Experimental research on influence of curing environment on mechanical properties of coal gangue cementation

Abstract: To investigate the impact of curing environments on the mechanical properties of coal gangue cementation (CGC), various curing methods were established, including standard bag curing, standard curing, natural sealing curing, natural curing, water curing, and varying curing ages. By examining the uniaxial compressive strength (UCS) and stress–strain relationship of CGC by applying axial loads, the influence mechanism was analyzed in terms of both physical and chemical reactions. Furthermore, a mechanistic structural model was established to illustrate the impact of the curing environment on the mechanical properties of CGC. The primary substances and reasons affecting the mechanical properties of CGC were analyzed through the use of scanning electron microscopy and X-ray diffraction techniques. Evaluation of influence factors on CGC mechanical properties by grey correlation degree. The findings indicate that curing temperature, humidity, and carbonization are the principal factors influencing the UCS. Maintaining constant temperature and humidity while isolating CO2 is conducive to improving the UCS. The hydration products, such as needle-like ettringite and white fibrous calcium silicate hydrogel, fill the internal voids of CGC and are the primary substances affecting UCS. The hydration products formed during standard curing and natural curing of CGC can undergo carbonation with CO2 to form CaCO3, which interacts with ettringite and hydrated calcium silicate to provide strength support for CGC. However, beyond a certain age, CO2 will progressively diminish the UCS; the larger the contact area and the longer the exposure time to the gel materials in CGC, the faster the UCS decreases.

Keywords: coal gangue cement, maintenance environment, influence mechanism structure model, uniaxial compressive strength, grey correlation degree

1 Introduction

As mining operations continue and secondary utilization of mines expands, the mine dynamic disasters and other safety concerns are increasing, which seriously threaten people's life safety. Consequently, the durability of filling paste used in coal mines has garnered significant attention. Simultaneously, the environmental issues arising from the accumulation of mine solid waste are escalating, imposing certain impacts on the ecological environment and people’s lives [1–3]. Coal gangue cementation (CGC) primarily utilizes coal mine solid wastes, such as coal gangue and fly ash, as the main filling materials, which play a crucial role in preventing dynamic disasters and addressing the environmental challenges present in mining operations [4–6]. The durability of CGC is influenced by numerous factors, including water-reducing agents [7], binders [8], and the incorporation of various fiber types and dosages [9,10]. Concurrently, the subterranean conditions of the mine also exert an effect on the mechanical properties of CGC, such as curing temperature [11] and sulfate erosion from mine water [12]. Furthermore, the conservation environment is among the principal factors impacting the mechanical properties of CGC, which is directly linked to the safety of coal mining operations as well as the subsequent development and utilization of land resources. Therefore, this research investigates the influence of curing environments on the mechanical properties of CGC through laboratory testing. The pursuit of identifying the optimal curing environment for CGC is of great importance for the safe operation of coal mines and offers technical support for the study of uniaxial compressive strength (UCS) in CGC.
In terms of filling material composition, CGC is categorized as lean concrete. Therefore, this article primarily investigates the effects of various curing environments on concrete. The research has achieved notable advancements in air curing, wet curing, brushing curing, natural curing, plastic film wrapping curing, water curing, sunlight curing, and other techniques. The findings indicate that allowing recycled coarse aggregate to cure in air can enhance the strength of recycled concrete [13]. The longer the wet curing time is, the smaller the variation range of the surface resistivity of concrete is [14]. Compared to brushing curing agent or natural curing, plastic film wrapping curing proved to be superior, effectively minimizing the free shrinkage of concrete [15]. The strength of high-calcium fly ash-based single-component geopolymer concrete gradually increased under both room temperature and water curing conditions, exhibiting remarkable deformation performance and durability [16]. Utilizing plastic packaging for curing helps maintain a higher concentration of alkalis on the surface layer of the concrete, which could potentially boost the pozzolanic activity of the surface fly ash [17].

