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Research Article

Early Mechanical and Microstructure Evolution Characteristics of Concrete in Steam Curing Condition

Shengrong Liao,[1,2] Chunming Xiao,[1,2] Yuhao Cui ,[3] and Yan Xue[4]

[1]*Road and Bridge International Co., Ltd., Beijing 101100, China*
[2]*Road & Bridge Southern China Engineering Co., Ltd., Zhongshan, 528400 Guangdong, China*
[3]*International Joint Research Laboratory of Henan Province for Underground Space Development and Disaster Prevention, School of Civil Engineering, Henan Polytechnic University, Jiaozuo 454000, Henan, China*
[4]*Huanghe Jiaotong University, Jiaozuo, 454000 Henan, China*

Correspondence should be addressed to Yuhao Cui; hpu_yhcui@126.com

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In order to study the effect of steam curing on early mechanical properties of concrete, the strength, dynamic elastic modulus, and microstructure characteristics of concrete under different curing methods were tested. The results show that the early strength growth rate of steam curing concrete is obviously higher than that of standard curing. The strength development of concrete during steam curing can be divided into three stages. Stage I and stage II (0 h-30 h) are critical periods for concrete strength growth. The dynamic elastic modulus of steam-curing concrete is mainly formed in the early stage and shows a linear rapid growth characteristic. The growth rate of the dynamic elastic modulus of concrete under standard curing condition is relatively slow, but in the later curing period (30 h-48 h), the growth rate of dynamic elastic modulus of concrete is significantly higher than that of steam curing concrete. Steam curing can accelerate the production of cement hydration products which rapidly increases the early strength of concrete. Under the standard curing condition, the hydration product structure of concrete is more compact, which is conducive to the growth of dynamic elastic modulus in a later period. This study provides a theoretical reference for the application of steam curing in engineering, which is important to ensure the production efficiency and quality of concrete in engineering.

1. Introduction

The curing system and method will significantly affect the early strength of concrete components and become an important measure to ensure the efficiency and quality of concrete production [1, 2]. Due to engineering requirements, the construction period should be shortened as much as possible, and the turnover rate of prefabricated formwork should be improved as much as possible. The cement hydration process is accelerated by the atmospheric pressure and high-temperature steam of steam curing [3, 4]. Thus, the concrete strength grows fast, which can effectively solve this problem. Therefore, steam curing is often used in the production of precast concrete components such as bridge beams and tunnel segments. As the steam curing system is controllable, the curing process is not affected by the external environment temperature, and the quality of precast concrete element can be effectively guaranteed.

The results show that steam curing may affect the brittleness of concrete surface pores and hydration reaction and deteriorate the mechanics and durability of steam curing concrete. Kjellsen et al. [5–7] showed in their study that the diffusion time of hydration products in short ages under high-temperature curing is insufficient, and the pore structure is coarser, which leads to the reduction of concrete strength. Vandamme et al. [8] showed that heat treatment almost did not affect the amount and degree of hydration products formed but was conducive to the formation of a more dense hydration phase, which reduced the total porosity of the gel.

Table 1: Physical and mechanical properties of cement.

Specific surface area (m^2/kg)	Density (g/cm^3)	Setting time (min)		Compressive strength (MPa)		Flexural strength (MPa)	
		Initial set	Final set	7 d	28 d	7 d	28 d
410	3.15	172	242	35.8	51.4	5.4	8.7

Table 2: Concrete mix proportions (kg/m^3).

Cement	Sand	5-10	10-20	Water	Water reducer	Unit weight
480	755	200	830	160	5.8	2430.8

C-S-H gel is the main hydration product of concrete (about 70% of the total hydration product) and the source of strength of concrete. C-S-H gel can be divided into low-density C-S-H (LD C-S-H) gel and high-density C-S-H (HD C-S-H) gel according to the difference of density. Richardson et al. showed that there was more HD C-S-H gel in cement during steam curing. In addition, different steam curing temperature would also change the degree of polymerization of C-S-H gel. Gallucci et al. [9] showed that c-S-H gel generated under steam curing has a higher degree of polymerization and fewer and denser interlayer pores compared with standard curing, but the volume of hydration products generated is reduced, and pore structure is coarser. Long et al. [10, 11] found that steam curing would coarser surface pores of concrete and increase brittleness. Yazici and Arel [12–14] found that steam curing can significantly improve the early performance of concrete but is detrimental to the long-term performance. The increase of hydration temperature can lead to an increase in capillary porosity but can improve the density of C-S-H gel and reduce the gel porosity [15].

