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Experimental Study on Macro-performance of Long-age Hydraulic Concrete Based on High Temperature Accelerated Curing

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Abstract. *In view of time-consuming and expensive for the long-age mechanical property test of hydraulic concrete, the change rule for the mechanical properties of hydraulic concrete with long-age is still unclear. Based on the equivalent age theory, the high-temperature curing method was employed to accelerate test. First, the macro-mechanical properties tests of hydraulic concrete at different curing ages (90d, 180d, 1a, 2a, 3a) and different fly ash contents (0%, 15%, 35%) were designed and carried out. Then the change rule of mechanical properties of hydraulic concrete at long-age were analyzed. In addition, the macro test results of concrete core specimen of a gravity dam which has been operated more than 40 years were adopted to feedback the above test results. The research results showed that the fly ash content had a significant influence on the activation energy* E_a *of hydraulic concrete. To reach the same hydration degree of design long-age, the curing time increased with the increasing of fly ash content. Within the curing age of 3a, the compressive and splitting tensile strength of concrete increased with the increasing of curing age. The strength values of cement concrete and concrete with 15% fly ash content were close to each other, while the strength values of concrete with 35% fly ash content were smaller than the cement concrete and concrete with 15% fly ash content. The consistency and reliability of the rule that the concrete strength continues to increase with age was further verified by combining the macroscopic test results and the strength growth rate calculation results of a gravity dam concrete core specimen that had been in service for more than 40 years.*

Keywords: *Long-age, Hydraulic Concrete, Equivalent Age Theory, High Temperature Curing, Macro-mechanical Properties.*

1 Introduction

The durability and service life of concrete dams are significantly influenced by the long-term performance of concrete. To ensure that concrete water engineering are safe to operate, regular assessments of their health and safety are required (Chinese Standard SL 258-2017:2017). The strength parameters at the design age are typically used to review the calculated stresses when dam structural safety is assessed using computational analysis (Chinese standard SL 319-2018:2018). The majority of the early water conservancy and hydropower engineering design and acceptance indices are built on the concrete strength values obtained at the standard curing age of 28 days. However, as more high dams and extra-high dams have been built, are being built, or are being proposed for construction in

China in the 21st century, so has the design age risen to meet the demand for concrete dams for economy and safety (Wang 2009).

The results of compressive strength tests of concrete conducted in the field at the Wujiangdu and Hoover dams (Shao 1991, Fan et al. 2016), as well as those conducted by Withey (1961), Yuan (2007) and Li (2009), all show that the compressive strength of concrete growth slowly over time and the duration of growth exceeds ten years. It is obviously difficult to determine the genuine safety factors of concrete dams in long-term operation when their strength and stability are simply assessed using design age parameters. Nevertheless, because of the time-consuming and expensive indoor tests on the long-age mechanical properties of hydraulic concrete, pertinent experimental studies are still lacking and it is still unclear how hydraulic concrete mechanical properties change with age. This severely limits the ability to assess the durability and life of hydraulic concrete structures that are in long-age use.

In order to solve the aforementioned issues, this paper investigated the relationship between the mechanical properties of hydraulic concrete and long-age based on the equivalent age theory and the method of high-temperature accelerated curing, which is of great significance to improve the understanding of the long-age mechanical properties of hydraulic concrete and to precisely evaluate the strength and durability of concrete dams in long-term operation.

2 Design of Long-age Test Scheme for Hydraulic Concrete

2.1 Equivalent Age Theory and Activation Energy of Concrete

Equivalent age is frequently used to describe the temperature and age in the cement hydration process on the adiabatic temperature rise, strength and modulus of elasticity and other thermal and mechanical properties (Jin et al. 2021). It refers to the concrete with same mix ratio in different temperature-time courses to achieve the same degree of hydration and the need to curing time at the reference temperature (20°C). By using the equivalent age method, the hydration process of concrete cement under various curing temperatures can be converted into the hydration process of cement under a fixed reference temperature (20°C), allowing for comparison of the reaction state of concrete cement hydration under various curing temperatures. Nowadays, the Arrhenius function (Huang et al. 2021) is frequently used to calculate equivalent ages:

$$\tau_e = \int_0^{\tau} \exp\left[\frac{E_a}{R}\left(\frac{1}{273+T_r} - \frac{1}{273+T}\right)\right] d\xi \tag{1}$$

where τ_e is the equivalent age (d); τ is the design age (d); E_a is the concrete activation energy (kJ/mol); R is the universal gas constant (kJ/mol·K); E_a/R is the ratio of concrete activation energy to gas constant, generally take $E_a/R=Q$; T_r is the reference temperature (20°C); T is the kelvin temperature (°C).