The UCS of concrete is influenced by humidity and temperature in various curing environments, primarily reflected in the density of its internal structure [18]. Steam curing has been found to optimize both the compressive strength and microstructure of concrete when the amounts of fly ash and slag are kept constant [19]. The compressive strength of ecologically ultra-high-performance concrete (EUHPC) subjected to steam curing was notably superior to that achieved through standard curing processes. Additionally, steam curing can decrease the porosity of EUHPC, resulting in a denser microstructure under these conditions [20]. The studies referenced above demonstrate that the curing environment has a significant impact on the UCS of concrete. However, only a limited number of scholars have investigated the effects of various curing conditions on coal mine backfill materials. Given that CGC is a type of lean concrete, its UCS is also likely to be directly influenced by the curing environment. There is a scarcity of reports on this aspect within the research literature, necessitating experimental research to investigate the mechanical behavior of CGC under different curing environments.

To investigate the influence of the curing environment on the mechanical properties of CGC, this experiment primarily employed five different curing conditions: standard bag curing environment (SBM), standard curing environment (SM), natural sealed curing environment (NSM), natural curing environment (NC), and water curing environment (WC). The experiment analyzed the influence of curing environments on the mechanical strength of CGC from a macroscopic perspective through uniaxial loading, revealing the stress-strain relationships. Additionally, a mechanism structure model was established to explain the effect of curing environments on the mechanical properties of CGC. Concurrently, X-ray diffraction (XRD) and scanning electron microscopy (SEM) were employed to elucidate and validate these macroscopic observations from a microscopic perspective, thereby establishing a theoretical foundation for studying the durability of mine backfill materials.

2 Test material and scheme

As a key element of green mining practices in coal mines, paste-filling technology is vital for supporting overlying strata and significantly alleviating or substantially diminishing surface subsidence. Consequently, the fill material, being a vital element of paste filling, has garnered considerable attention from numerous experts and scholars. In the production of coal mine filling bodies, the mixture usually comprises Portland cement, fly ash, and an appropriate amount of coal gangue along with additives. Subsequently, an appropriate amount of water is added and uniformly mixed to coalesce the components into a plastic slurry. This slurry is then pumped into the goaf.

2.1 Test material

The coal gangue utilized in the experiment originates from Daizhuang Coal Mine in Zibo, Shandong Province. The primary chemical compositions are depicted in Figure 1(a). The cement employed is No. 32.5 ordinary Portland cement manufactured by Shandong Shanshui Cement Group Co., Ltd. The principal components are listed in Table 1. The fly ash is sourced from Qingdao Huangdao Power Plant. The main physical properties are detailed in Table 2, and the primary chemical composition is illustrated in Figure 1(b).

2.2 Preparation of CGC

The CGC ratio is determined based on the principles of cement conservation and optimal utilization of solid wastes (coal gangue and fly ash); the ratio of cement to fly ash to coal gangue is set at 1:4:6. According to prior research conducted by Koohestani et al. [21], a solid concentration of
70–76% is deemed appropriate for gravity transport or pumping through pipelines. With a mass concentration of 72%, the measured slump is 20.5 cm, the initial set time is 4.1 h, and the final set time is 8 h, which satisfies the requirements for pumping mine fill paste. The CGC is prepared according to this ratio. The mixed filling material is then loaded into a 70.7 mm × 70.7 mm × 70.7 mm mold, and the mold is removed after 1 day.