In general, steam curing can significantly promote the rapid growth of mechanical properties of concrete in the early stage, but high-temperature steam curing can make hydration products rapidly deposit on the surface of unhydrated cement particles, forming a dense shell, blocking the contact between free water and unhydrated cement particles, affecting the late hydration degree, and resulting in the later strength reduction. At the same time, the rapid hydration reaction under steam curing coarsens the pore structure of the surface and does not take advantage of the filling of hydration products in the later stage, which affects the improvement of mechanics and durability in the later stage [16]. At present, the research on mechanical properties of steam curing concrete mainly focuses on the end of steam curing, and there are few studies on the early mechanical properties and microstructure change of steam curing concrete [17, 18].

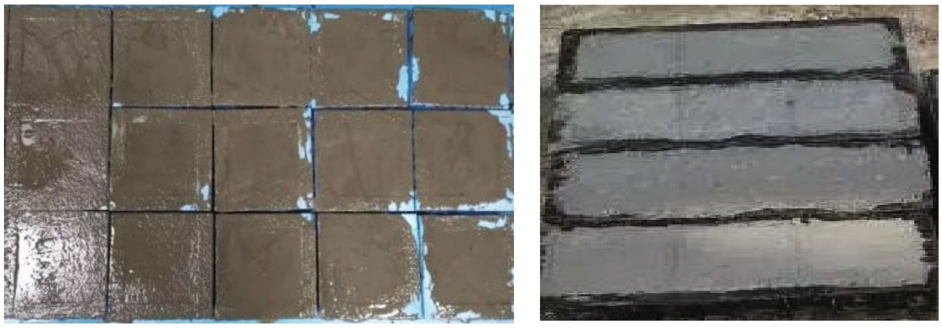
The effect of steam curing on the early mechanical properties of concrete is investigated in this experiment. This paper provides a theoretical reference for the application of steam curing in engineering by studying the strength, dynamic elastic modulus, and microstructural properties of concrete under different curing methods. Thus, it ensures the production efficiency and quality of concrete, which is important for the progress of the project and the safety of the project.

2. Materials and Test Design

2.1. Material. The test material comes from steam maintenance prefabricated T beam production factory of a highway bridge in Guangxi. The cement is P.O 42.5 ordinary Portland cement produced by Guangxi Youjiang Cement Factory with fineness of 2.0%. See Table 1 for the physical and mechanical properties of cement. The fine aggregate is machine-made sand with fineness modulus of 2.64 and mud content of 0.5. Coarse aggregate is gravel with particle sizes of 5 mm-10 mm and 10 mm-20 mm and sand at a rate of 42%. The water reduction rate of polycarboxylic acid superplasticizer was 30%. The standard value of the 28-day compressive strength of the prepared concrete is 55 MPa, and the concrete mix proportions are shown in Table 2.

2.2. Test Specimen. In order to guide the field engineering, the concrete of this test specimen is made of high-performance concrete mixed on site. When casting the prefabricated T beam, the test specimens of compressive, flexural, and splitting tensile strength were prepared simultaneously (Figure 1). The compressive strength and splitting tensile strength were tested with specimens of 150 mm × 150 mm × 150 mm. The flexural strength of 150 mm × 150 mm × 550 mm was tested.

2.3. Curing Method. In order to study the effect of curing methods on the mechanical properties and microstructure of concrete at an early stage, two curing methods were adopted in the test: standard curing and steam curing. According to the curing process of the prefabricated T beam on site, the T beam shall be disassembled 12 hours after pouring. After pouring for 12 hours, the specimen was removed and placed in the standard curing room and T beam steam curing room, respectively, for curing. The standard curing temperature is 20 ± 2 ∘ C, and relative humidity is greater than 95% of the standard conditions. Existing studies have shown that 50°C is a more suitable temperature for steam curing, which not only has less influence on the microstructure of cement hydration products but also is suitable for on-site construction characteristics and economy. The steam curing temperature in this test is 50°C, and heating rate is 10°C/h, shown in Figure 2. Steam curing schema is shown in Figure 3. The mechanical properties of the specimens were tested after curing for 6 h, 12 h, 18 h,



(a) Compressive and split tensile test specimens (b) Flexural test specimen

Figure 1: Strength test specimen.

