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Abrasion-Resistant and Temperature Control of Lining Concrete for Large-Sized Spillway Tunnels

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Abstract: With regard to the high anti-scouring and abrasion-resistant performance requirements and great temperature control difficulties of lining concrete for large-sized spillway tunnels, in this study, a performance test was conducted on anti-scouring and abrasion-resistant concrete. The finite element method was used to analyze the temperature change rules of sidewall C₉₀50 (design strength of concrete is 50 MPa at 90 days) lining concrete for the spillway tunnel. Further, a new cooling measure was proposed for adopting “early-throughput, high-flow and short-duration”. As indicated by the results of this study, fly ash could reduce water consumption and micro-cracks via its “morphological effect”. Silica fume could improve the early strength of cement concrete and make up for the strength loss caused by fly ash. Polyvinyl alcohol (PVA) fiber could enhance concrete durability. The doping of these three additives reinforced the strength and abrasion resistance of concrete. The results showed that the temperature of the lining concrete presented a change trend of “rapid increase first, followed by a slow decrease”. The peak temperature was reached roughly 2 days after casting. In addition, properly increasing throughput flow or decreasing throughput temperature in the early stage of casting could significantly reduce the highest temperature and maximum temperature difference of concrete. Based on the results from the numerical simulation of temperature control effect, it was proposed to adopt “early-throughput, high-flow, and short-duration” for temperature control and cracking prevention. Specifically, within 2 days after casting, cooling water at roughly 12 °C was guided in at a flow of approximately 3.5 m³/h. Within 3–7 days after casting, river water at around 17 °C was guided in at a flow rate of approximately 1.8 m³/h. After 7 days, the cooling effect can be well achieved by only using the surface flowing water for curing. According to the field monitoring data, the changes in measured temperature were basically consistent with those from numerical simulations, and detection on the temperature of the sidewall lining concrete showed that a qualification rate of >91% was satisfactorily obtained by using the proposed approach.

Keywords: spillway tunnel; concrete; anti-scouring and abrasion-resistant; temperature control; crack prevention measure

1. Introduction

In China, large-sized hydropower projects are mainly distributed in western alpine and gorge regions. Restricted by topography, geology and other conditions, there are numerous spillway tunnels of large-size, high single-tunnel discharge with high flow rate. For example, under the verified flood level, the spillway tunnel of Dagangshan hydropower station has a maximum flood discharge capacity of 3352 m³/s and the highest flood discharge flow rate of approximately 42 m/s. The average annual service time of the spillway tunnel is more than 2000 h, and the high frequency of use ranks the top

of the same type of power stations in China. Therefore, higher requirements are put forward for the anti-scouring and abrasion resistance of the concrete in the spillway tunnel. Therefore, anti-scouring and abrasion-resistant concrete is generally adopted in construction; however, this gives rise to a series of problems, such as high temperature control requirements and difficult crack control. In the case of temperature cracking being accompanied with long-term scouring by high-velocity water flows carrying sediments, it will further result in cavitation erosion and seriously threaten the safe and stable operation of spillway tunnels and hydropower stations, not to mention the extremely high cost of repair. In this sense, studying the anti-scouring and abrasion-resistant performance and temperature control technology of lining concrete for large-sized spillway tunnels is of vital theoretical significance and practical value.

