A study on factors influencing compressive strength of CO₂-cured concrete

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ABSTRACT: CO₂ curing of concrete is an effective process to cure concrete products and utilize CO₂. To improve the CO₂ curing efficiency and strength of CO₂-cured concrete blocks, factors influencing the compressive strength of CO₂-cured concrete, such as specimen molding pressure, procuring relative humidity, pre-curing time, effective water to cement ratio, the degree of vacuum in curing chamber, CO₂ pressure and concentration, were experimentally investigated. The results indicated that the strength of concrete specimens after CO₂ curing correlated well with the CO₂ curing degree. The suitable conditions, which could not only improve the curing efficiency, but also improved the strength of cured concrete products, include: molding pressure of 15 ~ 25MPa, pre-curing of three hours at relative humidity between 60-70%, effective water to cement ratio between 0.15 and 0.25, the degree of vacuum in curing chamber at -0.06 ~-0.09MPa, CO₂ pressure and concentration at 0.20 ~ 0.40MPa and 60% respectively.

1. INTRODUCTION

Emission reduction, recycling, and utilization of CO₂ are currently a universal subject on sustainable development of human society. CO₂ curing of concrete block provides a new way for the use of CO₂. It mainly relies on the chemical reactions between CO₂ and cement clinker inside the concrete specimens, which can make the concrete to harden quickly. Compared with the steam curing of concrete, CO₂ curing of concrete can reduce energy consumption, improve performance and ensure the quality of concrete products. With a wide range of researches, the cost for the recovery of CO₂ will reduce. The United States plans to cut the cost recovery down to 15 U.S. dollars/ton [1]. It then will provide opportunities for collection and wide application of CO₂. At present, CO₂ emissions of cement industry to the atmosphere take account of 5%. CO₂ curing of concrete combines CO₂ utilization with concrete materials science, which is not only beneficial to sustainable development of the concrete industry, but also of great significance for the greenhouse gas emission reduction and global climate change.

Young et al [2] found that the strength of CO₂ cured concrete increased with the increase of curing degree, but there is a non-linear relationship between the degree of CO₂-curing and the compressive strength. Goodbreak [3] suggested that strength increase after CO₂ curing was due to the reduction of porosity of samples. There is an approximate linear relationship between the sample gaps filled reaction products, porosity reduction and the degree of curing. Shi and Zou [4] studied some factors affecting CO₂ curing of lightweight concrete products, including curing time, CO₂ pressure and water to cement (W/C) ratio. Shi and Wu [5] studied the water absorption, dry shrinkage, energy consumption and cost estimates of CO₂
cured blocks. They concluded that CO₂ cured blocks demonstrated better performances than steam cured concrete blocks. Converting a steam curing plant to CO₂ curing could save about $4 \times 10^9$ kJ and consume about 930 tonnes (1025 tons) of CO₂ per year.

In the process of CO₂ curing of concrete, it is often to optimize the conditional parameters to improve the reaction rate, thus to achieve high degree of curing. Young et al [2] pointed out that with the increase of CO₂ pressure, it is more effective for CO₂ to reach the reaction zone and to improve the chemical reaction rate. There are also some researches on the effects of moisture content on the reaction rate. Young et al [2] found that, during the curing process, most of the reaction occurred mainly on the sample surface. Young thought this due to the early heat generated from the reactions resulting in water evaporation, which makes difficult for CO₂ to permeate into the sample center. Liu et al [6] showed that the optimal water to binder ratio was 0.5 for CO₂ curing technologies, because of its high degree of CO₂ curing and bending strength.

This paper studies the effects of several different factors on the CO₂ curing degree and compressive strength of CO₂ cured concrete, so to find out the optimal curing parameters.

2. RAW MATERIALS AND TESTING METHODS

2.1 Raw materials

P. I Portland cement was used in this study. Its chemical composition is shown in Table 1. A well graded sand with fineness modulus of 2.6 from Xiangjiang River, Hunan province, was used, The apparent density of the sand is 2.61 g/cm³. A continuous graded gravel with size between 5 ~ 10mm, flakiness content of 9.2%, crushing value of 7.8% was used. CO₂ gas with a concentration of 99.8% was used.