Eq (1) demonstrates that the E_a is a significant parameter affecting the equivalent age of concrete, but the existing literature reports that the ratio of concrete activation energy to gas constant (Q) varies greatly, which has a direct impact on the analysis of E_a and τ_e under high temperature accelerated curing (Zhu 2012, Bazant and Jirasek 2018). At the same time, because E_a is affected by the type of concrete cementing materials, admixtures, cement fineness, water-cement ratio and other factors, so E_a as a fixed value is difficult to accurately predict the strength of concrete and must to be determined through specific tests and calculations (Yang et al. 2020).

2.2 Estimation of Concrete Activation Energy

The activation energy (E_a) can be estimated by using the adiabatic temperature rise process line at different initial temperatures or the compressive strength values at different curing temperatures (Kuryłowicz-Cudowska and Haustein 2021). When the compressive strength values at different curing temperatures are used to estimate E_a, in order to consider the effects of temperature and fly ash admixture on E_a at the same time, the empirical function of Kim (Kim 2001) is used to estimate E_a in this paper, and its specific equation is as follows：

$$\frac{S}{S_u} = R_u \left\{ 1 - \frac{1}{\sqrt{1 + A[e^{-\frac{E_a}{RT}e^{-\alpha t}} + e^{-\frac{E_a}{RT}e^{-\alpha t_0}}](t - t_0)}} \right\} \tag{2}$$

where R_u is the extreme relative strength, and $R_u = S_u / S_{28}$; t_0 is the intensity start development time(d)；the study regression results show that A varies slightly with the change of concrete mix ratio and does not vary with temperature and age, thus A can be assumed to be constant and is generally taken as $A=10^7$; α is the constant.

2.3 Raw Materials and Mixture Proportions of Concrete

The tests used cement was P·O 42.5 Huaxin ordinary Portland cement produced by the China Gezhouba Cement Plant. The fly ash was Grade II fly ash (Class F) produced in Yichang City. The water was laboratory tap water (in line with the Chinese national water standard). The fine aggregate was well-graded fine sand with a fineness modulus of 2.03, which was collected from the Yangtze River (Yichang section). The coarse aggregate was crushed granite with particle sizes of 5–40 mm, of which the particle size of small stone was 5–20 mm and the particle size of medium stone was 20–40 mm. Polycarboxylate superplasticizer produced by the Qingdao Hongxia company (Qingdao, China) was selected as the water-reducing agent.

The mix proportions of the secondary aggregate grading concrete are given in Table 1. The water/binder ratio was 0.5, the fly ash content was 0%, 15% and 35% as well as the test groups were numbered C30, C30-FA15 and C30-FA35, respectively.

Table 1 Test mix proportion of long-age mechanical properties of hydraulic concrete

No.	W/B	Amount per unit volume/(kg·m^{-3})					
		Water-reducing agent	Cement	Water	Fly ash	Fine aggregate	Coarse aggregate
C30	0.5	1.716	264	132	0	761.26	1477.74
C30-FA15			224.4		39.6		
C30-FA35			171.6		92.4		

2.4 Activation Energy Test Scheme of Hydraulic Concrete

According to the test mix proportions in Section 1.3, with reference to the ASTM C1074 (2019), a total of four test ages (3d, 7d, 14d, 28d) were designed under three curing temperatures (5 ℃, 20 ℃, 40 ℃) and three fly ash contents (0%, 15%, 35%). Three test pieces were formed under each fly ash contents based on the curing temperature and design age, and a total of 108 cube specimens were formed (150mm × 150mm × 150mm）. After the specimens were cured to the test age, carried out the compressive strength test and the E_a was calculated with the average value of the strength of three specimens as the index combined with Eq (2). The specific test scheme is shown in Table 2.

