



# Effect of Varied Steam Curing Regimes on Mechanical Strength and Durability of Concrete

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**Abstract.** To enhance the efficiency of bridge pre-cast construction, this study elucidates the benefits of steam curing by analyzing the effects of different curing regimes on the mechanical properties, durability and pore structure of concrete. The findings indicate that steam curing can markedly enhances the compressive strength and elastic modulus of concrete within the initial seven days, and maintains comparable long-term mechanical performance to that achieved through normal temperature curing. Additionally, concrete subjected to steam curing exhibits superior performance in terms of resistance to carbonation and chloride ion penetration, particularly in early ages. The resistance to carbonation and chloride ion penetration are improved significantly with prolonged constant temperature exposure and extended static resting times. Although steam curing may slightly degrade the pore structure to be slightly inferior to room temperature curing, appropriately extending the static resting times can effectively mitigate this effect. Practical applications in engineering demonstrate that selecting a steam curing regime with a constant temperature of 55°C and an 8-hour static resting times allows the completion of prestressed tensioning 5 days ahead of schedule, thereby substantially enhancing construction efficiency.

**Keywords:** Concrete Curing, Steam Curing, Mechanical properties, Durability, Pore Structure of Concrete.

## 1 Introduction

In recent years, traditional cast-in-place concrete construction has encountered significant challenges, including substantial resource consumption, severe environmental damage, high carbon emissions, and a scarcity of skilled labor [1]. Prefabricated building technology as an environmentally friendly alternative [2], prefabricated building technology and industrial construction production in many developed countries has aroused great concern, is also strongly advocated and promoted by Chinese policy [3]. Consequently, precast concrete (PC) has emerged as the predominant material in precast construction.

For PC manufacturers, achieving high-efficiency production is essential to enhance output and ensure timely deliveries [4]. The critical technical requirement for PCs is to obtain higher early strength to accelerate the turnover of templates or molds, particularly as many PC components are uniform or require tensioning of prestressing tendons [5]. Hence, accelerated curing methods are typically employed in PC production, tailored to the specific characteristics of various concrete types. These methods include steam curing, spray curing, electrical heating of reinforcement, direct application of electrical current to the concrete, and microwave heating [6]. It takes 7 days for a PC beam to satisfy the prestressed tensile strength requirements by spray curing, with curing time comprising over 60% of production time, thus hindering the swift construction of large-scale prefabricated beams [7].

Steam curing significantly enhances the early strength of concrete, expedites mold turnover, shortens production cycle, and boosts construction efficiency [8]. However, compared to standard-cured concrete, steam-cured concrete exhibits higher porosity, greater early compressive strength, and diminished long-term mechanical properties and durability [9]. This degradation in long-term performance primarily stems from the thermal effects of early high temperatures. Verbeck et al. [10] observed that the formation of a dense gel shell, resulting from rapid hydration at elevated temperatures, restricts the complete hydration of cementitious materials. Ramezani-pour et al. [11] investigated the durability and microstructure under various steam curing conditions. Their findings demonstrated a decrease in water permeability resistance with an increase in steam curing temperature from 60°C to 70°C. Detwiler et al. [12] determined that elevating the steam curing temperature not only expedites the early strength development of concrete but also degrades its micropore structure. These findings collectively suggest that while steam curing enhances the early strength of concrete, it detrimentally impacts its durability and microstructure in subsequent stages. Consequently, there exists substantial significance in systematically examining the influence of diverse steam curing regimens on the mechanical strength and durability of concrete in engineering applications.

There exists a paucity of research concerning the impact of various steam curing regimens on the performance of precast concrete in practical engineering applications. Moreover, within the existing literature, the comparative analysis of diverse steam curing protocols is seldom employed in practical engineering contexts. Drawing upon the prestressed concrete (PC) precast box girder project at Zhanjiang Airport Expressway, this study investigates the effects of different steam curing regimens and standard temperature curing on the mechanical properties, carbonation characteristics, and permeability of precast concrete. Through analysis of the microscopic pore structure, the influence of steam curing regimens on the internal structural evolution of concrete is explored, culminating in the proposal of a pragmatic steam curing regimen for application in engineering practice.

