

Mechanical and microstructural characterization on novel flowable solidified soil from completely decomposed granite and bio-carbonated reactive magnesia cement

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ABSTRACT Advancing sustainable infrastructure requires integrating biotechnological processes with geomaterial valorization. This study evaluates a novel flowable solidified soil (FSS) produced from completely decomposed granite (CDG) and bio-carbonated reactive magnesia cement (RMC), using polycarboxylate (PCE) and melamine water-reducing admixtures to optimize performance. Laboratory tests investigated the slump flow, density, unconfined compressive strength (UCS), secant modulus of elasticity (E_{50}), degree of carbonation (DC), composition and microstructure of bio-carbonated specimens (BC-specimens) with different bacterial solution (BS) and admixture contents. The results show that all BC-specimens met FSS flowability and strength requirements. Increasing BS content enhanced slump flow and DC but reduced density and UCS due to increased porosity. Both admixtures markedly enhanced flowability (maximum slump flow 30.60 cm at 55% BS and 1% melamine), while density and E_{50} changed little. However, PCE reduced DC and UCS, whereas melamine enhanced both, achieving a maximum UCS of 1.47 MPa at 45% BS and 1% melamine. PCE induced air entrainment and inhibited the bio-carbonation through steric hindrance and Mg^{2+} complexation, while melamine improved particle dispersion and Mg^{2+} availability. Overall, the proposed FSS is feasible, and melamine is recommended for practice. These results provide guidance for developing more sustainable FSS.

KEYWORDS FSS, CDG, RMC, bio-carbonation, water-reducing admixture

1 Introduction

Flowable solidified soil (FSS) is a typical controlled low-strength material. Owing to its moderate strength, high flowability, and low permeability, FSS has been widely applied to backfilling of foundation pits, pipelines,

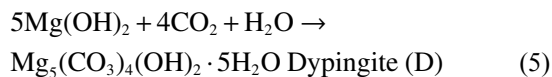
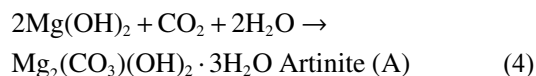
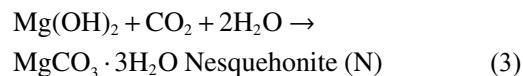
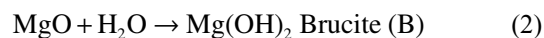
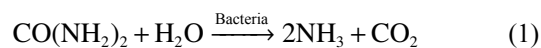
retaining walls, and underground voids [1,2]. According to the Chinese standard T/BGEA 001-2019 [3], the minimum compressive strength and the required slump range for roadbed backfill FSS are 0.4 MPa and 80–150 mm, respectively. FSS is typically produced by mixing excavated soil with cementitious binders, water, and admixtures [4]. Ordinary Portland cement (OPC) is

the most commonly used binder. However, its production requires high calcination temperatures ($> 1400\text{ }^{\circ}\text{C}$), which consumes substantial energy and contribute to greenhouse gas emissions [5]. It is reported that OPC production contributes approximately 7% of global anthropogenic CO_2 emissions, and the percent increases higher in recent years [6,7]. With increasing emphasis on environmental sustainability, the carbon footprint and resource efficiency of conventional FSS have attracted growing concern. Accordingly, there is a need to develop a novel FSS with highly efficient and low-carbon properties.

Completely decomposed granite (CDG) is a residual soil formed by prolonged and intensive weathering of granite [8]. CDG often contains by the factors of low strength, high compressibility, and pronounced softening and disintegration upon water exposure, which can result in negative outcomes, including foundation liquefaction and slope instability [9]. In regions with widespread granite distribution, such as southeastern coastal China, the large amount of CDG generated annually from urban construction occupies land and causes environmental concerns [10]. Therefore, its resource utilization is the essential pathway to addressing the accumulation of construction spoil. Although weathered, CDG particles retain a certain skeletal structure. CDG can form a solidified soil with high strength and good integrity with the suitable binders, meeting the requirements for most backfilling and structural applications [11]. Additionally, the particle size distribution of CDG typically falls between sand and silt, making it easier to formulate into a flowable material [12]. Moreover, using CDG as the basic material for FSS preparation enables the direct utilization of waste CDG from excavation or tunneling, eliminating costs associated with off-site disposal and the procurement of new materials, thereby reducing overall costs by 30%–50% [13,14]. This approach provides a practical and cost-effective pathway for waste valorization and resource-efficient FSS applications.

Reactive magnesia cement (RMC) has attracted considerable attention because it can uptake CO_2 and thereby contribute to carbon sequestration [15]. RMC can be produced at relatively low calcination temperatures ($750\text{ }^{\circ}\text{C}$), and its raw materials may be sourced from seawater, which can reduce the environmental burden relative to OPC [16,17]. However, in geotechnical applications, capturing and supplying CO_2 to promote carbonation reactions is often challenging. To address this limitation, Yang et al. [18] proposed an approach that couples RMC bio-carbonation with the urea hydrolysis in microbially induced calcite precipitation (MICP). In this approach, ureolytic bacteria hydrolyze urea to generate carbonate species, which accelerate RMC carbonation and promote the formation of hydrated magnesium carbonates (HMCs), including nesquehonite (N), artinite

(A), dypingite (D), and hydromagnesite (H) (Eqs. (1)–(6)) [19,20]. Previous studies have demonstrated the feasibility of stabilizing various geomaterials using bio-carbonated RMC, including soil [18], electrolytic manganese residue [21], dredged sludge [22], and construction and demolition waste [23]. Compared with typical MICP and RMC carbonation, the bio-carbonated RMC treatment is simple and efficient, requiring only a single mixing operation [24,25]. This eliminates the need for the lengthy cyclic grouting used in typical MICP and the extended pressure curing required for typical RMC carbonation [26,27]. It also overcomes the limitation of typical RMC carbonation, which cannot be applied in flowable placements, while achieving better performance improvement than typical MICP [28,29]. Moreover, the RMC bio-carbonation is well suited to flowable placement due to its high liquid-phase content and early-age retardation [30,31]. Therefore, bio-carbonated RMC holds promise for the preparation of novel FSS that combines high flowability with strength.



The high flowability of FSS is typically achieved by increasing the water content, but higher water content generally reduces strength. To resolve the conflict between flowability and strength, water-reducing admixtures are commonly incorporated in construction materials. Typical water-reducing admixtures include polycarboxylate (PCE), melamine, naphthalene, and lignin types [32]. As a representative early-stage water-reducing admixture, melamine improves flowability efficiently mainly by dispersing particles through electrostatic repulsion [33]. On the other hand, PCE emerged, achieving higher water reduction and enhanced slump retention through synergistic electrostatic repulsion and steric hindrance [34]. PCE have become the predominant modern water-reducing admixtures. However, previous studies have also revealed that PCE has the potential to change the hydration of OPC and RMC relevant to RMC bio-carbonation, modify the morphology of hydration products [35]. At present, the

mechanisms by which water-reducing admixtures affect the RMC bio-carbonation process remain poorly understood. Therefore, systematic investigations are needed to elucidate these effects and identify suitable types and contents of water-reducing admixture for bio-carbonated RMC systems.

Accordingly, this study proposes a novel FSS from CDG and bio-carbonated RMC, incorporating two typical water-reducing admixtures (PCE and melamine). The feasibility and performance of the novel FSS, as well as the bacterial solution (BS) and water-reducing admixture effects on the mechanical performance and underlying mechanisms should be explored and systematically investigated.

In this study, through a series of laboratory tests, the effects of BS and water-reducing admixture content on the slump flow, density, mechanical properties, and degree of carbonation (DC) of bio-carbonated specimens (BC-specimens). The composition and microstructure effects of PCE and melamine were also investigated. The results are expected to facilitate the efficient utilization of CDG, expand the engineering applications of bio-carbonated RMC, and provide valuable insights for developing more sustainable FSS.

2 Materials and methods

2.1 Materials

2.1.1 Completely decomposed granite

The CDG used in this study was collected at a depth of 8–11 m in Tsim Sha Tsui, Kowloon, Hong Kong, China. After sampling, the CDG was crushed to pass a 5 mm sieve and then dried at 105 °C for 24 h. The particle size distribution of the CDG (Fig. 1) is determined in accordance with ASTM D2487-11 [36]. The uniformity coefficient C_u and coefficient of curvature C_c were 0.56 and 0.89, respectively, suggesting a poorly graded soil with a discontinuous gradation. The bulk density was measured as 2.59 in accordance with GB/T 50123-2019 [37].

2.1.2 Reactive magnesia cement

The RMC used in this study was supplied by Shanghai Yuanjiang Chemical Co., Ltd., China. According to Chinese standard YB/T 4019-2020 [38], the chemical activity time was 12–25 s and the active MgO content

was 74%–80%. The physical properties and chemical composition of RMC are summarized in Table 1. The particle size distribution curve is presented in Fig. 1. It can be observed that most particles are smaller than 0.02 mm, indicating that RMC is substantially finer than CDG, which can effectively fill the pores of CDG.

2.1.3 Bacterial solution

The ureolytic bacteria used in this study was *Sporosarcina pasteurii* (ATCC 11859), a strain widely used in biomineralization field. The preparation procedure for the BS is shown in Fig. 2(a). An NH_4 -YE medium (20 g/L Yeast Extract, 10 g/L $(\text{NH}_4)_2\text{SO}_4$, and 15.73 g/L Tris-base) was prepared for culturing *Sporosarcina pasteurii*. The medium was sterilized at 121 °C and 0.1 MPa for 20 min and then cooled to room temperature ((25 ± 2) °C). Subsequently, *Sporosarcina pasteurii* was inoculated at 5% and incubated in a shaking incubator at 30 °C and 200 r/min for 24 h. Following Whiffin [39], the optical density at 600 nm (OD_{600}) of the BS was 1.25, and the urease activity was 9.3 U (1 U = 1 mmol/L urea hydrolyzed/min).