Table 2 Test scheme for activation energy of hydraulic concrete

No.	Fly ash content/%	Curing temperature/℃	Test age/d	Number of specimens/pc	Total number of specimens/pc
C30	0	5/20/40	3/7/14/28	36	108
C30-FA15	15			36	
C30-FA35	35			36	

2.5 Long-age Macro-mechanical Properties Test Scheme of Hydraulic Concrete

According to the test mix proportions in Section 1.3, a total of five test ages (90d, 180d, 1a, 2a, 3a) were designed under three fly ash contents (0%, 15%, 35%). Under each fly ash contents, three test pieces were formed based on the design age and a total of 72 cube specimens were formed (150 mm × 150mm × 150 mm), in which 45 specimens were formed for compressive strength test and 27 specimens were formed for splitting tensile strength test. The specimens were cured by high temperature accelerated curing (temperature=40 ℃, RH ≥ 95%) to the corresponding test age, and then carried out the compressive strength test and splitting tensile strength test. The specific test scheme is shown in Table 3.

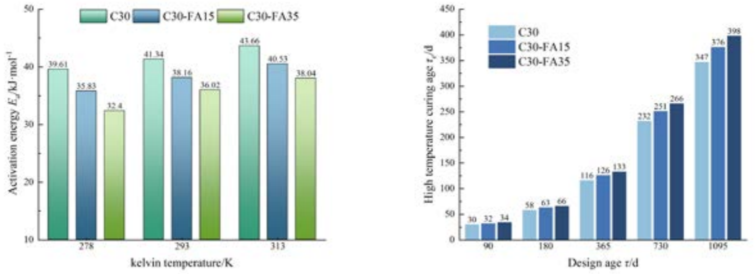
Table 3 Test scheme for macro-mechanical properties of hydraulic concrete at long-age

	No.	Fly ash content/%	Curing way	Age/d	Number of specimens/pc	Total number of specimens/pc
Compressive strength test	C30	0	High temperature accelerated curing（temperature=40℃，RH≥95%）	90d/180d/1a/2a/3a	15	45
	C30-FA15	15			15	
	C30-FA35	35			15	
Splitting tensile strength test	C30	0		90d/180d/1a	9	27
	C30-FA15	15			9	
	C30-FA35	35			9	

3 Long-age Test Results and Analysis of Hydraulic Concrete

3.1 Analysis of Age Calculation Based on High Temperature Curing Method

The calculation results of concrete activation energy (E_a) and high temperature curing age (τ_e) are shown in Fig. 1.



(a) Concrete activation energy (E_a) (b) High temperature curing age (τ_e)

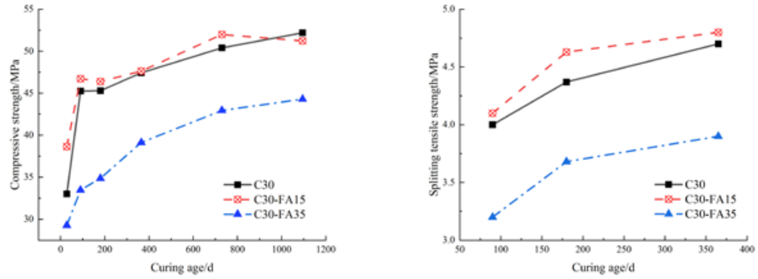
Fig. 1 Calculation results of concrete activation energy E_a and high temperature curing age τ_e

Fig. 1 show that E_a decreased as fly ash content increased at constant temperature; E_a progressively increased as temperature increased when fly ash content remained the same; the time required to reach the same design long-age hydration increased as fly ash content increased, and this variability of curing time gradually increased as design age increased.

3.2 Long-age Macro-mechanical Properties Test of Hydraulic Concrete

3.2.1 Test results

According to the long-age test scheme of hydraulic concrete in Section 1.5, the long-age compressive strength test and Splitting tensile strength of hydraulic concrete with different fly ash contents were carried out, and the test results are shown in Fig. 2.



