 mm (as
280 stipulated in Sec 3.1.1). These observations propose that under given conditions, the plausible fresh density
281 range of RMSM fluctuates between 1677 kg/m^3 and 1715 kg/m^3 . W/S evidently exerts a considerable
282 reduction effect on the compressive strength, manifesting an inherent conflict between flowability and
283 compressive strength. Polycarboxylate superplasticizer (PCE), a potent water-reducing agent ubiquitous in
284 concrete production, if employed in the production of red-bed mudstone-based RMSM, would permit RMSM

285 to meet the minimum flowability requirement at a lower W/S and attain higher compressive strength at a
286 consistent C/S. This method promises significant economic and environmental advantages.

287 **3.4 Deformation law**

288 *3.4.1 Stress-strain curves*

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

292 The stress-strain curves of RMSM exhibit a single peak shape or stable peak shape, broadly divided into
293 four stages: elastic, yield, stable, and softening. In the elastic stage, the stress growth rate is large and it
294 increases almost linearly with strain. No significant cracks are evident on the surface of the test specimen
295 Upon entering the yield stage, the stress-strain curve deviates from the straight line, and the stress growth rate
296 slows, then the strength reaches its peak. Meanwhile, the first crack or several longitudinal cracks appear in
297 the test specimens. Microcracks rapidly form in the area near the surface cracks. Post-peak, the curve enters
298 the softening stage where stress decreases with increasing strain and some test specimens display relatively
299 uniform crack development and spalling appears on the side. This can be attributed to the presence of pores
300 of the test specimen. Cracks then extend from weak point to the upper and lower ends of it, creating
301 longitudinal penetrating cracks. The test specimens fractured vertically into multiple smaller blocks,
302 configuring a quadrangular pyramid with an approximate angle of 45°, resulting in a strength decrement. Fig.
303 12 displays the representative failure pattern of an RMSM specimen. Notably, in comparison to the pre-test
304 specimen, there is a substantial reduction in height, signifying the specimen underwent significant plastic
305 deformation.

306 A stable phase is only achieved at certain C/S or W/S. With a fixed C/S at 10%, a significant period of

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

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

$$318 \mu = \varepsilon_{\mu} / \varepsilon_f \quad (2)$$

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

321 Multivariate regression analysis on the 16 experimental results generated the best-fit curves for various
322 C/S and W/S, as depicted in Fig. 13. The regression analysis revealed an R^2 value of 0.982, signifying that the
323 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
324 60%, μ rises from 2.21 to 4.21, experiencing respective growth rates of 22.2%, 50.7%, and 90.5%. Conversely,
325 when C/S is anchored at 25%, μ escalates from 1.61 to 2.31, registering growth rates of 10.6%, 31.6%, and
326 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
327 impact on μ diminishes as C/S increases. The regression analysis reveals a strong linear positive relationship
328 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:

$$E_{50} = \sigma_{0.5} / \varepsilon_{0.5} \quad (3)$$

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 $E_{50} = (54 \sim 240) q_u$ 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

351 widespread application (Zhou et al. 2023). This section compares the construction cost and carbon footprint
352 of three backfill methods: soil cement, RMSM, and concrete, applied to a 0.5 m × 2 m × 1 km municipal
353 pipeline trench. For simplicity, the single-track distance for comparison was set at 10 km, with material
354 proportions and consumption detailed in Table 4. Costs were estimated excluding mechanical expenses, except
355 for transportation, as shown in Table 5. RMSM saved 6.17k USD and 30.8% compared to soil cement,
356 reducing the construction period by 40%. Against concrete backfill, RMSM saved 55.42k USD and 80.0%.
357 The unit prices and proportions of soil cement and concrete used in this study's estimations were extracted
358 from conditions that may vary, possibly introducing errors, yet still demonstrating RMSM's cost and efficiency
359 benefits.

360 For carbon footprint comparison, the Functional Unit defined as CO₂-equivalent emitted (kgCO₂-e/kg)
361 for backfilling 1 m³ of space was used. CO₂ emissions from the entire production cycle were considered for
362 each material, with values sourced from literature and summarized in Table 6. For cement (E₂), emissions
363 include mining of raw materials, manufacture, and transportation of cement. Emissions for fine (E₄) and coarse
364 aggregates (E₅) encompass quarrying, crushing, and transport to concrete manufacture (Turner and Collins
365 2013). The CO₂ emissions from batching, carriage, placing, and pouring of concrete (E₆) and RMSM's similar
366 production processes were also considered (Turner and Collins 2013), alongside soil cement preparation and
367 transportation emissions (E₇) (Quan et al. 2023). The carbon footprints for preparing 1.0 m³ of soil cement,
368 RMSM, and concrete were calculated as 165.7 kgCO₂-e/m³, 122.8 kgCO₂-e/m³, and 398.3 kgCO₂-e/m³,
369 respectively. RMSM's CO₂ emissions were reduced by 42.9 kgCO₂-e/m³ (25.9%) compared to soil cement,
370 and by 275.5 kgCO₂-e/m³ (69.2%) compared to concrete. RMSM also reduced dust pollution by 70% and
371 labor costs by 84% compared to soil cement (Jian et al. 2022; Tran et al. 2023). Additionally, RMSM has the
372 potential to further utilize solid waste as a cement substitute, such as phosphogypsum (Jian et al. 2022) , red

373 mud (Wang et al. 2022) and blast furnace slag (Sheen et al. 2013), reducing cement use and CO₂ emissions.
374 Therefore, RMSM is a sustainable and environmentally-friendly backfill option, particularly for pipeline
375 trench applications, compared to soil cement and concrete.

376 **4 Conclusions**

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

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

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

394 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 CO₂ 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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592

593 **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

594

595

596 **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

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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

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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

603 **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 persons in 1 day	4 persons in 1 day
		4.20k USD	0.17k USD	0.17k USD
Total cost		20.01k USD	13.84k USD	69.26k USD

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606 **Table 6.** CO₂ 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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