2.1.4 Water-reducing admixture

The PCE and melamine used in this study were supplied by Shanghai Chenqi Chemical Technology Co., Ltd., China. Their primary properties are summarized in Table 2.

2.2 Specimen preparation

In this study, a series of BC-specimens were prepared

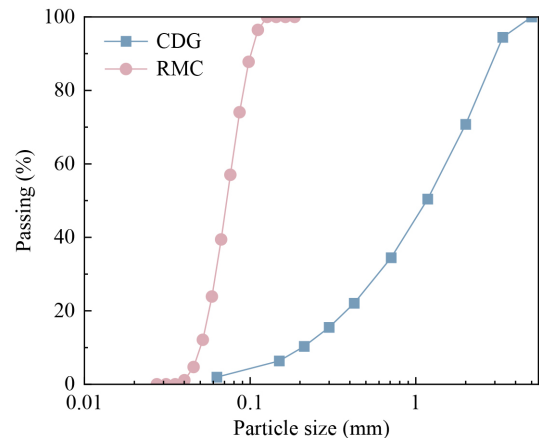


Fig. 1 Particle size distribution curves of CDG and RMC.

Table 1 Physical properties and chemical composition of RMC

Material	Physical property		Chemical composition (%)			
	Specific gravity (g/cm^3)	Specific surface area (m^2/g)	MgO	CaO	Cl^-	SO_4^{2-}
RMC	3.0	5–20	99	0.5	0.05	0.28

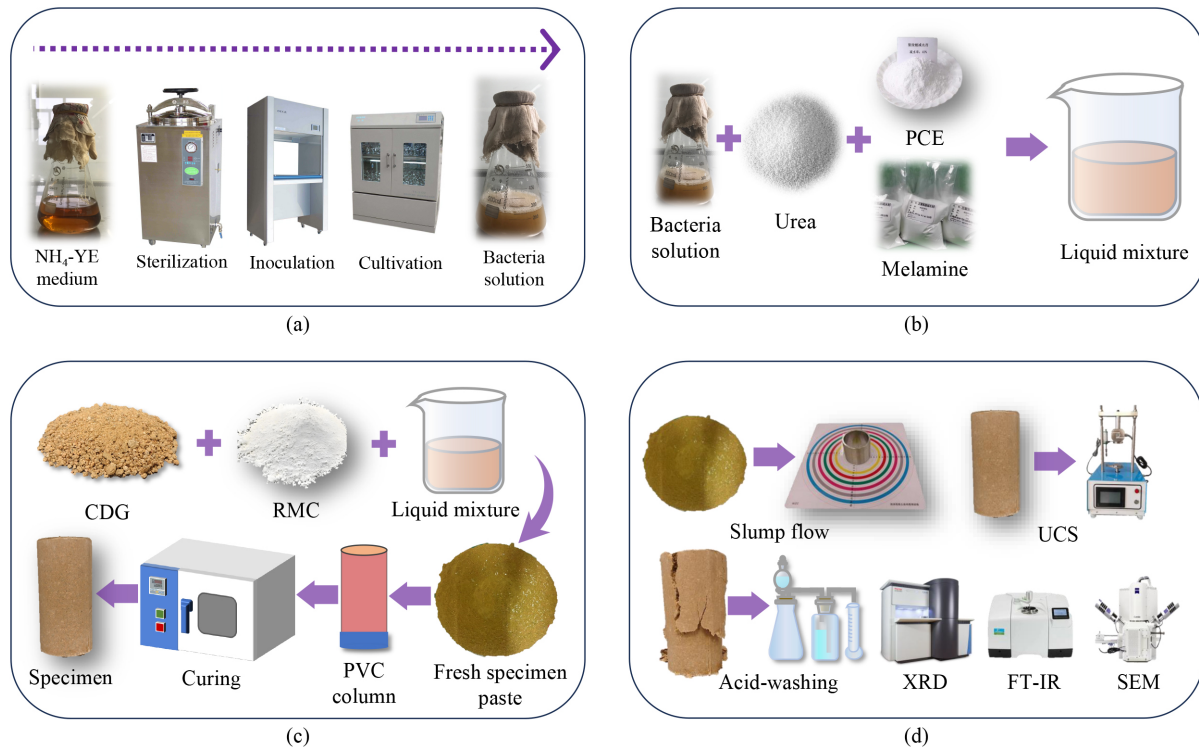


Fig. 2 Preparation and testing procedure of the BC-specimens: (a) bacterial solution preparation; (b) liquid mixing; (c) specimen preparation and curing; (d) test methods.

Table 2 Properties of PCE and melamine

Material	Appearance	pH value	Density (kg/m^3)	Water reducing ratio (%)	Chloride content (%)
PCE	white powder	5–7.5	400–600	< 28	≤ 0.10
Melamine	white powder	9–11.4	450–750	< 12	–

with different BS contents (45%, 50%, and 55%) and water-reducing admixture contents (0%, 0.1%, 0.25%, 0.5%, and 1%) of PCE and melamine. The BS content (45%–55%) was determined through preliminary experiments. Insufficient BS results in poor flowability, whereas an excessive content tends to cause bleeding and segregation, thereby weakening the uniformity and strength development of the specimens. The water-reducing admixture content (0%–1%) was selected based on relevant published literature [33–35]. This range can cover the effective working interval and avoid negative effects caused by excessive content, including retardation, excessive air entrainment, and strength reduction. In addition, the RMC content was set at 10% because an excessively high RMC content would significantly increase the construction cost and make the paste too

viscous to satisfy the flowability requirement, while an insufficient content would fail to reach the target strength. The urea concentration was set at 2.5 mol/L [23]. The calculation formulas for the content of RMC, BS, and water-reducing admixture are given in Eqs. (7)–(9). The detailed mix proportions for each group of BC-specimens are listed in Table 3. As we all known, conventional cementitious materials generally achieve stable mechanical properties at 28 d. To maintain consistency with previous studies, 28 d was selected as the standard curing age. The early-strength characteristics of magnesia-based bio-cement have been well verified in the literature, confirming its early-age effectiveness for FSS applications [23,25].

$$C_{\text{RMC}} = \frac{m_{\text{RMC}}}{m_{\text{CDG}}} \times 100\%, \quad (7)$$

Table 3 Detailed mix proportions of BC-specimens

No.	RMC content (%)	BS content (%)	Water-reducing admixture type	Water-reducing admixture content (%)
BC	10	45, 50, 55	–	0
BCP	10	45, 50, 55	PCE	0.1, 0.25, 0.5, 1
BCM	10	45, 50, 55	melamine	0.1, 0.25, 0.5, 1

$$C_{BS} = \frac{m_{BS}}{m_{CDG} + m_{RMC}} \times 100\%, \quad (8)$$

$$C_W = \frac{m_W}{m_{RMC}} \times 100\%, \quad (9)$$

where m_{RMC} denotes the weight of RMC (g); m_{CDG} denotes the weight of CDG (g); m_{BS} denotes the weight of BS (g); m_W denotes the weight of water-reducing admixture (g).

The preparation procedure for BC-specimens is shown in Figs. 2(b) and 2(c), and the specific steps are as follows: First, the BS, urea, and water-reducing admixture were mixed according to the mix proportions in Table 3 to obtain a liquid mixture. Next, CDG and RMC were added to the liquid phase and mixed thoroughly until a uniform fresh paste was obtained. Then the fresh paste cast into PVC column molds ($\Phi 50 \text{ mm} \times 100 \text{ mm}$) and vibrated to improve compaction. Finally, the BC-specimens were cured for 28 d (30 °C, 95% relative humidity (RH)). A total of 27 groups of 81 BC-specimens were prepared, and each group was prepared in triplicate.

2.3 Testing methods

2.3.1 Slump flow

Slump flow tests (Fig. 2(d)) were conducted on the fresh paste to systematically evaluate the effects of BS and water-reducing admixtures content on the flowability of BC-specimens. First, the fresh paste was filled into a cylindrical mold ($\Phi 80 \text{ mm} \times 80 \text{ mm}$). The mold was then lifted vertically at a slow, constant rate, allowing the paste to spread under its self-weight. After the spread stabilized, the maximum diameters in two orthogonal directions were measured using a straightedge, and their average was the slump flow. The test process followed the Chinese standard T/BGEA 001-2019 [3].

2.3.2 Unconfined compressive strength (UCS)

UCS tests (Fig. 2(d)) were conducted on the BC-specimens cured for 28 d to evaluate the effects of BS and water-reducing admixture content on the mechanical properties. The BC-specimens were loaded at a constant displacement rate of 1 mm/min, and the test was terminated after the axial stress reached the peak value and decreased to 80% of the peak. All UCS tests were performed in accordance with ASTM D2166/D2166M-18 [40].

2.3.3 Degree of carbonation

For better quantify the influence of BS and water-reducing admixture content on the bio-carbonation of BC-specimens, acid-washing tests (Fig. 2(d)) were

conducted. After UCS testing, representative specimen fragments were collected for acid washing. The fragments were reacted with 50 mL of 0.1 mol/L HCl, which dissolved carbonate phases and released CO_2 . The released CO_2 volume was measured using a water displacement method, and the molar amount of carbonate was calculated from the measured gas volume (Avogadro's law). However, owing to the inherent complexity of bio-carbonated RMC, directly quantifying the amount of HMCs formed remains challenging. Accordingly, the DC, proposed by Wang et al. [41], was adopted to characterize the extent of RMC bio-carbonation and the relative formation of HMCs. The DC calculation is shown in Eq. (10):

$$DC = \frac{M_{\text{CO}_3^{2-}}}{M_{\text{MgO}}}, \quad (10)$$

where $M_{\text{CO}_3^{2-}}$ denotes the molar amount of the carbonate (mol); M_{MgO} denotes the molar amount of MgO (mol).