Generally, anti-scouring and abrasion-resistant concrete is used for spillway tunnel lining and the performance of this type of concrete mixed with fly ash, silica fume and fiber has been extensively investigated. Turk et al. [1] found that class F fly ash concrete with up to 15% cement replacement was acceptable for structural applications of abrasion erosion resistance. Naik et al. [2] and Ukita et al. [3] reported that if 15% of cement was replaced with fly ash, the abrasion increased with the fineness of fly ash. However, with a fly ash content of 30%, the abrasion resistance of concrete turned out to be lower than that without fly ash. Siddique [4] found that abrasion resistance could be improved approximately by 40% when 40% fine aggregate was replaced with fly ash. Yen et al. [5] concluded that if the replacement percentage exceeded 15%, fly ash concrete showed lower resistance to abrasion-erosion compared to non-fly ash concrete. The utilization of silica fume was a typical strategy to improve the abrasion erosion resistance of concrete [6–8]. However, the amount of silica fume should be considered with caution as excessive silica fume might lead to cracks. Ghafoori and Diawara [9] found that the resistance to wear of concrete containing silica fume as a fine aggregate replacement was consistently better with increasing amounts of silica fume up to 10%. Zeng and Chung [10] found the abrasion resistance of concrete was improved by the addition of silica fume due to the increase in tensile modulus. Liu [11] reported that the abrasion resistance increased with respect to the increase in silica fume addition. For concrete with a 1-mm width surface crack, and if the water flow impinged directly into the crack, the abrasion rates were nearly 13% and 25%, respectively, higher than that of the intact mixture. The toughness and durability of concrete can be significantly improved by the addition of fibers. Sonebi and Khayat [12] found that the incorporation of latex and steel fiber did not improve significantly the mechanical and hydraulic abrasion resistance of such high-strength concrete (HSC). Nanni [13] found that the addition of steel or synthetic fibers did not cause any appreciable change in the abrasion resistance of concrete. Siddique et al. [14] found that the inclusion of polyester fibers in high volume fly ash concrete (HVFA) improved abrasion resistance. Gong et al. [15] studied the ultimate bearing capacity of the conventional reinforced concrete (RC) and the steel fiber-reinforced concrete (SFRC) joints under different loading conditions with a special attention on the corresponding cracking process. The experimental results demonstrated that the peak bearing capacity of the SFRC joints was slightly higher than that of the RC joints.

The temperature control and crack prevention problems with large-volume lining concrete for spillway tunnels have always been a focus and difficulty of related studies. Taking the water supply tunnel project of the Three Gorges Dam's permanent ship lock as an example, based on the measurements of temperature and stress, Fang et al. [16] carried out the finite element simulation for analysis of the temperatures and stresses in sidewall and top arch in the construction period. Duan et al. [17] conducted a field temperature test on both casting temperature-controlled concrete and conventional concrete and analyzed the distribution of the temperature field in the lining concrete and its change over time. Wang et al. [18] simulated the effects of crack prevention under multiple temperature control measures. Duan et al. [19] used a self-coded program called SPS_FET2D to simulate the construction process of the Xiaolangdi Spillway Tunnel Project and discussed the cause and mechanism of cracking. Wu et al. [20] explored the effect of throughput duration on pipe cooling via analyzing the data from the Xiluodu Diversion Tunnel Project. Guo et al. [21] probed into the

throughput cooling effect of lining concrete of different thicknesses. Chen et al. [22] investigated the effects of cavern and surrounding rock temperature on the temperature and thermal stress of lining concrete for spill tunnels. Feng et al. [23] studied the effects of the final adiabatic temperature rise magnitude and its rate of concrete on the temperature and thermal stress field in the lining concrete. Using the Sanbanxi Spillway Tunnel Project as an example, Zhao et al. [24] explored the variations of temperature field and thermal stress redistribution in sidewall lining concrete and investigated the initiation and development processes of cracks.

This study selected the spillway tunnel of the Dagangshan Hydropower Station as a case study. Laboratory tests were conducted on the anti-scouring and abrasion-resistant performance of the lining concrete, from which the optimized contents of fly ash, silica fume and PVA fiber were determined. Meanwhile, concrete temperature control numerical simulations were performed to investigate the variations of temperature field in the anti-scouring and abrasion-resistant concrete under different throughput conditions. It is also proposed to adopt “early-throughput, high-flow and short-duration” for temperature control and cracking prevention. The effect of throughput cooling was analyzed according to temperature control monitoring data in the field. The presented analysis of experimental data, together with the proposed strategy for temperature control offered, reference information for similar projects.