(a) Steam curing specimen (b) Prefabricated T beam curing chamber

Figure 2: Steam curing chamber.

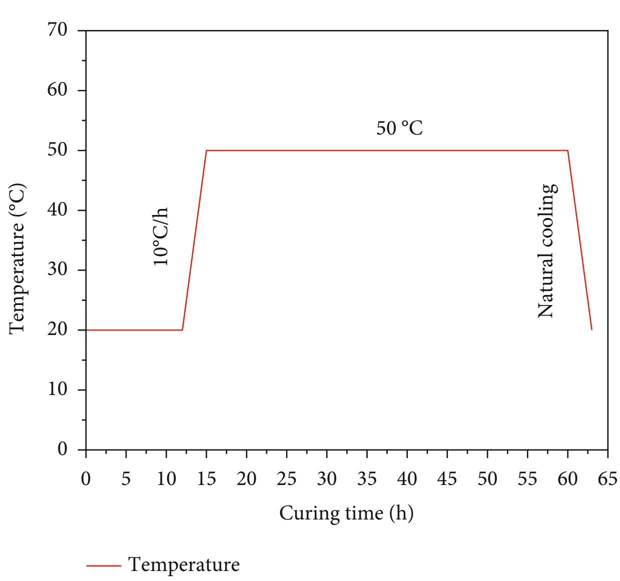


Figure 3: Steam-curing schema.

Figure 4: Test specimens for dynamic modulus of elasticity.

24 h, 30 h, 36 h, 42 h, and 48 h, respectively, in two curing chambers.

2.4. Experimental Testing

2.4.1. Concrete Strength Test. Under the steam curing condition, the strength of concrete was tested every 6 hours from

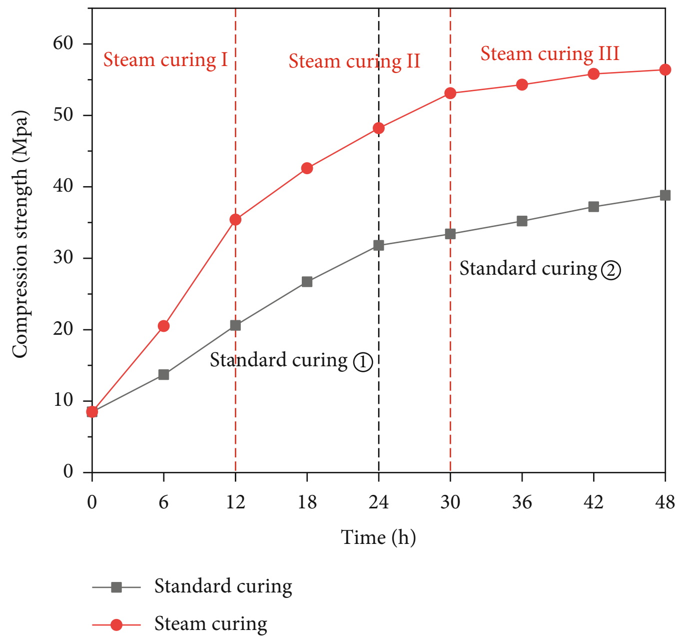


Figure 5: Compressive strength of steam curing concretes.