(a) compressive strength (b) splitting tensile strength

Fig. 2 Test results of long-age compressive strength and splitting tensile strength

As show in Fig. 2, excepted for a few fluctuations in the test values, the long-age mechanical properties of concrete with three types of fly ash content gradually increased with the growth of age, and the growth was faster in the early stage and slower in the later stage; the test values of compressive strength and splitting tensile strength of cement concrete and concrete with 15% fly ash concrete were relatively similar; the compressive strength and splitting tensile strength of concrete with 35% fly ash content were smaller than those of cement concrete by 3.73MPa-11.80MPa and 0.69MPa-0.80MPa respectively, while they were smaller than those of concrete with 15% fly ash content by 5.06MPa-13.27MPa and 0.90MPa-0.95MPa, thus the concrete strength of 35% fly ash content was generally small.

3.2.2 Verification of the test law

The growth rates of compressive strength and splitting tensile strength were calculated and analyzed based on the strength standard values by the macroscopic test results of a concrete core specimen of a gravity dam that has been in operation for more than 40 years, and the results and rules were then verified. The compressive strength of the concrete core specimen obtained by wet cutting with a length-to-longitude ratio of 1:1 was 51.6 MPa, and the splitting tensile strength was 4.80 MPa.

The upstream side of the gravity dam concrete core specimen was labeled 200, while the downstream side was labeled 250, with the corresponding strength grades of C18 and C23 (Chinese standard GB 50010-2010:2010). The standard compressive strength values calculated using the interpolation method was 12.0MPa and 15.4MPa, respectively. Combined with the regression Eq (3) of the compressive and splitting tensile strength test values, the standard values of the splitting tensile strength of the core specimen can be calculated based on the standard values of the compressive strength, which were 1.40MPa and 1.70MPa, respectively. Table 4 displays the calculated compressive and splitting tensile strength growth rates of concrete specimens and core specimen with varying fly ash content.

$$f_{ts} = 0.198136 f_{cu}^{0.7864} \tag{3}$$

where f_{ts} is the splitting tensile strength (MPa); f_{cu} is the compressive strength of concrete standard cube (MPa).

Table 4 Calculation results of concrete compressive strength and splitting tensile strength

No.	Strength grade	Measured strength value/MPa		Strength standard value/MPa		Intensity growth rate/%	
		Compressive strength	Splitting tensile strength	Compressive strength	Splitting tensile strength	Compressive strength	Splitting tensile strength
C30	$C_{28}30$	52.21	4.86	33.00	3.31	58.21	46.93
C30-F15	$C_{28}30$-F15	51.23	4.71	34.33	3.43	49.23	37.30
C30-F35	$C_{28}30$-F35	44.32	3.94	29.27	2.76	51.42	42.69
Core specimen	C18	51.60	4.80	12.00	1.40	330.00	242.86
	C23			15.40	1.70	235.06	182.35

According to the data in Table 5, the compressive strength of the concrete core specimen increased by 330.00% and 235.06% as well as the splitting strength increased by 242.86% and 182.35% after more than 40 years of dam operation, which was significantly higher than the standard strength values. The consistency and reliability of the rule that concrete strength increases with age is further validated based on the test results of this paper and combined with the test results of Hoover Dam and Wujiangdu Dam.

4 Conclusion

(1) The amount of fly ash content had a significant effect on the activation energy (E_a) of hydraulic concrete, which primarily showed that E_a decreased with increasing fly ash content when the temperature remained constant, and further prolonged the time to reach the same design long-age based on the high temperature curing method.

(2) The compressive strength and splitting tensile strength of hydraulic concrete gradually increased with increasing curing age, and the growth was faster in the early stage and slower in the later stage. The strength values of concrete with cement concrete and 15% fly ash content were closer in the long age, while the strength value of concrete with 35% fly ash content was smaller. When the macroscopic test results of concrete core specimen from a gravity dam that has been in operation for more than 40 years was combined with the strength growth rate calculation results, the consistency and reliability of the law that concrete strength increased continuously with age was confirmed.

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