## 2 Engineering Situations

The Zhanjiang Airport Expressway, serving as the sole high-speed conduit to Zhanjiang Wuchuan Airport, necessitates the prefabrication of 1255 PC box girders during the project's early stages, despite a truncated construction window of only 13 months. The adoption of traditional natural spray curing methods would inevitably derail the beam fabrication schedule. Consequently, this endeavor proposes the implementation of a novel beam production methodology that integrates self-propelled pedestals and steam curing. This approach seamlessly links the steel processing, rebar binding, concrete pouring, steam curing, tension grouting, and beam lifting phases, thereby enhancing operational continuity. By leveraging steam curing to expedite concrete hydration reactions, the efficiency of beam fabrication undergoes a significant boost. This innovative process aims to rectify challenges such as limited construction space, stringent deadlines, suboptimal productivity, adverse working conditions, and labor-intensive operations. Moreover, it seeks to preempt potential construction quality issues stemming from extensive operational management, thereby establishing a solid foundation for timely and high-quality project completion.

## 3 Experimental Study

### 3.1 Raw Materials

Ordinary Portland cement with a strength grade of 52.5R, in accordance with the Chinese standard GB 175-2007, was used. River sand with a fineness modulus of 2.48 and natural gravel with a continuous gradation of 5-20 mm were employed as fine and coarse aggregates, respectively. Moreover, a polycarboxylate-ether type High-Range Water Reducer Admixture (HRWRA) from Guangdong Qiangshi Building Materials Technology Co., Ltd, was consumed to achieve the required workability for the mixtures. The water cement ratio is 0.33, and the specific mix ratio is shown in Table 1.

**Table 1.** Concrete mixture design (unit: kg/m<sup>3</sup>).

Cement	Sand	Hand Stone	Middle Stone	Water	Water Reducer Admixture
490	665	114	1020	162	5.390

### 3.2 Curing Regimes

The steam curing regimes is divided into three different constant temperature (50 °C, 55 °C, 60 °C) and static resting times (5h, 8h, 11h). The rising and cooling rate is controlled at 10 °C/h, and the steam curing parameters are set as table 2.

**Table 2.** Curing regimes parameters.

Cement	Curing Method	Constant Temperature (°C)	Heating Rate (°C/h)	Static Resting Time (h)
P1	Steam curing	50	10	5
P2		55	10	5
P3		55	10	8
P4		55	10	11
P5		60	10	5
P6		Normal temperature curing		

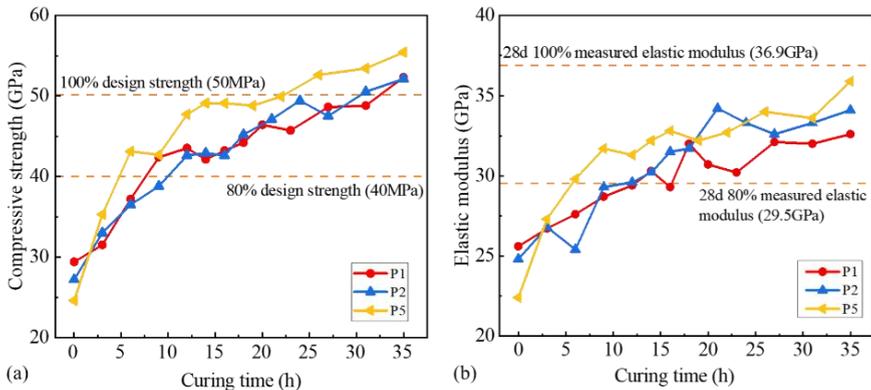
### 3.3 Measurement Method

The compressive strength and elastic modulus of concrete were tested using cubic specimens in accordance with Chinese standard GB/T 50081-2019. The carbonation resistance and chloride ion corrosion resistance of concrete were tested following the guidelines of Chinese standard GB/T 50082-2009. The pore structure test under different curing regimes was carried out by nitrogen adsorption method.