2.3.4 Composition and microstructure

To characterize the effects of PCE and melamine on the composition and microstructure of BC-specimens, The BC group at 50% BS were used as the control. For comparison, the BCP and BCM groups were prepared at 50% BS with 1% water-reducing admixture content. These fractured BC-specimens after UCS testing were freeze-dried and sieved through a 0.075 mm mesh. X-ray diffraction (XRD, K-Alpha, Thermo Fisher Scientific) was performed to identify mineral phases at the scanning rate of 4°/min over the 2θ range of 5°–75°. Fourier transform infrared spectroscopy (FT-IR, UATR Two, PerkinElmer) was used to examine functional groups over 4000–400 cm^{-1} . For microstructure observation, freeze-dried BC-specimens were cut into 5 mm $\times$ 5 mm $\times$ 5 mm cubes and examined using scanning electron microscopy (SEM, TESCAN VEGA3, secondary electron mode) at magnifications of 100 $\times$ and 2000 $\times$.

3 Results

3.1 Slump flow

Figure 3 illustrates the variation in slump flow of BC-specimens with PCE and melamine. The slump flow increases monotonically with higher BS content. Regarding the BS content effects, the slump flow increases from 17.35 cm (45% BS content) to 24.35 cm (55% BS content), corresponding to increases of 40.35% compared to that of 45% BS content. The similar trends are observed in BCP and BCM groups. These results demonstrate that higher BS content improves the flowability of BC-specimens.

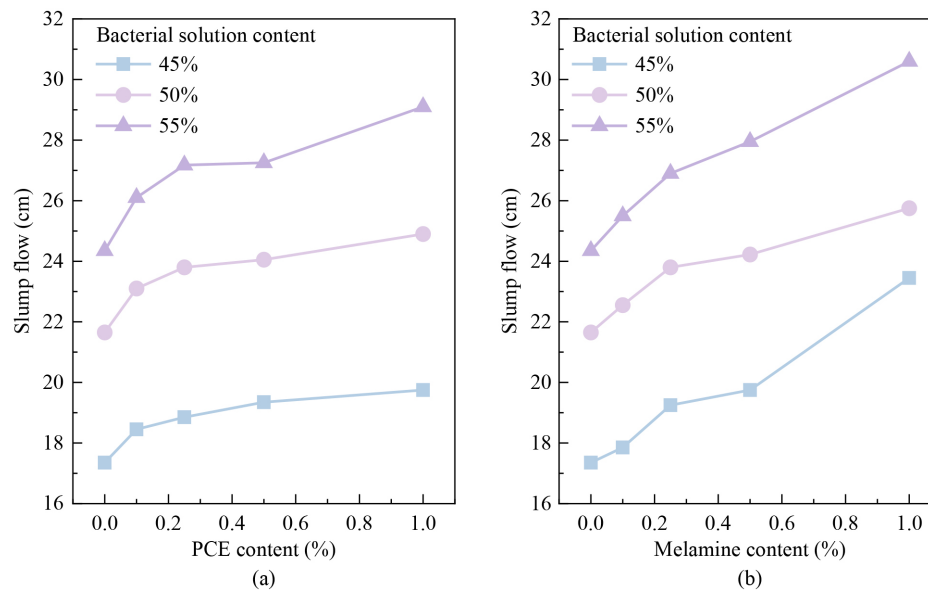


Fig. 3 Slump flow of BC-specimens with PCE and melamine: (a) PCE; (b) melamine.

Further analysis indicates that slump flow also increases with higher water-reducing admixture content. This trend is consistent with the typical rheological response of cementitious pastes to water-reducing admixtures. As the water-reducing admixture content increases from 0% to 1%, the slump flow of BCP and BCM groups (50% BS content) increases from 21.65 to 24.90 and 27.75 cm, increasing by 15.01% and 18.94%, respectively. Comparable trends are observed at other BS contents. Overall, melamine produces a greater increase in slump flow than PCE at the same BS content, indicating greater flowability enhancement of BC-specimens.

3.2 Density

Figure 4 illustrates the density variations of each tested BC-specimens. Clear differences are observed among the different BS groups. To facilitate comparison, the average

density of each group was used for subsequent analysis. The density decreases slightly with higher BS content. Regarding the BS content effects (Fig. 4(a)), the density decreases from 1.76–1.77 g/cm³ (45% BS content) to 1.71–1.72 g/cm³ (55% BS content), corresponding to a reduction of 2.41%–2.94%. These results indicate that higher BS content produces a decrease in BC-specimen density.

Further analysis is conducted to assess the effect of water-reducing admixtures on the density of BC-specimens. No clear monotonic relationship between admixture content and density can be observed. Overall, the density remains approximately constant or varied only slightly. At the BS contents of 45%, 50%, and 55%, the density ranges are 1.76–1.78, 1.73–1.76, and 1.71–1.72 g/cm³, respectively. Comparisons between PCE and melamine, the effect of water-reducing admixtures on density is minor as no clear trends can be observed, suggesting that the type and content of water-reducing

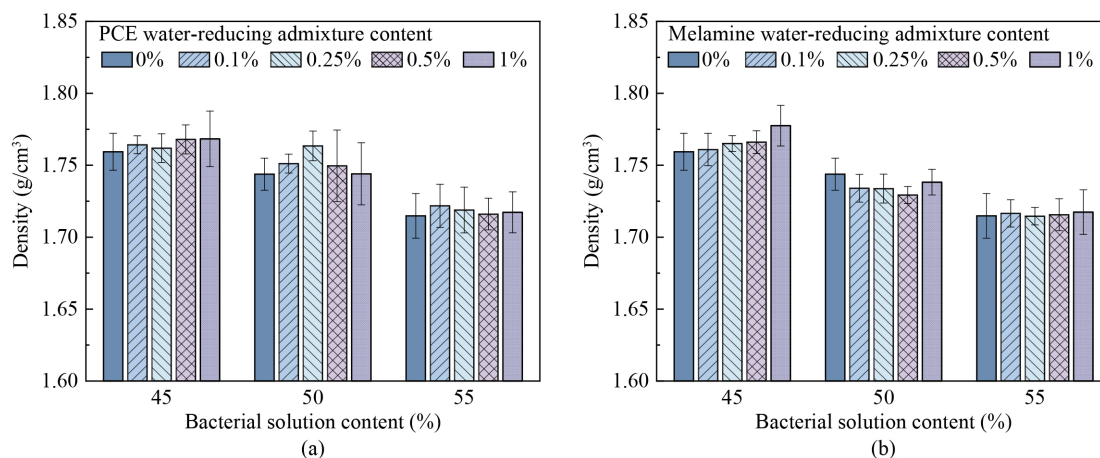


Fig. 4 Density of BC-specimens with PCE and melamine: (a) PCE; (b) melamine.

admixture are not dominant factor controlling density variation.

3.3 Stress–strain curves

Figures 5 and 6 show typical stress–strain curves for BC-specimens with PCE and melamine, respectively. For all the tested curves, the axial stress increases linearly with axial strain during the initial stage, representing the elastic deformation phase of BC-specimens. Subsequently, the rate of increase in axial stress gradually slows down, continuing to rise nonlinearly to a peak, representing the plastic deformation stage. Beyond the peak, as axial strain further increases, the curve exhibits a downward trend, indicating that the BC-specimens exhibit obvious strain-softening characteristics.

As shown in Figs. 5 and 6, the peak stress decreases with higher BS content but shows different changes with water-reducing admixtures. In contrast, the strain at peak stress increases, suggesting a progressive shift toward more ductile failure. For the BCP group, the peak strain increases from 1.10%–1.56% (45% BS content) to 1.18%–1.80% (55% BS content). Similarly, it increases from 1.09%–1.68% to 1.27%–2.00% in BCM group. These observations indicate that higher BS content substantially alters the stress–strain curves. The BC-specimens failure mode shifts from brittle to more ductile behavior. In contrast, water-reducing admixture content has a weaker effect on the stress–strain curves, causing only slight quantitative changes rather than any pronounced change in the overall curve shape.

3.4 Unconfined compressive strength and E_{50}

The UCS and E_{50} of BC-specimens are determined from the stress–strain curves. The UCS and E_{50} represent the strength and stiffness of the material, respectively. Figures 7 and 8 summarize the UCS and E_{50} results for BC-specimens with PCE and melamine, respectively. It can be found that the UCS decreases monotonically with higher BS content (Figs. 7(a) and 8(a)). The UCS decreases from 1.36 MPa (45% BS content) to 0.73 MPa (55% BS content), corresponding to reduction of 46.32% compared to the 45% BS content. These results indicate that higher BS contents hinder strength development of BC-specimens. Moreover, at the same BS content, the UCS decreases with higher PCE content (Fig. 7(a)). For example, at the 45% BS content, the UCS decreases from 1.36 MPa (BC group) to 1.21 MPa (BCP group) with 1% PCE content, corresponding to an 11.03% reduction. In contrast, the UCS increases with higher melamine content (Fig. 8(a)). At the 45% BS content, the UCS reaches 1.47 MPa (BCM group) at the 1% melamine content, representing an 8.09% increase compared to the BC group. Overall, PCE decreases the strength of BC-specimens, whereas melamine enhances the strength.

