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Construction and demolition waste stabilization through a bio-carbonation of reactive magnesia cement for underwater engineering

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ABSTRACT

Bio-carbonation of reactive magnesia cement (RMC), an innovative and potentially sustainable cementing technology, has been proposed as a promising strategy to stabilize the construction and demolition wastes (CDW) for underwater engineering. A series of underwater bio-carbonation experiments on CDW samples with various RMC content and bacteria concentration were conducted to verify the feasibility of the method. Experimental results showed that bio-carbonation of RMC had the ability to stabilize CDW subjected to the underwater environment. The unconfined compressive strength (UCS) of the bio-carbonized CDW samples was up to 1006.04 kPa with 12% of RMC content, which was 11.2 times of samples stabilized by RMC hydration only. The stabilization effect was facilitated by the increase of the RMC content and bacteria concentration. The UCS of the sample with 12% of RMC content was 10.64 times as much as that of the sample with 4% of RMC content. The UCS of the sample stabilized with concentrated bacteria solution was increased by 218.19%. The high RMC content and bacteria concentration also changed the sample failure characteristics from ductility to brittleness. Based on the measurements of the degree of carbonation (DC), urea utilization ratio (UUR), and microstructure observations, the CDW stabilization mechanism through the bio-carbonation of RMC was discussed. The increasing UCS of the bio-carbonized CDW samples can be attributed to the formation of the brucite and hydrated magnesia carbonates (HMCs) by the combined effects of hydration of RMC and the carbonation of brucite. The formed brucite and HMCs provide excellent filling, bonding, and coating effects between the CDW particles than that of brucite only. The higher RMC content and bacteria concentration promote the urea hydrolysis and RMC carbonation processes, resulting in forming more brucite and HMCs. The large amount of HMCs forms a stable spatial network structure that facilitates stabilization performance and improves the mechanical properties. The coupling effect of the high adsorption characteristic of RMC, CDW, and the fast bio-carbonation ratio makes it possible for the proposed method to be applied to underwater engineering.

1. Introduction

Along with the acceleration of urbanization, a large amount of construction and demolition waste (CDW) has been generated from construction-related activities [11,26]. Direct landfill without any treatment was the most common way to dispose of the CDW in the past, often wasting enormous valuable resources, causing severe

environmental problems [23,37]. On the other hand, available construction materials, such as sand and gravel aggregates, are decreasing rapidly with the increasingly strict requirements of ecological environment protection [20,19]. Many attempts indicate that the re-utilization of CDW as construction resources is the most economical and environmentally friendly strategy. Coupling with the use of Portland cement (PC), CDW could be applied in various infrastructure and underground

Abbreviations: RMC, Reactive magnesia cement; CDW, Construction and demolition wastes; UCS, Unconfined compressive strength; HMCs, Hydrated magnesia carbonates; MICP, Microbial induced calcite precipitation; PC, Portland cement; DC, Degree of carbonation; UUR, Urea utilization ratio; SEM, Scanning electron microscopy.

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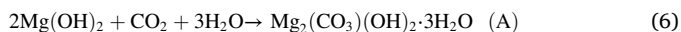
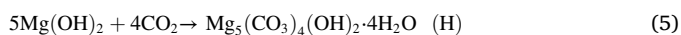
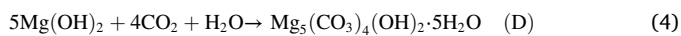
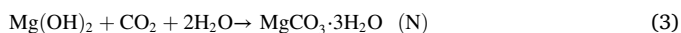
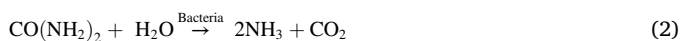
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constructions, such as backfilling materials for road subgrades, mined-out areas [33,30], and underground caverns [41], etc.

Portland cement (PC) has made an outstanding contribution to urban construction over the last hundred years. However, the adverse effects of PC on the ecological environment, such as the greenhouse effect, have been paid more attention by various countries due to the high carbon emissions in the production process [2,10,17]. It is well known that scientists around the world have made great efforts to reduce carbon emissions. Consequently, it is more urgent than ever before to propose a new type of green cement material.

In recent years, bio-cementation through the microbial induced calcite precipitation (MICP) process has been proposed as a promising eco-friendly soil stabilization approach and a potential alternative to cement for shallow underground constructions [18,9,25,29]. However, the application of MICP technology on the stabilization of the CDW recycled aggregates for deep underground constructions with high groundwater levels (hereinafter referred to as underwater engineering), i.e., mine backfill, faces enormous challenges. The total amount of calcium carbonate produced by each cycle of MICP treatment is relatively small. Thus, it needs several cycles of MICP treatment to achieve the desired stabilization effect. This is not conducive to stabilizing the CDW uniformly and efficiently because of the complex geological conditions of deep underground and the long transport distance of cementation materials. Additionally, the bacteria and cementation solutions can be easily diffused in the underwater environment, reducing MICP treatment effectiveness. From the above statements, it is clear that the optimal biocementation method for CDW stabilization is that the method not only can achieve a satisfactory stabilization effect with one-time treatment but also can work underwater.

Another latest biocementation technology, namely bio-carbonation of reactive magnesia (MgO) cement (RMC), might be a promising method. The bio-carbonation process of RMC involves hydration of MgO with water to form brucite ($\text{Mg}(\text{OH})_2$), as shown in Eq. (1). Meanwhile, urea is hydrolyzed into carbon dioxide (CO_2) and ammonia (NH_3) by the effect of bacteria, as shown in Eq. (2). Then, the brucite (B) can be carbonized into various types of hydrated magnesia carbonates (HMCs) subjected to different conditions with excellent bonding properties, including the nesquehonite (N), dypingite (D), hydromagnesite (H), and artinite (A) [12,13,16,27,36,38], see Eqs. (3)–(6).