2. Anti-Scouring and Abrasion-Resistant Performance Test on Concrete

2.1. Project Overview

Dagangshan Hydropower Station is the 14th cascade hydropower station planned to be built on the main stream of the Dadu River. The main body of the dam is a concrete double-curvature arch dam with a maximum height of 210 m and the total installed capacity is 2.6 million kW, as shown in Figure 1. Its spillway tunnel project is arranged on the right bank of the Dadu River and consists of an intake, trunk, outlet and downstream protection project. Its trunk is a free-flow tunnel of one-slope mode with a tunnel length of 1077.50 m, a starting-point bottom elevation of 1098.32 m and a longitudinal gradient $i = 0.1039$; its section adopts a circular-arch straight wall form and has a net section size of 14.00–16.00 m $\times$ 18.00–20.00 m (width $\times$ height), as shown in Figure 2. Under the verified flood level, it has a maximum flood discharge capacity of 3352 m³/s and the highest flood discharge flow rate of approximately 42 m/s. Its sidewall uses C₉₀50 anti-scouring and abrasion-resistant concrete, with an engineering volume of 34,300 m³. In this case, the working conditions of high hydration heat, high heat production, high flow rate and high flow and the problem of hydration heat have imposed relatively high requirements on the anti-scouring and abrasion-resistant performance, as well as temperature control and crack prevention technology of lining concrete for spillway tunnels. With regard to the high anti-scouring and abrasion-resistant performance requirements and great temperature control difficulties of lining concrete for large-sized spillway tunnels, these two issues were investigated by experimental and numerical simulation methods, respectively. Material test, numerical simulation and other methods were used to study the anti-scouring and abrasion-resistant performance and temperature control technology of concrete for the spillway tunnel.

Figure 1. Three-dimensional rendering of Dagangshan Hydropower Station.

Figure 2. The type and size of lining concrete of spillway tunnel section (unit: cm).

2.2. Materials, Mix Proportions, and Test Method

A performance test was conducted on silica fume concrete and silica fume + PVA fiber concrete of different mix proportions, and the mix proportion parameter was optimized for anti-scouring and abrasion-resistant concrete according to the test results. Finally, the mix proportion of the anti-scouring and abrasion-resistant concrete used during construction was determined.

2.2.1. Materials

The chemical compositions of the cement, fly ash and silica fume are listed in Table 1. The polyvinyl alcohol fiber (PVAF) had a density of 1.28 g/cm³, a tensile strength of 1565 MPa, an elastic modulus of 38.0 GPa and an elongation at break of 8.0%, which was thus characterized by high strength and high elastic modulus. The dosages of the JM-PCA (a type of polycarboxylic acid high-performance water-reducing agent) and NOF-AE (a type of air-entraining agent adopted) in the test were 0.8% and 0.4/10,000, respectively. The coarse and fine aggregates were produced artificially by Gezhouba Aggregate Plant, Dagangshan Hydropower Station. The fine aggregate had a fineness modulus of 2.64 and an average particle size of 0.388 mm. The coarse aggregate had an elongated and flaky particle content in the range 0.4–3.3% and a crushing index of 15.5%. The strength performance of artificial aggregate was relatively satisfactory.

Table 1. Chemical compositions of cement, fly ash and silica fume (%).