## 4 Results and Discussion

### 4.1 Compressive Strength

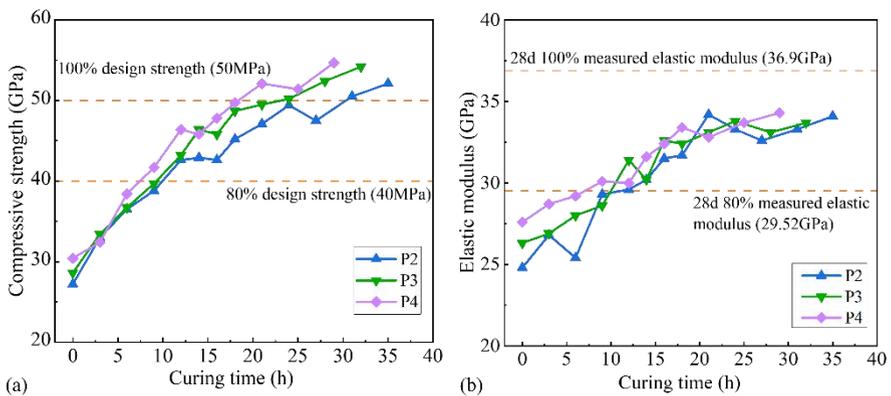
According to Chinese standard JTG/T 3650-2020, the strength of concrete should not fall below 80% of the design strength grade, and the elastic modulus should remain above 80% of the 28-day elastic modulus of concrete.



**Fig. 1.** The variation of mechanical properties of concrete with curing time under different constant temperature steam curing regimes. (a) Early age compressive strength. (b) Early age elastic modulus.

**Fig. 1** illustrates the variation in concrete's mechanical properties during early age under different constant temperature. With the static resting times of 5 hours, the higher constant temperatures of steam curing, the more significant the increase of early age strength and elastic modulus of concrete, as shown in **Fig. 1**. This indicates that the rate of early cement hydration rises with temperature, aligning closely with findings in [8].

**Fig. 2** illustrates the variation in the mechanical properties of concrete at early ages under varying durations static resting times. When maintained at a constant temperature of 55 °C, with the increase of static resting times, the early strength and elastic modulus of steam cured concrete also increase, as shown in **Fig. 2**. Notably, when the static resting times reaches 11 hours, it necessitates a steam curing period of 15 hours for the early strength of concrete to meet the requirements of prestressed tension in the Chinese standard JTG/T 3650-2020. Relative to the static resting times of 5 and 8 hours, the regime reduces steam curing time of concrete by 6 and 2 hours respectively, which improves the efficiency of beam making.

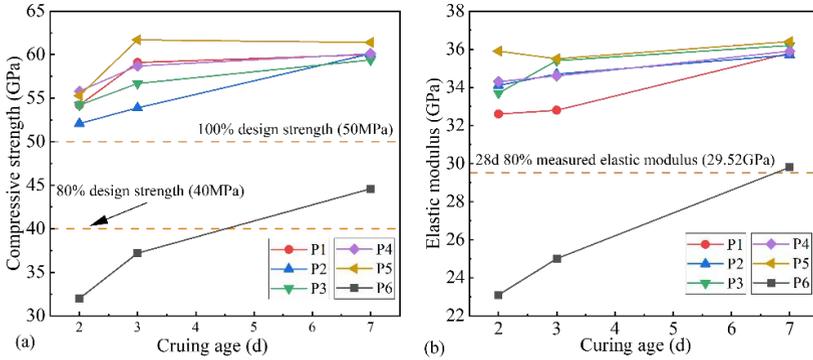


**Fig. 2.** The variation of mechanical properties of concrete with curing time under different static resting times steam curing regimes. (a) Early age compressive strength. (b) Early age elastic modulus.

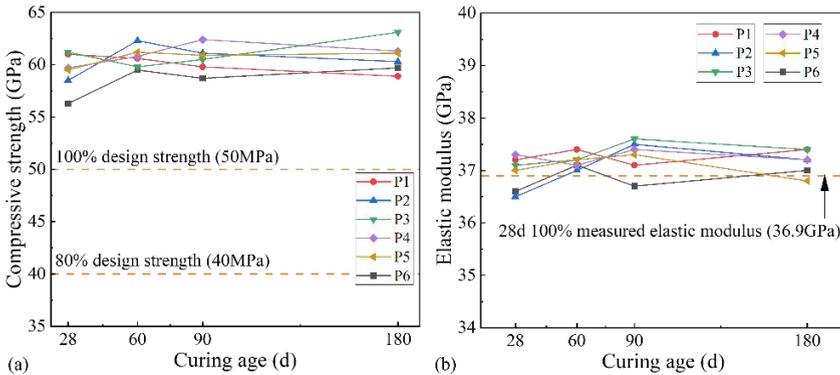
**Fig. 3** illustrates the variation in the mechanical properties of concrete at early ages under different curing regimes. As shown in **Fig. 3**, steam-cured concrete exhibits notably superior compressive strength and elastic modulus within the initial 7 days compared to specimens cured at ambient temperature. Remarkably, steam-cured concrete attains prestressed tension requirements outlined in the Chinese standard JTG/T 3650-2020 by the 2<sup>nd</sup> day. Compared to the normal temperature curing regimes, the time required for concrete to reach the tension requirements under steam curing is shortened by 5 days, indicating that steam curing can enhance the early cement hydration process and accelerate the improvement of early strength and elastic modulus.