After a first attempt to heal the concrete crack and excellent treatment results were obtained [27], the bio-carbonation of RMC technology was also applied to improve the mechanical properties of soil. Yang et al. [38] found that the unconfined compressive strength (UCS) of soil was improved significantly by bio-carbonation of RMC, and its values were influenced by RMC content, urea concentration, and water content. The technology was also employed to improve the UCS of electrolytic manganese residue tailings up to 5.2 MPa [8]. Furthermore, the fresh properties and mechanical properties of the pure bio-carbonized RMC were also investigated [36,16]. Unlike the MICP treatment, these studies showed us that bio-carbonation of RMC technology could stabilize the soil to a few megapascals with one-time treatment under ambient conditions. However, the application of bio-carbonation of RMC on CDW for underwater engineering has not been reported yet. It is essential to investigate the feasibility, stabilization mechanism, and

influence factors of applying bio-carbonation of RMC on CDW stabilization in the underwater environment.

This study was a first attempt to stabilize CDW using the bio-carbonation of RMC for the application of underwater engineering. A series of underwater bio-carbonation experiments on CDW with various RMC content and bacteria concentration were carried out to simulate the underwater engineering environment and verify the method feasibility. Unconfined compressive strength (UCS) of the bio-carbonized samples were tested to assess the stabilization performance. Degree of carbonation (DC), urea utilization ratio (UUR), and microstructure characteristics were employed to analyze the stabilization mechanism. In addition, the effects of bacteria concentration and RMC content were discussed according to the experimental results.

2. Materials and methods

2.1. Materials

2.1.1. Construction and demolition waste

In this study, original CDW materials were obtained from the construction site in Jining, Shandong Province, including concrete, brick, and other building materials. The specific composition is listed in Table 1. The CDW is a sand-like particle material after crushing through a jaw crusher and sieving through a 2 mm sieve. The basic physical properties are also shown in Table 1 and the particle size distribution can be found in Fig. 1.

2.1.2. Bacteria solution

Sporosarcina pasteurii (ATCC 11859) was utilized as the ureolytic bacteria in this study. The bacteria colonies were inoculated into a pre-sterilized $\text{NH}_4\text{-YE}$ medium by 1% of total volume and cultivated under an aerobic condition at a 30 °C shaker at 200 rpm for 24 h. The harvested bacteria solution was called ordinary bacteria solution. Another type of concentrated bacteria solution was also prepared by centrifuged at 5000 r/min for 5 min [14]. The bacteria concentration (OD_{600}) of the ordinary and concentrated bacteria solutions was 1.59 and 2.05, respectively, and their corresponding urease activity was 4.10 U (1 U = 1 mM-urea hydrolyzed/min) and 6.53 U, respectively.

2.1.3. Reactive magnesia cement

The used magnesia cement was a type of reactive magnesia cement (RMC). The chemical activity of RMC was tested by a standard method, namely citric acid neutralization method (Chinese standard YB/T 4019–2006) [31], which was widely used for the chemical activity measurement of caustic burned magnesia. Its chemical activity was in the range of 12–25 s. The particle size distribution of RMC was tested by a Laser Particle Size Analyzer and can be found in Fig. 1. Other detailed information, including chemical composition and physical properties, are shown in Table 2.

2.2. Sample preparation

As shown in Table 3, five groups of samples mixed with various RMC contents and bacteria solution concentrations were prepared. Samples in every group were prepared in triplicate. The effect of RMC content was studied with 4%, 8%, 12% [38], respectively. Two types of bacteria concentrations, including the ordinary and concentrated bacteria solutions, of which the OD_{600} were 1.59, 2.05, respectively, were also

Table 1
Composition and basic physical properties of CDW.

	Composition (%)			Physical properties	
	Brick	Concrete	Others	Specific gravity (g/cm^3)	Bulk density (g/cm^3)
CDW	≥ 30	≥ 67	≤ 3	2.68	1.30

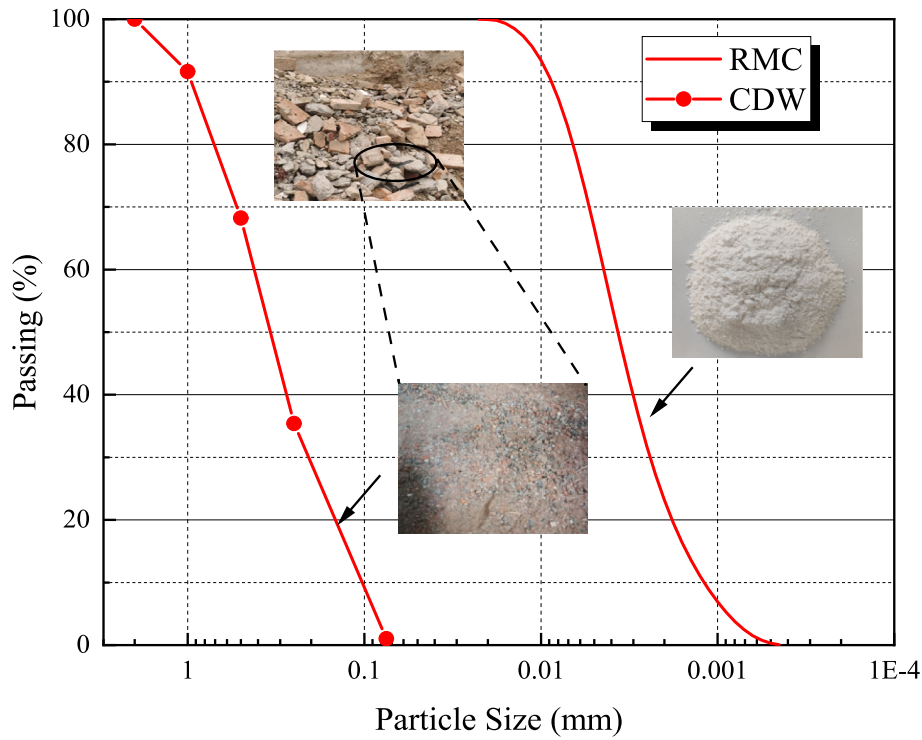


Fig. 1. The particle size distribution of CDW and RMC.

