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Performance of Low-Carbon Mortar Prepared with CO_2-Carbonated Carbide Slag as a Partial Cement Substitute

Chao LIU*, Chao YANG, Chao ZHU

Xi'an University of Architecture and Technology, Xi'an, Shanxi, 710055, China

*Corresponding Author: CHao LIU, E-mail:chaoliu@xauat.edu.cn

Abstract

To explore the feasibility of using CO_2-carbonated carbide slag in low-carbon cementitious materials, this study investigated the basic properties of raw carbide slag and CO_2-carbonated carbide slag, and further used CO_2-carbonated carbide slag as a partial cement substitute to prepare low-carbon mortar. Five replacement ratios of CO_2-carbonated carbide slag, namely 0%, 5%, 10%, 15% and 20%, were designed to evaluate their effects on mortar flowability, compressive strength, water absorption, bulk density, leaching pH and Ca^{2+} release behavior. The results showed that CO_2 carbonation increased the $CaCO_3$ content of carbide slag from 4.0 wt.% to 41.6 wt.%, decreased the $Ca(OH)_2$ content from 92.0 wt.% to 48.2 wt.%, and reduced the pH from 12.60 to 10.55, indicating that carbonation can reduce alkalinity and form carbonate-rich products. When the replacement ratios of CO_2-carbonated carbide slag were 5% and 10%, the 28-day compressive strengths of mortar were 50.2 MPa and 49.6 MPa, respectively, slightly higher than that of the control group (48.5 MPa). When the replacement ratio increased to 20%, the 28-day compressive strength decreased to 41.3 MPa. The water absorption and bulk density results indicated that 5%-10% replacement was beneficial to improving mortar compactness, whereas excessive replacement weakened the dense structure. Leaching tests showed that the leachate pH and Ca^{2+} concentration slightly decreased with increasing replacement ratio, suggesting that CO_2-carbonated carbide slag did not increase the risk of alkaline release. Overall, CO_2-carbonated carbide slag can be used as a partial cement substitute in low-carbon mortar, and a replacement ratio of 5%-10% is considered suitable.

Keywords: *carbide slag; CO_2 carbonation; low-carbon mortar; cement replacement; compressive strength; environmental compatibility*

1 Introduction

With increasing demand for carbon reduction in the construction materials sector, the utilization of industrial solid wastes for low-carbon cementitious materials has attracted growing attention. Carbide slag is a large-volume alkaline industrial by-product generated during acetylene production by calcium carbide hydrolysis. It is mainly composed of $Ca(OH)_2$ and contains small amounts of $CaCO_3$, CaO, SiO_2, Al_2O_3, Fe_2O_3 and MgO[1-6]. Due to its strong alkalinity and relatively high moisture content, long-term stockpiling of carbide slag may cause land occupation, dust emission and alkaline leachate problems. However, the abundant $Ca(OH)_2$ in carbide slag also gives it high reactivity toward CO_2, allowing it to generate $CaCO_3$ through carbonation, reduce material alkalinity and achieve CO_2 mineral fixation[7,8].

Previous studies have shown that carbide slag can be used in CO_2 mineralization, alkali-activated cementitious materials and construction materials[1,2,4,9-11]. Nevertheless, raw carbide slag has strong alkalinity and variable composition, and its direct incorporation into cement-based materials may affect workability, pore structure and environmental safety[9,11,12]. After CO_2 carbonation, part of the $Ca(OH)_2$ in carbide slag is converted into $CaCO_3$, resulting in lower alkalinity. Meanwhile, the generated $CaCO_3$ fine particles may act as fillers and nucleation sites in cement-based systems[13,14]. Therefore, CO_2-carbonated carbide slag has potential as a partial cement replacement component

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in low-carbon mortar.

However, CO_2-carbonated carbide slag has limited intrinsic cementitious activity, and its replacement ratio should be carefully controlled. Moderate incorporation may improve particle packing and matrix compactness, whereas excessive cement replacement may reduce the effective clinker content, decrease hydration product formation and weaken mortar strength[14,15]. In addition, whether the incorporation of carbonated carbide slag affects alkaline release or Ca^{2+} leaching requires further evaluation[8,12,16]. In this study, CO_2-carbonated carbide slag was used as a partial cement substitute to prepare low-carbon mortar with different replacement ratios. The workability, compressive strength, water absorption, bulk density and leaching behavior of the mortars were systematically analyzed to preliminarily evaluate the feasibility of using CO_2-carbonated carbide slag in low-carbon cementitious materials.