**Fig. 4** illustrates the fluctuations in the mechanical properties of concrete across various curing regimes. As shown in **Fig. 4**, the evolution of concrete's later strength and elastic modulus across different curing regimes reveals a consistent growth

pattern between steam curing and normal temperature curing. Furthermore, the majority of specimens subjected to steam curing regimes higher strength and elastic modulus values compared to those under normal temperature curing conditions.



**Fig. 3.** The variation of mechanical properties of concrete with curing age under different steam curing s. (a) Early compressive strength. (b) Early elastic modulus.

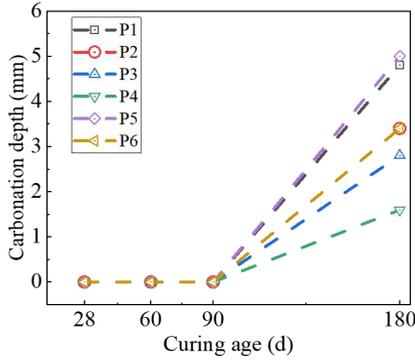


**Fig. 4.** The variation of mechanical properties of concrete with curing age under different steam curing regimes. (a) Long term compressive strength. (b) Long term elastic modulus.

### 4.2 Resistance to Carbonation

**Fig. 5** shows the variation in concrete carbonation depth across different curing regimes. As shown in **Fig. 5**, the carbonation depth for all experimental concrete groups remains below 10 mm. According to the Chinese standard GB 50164-2011 evaluation standard, the carbonation resistance meeting the 'good' rating. Prior to 90 days, the carbonation depth of concrete under both ambient and steam curing conditions is negligible, and it exhibits a marked increase thereafter. By 180 days, concrete cured at 55 °C demonstrates superior carbonation resistance compared to that cured at room temperature. Conversely, concrete cured at both 50°C and 60°C shows inferior carbonation resistance relative to room-temperature curing. Moreover, the

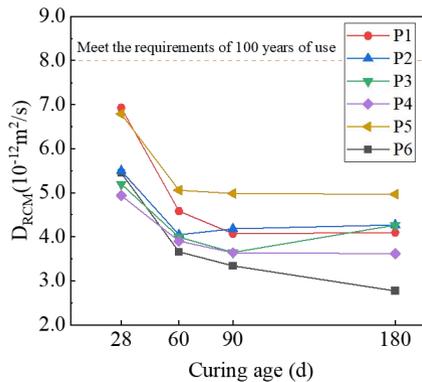
carbonation resistance of concrete under a steady 55°C steam curing regime significantly enhances with prolonged static resting times.



**Fig. 5.** The variation law of concrete carbonation depth under different curing regimes.

### 4.3 Resistance to Chloride Penetration

**Fig. 6** shows the change law of concrete resistance to chloride ion erosion under different curing regimes. As shown in **Fig. 6**, the non-steady-state chloride ion migration coefficient of concrete remains below  $8.0 \times 10^{-12} \text{m}^2/\text{s}$  across all ages. According to the Chinese standard JGJ/T 3310-2019, all concrete test groups demonstrate compliance with the requirement for a 100-year service life. Furthermore, an observable decline in the chloride ion migration coefficient is evident across all specimens as concrete ages. Beyond 28 days, the resistance to chloride ion permeability of steam curing concrete is inferior to that of normal temperature curing concrete. Notably, when the concrete is subjected to curing at constant temperature of 60 °C, the chloride ion migration coefficient reaches its minimum value after 5 hours of static cessation. Additionally, under constant temperature conditions of 55 °C, the resistance to chloride ion permeability in concrete improves with prolonged static resting times.

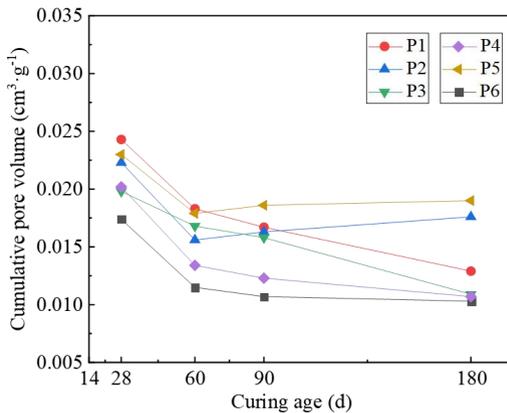


**Fig. 6.** The variation of chloride ion migration coefficient of concrete with curing age under different steam curing regimes.