Table 2
Chemical composition and physical properties of RMC.

	Chemical composition (%)				Physical properties	
	MgO	CaO	SiO ₂	Fe ₂ O ₃	Specific gravity (g/cm ³)	Specific surface area (m ² /g)
RMC	98	0.73	1.07	0.11	3.0	2.38

Table 3
Detailed information of sample preparation.

Mix	Compositions					
	CDW (g)	RMC (g)	Urea solution (g)	Bacteria solution (g)	Water (g)	Concentrated bacteria solution (g)
S1	96	4	16	16		
S2	92	8	16		16	
S3	92	8	16	16		
S4	92	8	16			16
S5	88	12	16	16		

investigated. Furthermore, a control sample without bacteria treatment was also prepared. The mass ratio of solid to liquid content in each group of sample is 100:32, which was determined by a series of preliminary experiments that can ensure an excellent stabilization effect. Preliminary experiments also showed that no bio-carbonation occurred without RMC. Thus, only samples with RMC were considered in this study.

All samples were prepared in a PVC column mold with an inner diameter of 37 mm and a height of 74 mm. As shown in Fig. 2, a total of five steps were carried out for the sample preparation. Firstly, the oven-dried CDW and RMC were mixed evenly in proportion. Secondly, bacteria solution and urea solution (2 mol/L) were mixed with the volume ratio of 1:1 [27]. Thirdly, the liquid mixture was immediately poured into the solid mixture after step two and mixed until uniformly distributed. Then the prepared final mixture was compacted to the target density of 1.80 g/cm³ in the column mold. Fourthly, all the prepared samples with the molds were immersed into a water tank with over 100 L of deionized water immediately (the liquid level exceeded the upper surface of the samples by 3 cm). The large amount of deionized water could eliminate the effect of curing water volume on the

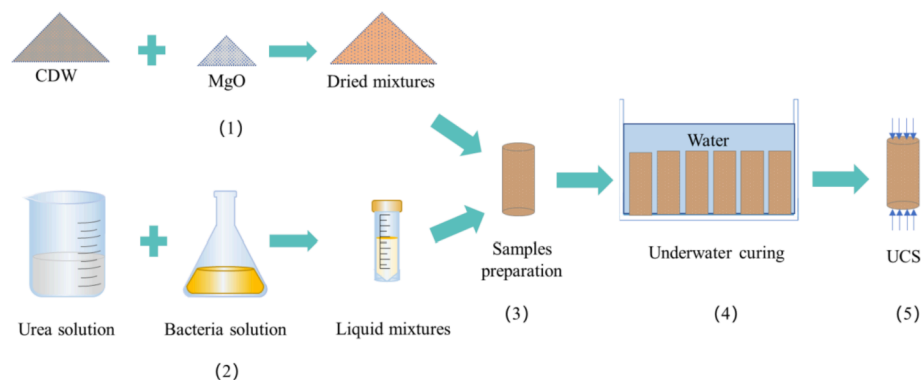


Fig. 2. Schematic diagram of sample preparation and testing process.

samples, even if there was a small amount of leaching of urea and bacteria. The curing temperature was set to 30 °C that the urease activity could be maintained at a high level [5]. Finally, the samples were demolded after 24 h and continued to be cured in the underwater environment for seven days prior to being tested.

2.3. Testing methods

2.3.1. Unconfined compressive strength

To obtain the effectiveness of the proposed method on the CDW stabilization after underwater curing, UCS of the bio-carbonized CDW samples were measured by unconfined compressive tests in accordance with ASTM D2166/D2166M-16 standard at a constant loading rate of 1 mm/min [3]. Notably, the bio-carbonized CDW samples were saturated before the testing.

2.3.2. Degree of carbonation and urea utilization ratio

The carbon dioxide produced by bacteria hydrolysis of urea played an essential role in the bio-carbonation reaction for CDW stabilization. In this study, the amount of carbon dioxide engaged in the reaction was measured by the acid washing method. 10 g sub-samples after UCS tests were collected from each group of samples, crushed into fragments. The emitted carbon dioxide volume of bio-carbonized CDW after 0.1 mol/l HCl solution treatment was recorded by the gas drainage method (a method often used for the collection and measurement of insoluble gas). The molar number of carbon dioxide was calculated according to Avogadro's Hypothesis [24,22,4]. DC was employed to indicate the effectiveness of the carbonation reaction of each sample, which can be calculated by Eq. (7) [32,40].

$$\text{Degree of Carbonation} = \frac{M_{\text{CO}_2}}{M_{\text{MgO}}} \quad (7)$$

where M_{CO_2} refers to the molar amount of carbon dioxide contained in the products and measured by acid washing method; M_{MgO} refers to the total number of moles of RMC used in the experiment.

To characterize the efficiency of urea utilization after bio-carbonation reaction, UUR was proposed and defined as the ratio of the molar amount of utilized urea to the total molar amount of urea mixed in the samples. According to the principle of conservation of carbon, the amount of utilized urea equals the amount of carbon dioxide within the products. It can be calculated by Eq. (8):

$$\text{Urea Utilization Ratio} = \frac{M_{\text{CO}_2}}{M_{\text{Urea}}} \times 100\% \quad (8)$$

where M_{Urea} refers to the molar amount of urea mixed in the experiment.