Materials	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	CaO	MgO	SO ₃	Loss of Ignition
Cement	20.87	4.80	3.97	61.78	4.04	2.28	0.79
Fly ash	53.71	9.72	22.94	7.94	2.28	0.35	2.33
Silica fume	95.86	0.14	0.30	0.98	0.35	-	1.72

2.2.2. Mixture Proportions

Raw material was used to verify various tests. The mix proportion parameters of anti-scouring and abrasion-resistant concrete, including water–cement ratio, water, cement, fine aggregates and coarse aggregates, were firstly optimized based on analyses of the experimental results, as shown in Table 2. On the basis of indoor tests, the construction mix proportion was further optimized through field trial mixing, and the corresponding concrete performance test was carried out, as shown in Tables 3 and 4. In order to further study the influence of fly ash, silica fume and PVA fiber on the behavior of abrasion-resistant concrete, eight batches of concrete mixtures were made for testing, and the mixture details are listed in Table 2. They can be broadly divided into three groups: F10S5P0, F15S5P0 and F20S5P0 for the first group; F20S5P0, F20S7P0 and F20S9P0 for the second group; F20S5P0.8, F20S5P0.9 and F20S5P1.0 for the third group. Here, “F”, “S” and “P” in the notations represent the mixtures containing “fly ash”, “silica fume” and “PVA fiber”, respectively. The numbers following “F”, “S” and “P” represent the mass percentages of fly ash, silica fume and PVA fiber in the concrete mixture. The water to binder ratio for all the eight batches was maintained at 0.40. Water-reducing admixture of JM-PCA and air-entraining admixture of NOF-AE had the dosage of 0.8% and 0.004%, respectively. The construction mix proportions of two graded C9050 fly ash and silica fume concretes and their performances are listed in Tables 3 and 4.

Table 2. Mix proportion of concrete (unit: kg/m³).

Mixture No.	Water–Cement Ratio	Water	Cement	Fly Ash	Silica Fume	PVA Fiber	Fine Aggregates	Coarse Aggregates	Water Reducing Agent	Air Entraining Agent
F10S5P0	0.40	128	272	32	16	0	755	1370	2.56	0.0128
F15S5P0	0.40	130	276.25	32.5	16.25	0	755	1370	2.60	0.013
F20S5P0	0.40	132	280.5	33	16.5	0	755	1370	2.64	0.0132
F20S7P0	0.40	128	233.6	64	22.4	0	755	1370	2.56	0.0128
F20S9P0	0.40	128	227.2	64	28.8	0	755	1370	2.56	0.0128
F20S5P0.8	0.40	140	262.5	70	17.5	0.7	755	1370	2.80	0.014
F20S5P0.9	0.40	144	270.0	72	18.0	0.9	755	1370	2.88	0.0144
F20S5P1.0	0.40	148	277.5	74	18.5	1.1	755	1370	2.96	0.0148

Table 3. Construction mix proportion of two graded C₉₀50 fly ash and silica fume concrete (unit: kg/m³).

Construction Method	Preparation Strength (MPa)	Water–Cement Ratio	Binder Materials	Sand Rate (%)	Quantity of Concrete per Cubic Meter							
					Water	Cement	Fly ash	Silica Fume	Fine Aggregates	Coarse Aggregates	JM-PCA	NOF-AE
Normal concrete	59.1	0.33	379	38	125	284	76	19	718	1172	3.411	0.015
Pumping concrete	59.1	0.33	415	40.5	137	311	83	21	738	1087	3.735	0.017

Note: the concrete mix proportion is calculated by the absolute volume method, and the air content is 3%.

Table 4. Performance of two graded fly ash and silica fume concrete mixture.

Construction Method	Water–Cement Ratio	Binder Materials (kg/m ³)	Sand Rate (%)	Air Contents (%)	Slump (cm)/Loss Rate (%)			
					0	30 min	60 min	90 min
Normal concrete	0.33	379	38	2.5	16.0/0	12.8/20.0	5.7/64.4	/
Pumping concrete	0.33	415	40.5	2.0	19.5/0	16.0/17.9	14.5/25.6	12.0/38.5

2.2.3. Test Method

The test was performed according to the ring method using a high-velocity water flow abrasion-resistance apparatus as the test device, shown in Figure 3 [25]. The test mold was a cone on the outside, 30 cm in inner diameter and 10 cm in height. After the preparation, the concrete specimen was placed in the quiescent state at room temperature for 24 h; after that, it was demolded and moved into a standard curing chamber at 20 ± 5 °C and >95% relative humidity for curing purpose. The specimen was soaked in water for saturation 2 day before reaching the test age and then taken out of the water, wiped and weighed for the scouring and abrasion test.