### 2.3 Test method

To investigate the influence of the curing environment on the mechanical properties of CGC, the CGC samples were removed from the molds and subjected to various curing environments: SM, SBM, NC, NSM, and WC. The curing duration for each environment was set at 3, 7, 14, 28, 40, 60, 90, and 120 days, respectively. UCS, XRD, and SEM tests

#### Table 1: Intensity data of CGC under comparison sequences

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<tr>
<th>Serial number</th>
<th>$X_1$-Curing mode</th>
<th>$X_2$-Curing age (days)</th>
<th>$X_3$-UCS (MPa)</th>
<th>Serial number</th>
<th>$X_1$-Curing mode</th>
<th>$X_2$-Curing age (days)</th>
<th>$X_3$-UCS (MPa)</th>
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were conducted for each curing age of CGC. SM involves preserving CGC in a curing box maintained at a temperature of 20°C with a relative humidity of 95%, where the space is not sealed. The SBM differs from SM in that it maintains a constant CO₂ concentration; NC allows the temperature and humidity surrounding the CGC to fluctuate naturally with the atmosphere, enabling direct exposure to CO₂. The indoor temperature ranges from 10 to 15°C, with humidity levels between 60 and 70%. The distinction between NSM and NC lies in the varying CO₂ concentrations. WC involves isolating the CGC from atmospheric air while maintaining a high-humidity environment.

The differences among the five curing environments in this experiment are manifested in three main aspects: humidity, temperature, and whether there is exposure to CO₂. Essentially, different curing environments under the same age conditions aim to subject the CGC to varying levels of humidity, temperature, and CO₂ concentration. The experimental technical route is illustrated in Figure 2.

2.3.1 UCS test

UCS is the most frequently employed method for evaluating the mechanical quality of CGC or cemented paste backfill (CPB). When the CGC reached the designated curing age, it was promptly removed from the constant temperature and humidity curing box to undergo the UCS test using the DY-2008DX automatic pressure testing machine (with a load capacity of 50 kN and a loading rate of 0.01 mm/s). Each curing age was tested three times, amounting to a total of 45 groups. The final test results were then averaged for accuracy.

After the UCS test, several small fragments were excised from the fractured CGC specimen and immersed in anhydrous ethanol to halt the hydration reaction. Prior to microscopic testing, these samples were placed in a vacuum drying environment maintained at 55°C, and samples were prepared in accordance with the requirements of the testing apparatus.

2.3.2 XRD test

XRD is a rapid analytical technique principally utilized for the identification of specific characteristic substances in crystalline materials. The sample was ground into a fine powder, and the irradiation wavelength of the CGC products was examined through XRD analysis (D/MAX-2400, Rigaku Corporation, Japan, continuous scanning mode, ranging from 5° to 60°, data point interval of 0.02°, scanning speed of 4°/min), thereby elucidating the impact of the curing environment on the mechanical properties of CGC.

2.3.3 SEM test

The cross-section of the sample was intercepted and scanned by SEM (JSM-6510LV, the magnification of the standard sample was 40–400,000 times, the acceleration voltage was 50 V to 30 kV, continuously adjustable, tilt angle was −10 to 70°) to investigate the microstructural characteristics of the CGC.

3 Test results and analysis

The durability of coal mine filling paste is intricately linked to the paste’s supporting capability, garnering significant attention from numerous scholars. The impact of the subterranean environment on the performance of the backfill
material is directly associated with the safety of coal mining operations, as well as the subsequent reclamation and repurposing of the land. Within this context, the maintenance environment plays a critical role, primarily encompassing factors such as temperature and humidity. Moreover, the effect of CO₂ on the backfill material is a significant factor that cannot be overlooked. Taking these considerations into account, UCS, XRD, and SEM tests were performed on CGC under varying curing conditions to assess the impact of the curing environment on the performance of the backfill.

3.1 Analysis of the stress–strain relationship curve

By comparing the total stress–strain curves from UCS tests on CGC specimens, it was observed that the shapes under different conditions were fundamentally consistent and followed the same pattern. Consequently, the simplified stress–strain curve of the CGC specimen under uniaxial compression is presented in Figure 3.

The stress–strain process of CGC can be broadly categorized into the following five stages.