2.3.3. Microstructure characteristics

In order to better understand the microstructure of the bio-carbonized CDW, representative samples collected from the crushed samples after UCS testing were dried and tested by scanning electron microscopy (SEM).

3. Results

3.1. Unconfined compressive behavior

In this study, all the CDW could be effectively stabilized in an underwater environment by bio-carbonation of RMC. We can observe from Fig. 3a that the UCS is affected by the RMC content and bacteria concentration, and UCS values range between 84.94 and 1006.04 kPa. In general, UCS values increase with the increase of RMC content, and the UCS value of sample S5 (12%) increases by 9.64 times as much as that of sample S1 (4%). When RMC content is 8%, the UCS of the sample with ordinary bacteria solution (S3) is 1.84 times as high as samples without bacteria treatment (S2). The comparison between S3 and S4 shows that

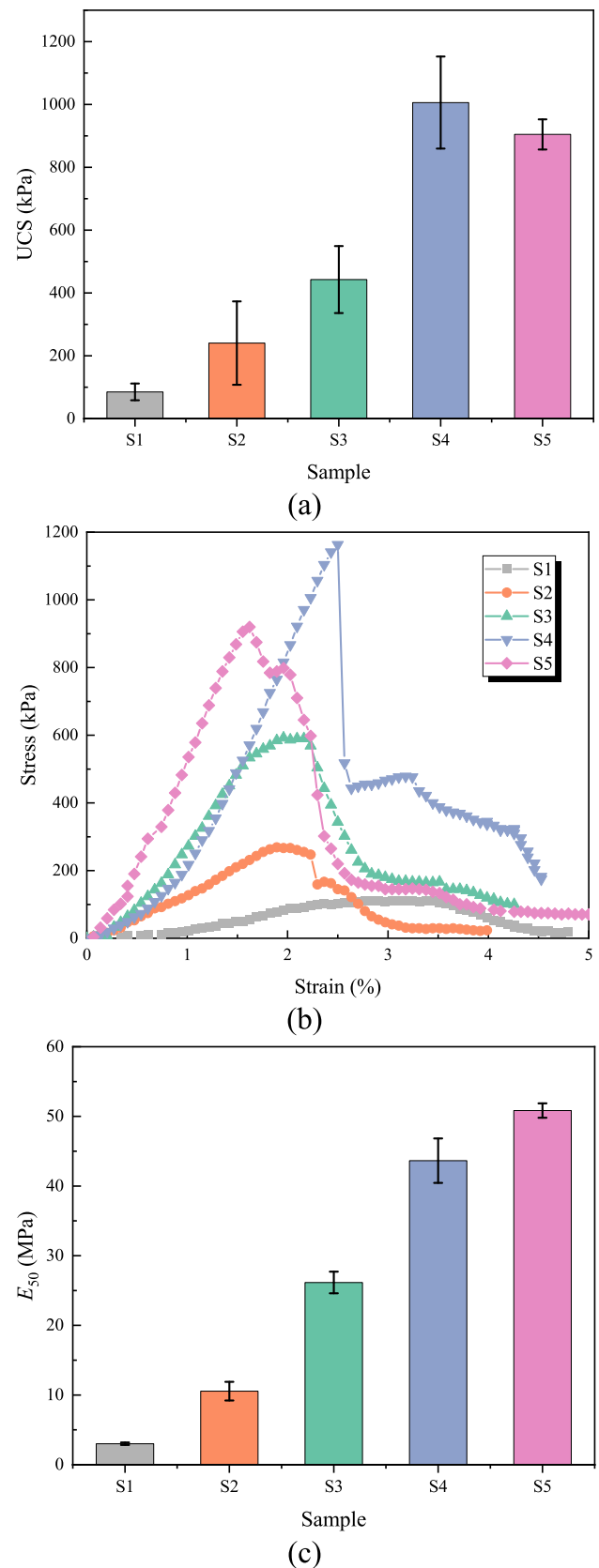


Fig. 3. The mechanical properties of bio-carbonized CDW including (a) UCS, (b) strain–stress curves, and (c) Young's modulus measured at the stress level equal to 50% of the unconfined compressive strength (E_{50}).

the UCS of sample S4 with concentrated bacteria solution increases by 1.18 times.

Fig. 3b shows the typical strain–stress of every group of bio-carbonized CDW samples. Samples with higher RMC content (S3 and S5) and samples with higher bacteria concentration (S4) show smaller failure strain and a rapid decrease in post-peak stress.

Fig. 3c shows Young's elastic modulus results measured at the stress level equal to 50% of the unconfined compressive strength (E_{50}). It can be found that E_{50} values are improved with the increase of RMC content and bacteria concentration. When mixed with the same concentration of bacteria solution, the E_{50} value of sample S5 (12% of RMC content) is 16.24 times as much as sample S1 (4% of RMC content). A comparison among samples S2, S3, and S4 with 8% of RMC content indicates that the E_{50} can be improved by 2.91 times using the concentrated bacterial solution. The deformation characteristics are generally changed from ductileness to brittleness with higher RMC content and bacteria concentration.

3.2. Degree of carbonation and urea utilization ratio

Fig. 4a shows the DC of the bio-carbonized CDW samples in the range of 0.118–0.338, while no carbonate can be tested in sample S2 without bacteria treatment. We can conclude that the bio-carbonation occurrence is due to the presence of bacteria. It is also interesting to note that the DC values increase with the decreasing of the RMC content. Compared to sample S1, the DC value of sample S5 is reduced by 65.98%. The DC value of sample S4 with high bacteria concentration has increased by 21.88% compared to sample S3.