Table 1 Chemical composition of P.I cement

<table>
<thead>
<tr>
<th>Oxides</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>CaO</th>
<th>MgO</th>
<th>SO₃</th>
<th>K₂O</th>
<th>Na₂O</th>
<th>R₂O</th>
<th>f-CaO</th>
<th>Li</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Percentage (%)</td>
<td>22.00</td>
<td>4.26</td>
<td>2.74</td>
<td>62.79</td>
<td>2.14</td>
<td>2.79</td>
<td>0.67</td>
<td>0.11</td>
<td>0.54</td>
<td>1.09</td>
<td>1.82</td>
</tr>
</tbody>
</table>

2.2 Sample molding

The samples were prepared using a pressure compaction process to simulate the production of concrete blocks. The specimen size was determined according to the provisions for hollow concrete block requirements in GB8239-1997 [7]. The compaction molds used for specimen compaction has a 5 cm inner diameter. The specimen height after compression was controlled at around 10 cm. After mixing, concrete mixtures were immediately placed in the compaction molds, and were pressured to the maximum pressure. There were kept for 60s at the maximum compaction pressure. After compaction, the specimens were squeezed out and placed into the pre-conditioning area.

2.3 Mix proportion

Strength design of this study was based on Chinese concrete block grade MU15, which requires a minimum compressive strength of 15 MPa. The mixing proportion of the concrete mixture is shown in Table 2.
Table 2 Mixing proportion of the concrete mixture

<table>
<thead>
<tr>
<th>Cement (kg/m³)</th>
<th>Sand (kg/m³)</th>
<th>Gravel (kg/m³)</th>
<th>Water (kg/m³)</th>
<th>Aggregate/Cement</th>
<th>W/C</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>1050</td>
<td>875</td>
<td>123</td>
<td>5.5</td>
<td>0.35</td>
</tr>
</tbody>
</table>

2.4 CO₂ curing of concrete

After the specimens were placed in the CO₂ curing chamber, it was vacuumed to a certain degree of vacuum in order to accelerate the initial penetration of CO₂ into concrete specimens. Then CO₂ was injected into the chamber from the storage tank till to a certain pressure. The pressure of the chamber was kept constant during the curing process. After curing, the compressive strength and the degree of CO₂-curing were determined as described in Section 1.4.

2.5 Determination of CO₂-curing degree

Degree of CO₂ curing is defined as the consumption of CO₂ during the curing to the maximum theoretical consumption of CO₂:

\[ \alpha = \left( \frac{m_1 - m_0 + m_{\text{vap}}}{m_{\text{max}}} \right) \times 100 \% \] (1)

Where: \( m_0, m_1, m_{\text{vap}} \) represent respectively the mass of specimen before/after curing and the mass of water evaporation during the curing process. \( m_{\text{max}} \) is the maximum theoretical consumption of CO₂, which is calculated by [8]:

\[ m_{\text{max}} = 0.785(CaO-0.7SO_3) + 1.09MgO + 1.42Na_2O + 0.93K_2O \] (2)

Where, each oxide represents its mass percent per unit by mass.

2.6 Testing of compressive strength

The compressive strength of concrete specimens were tested in accordance with GB/T 50080-2002 "Standard Test Method for physical properties of ordinary concrete mixtures"[9].

3. RESULTS AND DISCUSSIONS

3.1 Effect of pre-curing time and environmental relative humidity

The CO₂ consumption is usually low when pressure-compacted cement or mortars specimens are exposed to CO₂ immediately after molding [10]. In the earlier work, it studied the effects of pre-conditioning on the CO₂ curing of lightweight concrete blocks [11]. All these studies concluded that a proper pre-curing could be critical for reactions between CO₂ and cement minerals, and increase of CO₂ consumption. The effect of relative humidity and pre-curing time on the CO₂ curing degree is shown in Figure 1. It shows that, in different relative humidity conditions, the CO₂ curing degree varied with the pre-curing time. For pre-curing time shorter than 2 hours, the highest degree of CO₂ curing was achieved when relative humidity was controlled between 35% and 45%. When the pre-curing time was longer than 2 hours, the highest degree of CO₂ curing was obtained while the relative humidity was maintained at 60% to 70%.