The first stage, the initial deformation stage (section OA): in the simplified graph, the OA segment exhibits a subtle upward trend; however, the change is marginal, resulting in an insignificant increase in the slope of the curve. On the whole, the stress of CGC rises as deformation increases. This phenomenon occurs because, under the influence of the applied load, the cracks and pores within the CGC oriented perpendicular to the stress direction are compressed shut. During this process, the CGC exerts “passive support” to the roof and surrounding rock through roof subsidence and rock deformation. Therefore, in the practical application of filling mining, it is crucial to guarantee that the CGC is thoroughly connected to the top to mitigate the deformation of the roof and surrounding rock.

The second stage, which is the elastic deformation stage (section AB), the curve appears almost linear. This phase is characterized by a constant slope of the curve, indicating that the increase in strain relative to stress is minimal. During this stage, CGC exerts a significant influence on the support of the surrounding rock and effectively manages the deformation of the roof and the surrounding rock.

The third stage, known as the yield stage (section BC), is marked by a downward curvature in the curve. This phase corresponds to the crack expansion stage, where the slope of the curve gradually decreases. As external forces increase, the stress field values at the tips of micro-defects within the CGC reach their limit, known as the peak strength. During this stage, the CGC provides maximum support to the roof without incurring damage.

The fourth stage, termed the failure stage (section CD), is characterized by a sharp decline in the curve, signifying the CGC failure phase where the slope of the curve turns negative. In this period, the UCS of CGC progressively diminishes as strain continues to escalate, eventually reaching residual strength after point D. Despite the occurrence of some internal damage during this stage, CGC retains a significant residual strength, enabling it to withstand a certain degree of loading. The support provided by CGC to the roof remains highly beneficial in stage 5, particularly following point D. The curve tends to flatten out, indicative of the CGC residual deformation stage where the slope approaches 0. During this stage, the UCS of CGC remains at a relatively low level despite the continuous increase in strain. Yet, it still attains 1/3 of the peak strength, which still provides a significant degree of support and bearing capacity.

3.2 Strength test results and analysis

To investigate the influence of the conservation environment on the UCS of CGC, a UCS test was conducted, and the outcomes are presented in Figure 4. Relying on the UCS test data, the CGC UCS variation trend diagram under different curing environments is exhibited in Figure 5.
Figure 4 reveals that the UCS of SBM, WC, and NSM all enhance with age, although the rate of increase diminishes over time. The UCS of SM and NC initially increases but subsequently decreases, with the rate of decline escalating significantly after 60 and 28 days, respectively. Comparatively, the CGC of SBM, WC, and NSM displayed the highest relative growth rates in UCS at 84, 41, and 46%, respectively, when compared to the preceding age group for each. Overall, irrespective of age, the UCS of CGC is highest under SBM conditions; however, the growth rate significantly reduces after 40 days. Across the five conservation environments, the UCS of CGC demonstrated a growth trend prior to 28 days. Notably, the growth rate of UCS decreased significantly and stabilized after 28 days for WC and NSM. For SM, a marked decline was observed after 60 days, while for NC, the decrease became more rapid with the extension of age after 60 days.

In the cases of WC, NSM, and SBM, the CGC is shielded from CO$_2$ and situated within environments characterized by varying temperatures and humidity levels. The CGC of SBM conditions is placed within a curing box that maintains constant temperature and humidity, creating optimal conditions for the hydration reactions essential for CGC [22], and the enclosed space promotes the formation and development of hydration products, which are integral in providing strength support to CGC. Consequently, it exhibits the fastest growth rate and attains the highest UCS. The CGC of WC was persistently submerged in water, allowing for continuous infiltration of water into the CGC to participate in hydration reactions. The sluggish growth of UCS can be attributed to two factors: On the one hand, the lower temperature compared to other curing environments resulted in a diminished rate of hydration reactions; on the other hand, the excessive water that accumulates on the surface of cement and other reactants in the later stages of the process can hinder the hydration reaction, which leads to an insignificant rise in UCS, which then tends to stabilize. The temperature of CGC of NSM is higher compared to the WC method, which results in a more rapid hydration reaction rate for the filling material. However, this increased pace is not pronounced, leading to a growth rate in UCS for NSM that closely resembles that of the WC method.