Moreover, E_{50} also decreases with higher BC content (Figs. 7(b) and 8(b)). E_{50} decreases from 115.45 MPa (45% BS content) to 67.96 MPa (55% BS content), corresponding to a 41.13% reduction. This result suggests that higher BS content reduces the stiffness development in BC-specimens. Further analysis shows that BC content

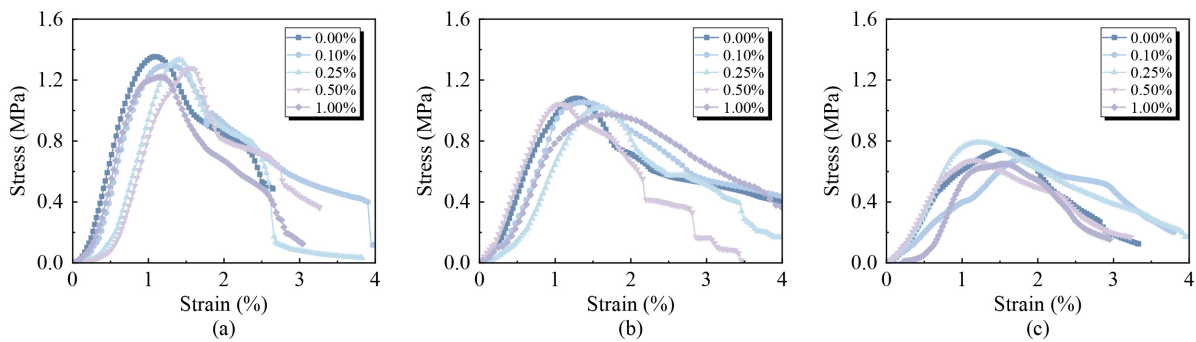


Fig. 5 Stress–strain curves of BC-specimens with PCE: (a) CBS = 45%; (b) CBS = 50%; (c) CBS = 55%.

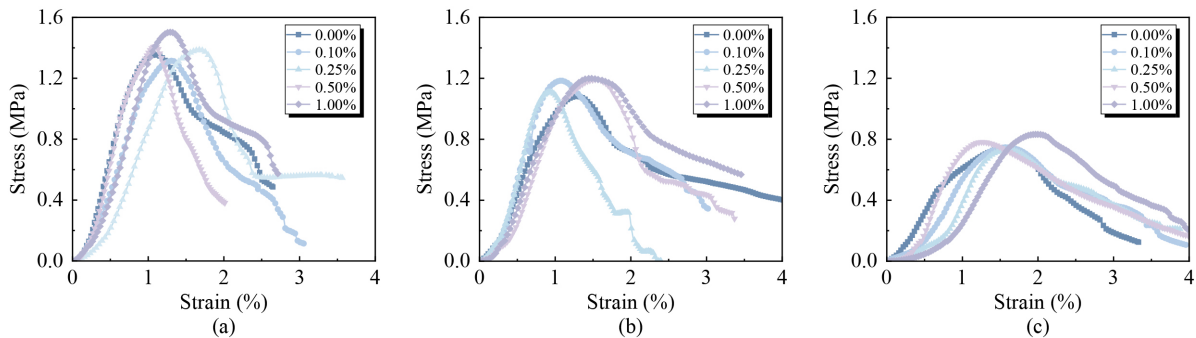


Fig. 6 Stress–strain curves of BC-specimens with melamine: (a) CBS = 45%; (b) CBS = 50%; (c) CBS = 55%.

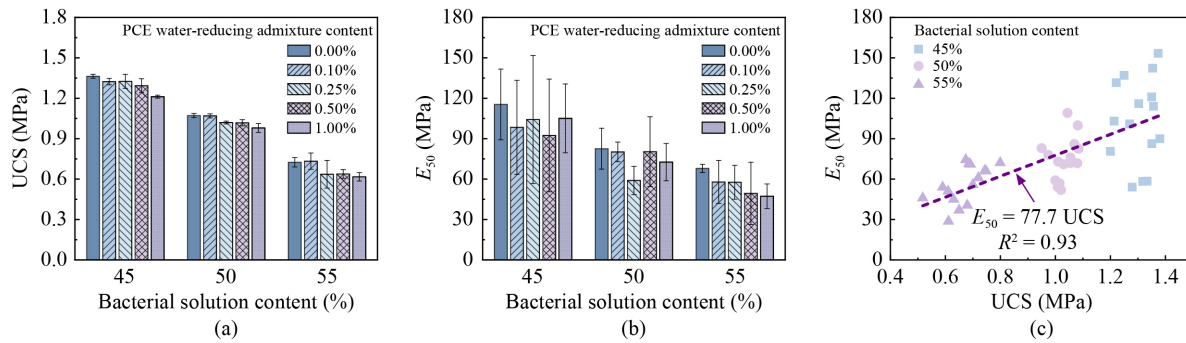


Fig. 7 Mechanical behavior of BC-specimens with PCE water-reducing admixtures: (a) UCS; (b) E_{50} ; (c) relationship between UCS and E_{50} .

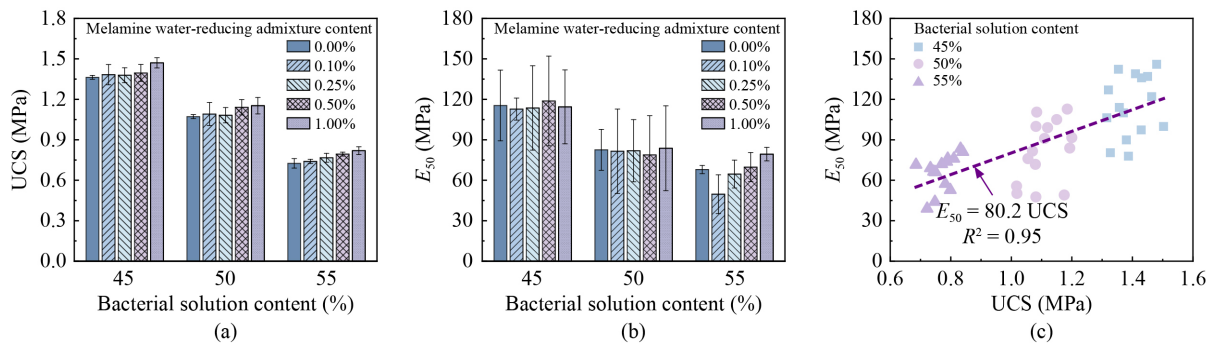


Fig. 8 Mechanical behavior of BC-specimens with melamine water-reducing admixtures: (a) UCS; (b) E_{50} ; (c) relationship between UCS and E_{50} .

variability in E_{50} is larger than the differences associated with changes in water-reducing admixture content, indicating a limited content effect on stiffness. Nevertheless, water-reducing admixture type influences stiffness to some extent. At the 45% BS content, the E_{50} values range of the BCP and BCM groups are 92.43–115.45 and 112.79–118.81 MPa, respectively. Compared with PCE, the melamine produces a narrower E_{50} range, indicating more stable stiffness. Overall, melamine has a smaller influence on stiffness variability than PCE on BC-specimens.

Figures 7(c) and 8(c) show the relationship between UCS and E_{50} for BC-specimens with PCE and melamine, respectively. It can be found that the higher BS content reduces the UCS and E_{50} in each group, both UCS and E_{50} exhibit a strong positive linear relationship ($R^2 > 0.93$), and the data is well described by a linear equation. This is consistent with the relationship between UCS and E_{50} in conventionally solidified soil [42]. This indicates that despite BS and water-reducing admixture both influence the strength and stiffness of BC-specimens, they do not alter the intrinsic correlation between UCS and E_{50} .

3.5 Degree of carbonation

Figure 9 shows the DC values of BC-specimens with PCE and melamine. The DC increases with higher BS

content. DC increases from 0.28 at the 45% BS content to 0.44 at the 55% in BC group, corresponding to increases of 57.14% compared to 45% BS content. These results suggest that higher BS content enhances HMCs formation and increases the degree of RMC bio-carbonation. For the BCP group (Fig. 9(a)), the DC variation is minimal at low PCE contents, while shows significant decreases at high PCE content ($> 0.25\%$). As the PCE content increases from 0% to 1%, the DC decreases from 0.28 to 0.24 at the 45% BS content, decreasing by 15.85%. In contrast, for the BCM group (Fig. 9(b)), the DC increases with higher melamine content. As the melamine content increases from 0% to 1%, the DC increases from 0.28 to 0.32 at the 45% BS content, increasing by 14.29%. These results indicate that melamine enhances the RMC bio-carbonation reaction, but higher PCE content ($> 0.25\%$) are unfavorable for HMCs formation.