Fig. 4a also shows the difference from the theoretical maximum DC values. The theoretical maximum value of the DC was defined as the ratio of the maximum molar number of carbonate engaged in bio-carbonation of RMC reaction to the maximum molar number of the mixed RMC. They also can be calculated by Eq. (7). It is assumed that all the mixed urea were hydrolyzed and engaged in bio-carbonation of RMC reaction, i.e., the maximum molar number of carbonate (M_{CO_2}) equals the mixed molar number of urea (M_{Urea}). In other words, the theoretical maximum value of the DC is dependent only on the molar number of mixed urea and RMC. In general, they decrease as RMC content increases when the amount of urea used in all the mixes is the same in this study.

As shown in Fig. 4b, UUR values of the bio-carbonized CDW samples range between 58.62% and 76.52%, while the UUR of the sample without bacteria treatment is 0. The UUR increases with higher RMC content and bacteria concentration. Compared to sample S1, the UUR of samples S3 and S5 increases by 9.82% and 20.56%, respectively. The UUR of sample S4 treated by high bacteria concentration increases by 18.87% in comparison to sample S3.

4. Discussions

4.1. Effect of RMC content

The UCS improvement, such as samples S1, S3, and S5, can be attributed to the RMC content increase. Sample S1 (4%) had the lowest UCS and apparent ductile deformation characteristics. It can be explained that there is too little RMC to be sufficiently distributed among all CDW particles and to provide a strong bonding effect. This can be verified by the SEM photos shown in Fig. 5a. Brucite and HMCs are sparsely distributed on CDW particles, and a large number of pores between the CDW particles still can be observed, indicating that the bonding effect is poor. Higher RMC content in samples S3 (8%) and S5 (12%) positively promoted the amount of brucite formed by the hydration of RMC, facilitating the bio-carbonation of RMC reaction and the production of HMCs. The filling and bonding effects are thus improved, resulting in higher UCS. It not only can be validated by the denser microstructure, visible carbonation products, and fewer pores in Fig. 5c

and 5e, but also can be approved by the increasing UUR.

On the other hand, when the RMC content reaches a certain value, the formed brucite and HMCs coat the CDW particles. Due to the high material strength [39], the nearby HMCs on different particles will form a spatial network structure that can endure compressive strength. Thus, UCS increases significantly, and the deformation process presents brittle failure characteristics. However, it is interesting to note that excessive addition of RMC can easily lead to the formation of microcracks due to the volume expansion of RMC during the hydration and carbonation process. An example is shown in Fig. 5f.

The negative correlation between the DC values and RMC contents indicates that when excess RMC was added, the effect of RMC content on the hydrolysis of urea was slight. It can be explained that with the increase of RMC content, the amount of produced brucite and the corresponding hydroxyl (OH^-) increases. When the liquid mixture of bacteria solution and urea stay stable, carbonates, an essential component of bio-carbonation of the RMC, does not increase substantially. It indicates that M_{CO_2} is almost the same for different RMC content. According to Eq. (7), when M_{MgO} increases dramatically but M_{CO_2} changes slightly, a negative correlation between DC value and RMC content can be observed.

In addition, 8% was identified as the optimal RMC content for the soil improvement in Yang's study [38], but not CDW's in this study. This indicated that the optimal RMC content of bio-carbonation of RMC for different geomaterials is different. It can be attributed to the fact that the bio-carbonation of RMC is a gradual expansion process of the RMC particles [1,32]. In Yang's study [38], the stabilized material was quartz sand, which was relatively dense and less compressible. A small amount of RMC could completely fill the pores of the quartz sand particles and obtain a significant stabilization effect. On the other hand, CDW particles are porous and have low particle strength after long-term weathering, which needs more RMC to fill the pores. Moreover, the difference in mechanical properties of geomaterials also causes the different mechanical properties in the bio-carbonized CDW. Thus, the optimum RMC content varies with geomaterials.

4.2. Effect of bacteria concentration

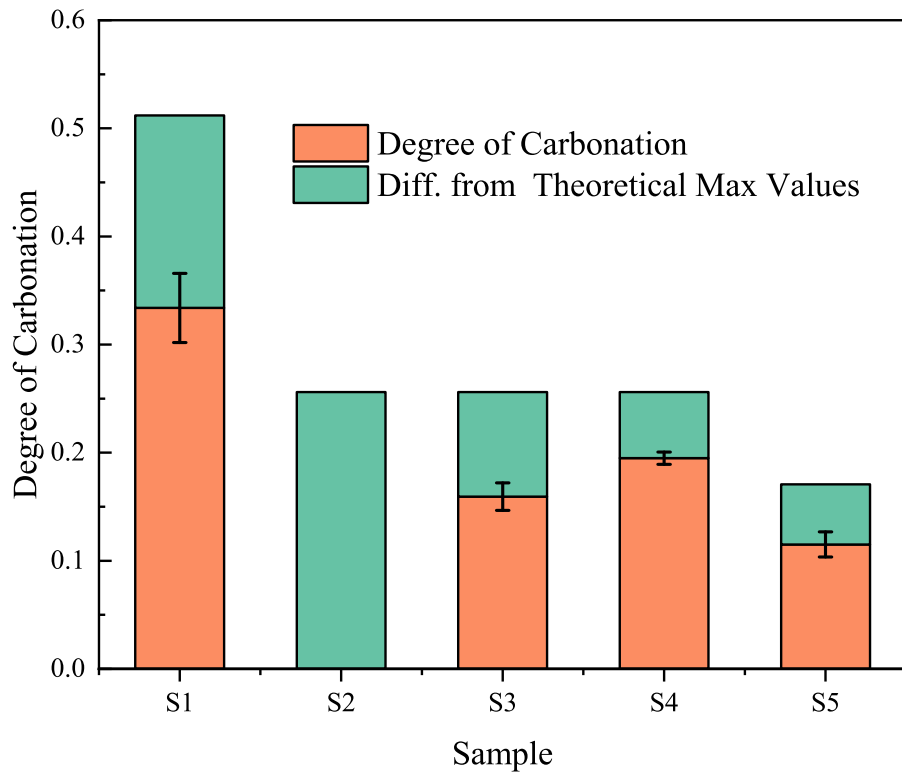
By comparing the experimental results of samples S3 and S4, we can find that the increase of the bacteria concentration can promote the mechanical properties of the bio-carbonized CDW samples. For example, sample S4 treated with concentrated bacteria solution had a remarkably elevated UCS and E_{50} compared to sample S3.