The CGC conditions of NC and SM differ in terms of temperature, humidity, and CO$_2$ concentration. The CGC environment for NC is fully exposed to the external air, which results in the loss of internal water, consequently leading to a deficiency in moisture content that impedes hydration reactions. As CO$_2$ fills the pores left void by water loss and subsequently carbonates with the internal hydration products, the resulting carbonated substances also come to fill the interior of the CGC. Consequently, the UCS has been observed to increase up until 60 days, followed by a significant decline after 28 days. Moreover, the rate of this decrease accelerates with time. This deterioration is attributed to the fact that the ettringite (AFt) phase cracks or even shatters under the corrosive influence of CO$_2$, thereby losing its load-bearing capacity, which in turn leads to a reduction in UCS. The temperature and
humidity conditions for SM are consistent and higher than those for NC, resulting in a slower rate of water loss for the CGC of SM. Additionally, the exposure time and surface area of contact between the CGC of SM and CO₂ are significantly less when compared to that of NC. As a result, the UCS of SM is greater than that of NC, and the downward trend began to emerge after 60 days.

It is evident that temperature, humidity, and the occurrence of carbonization are the principal factors influencing the UCS of CGC. Given that current literature on the impact of curing conditions on mine cemented backfill remains scarce, much of the existing research primarily focuses on the influence of curing conditions on traditional concrete. Since CGC is a type of lean concrete, it can be usefully compared with prior research on concrete to gain insights into its behavior. Xiao discovered that curing in water and standard curing effectively halt or decelerate the movement of water from within the concrete to the exterior. This allows for the adequate hydration of cement, resulting in a denser structure of the cement stone matrix [23].

Ma carried out a comparative analysis of the properties of manufactured sand concrete and natural sand concrete under steam curing and standard curing conditions; findings indicated that the dynamic elastic modulus and chloride ion penetration resistance of steam-cured concrete were inferior to those of concrete cured under standard conditions [24]. Yu investigated the effects of various curing methods on the strength of high-water expansion materials. The research revealed that the compressive strength of samples cured in standard bags consistently increased over time. In the absence of carbonation reactions, the environmental temperature is a significant factor influencing the rate at which the samples’ strength increased. Higher temperatures were shown to be beneficial for the hydration reactions within the samples, thereby expediting the rate of strength growth [25].

This article borrows the research methodology regarding the impact of the curing environment on concrete and applies it to CGC. Through our investigation, we arrive at conclusions that are akin to those of the aforementioned studies.

### 3.3 SEM result analysis

To delve into the internal structure of CGC under various curing conditions, SEM tests were performed, and the outcomes are presented in Figure 6. Considering the curing duration was 120 days, key representative ages (3, 28, and 120 days) were chosen for comprehensive analysis.

Figure 6 clearly illustrates that the internal void spaces of CGC in each preservation environment diminish progressively as the duration extends up to 28 days, resulting in a denser structure. At 3 days, voids are evident within the CGC (highlighted in yellow in Figure 6), particularly in NC, which contrasted sharply with SBM. This phenomenon is attributed to the discrepancy between internal and external humidity under the natural environmental conditions of NC. This differential caused water vaporization from within, which in turn reduced the rate of hydration, decreased the formation of hydration products, and consequently resulted in a loosening of the internal structure. The quantity of AFt and calcium silicate hydrate (C-S-H) (highlighted by the blue circle in Figure 6) increased substantially at 28 days compared to 3 days. It was closely arranged with other gels and filled in the void [26], resulting in a denser structure of CGC and a continuous narrowing of the particle spacing, ultimately enhancing the UCS [27,28]. The AFt within the CGC of SBM exhibited the densest and most compact structure compared to other age groups after 28 days (as depicted in Figure 6(c)). In the CGC of SM, AFt was observed to expand or even become crushed, AFt was virtually undetectable within the CGC of NC, while the C-S-H gel appeared clumpy due to carbonation reactions.