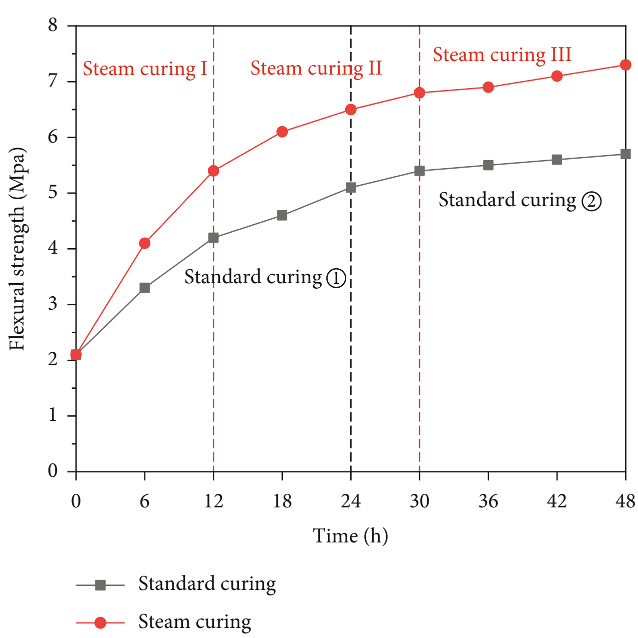


Figure 6: Flexural strength of steam curing concretes.

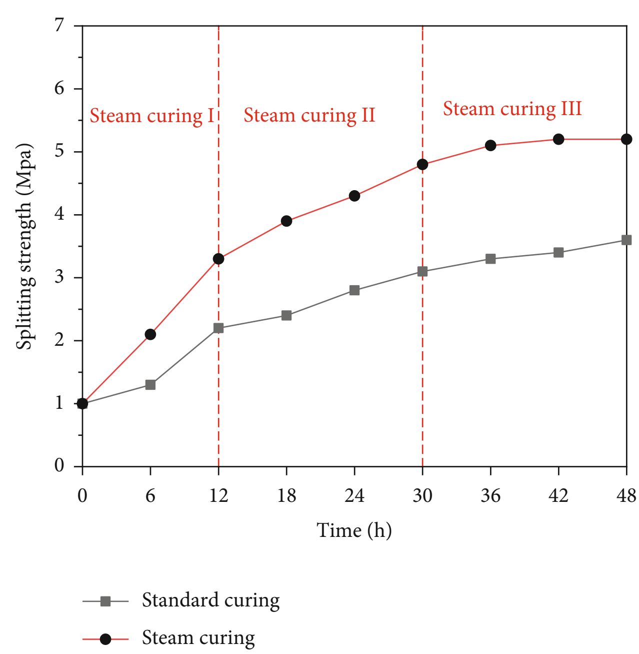


Figure 7: Splitting strength of steam curing concretes.

the heating stage, the physical and property test method standard (GB/T50081 2019) was used to test the compressive, flexural, and splitting tensile strength, and the strength test was completed within 5 minutes for each specimen. The same method was used to test the mechanical properties of the specimens under standard curing condition and compare them with the strength of concrete under steam curing condition.

2.4.2. Test Dynamic Elastic Modulus of Concrete. Existing studies show that the microscopic results of cement hydration products can be affected by steam curing [17, 18]. Therefore, it may cause cracks in the concrete, and its resistance to deformation is adversely affected if the steam curing regime is not reasonable.

The ability of concrete to resist deformation by forces is expressed by the dynamic elastic modulus [19]. The measurement of dynamic modulus of elasticity in the test was carried out according to the provisions of Standard for Test Methods of Long-term Performance and Durability of Ordinary Concrete (GB/T 50082-2009). The resonance method was used to measure the fundamental frequency vibration frequency of the specimen during transverse vibration. The

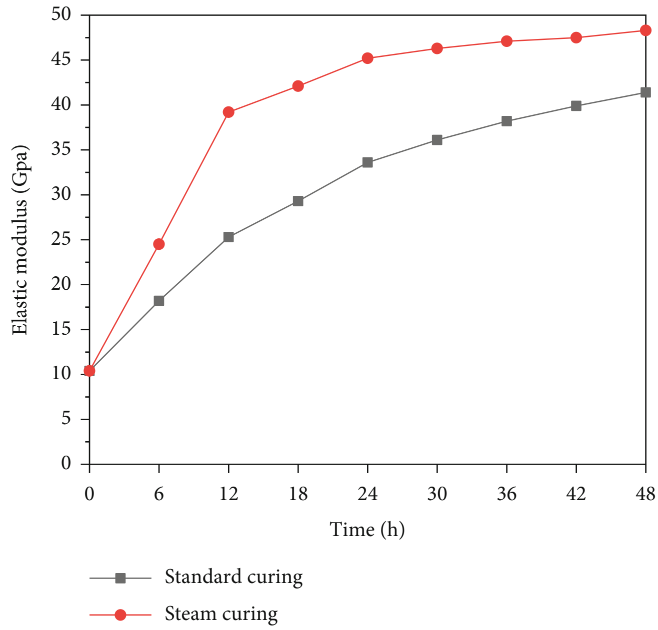


Figure 8: Elastic modulus of concrete.