This phenomenon can be explained by the higher urease activity of the high bacteria concentration can provide more carbonate ions and significantly improve the UUR [9,29], as shown in Fig. 4b. On the other hand, the concentrated bacteria solution contains more microorganisms, providing more nucleation sites to adsorb free magnesium ions due to their negatively charged surface [43], resulting in more HMCs combined with more production of the carbonate ions.

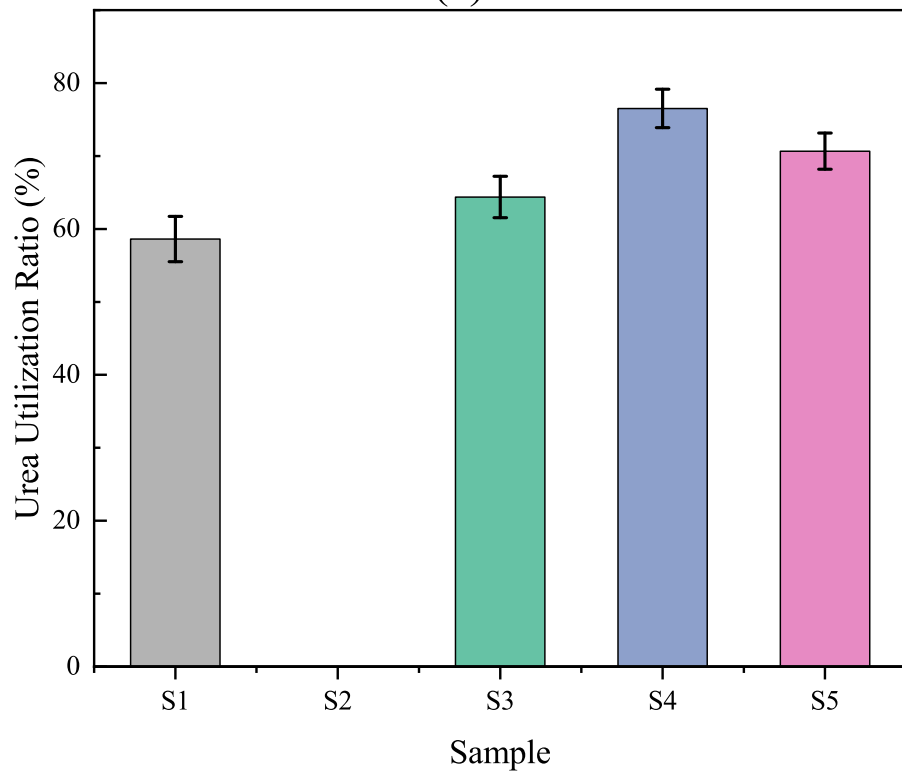
Moreover, high concentration of bacteria can promote a degree of crystallinity of bio-carbonation products. It can be explained that the high bacteria concentration facilitates the urea hydrolysis process, which increases the amount of available carbonate. According to the study of Dung (2021) [12], the higher the carbonate concentration, the better the degree of crystallinity of bio-carbonation products. A typical microstructure testing result of sample S4 is shown in Fig. 5d. We can observe from the SEM photo that two types of HMCs with high crystallinity degree, including flaky dypingite (D)/hydromagnesite (H) crystals, are well developed. These HMCs (D/H) crystals provide better filling, bonding, and coating effects, resulting in higher UCS.

4.3. Stabilization mechanism

For the CDW stabilization without bacteria such as sample S2, its mechanism can be explained as the pure hydration effect of RMC (as shown in Eq. (1)). This phenomenon can be verified by the SEM image



(a)



(b)

Fig. 4. (a) the degree of carbonation and (b) the urea utilization ratio of bio-carbonized CDW samples.