SBM, WC, and NSM isolate CO₂, yet under different temperature and humidity conditions. SBM provides an optimal environment for the hydration reaction of CGC by maintaining suitable temperatures and humidity levels. Hydration products, such as AFt, C-S-H, and hydrated calcium aluminate (C-A-H), can effectively fill the internal pores, thereby enhancing the material’s structural integrity. The internal structure density of CGC of NSM is denser than that of WC. This discrepancy arises because the temperature within WC is lower compared to NSM, and the elevated humidity levels in WC adversely affect the hydration reaction. As a result, the hydration reaction proceeds at a sluggish pace. In the later curing stages, the unhydrated material becomes gradually dispersed due to excessive water, leading to a reduction in the formation of hydration products. Consequently, UCS grows at the slowest rate, which is macroscopically reflected by an increase in void spaces.

CO₂ is present in both the NC and SM environments, where temperature and humidity vary. The NC and SM undergo different levels of carbonation. The temperature and humidity in NC are lower compared to SM, leading to a faster water loss rate in the CGC of NC. The pores formed after water loss are subsequently filled with air [29]. The internally generated Ca(OH)₂ (CH), AFt, C-S-H, and C-A-H undergo carbonation with CO₂ in the atmosphere, forming
CaCO$_3$ in the form of calcite, which can fill the pores of cement stone, and its volume expands by approximately 17% compared to the original reactant, thereby reducing internal porosity and enhancing density. This is also the reason why the UCS of SM has been increasing for the past 60 days. The increased porosity in NC prolongs the contact time between AFt, C–S–H, C–A–H within the CGC and CO$_2$ in the air, as well as expands the contact area between CGC and CO$_2$, consequently accelerating the rate of the carbonization reaction. The extent of carbonization in NC surpasses that of SM. As the curing period extends, AFt and C–S–H hydration products undergo complete erosion by CO$_2$, gradually losing their supportive capacity. Consequently, the UCS exhibits a downward trend.

### 3.4 XRD analysis

In order to quantitatively analyze the relationship between CGC and temperature, humidity, and CO$_2$ concentration, XRD tests were performed on CGC samples at ages of 3, 28, and 120 days. The test outcomes are presented in Figure 7.

Figure 7 reveals that at 3 days, with the exception of NC, diffraction peaks for AFt and CH appeared in each curing environment [30]. At 28 days, the diffraction peaks for AFt and CH in each curing condition were significantly intensified, whereas the diffraction peaks for SiO$_2$, C$_2$S, and C$_3$S gradually diminished, as depicted in Figure 7b. During the early stages of hydration, C$_2$S and C$_3$S engage in the
reaction to produce hydration products such as AFt and CH. As the hydration reaction progresses, fly ash becomes involved, leading to the formation of C–S–H, C–A–H, and AFt [31], which are continuously generated throughout the hydration process, providing early UCS for CGC. As the active effect of fly ash gradually materialized, the UCS of the filling materials improved in the later stages due to the enhanced phase boundary interaction, accelerated diffusion process, and increased rate of hydration reaction.

The diffraction peak of CaCO3 emerges at 2θ = 42.928 in both NC and SM, yet the peak for CaCO3 in SM is less distinct (as shown in the expanded section of Figure 7b). This discrepancy arises from the fact that the carbonization level in SM is lower than in NC, resulting in a smaller contact area and shorter contact time for the hydration products within CGC compared to NC. At 120 days, the diffraction peak intensities of AFt and CH in SBM have significantly increased compared to those at 28 days, whereas the diffraction peak intensities of SiO2, C2S, and C3S have nearly vanished. SBM offers a consistent temperature and humidity environment for CGC within an enclosed space, fostering the involvement of SiO2, C2S, C3S, and other substances in the hydration reaction, generating AFt, C–S–H, C–A–H, and CH [32], contributing to the UCS of CGC.