The moisture losses of specimens at different relative humidities during different pre-curing periods are shown in Figure 2. It can be seen from Figure 2 that, relative humidity has a great effect on moisture loss of the specimens. No matter at what relative humidity, the moisture loss rate was very high during the first 3 hours of pre-curing, especially when relative humidity was at 35% and 45%. During 3 ~ 24h period, the
moisture loss rate gradually became stable. The final stable value was inversely proportional to the relative humidity of the pre-curing environment. The higher the relative humidity was, the lower the final moisture loss rate was. Shi and Zou [12] pointed out that the specimen pre-conditioned in moist environment hydrated more than those pre-conditioned in dry environment. The moisture loss rate depends on the RH difference between specimen inside and the environment. High moisture loss decreases the water content inside the specimens. With the increase of pre-curing time, the relative humidity difference between specimen inside and the environment becomes smaller, thus, moisture loss does not change with pre-curing time after a certain period of time.

Although the CO₂ curing degree can reach high after a short period of pre-curing time in low relative humidity environments, fast loss of moisture may result in the cracking of concrete. Thus, it is necessary to control the moisture loss rate within certain range to achieve the required moisture content inside concrete specimens without causing the cracking of concrete.

![Figure 1](image1.png)

**Figure 1** Variation of CO₂-curing degree with pre-curing time at different relative humidities

![Figure 2](image2.png)

**Figure 2** Variation of moisture loss ratio with pre-curing time at different relative humidities

The relationship between CO₂ curing degree and the compressive strength of CO₂ cured concrete is shown in Figure 3. It can be seen that: there is a very good logarithmic relationship between the degree of CO₂ curing and the compressive strength. With the increase of CO₂ curing degree, the compressive strength of
specimens increased, but the strength increase rate gradually decreased. An increase in CO₂ curing degree increases the strength of CO₂ cured concrete, and the use of CO₂ as well. From the discussions above, in order to get the appropriate CO₂ curing degree, concrete should be pre-conditioned for more than 3 hours at relative humidity of 60-70%.

![Figure 3 Relationship between CO₂-curing degree and compressive strength](image1)

**3.2 Effect of effective water-to-cement (W/C) ratio**

Effective W/C ratio is defined as the ratio of mass of remained water in concrete after pre-conditioning to the mass of cement in the concrete. Figure 4 shows the relationship between CO₂ curing degree and the effective W/C. It can be seen from Figure 4 that as the effective W/C ratio increased, CO₂ curing degree increased. The maximum CO₂ curing degree was obtained when the effective W/C ratio was about 0.20. Then, as the effective W/C ratio further increased, CO₂ curing degree decreased. Thus, the optimum effective W/C ratio is between 0.15-0.25. This is because chemical reactions during CO₂ curing are mainly those between CO₂ and cement minerals. The reactions start with the dissolution of CO₂ in water. Thus, it needs certain amount of water inside the specimens. However, if too much water exists, or the effective water to cement ratio is too high, it inhibits the infiltration of CO₂ towards the inside of the specimens, and reduces the reaction rate. Therefore, the effective water-cement ratio needs to be controlled in a reasonable range so to achieve the fast penetration of CO₂ and reaction rates. This is in agreement with the previous work [13].

![Figure 4 Relationship between effective W/C ratio and CO₂-curing degree](image2)
3.3 Effect of molding pressure

Figure 5 is the relationship between molding pressure and compressive strength of CO₂ cured concrete. It indicates that as the molding pressure increased, the CO₂-curing degree of the specimen slightly decreased. It is because as the molding pressure increases, the porosity of concrete specimens is reduced, which enhances the difficulty for CO₂ to penetrate into the specimens, and reduces the reaction rates and CO₂-curing degree.

Figure 5 also shows that, as the molding pressure increases, the compressive strength of concrete increases slightly. The slight increase in strength could be attributed to the decrease of porosity inside the concrete specimens. As discussed above, the increase of molding pressure decreased the CO₂ curing degree, which has negative effect on the strength of concrete. This means that the positive effect on strength from porosity reduction is greater than the negative effect on strength from CO₂ curing reduction.