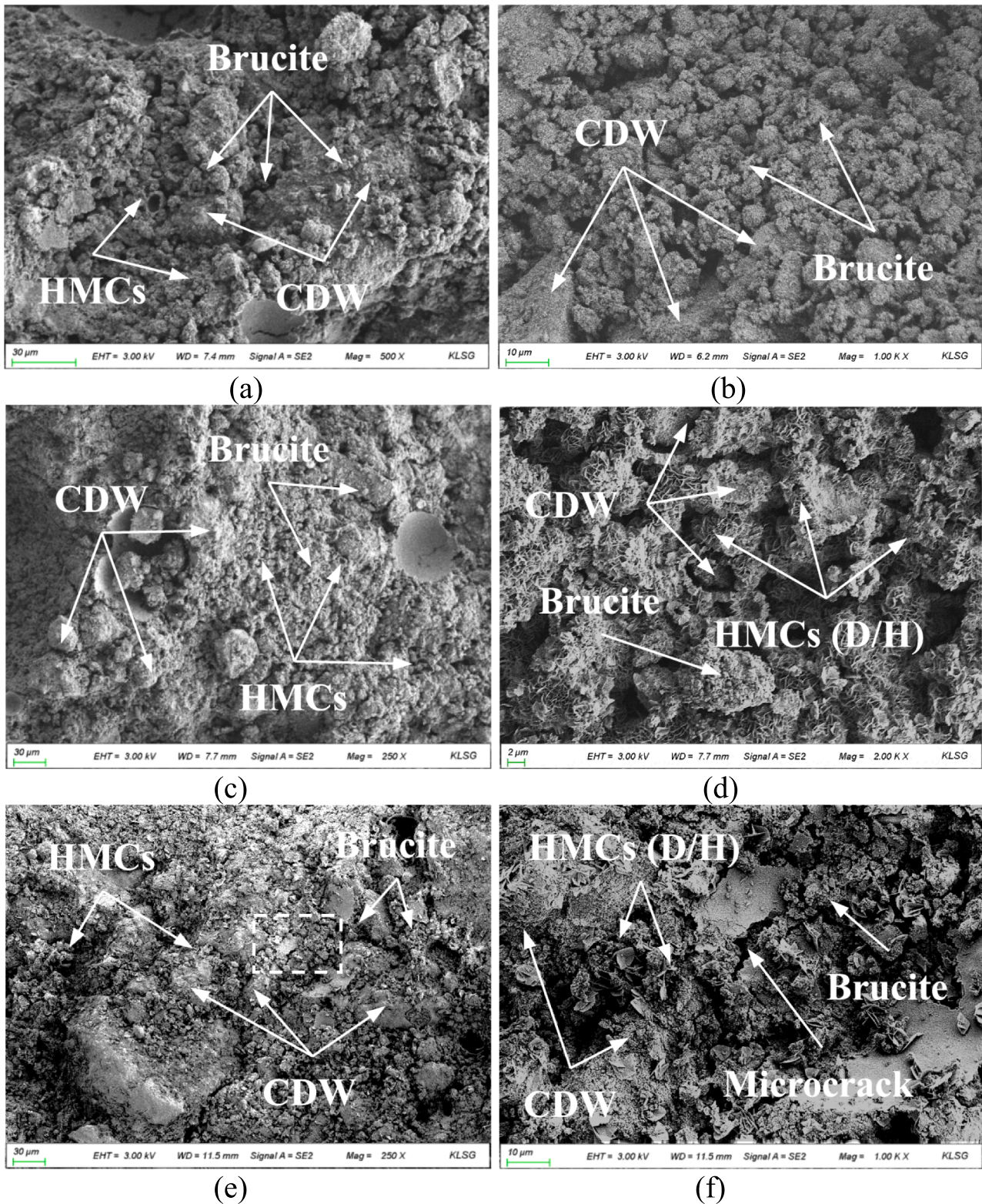


Fig. 5. The SEM images of the bio-carbonized CDW samples after 7 days of underwater curing of (a) S1, (b) S2, (c) S3, (d) S4, (e) S5, and (f) rectangular amplification region of (e).

(Fig. 5b), in which only the brucite can be observed from sample S2. Furthermore, the results of DC and UUR indicate that urea does not play a role in promoting bio-carbonation in the absence of bacteria. It is essential to observe from Fig. 5b that the brucite crystals are loose and show cluster characteristics, resulting in weak bonds [1]. Thus, the UCS of sample S2 was lower than other samples stabilized by bio-carbonation

with ductile failure characteristics.

For the CDW stabilization under the effect of ureolytic bacteria such as samples S1, S3, S4, and S5, its mechanism can be attributed to both the bio-carbonation and hydration effect of RMC. A schematic diagram is drawn to better understand the stabilization mechanism with bacteria, as shown in Fig. 6. Before the bio-carbonation process, the uniformly

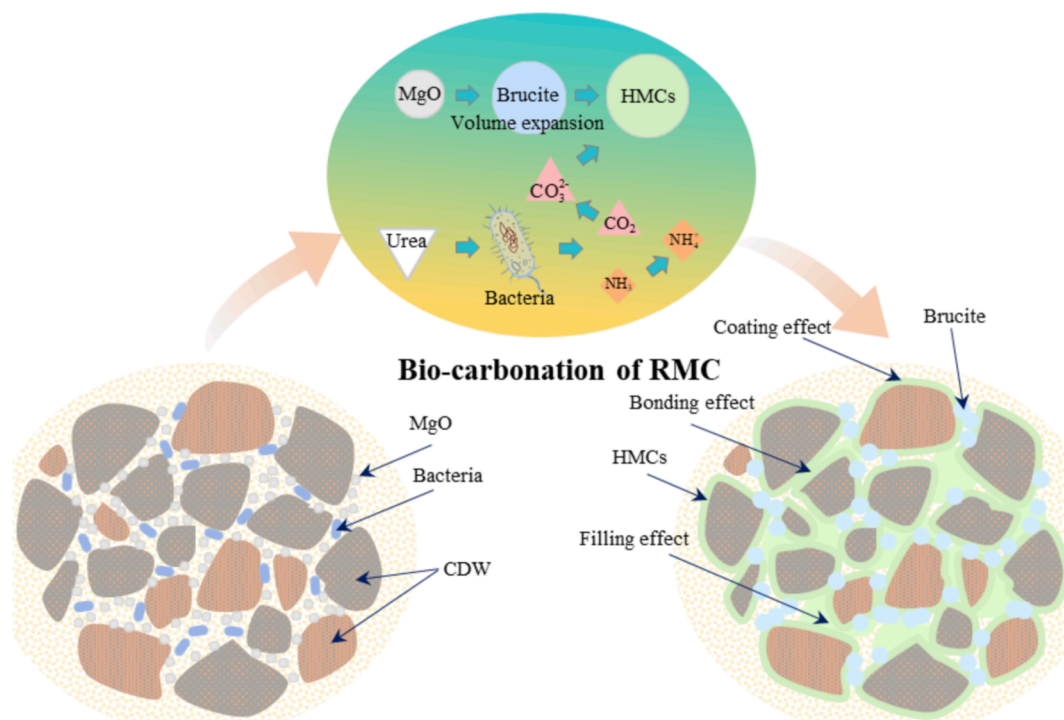


Fig. 6. The schematic diagram of the stabilization mechanism for the construction and demolition waste through the bio-carbonation of RMC.