specimen is the size of 100 mm × 100 mm × 400 mm (Figure 4). The water on the surface of the specimen was dried, and the quality of the specimen was measured before each test. And the 3D laser scanner was used to measure the dimensions of the specimen with the accuracy in the application that was 0.1 mm.

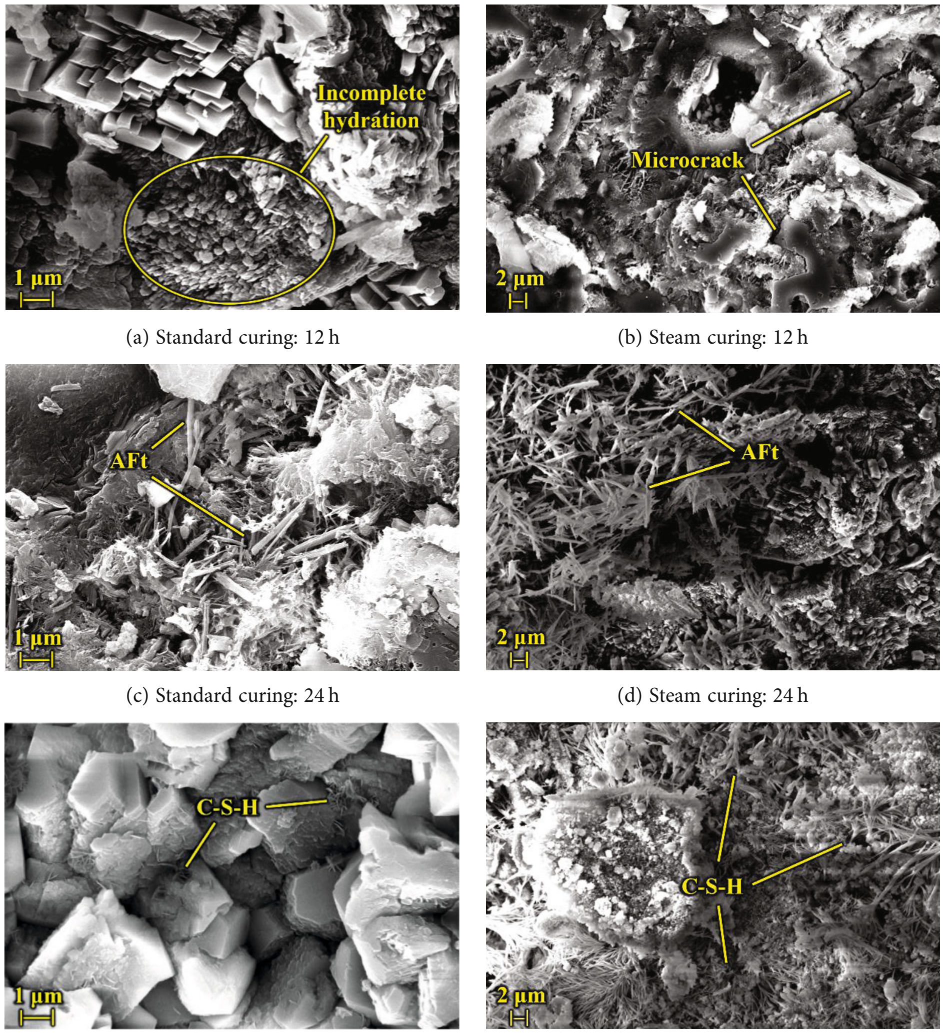
2.4.3. Microstructure Test. Merlin Compact scanning electron microscope was used to observe the microstructure of the specimen [20]. The effect of steam curing on the microstructure of specimens was discussed according to the microstructure test results. When the specimen is cured to age, the specimen is taken out and stored in a glass jar containing anhydrous ethanol for sealed storage to prevent the hydration process from continuing. The specimen is taken out before the SEM test and dried for test.