3.6 X-ray diffraction

Figure 10 shows the XRD patterns of BC-specimens. Quartz ($2\theta = 20.88^\circ, 26.64^\circ, 45.82^\circ, \text{ and } 59.90^\circ$) and kaolinite ($2\theta = 12.08^\circ, 20.18^\circ, 24.84^\circ, \text{ and } 36.54^\circ$) remain the principal minerals, with only minor changes in peak positions and intensities. This behavior is expected because quartz and kaolinite are the dominant composition in the CDG, which does not participate in RMC bio-carbonation process. In addition, peaks

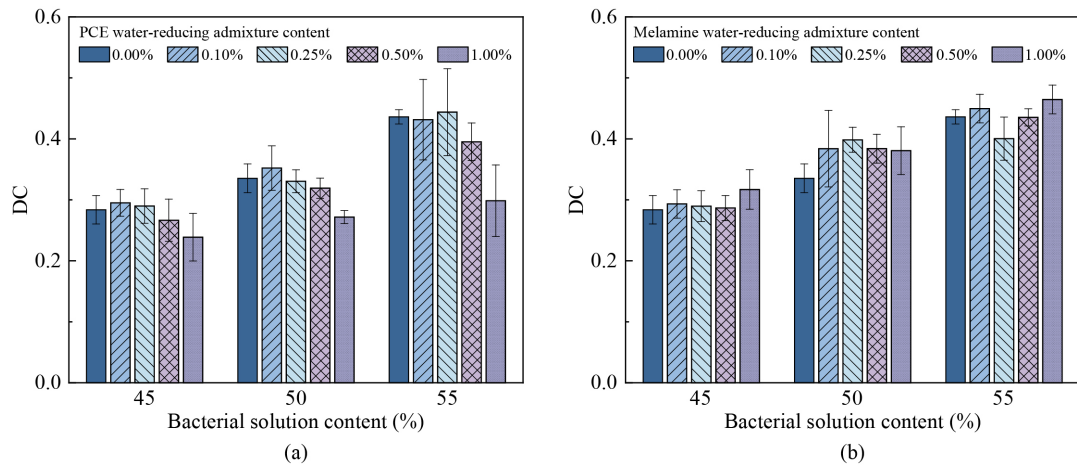


Fig. 9 DC of BC-specimens with PCE and melamine: (a) PCE; (b) melamine.

attributable to dypingite ($2\theta = 15.14^\circ$, 30.82° , and 38.44°) and hydromagnesite ($2\theta = 30.22^\circ$) are identified in all BC-specimens. Notably, compared to the BC group, the dypingite peak at $2\theta = 38.44^\circ$ shows lower intensity in the BCP group, but shows higher intensity in the BCM group. This demonstrates that the water-reducing admixture influences the morphology of HMCs in BC-specimens. Overall, the intensities of dypingite and hydromagnesite peak in the BC-specimens are lower and show minor variations. This can be attributed to the diverse composition of CDG, the complex process of bio-carbonated RMC, and the generation of amorphous HMCs. Therefore, XRD has limited capability in providing more detailed insights of HMCs, requiring more testing and analysis.

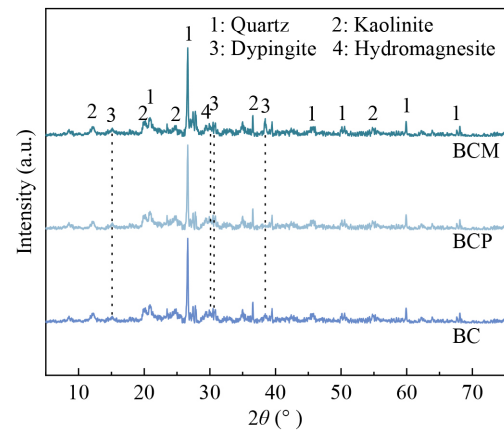


Fig. 10 XRD patterns of BC-specimens.

3.7 Fourier transform infrared spectroscopy

Figure 11 displays the FT-IR spectra of BC-specimens. It can be observed that the peaks of all BC-specimens are primarily concentrated in the range of $400\text{--}1500\text{ cm}^{-1}$. The peak at 1027 cm^{-1} corresponds to the antisymmetric stretching vibration of Si–O–Si bonds [43], confirming the presence of quartz in the BC-specimens. Additionally, the peaks of 1437 and 1486 cm^{-1} represent the antisymmetric stretching vibration of carbonate in HMCs [44], indicating the HMCs generation. Compared with the BC group, the BCP group exhibits lower intensities at 1437 and 1486 cm^{-1} , but the BCM group shows higher intensities. This indicates that PCE inhibits HMCs generation in the BC-specimens, but melamine promotes it. Overall, the PCE and melamine do not substantially alter the infrared spectral characteristics, because the low water-reducing admixture content in the BC-specimens.

3.8 Scanning electron microscopy

Figure 12 illustrates the SEM image of all BC-specimens. For BC group (Figs. 12(a) and 12(b)), CDG particle

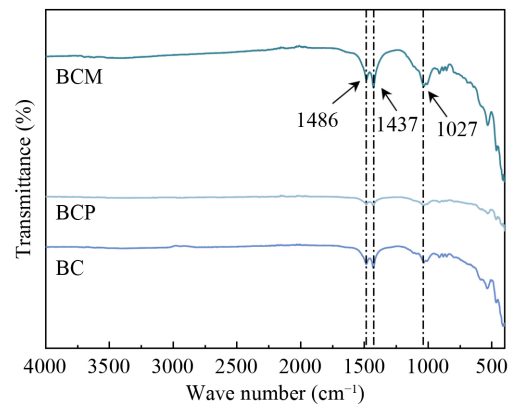


Fig. 11 FT-IR spectra of BC-specimens.

surfaces are covered by HMCs, mainly rosette-like dypingite/hydromagnesite (D/H). The three-dimensional network structure formed by HMCs significantly enhances the structural integrity and density of BC-specimens. Additionally, bubble shells are observed in BC group, approximately $270\text{ }\mu\text{m}$ in size. Compared to the BC group, the BCP group exhibits a more porous and loose structure with obvious cracks, as well as increases

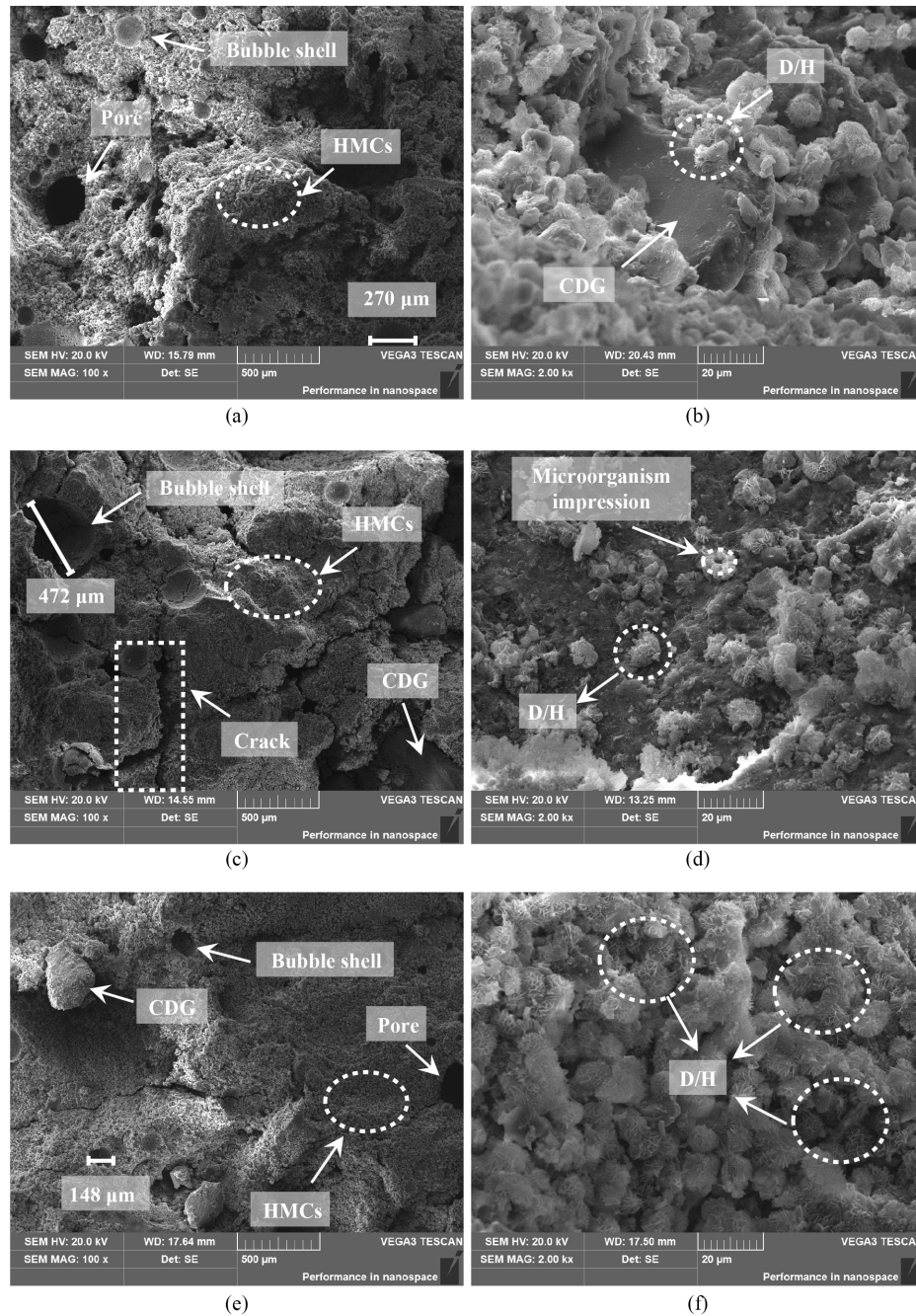


Fig. 12 SEM images of BC-specimens: (a) BC group, 100×; (b) BC group, 2000×; (c) BCP group, 100×; (d) BCP group, 2000×; (e) BCM group, 100×; (f) BCM group, 2000×.

the bubble shells quantity and enlarges the size to 427 μm (Fig. 12(c)). These results indicate that PCE has a detrimental effect on the microstructure of BC-specimens. Moreover, elliptical microorganism impressions are observed at the center of D/H (Fig. 12(d)), indicating that microorganisms play a crucial role in the nucleation process of HMCs. In contrast, the BCM group exhibits a more integrated structure with notably reduced porosity, and the bubble shell size is observed to decrease to 427 μm (Figs. 12(e) and 12(f)). This highlights that melamine positively contributes to optimizing the structural

integrity and density of BC-specimens.