2 Materials and Methods

2.1 Raw materials and preparation of CO_2 -carbonated carbide slag

The carbide slag used in this study was an industrial by-product generated during acetylene production by calcium carbide hydrolysis and is denoted as CS. Before testing, the raw carbide slag was dried in an oven at 105 ℃ to constant mass, followed by grinding and sieving to obtain a dried carbide slag powder with relatively uniform particle distribution. The raw carbide slag had strong alkalinity, with a pH of approximately 12.60, a $Ca(OH)_2$ content of approximately 92.0 wt.% and a $CaCO_3$ content of approximately 4.0 wt.%.

The CO_2-carbonated carbide slag is denoted as CCS. Based on the previous direct carbonation results of carbide slag, the optimized carbonation condition was adopted to prepare CCS. Specifically, the moisture content was adjusted to 20% on the basis of dried carbide slag, and CO_2 was introduced under ambient temperature and pressure for direct carbonation for 120 min. After carbonation, the samples were sealed and stored for subsequent use. Ordinary Portland cement was used as the basic cementitious material, standard sand was used as fine aggregate, and tap water or deionized water was used for mixing.

2.2 Mortar mix proportions and specimen preparation

To investigate the effect of CCS replacement ratio on mortar performance, five replacement ratios of 0%, 5%, 10%, 15% and 20% were designed. The 0% group was used as the ordinary cement mortar control group and denoted as M0; the other groups were denoted as M5, M10, M15 and M20, respectively. The water-to-binder ratio of all mortars was fixed at 0.50, and the binder-to-sand ratio was fixed at 1:3. The total binder mass was 450 g, the standard sand mass was 1350 g, and the mixing water mass was 225 g. This mix design was based on commonly used cement mortar testing proportions and allowed comparison of the effect of different cement replacement ratios on mortar performance[17]. The detailed mix proportions are shown in Table 1.

During mixing, cement, CCS and standard sand were first dry-mixed uniformly. Mixing water was then added, and stirring continued until a homogeneous mortar was obtained. The fresh mortar was placed into molds, compacted by vibration and then cured under standard curing conditions to ages of 3, 7 and 28 days. If standard mortar prisms are used, specimens of 40 mm × 40 mm × 160 mm can be adopted; if cubic specimens are used, the specimen size and loading method should be clearly specified in the experimental section.

Table 1 Mix proportions of mortars with different CCS replacement ratios.

Group	CCS replacement ratio (%)	Cement (g)	CCS (g)	Standard sand (g)	Water (g)	Water-to-binder ratio
M0	0	450.0	0	1350	225	0.50
M5	5	427.5	22.5	1350	225	0.50
M10	10	405.0	45.0	1350	225	0.50
M15	15	382.5	67.5	1350	225	0.50
M20	20	360.0	90.0	1350	225	0.50

2.3 Testing methods

The basic properties of CS and CCS were characterized by pH measurement, X-ray diffraction (XRD) and thermogravimetry/differential thermogravimetry (TG/DTG) to evaluate the effect of CO_2 carbonation on alkalinity and phase composition. XRD was used to analyze the characteristic peaks of $Ca(OH)_2$ and $CaCO_3$, whereas TG/DTG was used to estimate the contents of $CaCO_3$ and $Ca(OH)_2$.

The flowability of fresh mortar was measured to evaluate the effect of cement replacement by CCS on workability. Compressive strength tests were performed at curing ages of 3, 7 and 28 days. At least three parallel specimens were tested for each group, and the average value was used as the final result. After 28 days, water absorption and bulk density were measured. The water absorption was calculated using the following equation:

$$W_a = \frac{m_s - m_d}{m_d} \times 100\% \quad (1)$$

Where W_a is the water absorption, m_d is the dry mass of the specimen, and m_s is the saturated mass after water absorption.