On the other hand, the formation of the carbonation product CaCO3 results in a reduction of pH in the pore solution, while the CH crystallization phase dissolves to maintain high alkalinity within the pore solution, leading to a macroscopic decrease in UCS for CGC.

The diffraction peaks of CaCO3 in both SM and NC are significantly higher than at 28 days, with NC exhibiting a higher CaCO3 diffraction peak. The carbonization reaction occurs through direct contact between the CGC of NC and CO2, resulting in a larger contact area, faster carbonization reaction rate, and higher degree of carbonization compared to SM. Consequently, the diffraction peak intensity of CaCO3 in NC is significantly greater than in SM. WC and NSM showed no significant changes. The CGC of NSM is maintained at room temperature, whereas the water temperature in winter falls below room temperature, which slows down the hydration reaction under low-temperature conditions. Moreover, as the hydration reaction of WC progresses, excess water can disperse unhydrated substances, further hindering the hydration reaction. Hence, at 120 days, distinct SiO2, C2S, and C3S diffraction peaks are still present in both curing environments, indicating that there was no substantial increase in the UCS of CGC under these two conditions.

In summary, different curing conditions exert varying degrees of influence on the UCS of CGC. In the absence of carbonation reactions, ambient temperature, and humidity are crucial factors in determining UCS. However, when environmental temperature and humidity are kept constant, the carbonization reaction becomes a primary factor affecting UCS.

4 Discussion

In summary, different curing conditions have varying degrees of influence on the UCS of CGC. Without carbonation reactions occurring, environmental temperature and humidity are important factors determining its UCS. When the environmental temperature and humidity are constant, carbonation reaction becomes an important factor in determining its UCS.

Figure 8 shows the model of CGC strength variation mechanism under the conditions of temperature, humidity, and CO2. Through this model, we can observe the changes in the hydration products within CGC under three conditions, which can further explain the process of the UCS of CGC changes.

To investigate whether curing methods and curing ages can reflect the mechanical properties of CGC, Figures 9 and 10...
present the relationship curves between curing methods and UCS, as well as between curing ages and UCS, respectively. Through fitting, it is found that curing methods can better reflect the UCS of CGC.

To verify the fitting results, curing methods and curing ages were considered as the key factors influencing the mechanical properties of CGC. The correlation between CGC’s UCS and curing methods/ages was analyzed using the grey correlation degree method to determine the influence degree of each factor on CGC’s UCS, calculate the weights, and thereby achieve the evaluation of influencing factors on CGC’s UCS.

Taking the strength as the reference sequence, it can be expressed as

\[ X_0 = \{X_0(k), k = 1, 2, 3, \ldots, a\}. \]  

(1)

The curing method and curing age can be expressed as comparison sequences

\[ X_i = \{X_i(k), k = 1, 2, \ldots, a\}; \quad i = 1, 2, \ldots, b. \]  

(2)

This article selects two influencing parameters, with a total of 40 sets of data, where \(a = 40\) and \(b = 2\). By performing a first-order accumulation reduction on the reference sequence \(X_0\) and the comparison sequence \(X_i\), we obtain

\[
\begin{align*}
y_0(t + 1) & = X_0(t + 1) - X_0(t) \\
y_i(t + 1) & = X_i(t + 1) - X_i(t)
\end{align*}
\]

(3)

\((i = 1, 2, 3 \ldots, b; \quad t = 1, 2, \ldots, b = 1)\)

Figure 8: Mechanism model of CGC intensity change under temperature, humidity, and CO2 environment.