4 Discussion

4.1 Feasibility and mechanism

All these tested results demonstrated that the novel FSS by combining CDG and bio-carbonated RMC satisfied the flowability and strength requirements of the Chinese standard T/BGEA 001-2019 [3]. By adding water-

reducing admixtures (PCE and melamine), the flowability of all the specimens was significantly improved and the strength requirements were sustainably changed. Increasing BS content increased the slump flow and DC, but decreased the mechanical properties. The maximum slump flow (30.60 cm) occurred at 55% BS with 1% melamine (Fig. 3(b)). The maximum UCS (1.47 MPa) was obtained at the 45% BS with 1% melamine (Fig. 8(b)). With the higher water-reducing admixture content, the slump flow was improved. The UCS and DC generally decreased with higher PCE content, whereas both increased with higher melamine content. Overall, the BS content, as well as the water-reducing admixture type and content significantly changed the flowability, mechanical properties and the microstructures of the FSS.

It should be emphasized that all tests in this study were carried out under standard laboratory curing conditions (28 d, 30 °C, 95% RH). The conclusions are applicable to conventional backfill engineering scenarios under mild environmental conditions, including roadbed backfill, pipeline trench backfill, and foundation pit backfill. Actual field conditions such as temperature, humidity, groundwater environment, and construction technology may affect the working performance of FSS. Therefore, the laboratory results can provide a reliable reference for engineering design, but field applicability and scale effects need to be further verified in practical engineering. Moreover, this study only investigated a limited range of material mix proportions and mainly focused on basic flowability and mechanical properties. Other key engineering indicators such as shear strength, permeability, erosion resistance, and long-term durability have not been tested. Therefore, the engineering applicability of this novel FSS needs to be further verified.

The flowability of the BC-specimens primarily originates from the relatively high liquid-phase content introduced by the BS after all materials are mixed. As a

liquid medium, the BS provides the dispersion environment for CDG and RMC particles, which reduces their direct contact and agglomeration. Moreover, the BS can reduce the surface tension during the process of urea hydrolysis, thereby weakening particle agglomeration [45]. On this basis, water-reducing admixture molecules adsorb onto the particle surfaces. By enhancing electrostatic repulsion and steric hindrance, it further improves the flowability of BC-specimens.

The development of strength depends on the bio-carbonation reaction. As shown in Fig. 13, this process involves three stages: urea hydrolysis, RMC hydration, and carbonation [41]. First, ureolytic bacteria hydrolyze urea, producing ammonia and carbonates, which provide key reactants for carbonation. Concurrently, RMC hydration generates brucite with weak bonding properties. Subsequently, the carbonation reaction occurs between carbonates from urea hydrolysis and brucite from RMC hydration, producing HMCs with strong bonding properties. These HMCs form a three-dimensional network structure within the BC-specimen, effectively cementing the loose CDG particles, thereby imparting integrity and strength. The cured BC-specimens exhibit typical strain-softening behavior (Figs. 5 and 6). Under external loading, the HMCs skeletal structure occurs gradually failure, correspondingly accompanied by initial elastic deformation, plastic deformation, and final failure. Through the entire process mentioned above, the BS content, as well as the water-reducing admixture content and type significantly influence the macroscopic properties of the BC-specimens.

4.2 Effect of bacterial solution content

The results demonstrated that higher BS content significantly enhanced the slump flow (Fig. 3) and DC (Fig. 9) of the BC-specimens, but decreased the

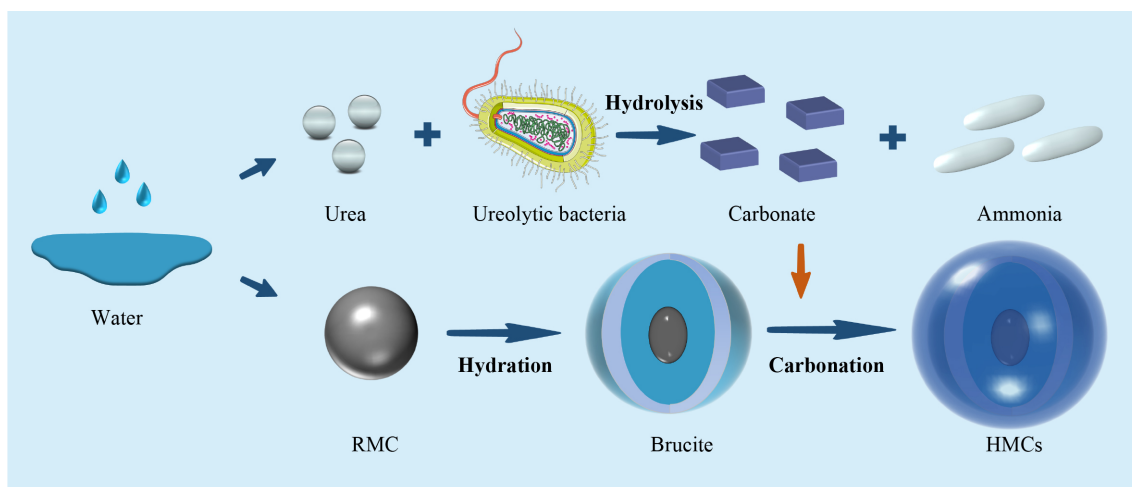


Fig. 13 The process of bio-carbonated RMC.

mechanical properties (Figs. 7 and 8). This is because BS acts as a liquid medium, directly improves the flowability of the BC-specimen. Furthermore, the high aqueous environment provides more moisture and space for microbial activity, which is conducive to the metabolic activity of bacteria and the hydration of MgO [46]. This promotes the hydration and carbonation of RMC, thereby increasing the HMCs formation. In addition, the higher BS content increases the total urea content in the system, providing a stronger precursor basis for RMC bio-carbonation, thereby increases the DC. However, the higher BS content increases the porosity of the BC-specimens [47]. This porosity increases offsets and even surpasses the strength gain from the bio-carbonation, ultimately decreasing the mechanical performance. Therefore, in the practical application of the FSS, an optimal BS content should be identified to achieve a balance between flowability and mechanical performance.

4.3 Effect of water-reducing admixtures

The results indicated that higher water-reducing admixtures content improved the flowability of BC-specimens, and melamine was observed to be more effective than PCE. Compared with the PCE, the melamine exhibited higher flowability, greater strength, and more compact microstructure at the same content. With the addition of 1% PCE and melamine, the slump flow increased by 13.83%–15.01% and 18.94%–35.16%, respectively (Fig. 3). Interestingly, higher PCE content reduced both the DC and UCS (Figs. 9(a) and 7(a)), whereas melamine enhanced these (Figs. 9(b) and 7(b)).

The water-reducing admixture type was the key factor influencing the flowability, bio-carbonation process and final strength of BC-specimens.

It is known that PCE molecule exhibits a comb-like structure [48]. As shown in Fig. 14, the anionic groups (e.g., carboxylate and sulfonate) on its backbone adsorb onto particle surfaces, enhancing electrostatic repulsion [49], and the hydrophilic polyether side chains extend into the solution to generate steric hindrance, collectively improving the flowability of BC-specimens [50]. Furthermore, it is found that PCE has no adverse effects on the ureolytic activity of *Sporosarcina Pasteurii* [51]. The polyether side chains of PCE can complex with Mg^{2+} , reducing the availability of reactants required for bio-carbonation [52]. In addition, the strong steric hindrance effect retards the hydration and carbonation processes of RMC [53]. Moreover, the air-entraining property of PCE also increases the number and size of bubbles within the BC-specimens (Fig. 12(c)), thereby reducing the strength of BC-specimens [54]. The higher PCE content further enhances the aforementioned effect. Therefore, in practical applications, the PCE content must be carefully controlled to ensure the required flowability while minimizing its adverse effects on bio-carbonation and strength.

Compared to PCE, melamine demonstrates comprehensive enhancing effects on the flowability, bio-carbonation reaction, and strength of BC-specimens. It is known that melamine acts as an anionic surfactant [32]. As shown in Fig. 14, its negatively charged groups adsorb directionally onto particle surfaces, imparting uniform surface charge. The resulting electrostatic repulsion between

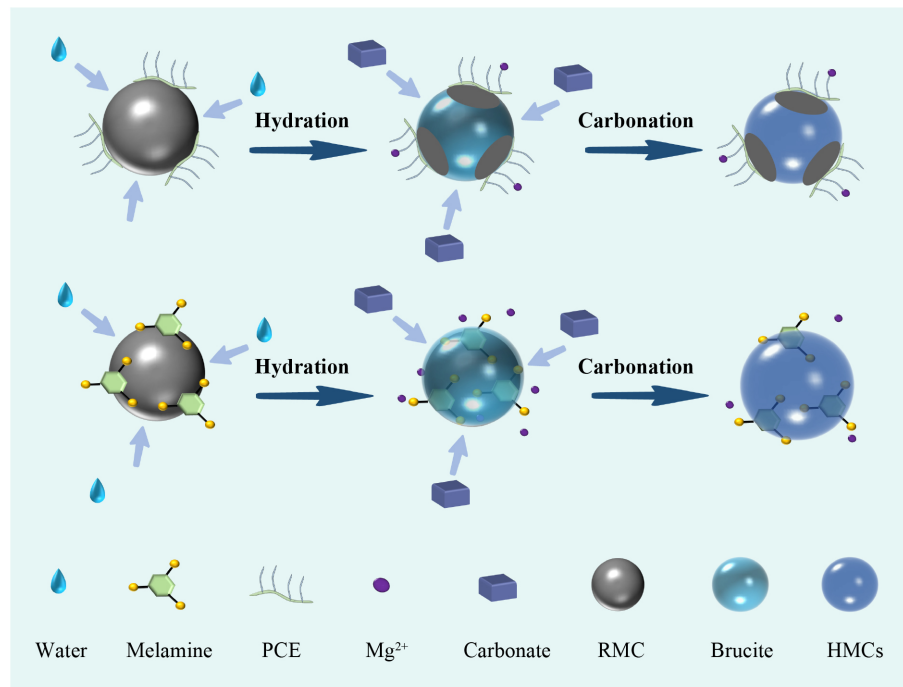


Fig. 14 Effect of PCE and melamine on the process of bio-carbonated RMC.

particles disrupts flocculated structures, thereby significantly improving the flowability of BC-specimens [55]. This dispersion effect is both direct and rapid [56]. Furthermore, its weaker steric hindrance does not impede the diffusion of water and carbonate in the system [57], leading to a continuous increase in DC with higher melamine content (Fig. 9(b)). This synergistic improvement in fluidity and carbonation contributes to enhanced mechanical properties. As a result, the maximum UCS of BC-specimens was 1.47 MPa at 45% BS with 1% melamine (Fig. 8(b)). Overall, melamine is recommended as the preferred water-reducing admixture for achieving a favorable balance between flowability and strength in practical applications.