distributed MgO is hydrated to form brucite, which can provide the prerequisites for the bio-carbonation of RMC, as shown in Eq. (1). Meanwhile, the mixed urea is hydrolyzed into carbon dioxide and ammonia under the effect of the ureolytic bacteria [35,18], as shown in Eq. (2). Then, the brucite is carbonated by the carbon dioxide to produce the HMCs under the nucleation effect of bacteria [32,7,36], as shown in Eqs. (3)–(6). The brucite and HMCs not only fill the particle pores, coat on the CDW particle surfaces, bind particles together, but also form a stable spatial network structure similar to Portland cement that facilitates stabilization performance and improves the mechanical properties [42,21]. This process can be verified by the microstructures shown in Fig. 5a, 5c-f, the RMC hydration products brucite and bio-carbonation products HMCs can be observed in each sample. On the other hand, the denser microstructure and fewer pores between CDW particles can also be found in the SEM image. It can be attributed to that the volume of MgO grain would expand during the hydrolytic and carbonation process, filling the pores of CDW particles [40]. For example, the density of MgO (3.58 g/cm^3) is higher than that of brucite (2.36 g/cm^3) and HMCs ($1.69\text{--}2.25 \text{ g/cm}^3$) [15].

A comparison and analysis of experimental results of samples S3 and S4 have given insight into the effect of the DC on the UCS improvement. When the RMC content is the same, the higher the DC, the larger the UCS. This is attributed to the high material strength and bonding effect of HMCs [7,13]. Thus, we can conclude that increasing DC is the best effective way to achieve a good stabilization effect. Experimental results show that DC is at a low-value level in this study. Therefore, corresponding systematic studies will be carried out in the future.

Furthermore, a significant difference between the obtained DC and theoretical max DC values can be observed (Fig. 4a). The difference between the obtained DC and theoretical max DC values can be attributed to inadequate urea hydrolysis by ureolytic bacteria and bio-carbonation of RMC reaction. The inadequate urea hydrolysis after mixing can be observed in Fig. 4b. It can be explained that the bacteria enzymes have a limited hydrolytic capacity. The proteins within bacteria, such as urease, would gradually deactivate and lose urea hydrolysis capacity in the presence of high urea concentrations [6]. On the other hand, the high pH values after RMC hydration (>10) reduced the

urease activity (optimum pH = 7), which also impeded the urea hydrolysis. Moreover, urea, carbonate, and bacteria can hardly avoid escaping in the underwater environment, even though the bio-carbonation of RMC can adsorb urea, carbonate, and bacteria to a great extent. Subsequent studies should aim to improve the DC to enhance the stabilization effect.

4.4. Feasibility of application on underwater engineering

This study demonstrated that the bio-carbonation of RMC is an effective strategy to stabilize the CDW particles in the underwater environment by only one time of treatment and has the feasibility to be applied on underwater engineering. The feasibility can be attributed to the fact that the RMC and CDW grains have a large specific surface area and strong adsorption ability [34,28], which could efficiently absorb bacteria, urea, and CO_2 during the treatment process and hinder their effusion from the samples during the underwater curing process. On the other hand, the high chemical activity of RMC (12–25 s) also facilitates the feasibility of the application in underwater engineering. RMC hydrates rapidly, especially when coupled with the bio-carbonation process. Hydration and bio-carbonation products quickly fill the CDW particle pores and restrain the migration of the bacteria, urea, and CO_2 underwater. In addition, the underwater environment could provide sufficient water for the RMC hydration, urea hydrolysis, and bio-carbonation reaction.

5. Conclusions

This study explored the feasibility and effectiveness of using bio-carbonation of RMC to stabilize CDW subjected to the underwater environment. We performed a series of lab-scale bio-carbonation of RMC tests on CDW with different RMC content and bacteria concentration. Major findings are summarized as follows.

- (1) Bio-carbonation of RMC has the ability to stabilize CDW particles effectively subjected to the underwater environment. The UCS value of bio-carbonized CDW was up to 1006.04 kPa with 12% of

RMC content, which was 11.2 times of CDW sample stabilized by the hydration of RMC only.

- (2) The stabilization effect was facilitated by the increase of the RMC content and bacteria solution concentration with high UCS and brittle failure characteristics. At the same bacteria concentration, the UCS of the sample with 12% of RMC content was increased by 9.64 times compared to the sample with 4% of RMC content. When the RMC content was the same, the UCS of the sample treated by concentrated bacteria solution was increased by 1.18 times.
- (3) Increasing DC is an effective way to achieve a good stabilization effect for CDW through bio-carbonation of RMC. The DC of the bio-carbonized CDW samples was in the range of 0.118–0.338. DC is controlled by the UUR, which was in the range of 58.62% to 76.52%. The higher the UUR, the greater the DC. High RMC content promotes UUR and inhibits DC, while high bacteria concentration promotes UUR and DC.
- (4) The CDW stabilization mechanism in terms of RMC bio-carbonation is attributed to the formation of brucite and HMCs by the combined effects of urea hydrolysis by ureolytic bacteria, hydration of RMC, and the carbonation of brucite. The brucite and HMCs not only fill the particle pores, coat on the particle surfaces, and bind particles together but also form a stable spatial network structure that facilitates stabilization performance and improves the mechanical properties.
- (5) The CDW stabilization by bio-carbonation of RMC was feasible to be applied to underwater engineering, mainly because RMC and CDW could adsorb bacteria and urea effectively, coupled with the rapid hydration action and filling effect of RMC.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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