To evaluate the alkaline release of mortar containing CCS, 28-day mortar specimens were crushed and immersed at a fixed liquid-to-solid ratio. The leachate pH and Ca^{2+} concentration were then measured. The 28-day strength retention was calculated as follows:

$$R_f = \frac{f_i}{f_o} \times 100\% \quad (2)$$

Where R_f is the 28-day strength retention, f_i is the 28-day compressive strength of mortar with a given CCS replacement ratio, and f_o is the 28-day compressive strength of the control group M0. The overall experimental workflow is shown in Figure 1.

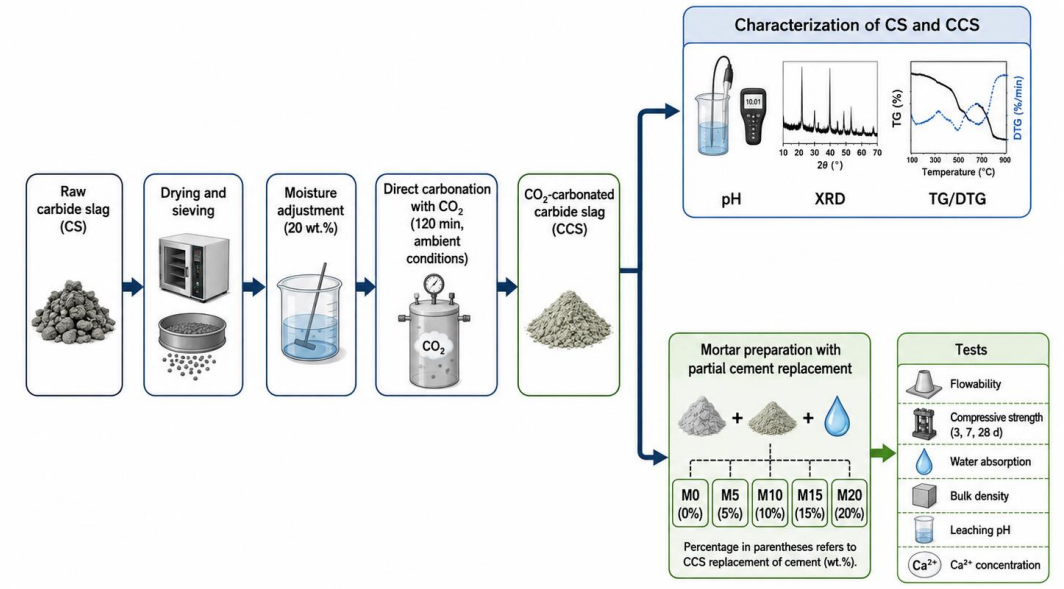

Figure 1 Experimental workflow for preparing low-carbon mortar with CO_2-carbonated carbide slag

3 Results and Discussion

3.1 Comparison of basic properties between CS and CCS

The basic properties of CS and CCS are listed in Table 2, and the related characterization results are shown in Figure 2. The raw carbide slag (CS) showed strong alkalinity, with a pH of 12.60, a $Ca(OH)_2$ content of 92.0 wt.% and a $CaCO_3$ content of only 4.0 wt.%. After CO_2 carbonation, the pH of CCS decreased to 10.55, the $CaCO_3$ content increased to 41.6 wt.%, and the $Ca(OH)_2$ content decreased to 48.2 wt.%. These results indicate that CO_2 carbonation promoted the conversion of $Ca(OH)_2$ into $CaCO_3$ and effectively reduced the strong alkalinity of carbide slag.

Table 2 Comparison of basic properties between CS and CCS.

Sample	pH	$CaCO_3$ content (wt.%)	$Ca(OH)_2$ content (wt.%)
CS	12.60	4.0	92.0
CCS	10.55	41.6	48.2

The XRD results further confirmed the phase changes before and after carbonation. CS exhibited strong characteristic peaks of $Ca(OH)_2$ and weak peaks of $CaCO_3$. After carbonation, the $CaCO_3$ peaks in CCS were enhanced, whereas the $Ca(OH)_2$ peaks were weakened. TG/DTG results also showed increased mass

loss in the $CaCO_3$ decomposition region and decreased mass loss associated with $Ca(OH)_2$ dehydration. These results indicate that CO_2 reacted with $Ca(OH)_2$ in carbide slag and generated considerable $CaCO_3$. Compared with raw carbide slag, CCS had lower alkalinity and higher carbonate content, making it more suitable as a substitute component in low-carbon cementitious materials.