#### 4.4 Pore Structure

The variations in the total pore volume of concrete subjected different curing regimes evolve over time, as shown in **Fig. 7**. Analysis of **Fig. 7** reveals that concrete cured at normal temperatures exhibits a superior pore structure compared to that of steam-cured concrete. With the increase of concrete age, the total pore volume of all specimens shows a downward trend. This decline stabilizes after 90 days, aligning with prior trends in resistance to chloride ion permeability. This phenomenon can be attributed to the internal pores within the concrete serving as conduits for the infiltration of chloride ions,  $\text{CO}_2$ , and water from the external environment, thereby diminishing its resistance to chloride ion permeability.

With increasing temperature maintained during the curing process, there is a gradual increase in the total pore volume of the concrete. The reason is that during the heating process of concrete steam curing, accompanied by the migration of surface water to the inside and the transformation between water and gas, it will be blocked by the viscous cementitious material of the medium, resulting in the deterioration of the pore structure of concrete. This mechanism underlies the notably poor resistance to chloride ion penetration observed in concrete subjected to a constant temperature of  $60\text{ }^\circ\text{C}$  with a curing pause of 5 hours. Conversely, under the condition of constant temperature of  $55\text{ }^\circ\text{C}$ , extending the curing pause from 5 to 11 hours significantly ameliorates the pore volume after 90 days of aging. Specifically, at 180 days of aging, the total pore volume of concrete for curing pauses of 8 and 11 hours are recorded  $0.0109$  and  $0.0107\text{ cm}^3/\text{g}$ , respectively, showing improvements of  $5.82\%$  and  $3.88\%$  over the normal temperature curing result of  $0.0103\text{ cm}^3/\text{g}$ . These findings suggest that prolonging the pause duration during steam curing can effectively mitigate the deterioration of the pore structure, thereby enhancing the overall pore structure of the concrete.



**Fig. 7.** The variation of total pore volume of concrete with curing time under different steam curing regimes.

## 5 Conclusions

In this paper, the mechanical properties, durability and pore structure of concrete under different curing regimes are studied. The major conclusions are as follows:

1. At 7 days, the compressive strength and elastic modulus of steam-cured concrete substantially surpass those of concrete cured at normal temperatures, though their long-term mechanical properties exhibit similar growth patterns. Elevated constant temperatures in steam curing markedly enhance the early-age strength and elastic modulus of the concrete. Moreover, maintaining a consistent temperature while extending the static resting times further amplifies these properties.

2. Both steam-cured and normally cured concretes exhibit commendable carbonation resistance. Prior to 90 days, all experimental groups showed no carbonation, and significant increases followed thereafter. By 180 days, concrete at a constant 55°C demonstrated superior carbonation resistance compared to that at room temperature, whereas concrete at constant temperatures of 50°C and 60°C displayed inferior resistance. Extended static curing times notably enhance carbonation resistance.

3. The chloride ion permeability of both steam-cured and normally cured concretes meets the 100-year service life standard. As concrete ages, the chloride ion migration coefficient in all specimens. Beyond 28 days, steam-cured concrete exhibits reduced resistance to chloride ion permeability compared to normally cured concrete, and prolonging the static resting times enhances this resistance.

4. The pore structure of concrete cured at ambient temperatures is superior to that of steam-cured concrete. With the increase of concrete age, the total pore volume of concrete shows a downward trend, and the downward trend tends to be gentle after the age reaches 90 days. Moreover, an elevation in constant temperature progressively increases the total pore volume of concrete. When the static resting times increased from 5 to 11 hours, the total pore volume of the 180 days was merely 3.88 % higher than that observed in ambient temperature-cured concrete, suggesting that prolonging the static curing period can effectively mitigate the deterioration of the pore structure associated with steam curing.

In summary, after considering the alterations in mechanical properties, durability, and pore structure under different curing regimes, 1255 PC box girders were cured under the steam curing regime with a constant temperature of 55 °C and a static resting times of 8 hours in practical engineering applications. Prestressed tensioning was completed five days earlier than under normal temperature curing, significantly enhancing construction efficiency.

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