It can be seen from Fig. 14 that the conversion degree of RMC to HMCs in the PCE is lower than that in the melamine, which is mainly attributed to the different molecular structures and adsorption behaviors of the two water-reducing admixtures. Melamine has little adverse effect on the carbonation hydration of RMC, allowing full conversion of RMC. In contrast, the long molecular chains of PCE wrap RMC particles and hinder the reaction process, resulting in incomplete conversion of RMC. Meanwhile, the dispersion efficiency of the two admixtures also contributes to this discrepancy in mineral conversion.

4.4 Advantages and limitations

The results indicated that the novel FSS from CDG and bio-carbonated RMC possessed significant technical advantages and engineering applicability. Firstly, this approach enables efficient resource recovery from CDG, reducing reliance on natural aggregates in backfilling projects. Secondly, as a low-carbon binder, RMC requires substantially lower energy consumption and generates fewer carbon emissions compared to OPC. Additionally, unreacted MgO and $\text{Mg}(\text{OH})_2$ can continuously absorb atmospheric CO_2 , further reduce carbon footprint and align with carbon neutrality goals. Furthermore, this study comprehensively investigated the effects of BS content and water-reducing admixtures on the flowability, bio-carbonation, mechanical properties and mechanism of BC-specimens, thereby broadening its potential application. Based on these advantages, this material and method can be widely applied in backfilling projects with strict environmental constraints and limited construction space, offering a sustainable and efficient solution for modern engineering practices.

However, this study has several limitations that should be addressed in future work. Firstly, only typically used PCE and melamine water-reducing admixtures with a content range of 0%–1% were investigated. But other water-reducing admixtures such as naphthalene and lignin types, and higher content ranges were not considered.

Secondly, the influence of water-reducing admixtures on the mechanisms of urea hydrolysis, RMC hydration, and carbonation remains incompletely understood, and more detailed microstructural characterization at finer scales is required to clarify these processes. Further experimental work should evaluate additional mechanical properties of BC-specimens, including shear strength, permeability resistance, and flexural strength. Moreover, the long-term durability under various environmental conditions should be investigated to better evaluate the practical engineering applicability of this FSS. It should be emphasized that the microstructural characterization in this study mainly relies on XRD, FT-IR and SEM observations, which are local and typical qualitative analysis methods. Therefore, the conclusions of this study are reasonable inferences based on micromorphology rather than strict quantitative conclusions. Further quantitative characterization (e.g., pore size distribution and porosity) will be supplemented in future research.

5 Conclusions

This study explored the feasibility of the novel FSS by combining the CDG and bio-carbonated RMC. Through a series of laboratory tests, the effects of BS, PCE and melamine water-reducing admixtures on the slump flow, density, mechanical properties, and DC were systematically revealed. The influence of PCE and melamine on composition and microstructure was also explored to reveal the fundamental origins. The main conclusions are summarized as follows.

1) The novel FSS prepared from CDG and bio-carbonated RMC is feasible. The slump flow increased with higher BS and water-reducing admixtures content. In contrast, The UCS decreased with higher BS and PCE contents, whereas it increased with higher melamine content. At the same BS and water-reducing admixture content, BC-specimens with melamine exhibited superior overall performance than those with PCE. The maximum slump flow of 30.60 cm occurred at 55% BS with 1% melamine, and the maximum UCS of 1.47 MPa was obtained at the 45% BS with 1% melamine. This novel FSS successfully combined high strength with excellent flowability.

2) Although higher BS content significantly improved flowability and the RMC bio-carbonation process, it adversely affected the development of mechanical properties. This is because BS acts as a liquid medium, providing the moisture and space necessary for microbial activity, thereby promoting the hydration and carbonation of RMC. However, the higher BS content also increased porosity, which offset and even surpassed the strength gain derived from bio-carbonation. Therefore, a suitable BS content must be identified to balance flowability and strength effectively.

3) The addition of PCE adversely affected the mechanical properties of BC-specimens and inhibited the bio-carbonation process of RMC. At 45% BS and 1% PCE content, the UCS and DC were 1.21 MPa and 0.24, respectively, corresponding to reductions of 11.03% and 15.85% compared to the BC group. This result was mainly attributable to the air-entraining property of PCE, its strong steric hindrance effect, and its complexation with Mg^{2+} , which collectively inhibited bio-carbonation and hindered the formation of HMCs.

4) Melamine enhanced the mechanical properties of BC-specimens and promoted the bio-carbonation process of RMC. At 45% BS and 1% melamine content, the UCS and DC reached 1.47 MPa and 0.32, respectively, representing increases of 8.09% and 14.29% compared to the BC group. This improvement was attributed to the abundant anionic groups on melamine molecules, which adsorbed onto particle surfaces and enhanced electrostatic repulsion and dispersion. Moreover, the adsorption of melamine can facilitate Mg^{2+} availability in the system, thereby promoting RMC bio-carbonation and HMCs formation.

Acknowledgements This work was supported by the National Natural Science Foundation of China (Grant No. 52578418). The authors also acknowledge the financial support from the Guangdong Basic and Applied Basic Research Fund (Nos. 2025A1515011924 and 2026A1515010812), Shenzhen Science and Technology Program (No. JCYJ202506041816 37050) and Environmental Conservation Fund from Environmental Protection Department of Hong Kong SARG (No. 2023-64).

Funding note Open access funding provided by The Hong Kong Polytechnic University.

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Competing interests The authors declare that they have no competing interests.

References

1. Lei B F, Pang S, Sun J C, Fan H H, Xie F H, Deng S, Chen S F. Rheological properties and freeze–thaw durability of fiber-reinforced flowable solidified soil incorporating multi-source waste. *Results in Engineering*, 2025, 28: 107892
2. Zhou Y X, Zhang R J, Yang X G, Hou L. The design methodology for proportioning fluidized solidified soil. *Journal of Building Engineering*, 2025, 111(15): 113127
3. T/BGEA 001-2019. Technical Standard for Backfilling Project by Using Premixed Fluidized Solidified Soil. Beijing: China Architecture & Building Press, 2019 (in Chinese)
4. Akhtar A, Sarmah A K. Construction and demolition waste generation and properties of recycled aggregate concrete: A global perspective. *Journal of Cleaner Production*, 2018, 186: 262–281
5. Luhar S, Cheng T W, Luhar I. Incorporation of natural waste from agricultural and aquacultural farming as supplementary materials with green concrete: A review. *Composites Part B: Engineering*, 2019, 175: 107076
6. Ali M B, Saidur R, Hossain M S. A review on emission analysis in cement industries. *Renewable and Sustainable Energy Reviews*, 2011, 15(5): 2252–2261
7. Hossain M A, Yin J H. Shear strength and dilative characteristics of an unsaturated compacted completely decomposed granite soil. *Canadian Geotechnical Journal*, 2010, 47(10): 1112–1126
8. Dassekpo J B M, Zha X, Zhan J P. Compressive strength performance of geopolymers derived from completely decomposed granite (CDG) and partial fly ash replacement. *Construction and Building Materials*, 2017, 138: 195–203
9. Zhan L T, Zhang Z, Chen Y M, Chen R, Zhang S, Liu J, Li A G. The 2015 Shenzhen catastrophic landslide in a construction waste dump: Reconstitution of dump structure and failure mechanisms via geotechnical investigations. *Engineering Geology*, 2018, 238: 15–26
10. Yan S, Tang H, Wu Z J, Li S T, Li P F. Study on strength characteristics and microstructure of completely decomposed migmatitic granite. *KSCE Journal of Civil Engineering*, 2023, 27(1): 80–97
11. Zhao Y R, Chen X S, Wen T D, Wang P H, Li W S. Experimental investigations of hydraulic and mechanical properties of granite residual soil improved with cement addition. *Construction and Building Materials*, 2022, 318: 126016
12. Bahmani S H, Huat B B K, Asadi A, Farzadnia N. Stabilization of residual soil using SiO_2 nanoparticles and cement. *Construction and Building Materials*, 2014, 64: 350–359
13. Kim Y S, Tran T Q, Kang G O, Do T M. Stabilization of a residual granitic soil using various new green binders. *Construction and Building Materials*, 2019, 223: 724–735
14. Latifi N, Eisazadeh A, Marto A, Meehan C L. Tropical residual soil stabilization: A powder form material for increasing soil strength. *Construction and Building Materials*, 2017, 147: 827–836
15. Soares E G, Castro-Gomes J. Carbonation curing influencing factors of carbonated reactive magnesia cements (CRMCM)—A review. *Journal of Cleaner Production*, 2021, 305: 127210
16. Mo L W, Panesar D K. Effects of accelerated carbonation on the microstructure of Portland cement pastes containing reactive MgO . *Cement and Concrete Research*, 2012, 42(6): 769–777
17. Dung N T, Unluer C. Performance of reactive MgO concrete under increased CO_2 dissolution. *Cement and Concrete Research*, 2019, 118: 92–101