Figure 3. A high-velocity water flow abrasion-resistance apparatus.

The scouring and abrasion medium used emery with a particle size in the range of 0.4–2.0 mm and a sand factor of 20% (mass ratio). The water flow had a nominal flow rate in the range of 10–40 m/s (freely adjustable) and was set at 40 m/s in this test. The specimens in each group were subjected to repeated scouring and abrasion for three times; the cumulative scouring and abrasion time was T . After the test, each specimen was taken out, flushed with water, wiped and weighed again. The anti-scouring and abrasion-resistant strength of concrete was calculated using the following formula [25]:

$$f_a = \frac{TA}{\Delta M} \quad (1)$$

where f_a represents the anti-scouring and abrasion-resistant strength of concrete, i.e., the time taken to scour and abrade a unit of mass on a unit area, $h/(g/cm^2)$; T represents the cumulative scouring and abrasion time of a specimen, h; A represents its scoured area, cm^2 , ($A = \pi DH$); D represents its inner diameter, 30 cm; H represents its inner ring height, 10 cm; ΔM represents the cumulative scouring and abrasion mass during T time interval, g.

A standard cubic specimen with an edge length of 150 mm was used, and each group consisted of three concrete blocks made and cured under the same conditions. The uniaxial compressive strength was expressed by the pressure per unit area when the specimen was damaged, as shown in Formula (2). The tensile strength of concrete was determined by splitting method, as shown in Formula (3).

$$f_{cu} = \frac{F}{A} \quad (2)$$

where f_{cu} is the compressive strength of concrete cube (MPa), F is the ultimate load (N) and A is the compression area (mm^2).

$$f_{ts} = \frac{2F}{\pi A} \quad (3)$$

where f_{ts} is splitting tensile strength of concrete (MPa), F is failing load (N) and A is the area of splitting surface of specimen (mm^2).

The dry shrinkage deformation of concrete is expressed by the shrinkage rate. The specimens of 100 mm × 100 mm × 500 mm were dried and shrank to the specified age under standard test conditions. The length of specimens before and after drying shrinkage was measured and the readings were repeated three times during each measurement. Taking the arithmetic mean value of the three measurements, the dry shrinkage rate can be calculated according to Formula (4).

$$\varepsilon_{st} = \frac{L_0 - L_t}{L_b} \times 100\% \quad (4)$$

where L_b is measuring gauge length of test piece; L_0 is the initial value of specimen length; L_t is the length value of the test piece measured at test period T (mm); ε_{st} is the dry shrinkage rate of concrete obtained when the test period is t days.

2.3. Test Results and Discussions

2.3.1. Fly Ash Effect

Figures 4 and 5 show the change trends of the compressive strength and anti-scouring and abrasion-resistant strength of concrete with the test age at different dosages of fly ash. In the process of the experiment, three groups of tests were carried out in parallel for the same measurement and the average value of the three measurements was taken in order to minimize experimental result errors.

Figure 4. Effect of fly ash dosage on compressive strength of concrete.

Figure 5. Effect of fly ash dosage on abrasion resistance of concrete.