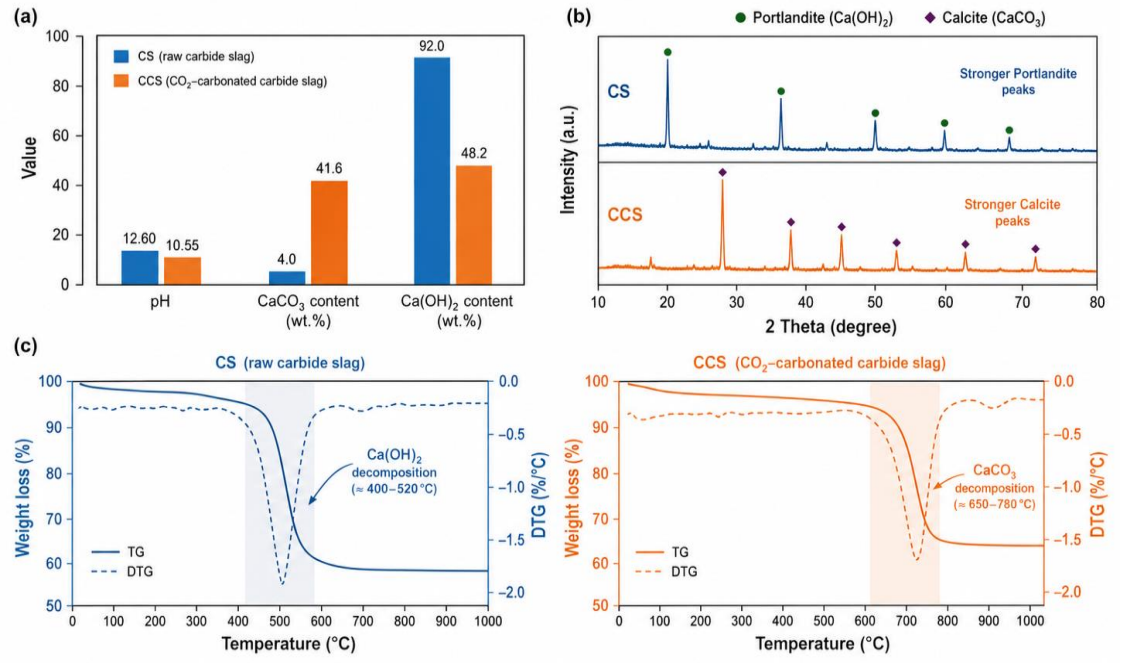

Figure 2 Comparison of basic properties between raw carbide slag (CS) and CO_2-carbonated carbide slag (CCS). (a) Basic properties; (b) XRD patterns ;(c) TG/DTG curves

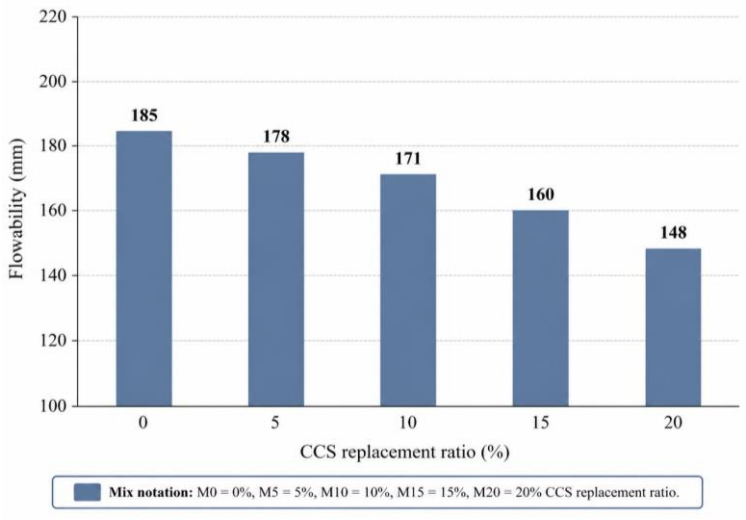

Figure 3 Flowability of mortars with different CCS replacement ratios

3.2 Effect of CCS replacement ratio on mortar flowability

The flowability of mortars with different CCS replacement ratios is shown in Table 3 and Figure 3. The flowability of the M0 group was 185 mm. As the CCS replacement ratio increased, mortar flowability gradually decreased. The flowabilities of M5 and M10 were 178 mm and 171 mm, respectively, indicating that good workability was still maintained. When the replacement ratio increased to 15% and 20%, the flowability decreased to 160 mm and 148 mm, respectively.