3. Results and Analysis

3.1. Mechanical Strength of Concrete under Different Curing Conditions. Figures 5–7 show the variation of compressive, flexural, and splitting tensile strengths of concrete with curing time during steam and standard curing. The compressive, flexural, and splitting tensile strengths were 8.5 MPa, 2.1 MPa, and 1.0 MPa, respectively, after the specimens were demolded. It can be seen that the development of concrete strength can be roughly divided into 3 stages in the process of steam curing. The first stage is the early stage of steaming (0 h-12 h), which is the fastest growing period of concrete strength. The steam curing strength can reach more than 50% of the design strength. The second stage is the stage of rapid growth of concrete strength (12 h-30 h), and the concrete strength growth is faster in this stage. The steam curing strength can reach more than 80% of the design strength. In the third stage (30 h-48 h), the concrete strength growth rate starts to decrease, but the concrete strength can still increase continuously. The first 30 h is the key period of concrete strength growth through the process of the steaming phase of the concrete strength growth law. The cement hydration reaction proceeds rapidly, and the concrete strength grows rapidly in the first and second stages. The concrete T beam members can meet the requirements for lifting and applying prestressing after this stage.

The strength development of concrete can be roughly divided into two stages under standard curing. The first stage is at the beginning of standard curing (0 h-24 h), which is the fastest growing period of concrete strength under standard curing conditions. However, the growth rate is significantly less than that of concrete under a steam curing environment. The second stage (24 h-48 h) is also the stage where the concrete strength grows faster. This stage of concrete strength continues to increase, but the growth rate is significantly less than the first stage. Therefore, the first 48 h of the standard curing process are the key period of strength growth.

3.2. Dynamic Elastic Modulus of Elasticity under Different Maintenance Conditions. The dynamic elastic modulus of concrete, also known as the origin tangent modulus of concrete, is an important indicator of the ability of concrete to resist deformation by forces [21]. As shown in Figure 8, the growth of the dynamic elastic modulus of concrete can be divided into two stages under steam curing conditions. In the first stage (0 h-12 h), the dynamic elastic modulus of concrete shows a linear and rapid growth characteristic and reaches 82% of the final dynamic elastic modulus in the middle. This indicates that the dynamic elastic modulus of steamed concrete is mainly formed in the presteaming period (0 h-12 h). In the second stage, the growth of dynamic elastic modulus slows down significantly.



(a) Standard curing: 12 h

(b) Steam curing: 12 h

(c) Standard curing: 24 h

(d) Steam curing: 24 h

(e) Standard curing: 48 h

(f) Steam curing: 48 h

Figure 9: Microstructure of hydration products under different maintenance methods.

The dynamic modulus of elasticity of concrete grows continuously, and the growth curve is relatively flat under standard curing conditions. The dynamic modulus of elasticity of concrete in standard curing grew more slowly than that in steam curing. However, the growth rate of dynamic modulus of elasticity of concrete was significantly higher than that of concrete under steam curing conditions in the late stage of standard curing (30 h-48 h).

Steam curing promotes the hydration reaction of cement in concrete, which accelerates the growth of dynamic elastic modulus. However, some of the tiny bubbles in the concrete are not discharged in time to harden in the steam curing process due to the rapid hydration of cement. Therefore, the internal microporosity of concrete increases, and the growth of dynamic modulus of elasticity is slow in the later stage. Steam curing may have caused the coarsening of the pore structure in the concrete, which affects the strength and durability of the later stage.

3.3. Hydration Products and Microstructure under Different Maintenance Conditions. The macroscopic mechanical properties of concrete under different curing conditions were affected by the degree of cement hydration, products, and microstructure. Figures 9(a) and 9(b) show the microstructure of cement paste after 12 hours of standard curing and 50°C steam curing. It can be seen that the coverage area of cement hydration products under standard curing is smaller, cement hydration is not sufficient, and the early strength of the specimens is low. The cement under steam curing condition is more fully hydrated, but the microstructure is affected by high temperature and shows some microcracks. Under improper steam conditioning conditions, not only the early hydration products of the cement are affected, but also the micropore structure. The higher the temperature, the more significant the effect on the pore structure.