As shown in Figure 4, the compressive strength of concrete decreased with increasing dosage of fly ash but increased with increasing test age. In the early stage of the test, the compressive strength of concrete increased rapidly but decreased at a relatively high dosage of fly ash. This was mainly because the failure of a large amount of fly ash particles to participate in the hydration reaction weakened the bonding between the cement paste and aggregate, which significantly reduced the compressive

strength of concrete in the early stage. For instance, at the age of 7 day, when the dosages of fly ash were 10%, 15% and 20%, the compressive strengths of the concrete specimen were 34.5, 32.0 and 29.4 MPa, respectively. Compared to the dosage of 10%, the compressive strengths of the concrete specimen at the dosages of 15% and 20% reduced by 7.25% and 14.78%, respectively. In the late stage of the test, because of the pozzolanic effect of fly ash, fly ash particles reacted with the $\text{Ca}(\text{OH})_2$ in the cement and generated calcium silicate hydrate (C-S-H) gel and calcium sulphoaluminate hydrate (C-A-S-H), which, as a cementing substance, gradually increased with increasing test age. Thus, although the strength of the concrete specimen in the early stage significantly decreased with the growth of age, the compressive strength of concrete rapidly increased in the later stage. At the test age of 90 day, when the dosages of fly ash were 10%, 15% and 20%, the compressive strengths of the concrete specimen were 55.2, 54.5 and 53.8 MPa, respectively, suggesting that the compressive strengths of the concrete specimen at different dosages were approximately equal to each other.

The anti-scouring and abrasion-resistant strength of the concrete specimen also decreased with increasing dosage of fly ash. As shown in Figure 5, at the test age of 28 day, when the dosages of fly ash were 10%, 15% and 20%, the anti-scouring and abrasion-resistant strengths of the concrete specimen were $12.48 \text{ h}(\text{g}/\text{cm}^2)^{-1}$, $12.0 \text{ h}(\text{g}/\text{cm}^2)^{-1}$ and $11.18 \text{ h}(\text{g}/\text{cm}^2)^{-1}$, respectively. At the test age of 90 day, when the dosages of fly ash were 10%, 15% and 20%, the anti-scouring and abrasion-resistant strengths of the concrete specimen were $13.32 \text{ h}(\text{g}/\text{cm}^2)^{-1}$, $12.88 \text{ h}(\text{g}/\text{cm}^2)^{-1}$ and $12.12 \text{ h}(\text{g}/\text{cm}^2)^{-1}$, respectively. Compared to the dosage of 10%, the anti-scouring and abrasion-resistant strengths of the concrete specimen at the dosages of 15% and 20% were reduced by 3.85% and 10.42% and 3.30% and 9.15%, respectively.

2.3.2. Silica Fume Effect

Table 5 provides the results of the test on high-strength concrete performance using silica fume. Figure 6 shows the change trends of the compressive strength, anti-scouring and abrasion-resistant strength and volumetric dry shrinkage rate of concrete with test age at different dosages of silica fume (5%, 7% and 9%).

Table 5. Test results of silica fume effect on concrete.

Mixture No.	Silica Fume Content/(%)	Compressive Strength/(MPa)			Abrasion Resistant/(h(g/cm ²) ⁻¹)		Volume Shrinkage/(×10 ⁻⁶)						
		7 day	28 day	90 day	28 day	90 day	3 day	7 day	14 day	28 day	60 day	90 day	
F20S5P0	5	29.4	46.2	53.8	11.18	12.12	-22	-75	-178	-240	-283	-309	
F20S7P0	7	30.8	52.2	58.8	12.02	13.04	-24	-88	-183	-248	-294	-326	
F20S9P0	9	32.1	55.3	61.9	13.74	14.46	-28	-90	-187	-259	-302	-338

Figure 6. Cont.

Figure 6. Effect of silica fume on concrete properties. (a) Compressive strength; (b) abrasion resistance; (c) volume shrinkage.