Regression analyses indicated that there is a good relationship between compressive strength (Y) and curing degree (X₁) and molding pressure (X₂), as shown in Equation (4). For compressive strength, the effect of CO₂-curing degree is about one-third of that of molding pressure. However, the greater the molding pressure is, the lower the CO₂-curing degree is. From practical aspect, it usually controls the molding pressure in the range of 20 ~ 25MPa.

\[ Y = 0.062X_1 + 0.22X_2 + 1.49 \quad (R=0.941) \quad (4) \]

![Graph showing the effect of molding pressure on CO₂-curing degree and compressive strength.](image)

3.4 Effect of vacuum degree

Figure 6 reveals the relationship between the degree of vacuum of curing chamber and CO₂-curing degree. It can be seen that, with increase of the vacuum degree of curing chamber, the CO₂-curing degree gradually increases, especially in the range of 0.00 ~ -0.06Mpa. This may be due to the decrease of air content in concrete as the vacuum degree goes down, which facilitates the penetration of CO₂ into concrete and the reactions between CO₂ and cement particles. When the degree of vacuum is less than -0.06MPa, the CO₂-curing degree change is not obvious. Consequently, in order to gain high CO₂-curing degree, it is better to vacuum the curing chamber to less than -0.06MPa. Taking into account of the energy conservation, the suitable range of vacuum degree is -0.06Mpa ~ -0.10MPa.
3.5 The effect of CO\textsubscript{2} pressure

The relationship between CO\textsubscript{2} pressure and the compressive strength and CO\textsubscript{2}-curing degree is shown in Figure 7. As can be seen from Figure, as the CO\textsubscript{2} gas pressure increases, the CO\textsubscript{2}-curing degree gradually increases. Thus, for a given curing time period, the increase of CO\textsubscript{2} pressure will lead to increase of CO\textsubscript{2}-curing degree. When the pressure reached 0.30MPa, the effect of CO\textsubscript{2} pressure is not so obvious. Therefore, it is not necessary to use CO\textsubscript{2} pressure greater than 0.3MPa for concrete curing purpose.

3.6 The effect of CO\textsubscript{2} Concentration

Figure 8 shows the variation of compressive strength with curing time under different CO\textsubscript{2} concentrations. For a given curing time, the lower the concentration is, the lower the compressive strength is. Lower CO\textsubscript{2} concentrations result in slower reaction rates and less reaction products. However, when the curing time is longer than 4 hours, the strength increase rate under low CO\textsubscript{2} concentrations is higher than that under high CO\textsubscript{2} concentrations. This phenomenon may be due to two reasons: (1) chemical reactions during the CO\textsubscript{2} curing are exothermic, which causes moisture evaporation and slows down the reactions at later stages. The higher the CO\textsubscript{2} concentration is, the more the released heat is, the more the evaporated moisture is, the slower the later reactions are. (2) High CO\textsubscript{2} concentration results in more initial reaction products,
which slows down the reaction rate at later stage. The results in Fig.8 indicate that the difference in compressive strength between 99.5% and 50% CO₂ concentration becomes very minimal after more than 4 hours of curing. Therefore, the CO₂ curing of concrete should use CO₂ concentration greater than 50%.

![Figure 8 Effect of CO₂ concentration on compressive strength of CO₂-cured concrete](image)

### 4. CONCLUSIONS

1) An increase in the CO₂-curing degree could improve the compressive strength of CO₂-cured concrete. There is a good logarithmic relationship between the CO₂-curing degree and compressive strength.

2) Low relative humidity of pre-curing environment improved the CO₂-curing degree significantly, but is not beneficial for late strength development. The pre-curing relative humidity should be controlled at 60-70% and the pre-curing time should be more than 3 hours.

3) The effective W/C ratio should be controlled between 0.15-0.25 in order to achieve the optimum CO₂-curing degree.

4) The molding pressure has negative effects on the CO₂-curing degree, but positive effect on compressive strength. The effect of CO₂-curing degree on the compressive strength is about one third of that of the molding pressure. Molding pressure should be controlled in the range of 20 ~ 25MPa.

5) The vacuum degree lower than -0.06MPa in curing chamber has no obvious effect on compressive strength and the CO₂-curing degree. Thus, the vacuum degree should be higher than -0.06MPa.

6) The effects of CO₂ pressure and concentration on compressive strength are similar to those on CO₂-curing degree. When they are over a certain value, they don’t obviously further increase compressive strength and curing degree. The CO₂ pressure should be controlled at more than 0.3MPa and the CO₂ concentration should be controlled above 50%.

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