The cement hydrated rapidly within 12-24 h, and the concrete strength was significantly enhanced. As shown in Figures 9(c) and 9(d), the specimens were fully hydrated, and the hydration products were significantly increased after 24 h of standard and 50°C steam curing, both of which produced a large number of needle and rod-shaped ettringite (AFt). The number of AFt generated by steam curing at

50°C was higher and more intensive compared to the standard curing at room temperature. This indicates that steam curing intensifies the hydration process of cement, and the strength of concrete under steam curing is significantly higher than that of standard cured concrete. From Figures 9(e) and 9(f), it can be seen that the number of AFt decreases, but the number of flocculent C-S-H gels increases significantly after 48 h of standard and 50°C steam conditioning. This is because AFt is not stable in the high-temperature state, and more stable C-S-H gels are generated. The structure of the cement hydration products is denser, further increasing the strength of the concrete due to the large number of C-S-H gels interlinked.

It can be seen that although the number of hydration products under standard curing is significantly smaller, the structure of hydration products is denser by comparing the microstructure of hydration products under different time periods. This is the main reason why the growth rate of dynamic elastic modulus of concrete at the late stage of standard curing is significantly higher than that of steam curing.

4. Conclusions

The effect of steam curing on the early mechanical properties of concrete is investigated in this experiment. This paper provides a theoretical reference for the application of steam curing in engineering, which is important for the progress of the project and the safety of the project. Based on the results and analyses presented in previous sections of this paper, the following conclusions can be drawn:

(1) The early strength growth rate of steam-cured concrete is significantly higher than that of standard curing. The development process of concrete strength during steam curing can be divided into three stages. The first stage (0 h-12 h) and the second stage (12 h-30 h) are the key periods of concrete strength growth, and the concrete strength grows rapidly. Steam curing strength can reach 50% and 80% of the design strength, respectively. Steam-cured concrete should focus on the mechanical properties of the first 30 h in practical engineering

(2) The dynamic modulus of elasticity of steamed concrete is mainly formed in the early stage of steaming (0 h-12 h). It shows a linear and rapid growth and reaches 82% of the final dynamic elastic modulus in the middle. The growth of the dynamic elastic modulus of concrete at standard curing is slower than at steam curing. However, in the later stages of standard curing (30 h-48 h), the growth rate of the dynamic elastic modulus of concrete was significantly higher than that of the steam-cured concrete

(3) AFt and C-S-H gels can be generated more rapidly during steam curing, and these hydration products effectively increase the early strength of concrete. However, the structure of the hydration products of concrete under standard curing conditions is denser, which facilitates the growth of dynamic elastic modulus in later stages

5. Prospect

The mechanism of early mechanical properties and microstructural mechanical properties changes of concrete under steam curing conditions is investigated to lay the theoretical foundation for the application of steam-cured concrete in engineering. However, the limitation of this study is the lack of research on the late strength and durability of concrete after steam curing, which needs to be further investigated in the future.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Shengrong Liao conceptualized, wrote, reviewed, and edited the paper. Yuhao Cui conducted the methodology, experiment, and formal analysis and wrote the original draft. Chunming Xiao conducted the data curation and investigation. Yan Xue was responsible for the resources and validation.

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References

[1] D. Adak, M. Sarkar, and S. Mandal, "Effect of nano-silica on strength and durability of fly ash based geopolymer mortar," *Construction and Building Materials*, vol. 70, no. 20, pp. 453–459, 2014.

[2] N. Shafiq, R. Kumar, M. Zahid, and R. Tufail, "Effects of modified metakaolin using nano-silica on the mechanical properties and durability of concrete," *Materials*, vol. 12, no. 14, p. 2291, 2019.

[3] V. Mechtcherine, "Novel cement-based composites for the strengthening and repair of concrete structures," *Construction and Building Materials*, vol. 41, pp. 365–373, 2013.

[4] T. Suwan, P. Jitsangiam, and P. Chindaprasirt, "Influence of nano-silica dosage on properties of cement paste incorporating with high calcium fly ash," *Key Engineering Materials*, vol. 4874, pp. 9–13, 2020.