Table 3 Flowability of mortars with different CCS replacement ratios.

CCS replacement ratio (%)	Flowability (mm)	Workability evaluation
0	185	Good
5	178	Good
10	171	Relatively good
15	160	Slightly decreased
20	148	Obviously decreased

The decrease in flowability may be related to the rough surface, relatively high water absorption and altered particle grading of CCS. A small amount of CCS could maintain acceptable mixing performance, whereas a high CCS content increased internal friction in the paste and reduced mortar flowability. These results suggest that the CCS replacement ratio should not be too high when no additional water reducer is used.

3.3 Effect of CCS replacement ratio on mortar compressive strength

The compressive strength results of mortars with different CCS replacement ratios are shown in Table 4 and Figure 4. Overall, the CCS replacement ratio had a clear effect on mortar strength. The 28-day compressive strength of M0 was 48.5 MPa. The 28-day strengths of M5 and M10 were 50.2 MPa and 49.6 MPa, respectively, which were 3.5% and 2.3% higher than that of M0. This indicates that low CCS replacement did not negatively affect mortar strength and even slightly improved it.

Table 4 Compressive strength of mortars with different CCS replacement ratios.

CCS replacement ratio (%)	3 d compressive strength (MPa)	7 d compressive strength (MPa)	28 d compressive strength (MPa)	28 d strength retention (%)
0	24.8	35.6	48.5	100.0
5	26.1	37.4	50.2	103.5
10	25.6	36.8	49.6	102.3
15	23.4	33.9	45.7	94.2
20	20.7	30.2	41.3	85.2

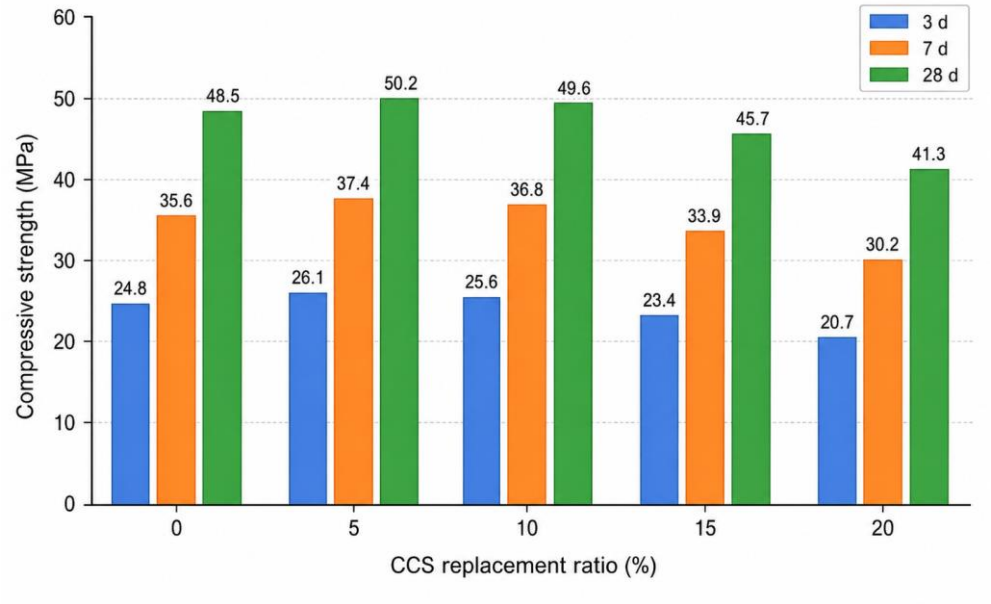

Figure 4 Compressive strength of mortars with different CCS replacement ratios at 3, 7 and 28 days