Figure 9: Curve of the fitting relationship between maintenance methods and compressive strength.
Based on the above formula, we perform accumulation reduction on $y_0$ and $y_i$ to further calculate the relative rate of change $k$ for the reference sequence $X_0$ and the comparison sequence $X_i$ as follows:

$$k(t + 1) = \frac{y(t + 1)}{X_i(t + 1)} = \sum_{i=0}^{b} x_i(t)/b, \quad (4)$$

$$k(t + 1) = \frac{y_0(t + 1)}{X_0(t + 1)} = \sum_{i=1}^{b} x_0(t)/b. \quad (5)$$

Finally, the correlation coefficients and correlation degrees between the reference sequence and the comparison sequences are calculated separately.

The correlation coefficients $k$ and correlation degrees $g$ between the reference sequence (strength $a$) and the two comparison sequences $b$ (curing method and curing age), representing the two influencing factors, are calculated separately as follows:

The correlation coefficients $r(k)$ and the degrees of grey incidence $r$ between the reference sequence (strength $X_0$) and the two comparison sequences $X_i$ (curing methods and curing ages) are calculated, respectively, as follows:

$$r(t) = \text{sign}(1 + |k(t)|) - |k_d(t)|). \quad (6)$$

Formula:

$$r = \sum_{t=2}^{n} r(t)/(n - 1); \quad \text{sign} = \begin{cases} 1, & y(t) \times x(t) \geq 0 \\ -1, & y(t) \times x(t) \leq 0 \end{cases}.$$  

The obtained reference sequence and comparison sequences are presented in Table 1.

Finally, the correlation degrees between the curing method, curing age, and strength are obtained, and the results are presented in Table 2.

By analyzing the results obtained from the correlation degree, it can be found that the correlation degree between the curing method and UCS is $y = 0.7296$, while the correlation degree between curing age and UCS is $y = 0.5494$. The correlation degree of the curing method to CGC strength is 25% higher than that of curing age, indicating that the influence of the curing method on CGC strength is greater than the influence of curing age. The curing method can better reflect the mechanical strength of CGC, which is consistent with the fitting results between the curing method and strength, as well as between curing age and strength.

5 Conclusions

The UCS test was employed to investigate the patterns of CGC strength variation under diverse curing environments. In conjunction with XRD and SEM analyses, qualitatively and quantitatively analyzed the material composition within CGC, the appearance of various products, and the patterns of wavelength variation. Subsequently, a model elucidating the mechanism of CGC strength variation was established. The principal findings are summarized as follows:

1) Temperature, humidity, and carbonation are the primary factors impacting the UCS of CGC. The UCS test revealed that the UCS of CGC improved under conditions of stable temperature and humidity isolated
from CO$_2$. In comparison with NC, the CGC of SBM exhibited the highest UCS, whereas WC had the lowest. In the early stage (3 days), the UCS of SBM, SM, NSM, and WC increased by 54, 37, 12, and 42%, respectively. In the later stage (28 days), the UCS of SBM, SM, and NSM rose by 74, 50, and 19%, respectively, while WC saw a decrease of 9%. The carbonization reaction in the CGC of SM and NC slowed down the hydration reaction rate of C$_3$S and C$_2$S, which led to a slower increase in the CGC of UCS compared to other curing environments.

2) SEM and XRD tests indicated that the principal substances affecting the UCS of CGC are hydration products, including AFt, CH, and C–S–H gel within the CGC. Varying curing environments can modulate the rate of CGC hydration reactions to different extents, altering the content of hydration products and consequently leading to shifts in the UCS of CGC. By analyzing the correlation between curing methods and CGC’s UCS, and the correlation between curing ages and CGC’s UCS, it is found that curing methods can better reflect the changes in CGC’s UCS, which is consistent with the factors affecting CGC’s UCS analyzed using grey relational degree.

A comprehensive analysis of these five curing environments reveals that the SBM approach more closely mimics the actual conditions of filling. After CGC is filled, it is placed in a sealed environment with high humidity and generally consistent temperature, which helps to maintain an increasing trend in the UCS of CGC and also ensures its long-term stability performance.

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**References**