[5] K. O. Kjellsen, R. J. Detwiler, and O. E. Gjørv, "Pore structure of plain cement pastes hydrated at different temperatures," *Cement and Concrete Research*, vol. 20, no. 6, pp. 927–933, 1990.

[6] K. O. Kjellsen, R. J. Detwiler, and O. E. Gjørv, "Development of microstructures in plain cement pastes hydrated at different

temperatures," *Cement and Concrete Research*, vol. 21, no. 1, pp. 179–189, 1991.

[7] J. I. Escalante-Garcıa and J. H. Sharp, "The microstructure and mechanical properties of blended cements hydrated at various temperatures," *Cement and Concrete Research*, vol. 31, no. 5, pp. 695–702, 2001.

[8] M. Vandamme, F. J. Ulm, and P. Fonollosa, "Nanogranular packing of C–S–H at substochiometric conditions," *Cement and Concrete Research*, vol. 40, no. 1, pp. 14–26, 2010.

[9] E. Gallucci, X. Zhang, and K. L. Scrivener, "Effect of temperature on the microstructure of calcium silicate hydrate (C-S-H)," *Cement and Concrete Research*, vol. 53, pp. 185–195, 2013.

[10] G. Long, Z. He, and A. Omran, "Heat damage of steam curing on the surface layer of concrete," *Magazine of Concrete Research*, vol. 64, no. 11, pp. 995–1004, 2012.

[11] R. Contamine, A. S. Larbi, and P. Hamelin, "Contribution to direct tensile testing of textile reinforced concrete (TRC) composites," *Materials Science & Engineering A*, vol. 528, no. 29-30, pp. 8589–8598, 2011.

[12] S. Yazici and H. Ş. Arel, "The influence of steam curing on early-age compressive strength of pozzolanic mortars," *Arabian Journal for Science and Engineering*, vol. 41, no. 4, pp. 1413–1420, 2016.

[13] M. Li, Q. Wang, and J. Yang, "Influence of steam curing method on the performance of concrete containing a large portion of mineral admixtures," *Advances in Materials Science and Engineering*, vol. 2017, Article ID 9863219, 11 pages, 2017.

[14] P. Jiang, L. Jiang, J. Zha, and Z. Song, "Influence of temperature history on chloride diffusion in high volume fly ash concrete," *Construction and Building Materials*, vol. 144, pp. 677–685, 2017.

[15] S. Bahafid, S. Ghabezloo, M. Duc, P. Faure, and J. Sulem, "Effect of the hydration temperature on the microstructure of class G cement: C-S-H composition and density," *Cement and Concrete Research*, vol. 95, pp. 270–281, 2017.

[16] J. Shi, B. Liu, F. Zhou et al., "Heat damage of concrete surfaces under steam curing and improvement measures," *Construction and Building Materials*, vol. 252, article 119104, 2020.

[17] A. M. Zeyad, B. A. Tayeh, A. Adesina et al., "Review on effect of steam curing on behavior of concrete," *Cleaner Materials*, vol. 3, article 100042, 2022.

[18] N. Hani, O. Nawawy, K. S. Ragab, and M. Kohail, "The effect of different water/binder ratio and nano-silica dosage on the fresh and hardened properties of self-compacting concrete," *Construction and Building Materials*, vol. 165, no. 20, pp. 504–513, 2018.

[19] P. D. Zhang, C. S. Sun, X. Fan, S. T. Li, L. J. Wang, and Z. Z. Cao, "Temporal and spatial evolution mechanisms of the water-conducting fractured zone of overlying strata in the kongzhuang coal mine," *Geofluids*, vol. 2023, Article ID 3790998, 13 pages, 2023.

[20] L. C. Wang, W. Zhang, Z. Z. Cao et al., "Effect of weakening characteristics of mechanical properties of granite under the action of liquid nitrogen," *Frontiers in Ecology and Evolution*, vol. 11, article 1249617, 2023.

[21] L. Wang, Y. Xue, Z. Cao, H. Kong, J. Han, and Z. Zhang, "Experimental study on mode I fracture characteristics of granite after low temperature cooling with liquid nitrogen," *Water*, vol. 15, no. 19, article 3442, 2023.