The improvement in strength at low CCS contents may be attributed to the filling effect of $CaCO_3$ fine particles. The $CaCO_3$ particles in CCS can fill voids between cement particles, improve particle packing and provide nucleation sites for hydration products, thereby increasing mortar compactness. When the CCS replacement ratio increased to 15% and 20%, mortar strength decreased. The 28-day compressive strengths of M15 and M20 were 45.7 MPa and 41.3 MPa, respectively, with strength retention values of 94.2% and 85.2%. This indicates that CCS cannot replace cement at high ratios. Because CCS has limited cementitious activity, excessive replacement reduces the effective clinker content and decreases hydration product

formation, thereby weakening mortar strength. Therefore, from the perspective of strength, a CCS replacement ratio of 5%-10% is considered appropriate.

3.4 Effect of CCS replacement ratio on water absorption, density and leaching behavior

The 28-day water absorption, bulk density, leachate pH and Ca^{2+} concentration of mortars with different CCS replacement ratios are shown in Table 5 and Figure 5. The M0 group had a water absorption of 7.8%, a bulk density of 2180 kg/m^3 and a leachate pH of 12.35. The water absorptions of M5 and M10 decreased to 7.2% and 7.4%, while their bulk densities increased to 2205 kg/m^3 and 2198 kg/m^3, respectively. This indicates that an appropriate CCS content improved mortar compactness, which is consistent with the compressive strength results.

When the CCS replacement ratio increased to 15% and 20%, the water absorption increased to 8.3% and 9.5%, respectively, while the bulk density decreased to 2165 kg/m^3 and 2138 kg/m^3. This indicates that high CCS contents increased internal porosity and made the mortar matrix relatively loose. These results further explain the strength reduction observed in the M15 and M20 groups.

The leachate pH and Ca^{2+} concentration slightly decreased with increasing CCS replacement ratio. The leachate pH and Ca^{2+} concentration of M20 were 11.88 and 435 mg/L, respectively, both lower than those of M0. This is mainly because part of $Ca(OH)_2$ in CCS had already been converted to $CaCO_3$ during carbonation, and its strong alkalinity and soluble calcium release capacity were lower than those of raw carbide slag. Therefore, the incorporation of CCS did not increase alkaline release from mortar; instead, it slightly reduced the leachate pH and Ca^{2+} concentration.