1. Lei B F, Pang S, Sun J C, Fan H H, Xie F H, Deng S, Chen S F. Rheological properties and freeze–thaw durability of fiber-

18. Yang Y, Ruan S Q, Wu S F, Chu J, Unluer C, Liu H L, Cheng L. Biocarbonation of reactive magnesia for soil improvement. *Acta Geotechnica*, 2021, 16(4): 1113–1125
19. Ruan S Q, Qiu J S, Weng Y W, Yang Y, Yang E H, Chu J, Unluer C. The use of microbial induced carbonate precipitation in healing cracks within reactive magnesia cement-based blends. *Cement and Concrete Research*, 2019, 115: 176–188
20. Hoang T, Dung N T, Unluer C, Chu J. Use of microbial carbonation process to enable self-carbonation of reactive MgO cement mixes. *Cement and Concrete Research*, 2021, 143: 106391
21. Chen Z, Fang X W, Long K Q, Shen C N, Yang Y, Liu J L. Using the biocarbonization of reactive magnesia to cure electrolytic manganese residue. *Geomicrobiology Journal*, 2021, 38(8): 709–718
22. Wang R, Tang C S, Pan X H, Wang D L, Dong Z H, Zhang X Y, Lu X C. Efficient stabilization of dredged sludge with high water content using an improved bio-carbonation of reactive magnesia cement method. *Journal of Rock Mechanics and Geotechnical Engineering*, 2024, 16(9): 3760–3771
23. Wang D L, Tang C S, Pan X H, Dong Z H, Wang R, Zhang J Z, Ji X L, Hu H C, Shi B. Construction and demolition waste stabilization through biocarbonation of reactive magnesia cement: Effect of urea concentration. *Journal of Materials in Civil Engineering*, 2025, 37(1): 04024450
24. Shi J Q, Xiao Z H, Xiao Y, Liu H L. Bio-molding of lunar regolith with bio-carbonized magnesium oxide. *Biogeotechnics*, 2025, 3(4): 100159
25. Xiao Y, Zhang Z C, Stuedlein A W, Evans T M. Liquefaction modeling for biocemented calcareous sand. *Journal of Geotechnical and Geoenvironmental Engineering*, 2021, 147(12): 04021149
26. Zhang J X, Yang X, Liu H L, Chu J. Role of bacteria on bio-induced calcium carbonate formation: insights from droplet microfluidic experiments. *Géotechnique*, 2024, 75(6): 787–799
27. Xiao Y, He X, Stuedlein A W, Chu J, Evans T M, van Paassen L A. Crystal growth of MICP through microfluidic chip tests. *Journal of Geotechnical and Geoenvironmental Engineering*, 2022, 148(5): 06022002
28. Liu H L, Xiao Y, Shi J Q, Cao B F, Sun J B. 3D printing lunar regolith simulant with microbial-carbonated magnesium oxide. *Biogeotechnics*, 2025: 100197
29. Zhao C, Xiao Y, Liu H L, Chu J. Effects of urease and cementing solution concentrations on micro-scale enzymatic mineralisation characteristics. *Géotechnique*, 2024, 75(6): 732–746
30. Rajasekar A, Wilkinson S, Moy C K S. MICP as a potential sustainable technique to treat or entrap contaminants in the natural environment: A review. *Environmental Science and Ecotechnology*, 2021, 6: 100096
31. Wang H X, Tong T Z, Sun X H, Miao L C, Chu J, Wang D L, Shi J Q, Wang Y. Low-carbon and highly efficient sand solidification based on the combined bio-carbonation of reactive magnesia and enzymatically induced carbonate precipitation. *Journal of Environmental Chemical Engineering*, 2025, 13(2): 115670
32. Lei L, Hirata T, Plank J. 40 years of PCE superplasticizers—History, current state-of-the-art and an outlook. *Cement and Concrete Research*, 2022, 157: 106826
33. Khayat K H. Viscosity-enhancing admixtures for cement-based materials—An overview. *Cement and Concrete Composites*, 1998, 20(2–3): 171–188
34. Liu J, Yu C, Shu X, Ran Q, Yang Y. Recent advance of chemical admixtures in concrete. *Cement and Concrete Research*, 2019, 124: 105834
35. Hay R, Khalil A, Otchere C, Alanis S, Celik K. Proportioning, carbonation, performance assessment, and application of reactive magnesium oxide cement-based composites with superplasticizers. *Journal of Materials in Civil Engineering*, 2023, 35(2): 04022405
36. ASTM D2487-11. Standard Practices for Classification of Soils for Engineering Purposes (Unified Soil Classification System). West Conshohocken, PA: ASTM, 2011
37. GB/T 50123-2019. Standard for Geotechnical Testing Method. Beijing: China Planning Press, 2019 (in Chinese)
38. YB/T 4019-2020. Determination of Chemical Activity of Light Calcined Magnesia. Beijing: Metallurgical Industry Press, 2020 (in Chinese)
39. Whiffin V S. Microbial CaCO₃ Precipitation for the Production of Biocement. Dissertation for the Doctoral Degree. Perth: Murdoch University, 2004
40. ASTM D2166/D2166M-18. Standard Test Method for Unconfined Compressive Strength of Cohesive Soil. West Conshohocken, PA: ASTM, 2018
41. Wang D L, Tang C S, Pan X H, Wang R, Shi M, Dong Z H, Zhang Y C, Shi B. A novel bio-carbonation method of reactive magnesia with urea pre-hydrolysis for geomaterial stabilisation. *Géotechnique*, 2023, 74(13): 1634–1648
42. Wu J, Liu L, Deng Y F, Zhang G P, Zhou N, Xiao H L. Use of recycled gypsum in the cement-based stabilization of very soft clays and its micro-mechanism. *Journal of Rock Mechanics and Geotechnical Engineering*, 2022, 14(3): 909–921
43. Criado M, Fernández-Jiménez A, Palomo A, Sobrados I, Sans J. Effect of the SiO₂/Na₂O ratio on the alkali activation of fly ash. Part II: ²⁹Si MAS-NMR survey. *Microporous and Mesoporous Materials*, 2008, 109(1–3): 525–534
44. Silva R V, Neves R, De Brito J, Dhir R K. Carbonation behaviour of recycled aggregate concrete. *Cement and Concrete Composites*, 2015, 62: 22–32
45. Weinstein L, McDonald A. The effect of urea, urethane and other carbamates on bacterial growth. *Science*, 1945, 101(2611): 44–45
46. Dong Z H, Pan X H, Tang C S, Wang D L, Wang R, Shi B. An efficient microbial sealing of rock weathering cracks using bio-carbonation of reactive magnesia cement. *Construction and Building Materials*, 2023, 366: 130038
47. Zhang C, Sun Y J, Yang Y. Bio-carbonation of reactive magnesia cement in geotechnical engineering practice: A state-of-the-art review. *Journal of Sustainable Cement-Based Materials*, 2024, 13(11): 1567–1581
48. Yamada K, Takahashi T, Hanehara S, Matsuhisa M. Effects of the chemical structure on the properties of polycarboxylate-type superplasticizer. *Cement and Concrete Research*, 2000, 30(2): 197–207
49. Tayebi M, Ilango N K, Nguyen H, Lori A R, Ranjbar N, Carvelli V, Kinnunen P. New insights into hydration of MgO in the presence of polycarboxylate ether superplasticizers. *Cement and*

- Concrete Composites, 2025, 162: 106153
50. Kjeldsen A M, Flatt R J, Bergström L. Relating the molecular structure of comb-type superplasticizers to the compression rheology of MgO suspensions. *Cement and Concrete Research*, 2006, 36(7): 1231–1239
51. Zhu Y Q, Li Y J, Sun X Y, Guo Z, Rui S J, Zheng D Q. A one-phase injection method to improve the strength and uniformity in MICP with polycarboxylic acid added. *Acta Geotechnica*, 2025, 20(5): 2279–2291
52. Mangi H N, Ma L Q, Sajib M H, Yan D T, Ahmad Q A, Ngo I, Yang X H. CO₂ carbonation process of cemented paste backfill material using polycarboxylate ether (PCE) and MgCl₂. *Results in Engineering*, 2025, 28: 107742
53. Zhu J F, Hui J, Luo H J, Zhang B, Wei X H, Wang F, Li Y F. Effects of polycarboxylate superplasticizer on rheological properties and early hydration of natural hydraulic lime. *Cement and Concrete Composites*, 2021, 122: 104052
54. Lei L, Zhang L. Synthesis and performance of a non-air entraining polycarboxylate superplasticizer. *Cement and Concrete Research*, 2022, 159: 106853
55. Grabiec A M. Contribution to the knowledge of melamine superplasticizer effect on some characteristics of concrete after long periods of hardening. *Cement and Concrete Research*, 1999, 29(5): 699–704
56. Li H, Wang Z H, Zhang Y W, Zhang G F, Zhu H M. Composite application of naphthalene and melamine-based superplasticizers in alkali activated fly ash (AAFA). *Construction and Building Materials*, 2021, 297: 123651
57. Tekin İ, Pekgöz M, Saleh N K, Kiamahalleh M V, Gholampour A, Gencel O, Ozbakkaloglu T. Compatibility of melamine formaldehyde- and polycarboxylate-based superplasticizers on slag/sintering ash-based geopolymer paste. *Construction and Building Materials*, 2025, 458: 139681