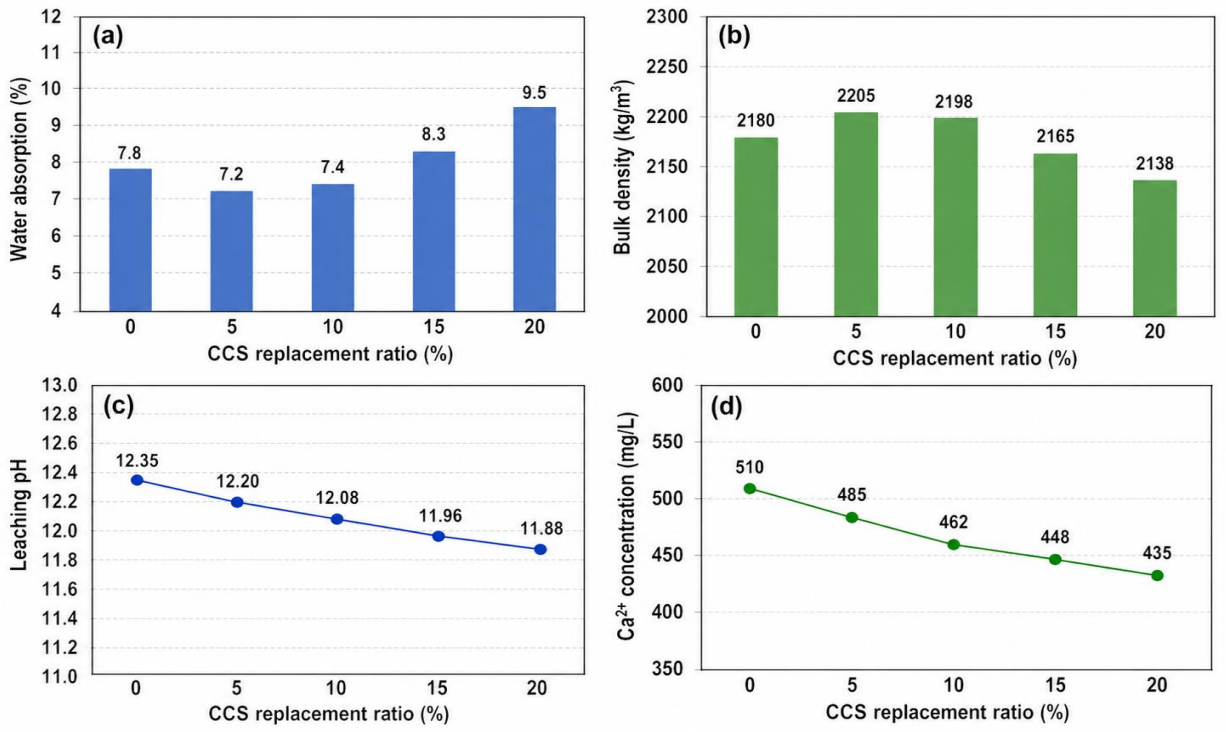

Figure 5 Physical properties and leaching behavior of mortars with different CCS replacement ratios

Table 5 Water absorption, bulk density and leaching results of mortars with different CCS replacement ratios.

CCS replacement ratio (%)	28 d water absorption (%)	Bulk density (kg·m^{-3})	28 d leachate pH	Ca^{2+} concentration (mg·L^{-1})
0	7.8	2180	12.35	510
5	7.2	2205	12.20	485
10	7.4	2198	12.08	462
15	8.3	2165	11.96	448
20	9.5	2138	11.88	435

3.5 Overall discussion

The above results indicate that the effect of CO_2-carbonated carbide slag on mortar performance was strongly dosage-dependent. At CCS replacement ratios of 5%-10%, $CaCO_3$ particles in CCS provided a filling effect in the mortar, improving matrix compactness. This was reflected by a slight increase in compressive strength and a decrease or slight change in water absorption. Meanwhile, carbonation reduced the $Ca(OH)_2$ content of carbide slag, so the incorporation of CCS did not significantly increase alkaline release from mortar.

When the CCS replacement ratio further increased to 15%-20%, the cement content in the system decreased, hydration product formation was reduced and flowability declined. These effects resulted in a looser mortar structure, lower compressive strength and higher water absorption. Therefore, CCS should not be used as a high-ratio cement replacement. Considering workability, compressive strength, water absorption and leaching behavior, a replacement ratio of 5%-10% is considered a reasonable range.

4 Conclusions

This study investigated the feasibility of using CO_2-carbonated carbide slag as a partial cement substitute for preparing low-carbon mortar. The results showed that CO_2 carbonation significantly changed the phase composition and alkalinity of carbide slag. The $CaCO_3$ content increased from 4.0 wt.% to 41.6 wt.%, the $Ca(OH)_2$ content decreased from 92.0 wt.% to 48.2 wt.%, and the pH decreased from 12.60 to 10.55. This indicates that carbonation promoted the conversion of $Ca(OH)_2$ into $CaCO_3$ and reduced the strong alkalinity of carbide slag.

The CCS replacement ratio had a significant effect on mortar workability and compressive strength. As the CCS replacement ratio increased, mortar flowability gradually decreased. When the CCS replacement ratios were 5% and 10%, the 28-day compressive strengths were 50.2 MPa and 49.6 MPa, respectively, slightly higher than that of the control group (48.5 MPa). When the replacement ratio increased to 20%, the 28-day compressive strength decreased to 41.3 MPa. Appropriate CCS incorporation can provide a filling effect and improve mortar structure, whereas excessive CCS reduces the effective cement content and hydration product formation, thereby weakening strength.

The water absorption, bulk density and leaching results showed that 5%-10% CCS was beneficial for improving mortar compactness, whereas 15%-20% CCS increased water absorption and decreased bulk density. The leachate pH and Ca^{2+} concentration slightly decreased with increasing CCS replacement ratio, indicating that CCS incorporation did not increase the risk of alkaline release. Based on strength, workability, water absorption and leaching behavior, CO_2-carbonated carbide slag can be used as a partial cement substitute in low-carbon mortar, with a suitable replacement ratio of 5%-10%.

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