As shown in Figure 6a, the compressive strength of concrete increased with increasing dosage of silica fume; at the same dosage of silica fume, the increase amplitude of the compressive strength of concrete in the late stage was higher than that of the compressive strength of concrete in the early stage. At the age of 7 day, when the dosages of silica fume were 5%, 7% and 9%, the compressive strengths of the concrete specimen were 29.4, 30.8 and 32.1 MPa, respectively. Compared to the dosage of 5%, the compressive strengths of the concrete specimen at the dosages of 7% and 9% increased by 4.55% and 9.18%, respectively. At the test age of 90 day, they increased by 8.50% and 15.06%, respectively. This was because the ordinary concrete was loose with significant volumes inside and the cement was irregular in shape with sharp edges and corners. Under the surface tension of pore water, there would be no complete contact among particles. After adding silica fume, because of their small size and spherical shape, silica fume particles would fill in those pores, react with Ca(OH)_2 and produce high-strength and high-stability C-S-H crystals. As a result, C-S-H crystals would block the pore canals, reduce large pores, change the internal pore structure of concrete and significantly improve its strength.

In addition, the silica fume added into concrete improved both the anti-scouring and abrasion-resistant performance and hardness of paste. The bonding status of the interface between the cement paste and aggregate could largely enhance the anti-scouring and abrasion-resistant performance of coarse aggregate and strengthen the anti-scouring and abrasion-resistant strength of concrete. In Figure 6b, at the age of 28 day, when the dosages of silica fume were 5%, 7% and 9%, the anti-scouring and abrasion-resistant strengths of the concrete specimen were $11.18 \text{ h(g/cm}^2\text{)}^{-1}$, $12.02 \text{ h(g/cm}^2\text{)}^{-1}$ and $13.74 \text{ h(g/cm}^2\text{)}^{-1}$, respectively. Compared to the dosage of 5%, the anti-scouring and abrasion-resistant strengths of the concrete specimen at the dosages of 7% and 9% increased by 7.51% and 22.90%, respectively, and at the test age of 90 day, they increased by 7.59% and 19.30%, respectively.

Doping silica fume could improve the strength performance index of concrete; however, silica fume concrete faced the problem of plastic dry shrinkage in the early stage and was extremely susceptible to shrinkage cracking. As shown in Figure 6c, the volumetric dry shrinkage rate of concrete increased with increasing dosage of silica fume. At the test age of 90 day, compared to the dosage of 5%, the volumetric dry shrinkage rates of the concrete specimen at the dosages of 7% and 9% increased by 5.50% and 9.39%, respectively. Meanwhile, due to the extremely rapid development of the early strength of silica fume concrete, the hydration heat release of concrete was extremely rapid as well, resulting in the high hydration heat-induced temperature rise of concrete, and could very easily produce a relatively high temperature stress in concrete. The easy concentration of this stress at the top of the shrinkage crack caused the crack to propagate and extend, and a penetrated crack was likely to develop. For this reason, the dosage of silica fume in concrete should be optimal to ensure the compliance of the anti-scouring and abrasion-resistant strength of concrete with engineering requirements and reduce the risks of shrinkage cracking and concrete cracking.

2.3.3. PVA Fiber Effect

Table 6 provides the results of the test on high-strength concrete performance using PVA fiber. Figure 7 shows the change rules of the compressive strength, splitting tensile strength and anti-scouring and abrasion-resistant strength of concrete with test age.

Table 6. Test results of polyvinyl alcohol (PVA) fiber effect on concrete.

Mixture No.	PVA Fiber Content/%	Compressive Strength/MPa			Split Tensile Strength/MPa			Abrasion Resistant/ $\text{h}(\text{g}/\text{cm}^2)^{-1}$	
		7 day	28 day	90 day	7 day	28 day	90 day	28 day	90 day
F20S5P0.8	0.8	29.5	43	55	2.51	3.2	3.65	10.25	11.09
F20S5P0.9	0.9	30	43.3	55.8	2.59	3.28	3.72	10.36	11.48
F20S5P1.0	1.0	30.1	44.4	56.5	2.65	3.38	4	10.35	11.62

Figure 7. Effect of PVA fiber on concrete properties. (a) Compressive strength; (b) split tensile strength; (c) abrasion resistance.

As shown in Figure 7a, after doping PVA fiber into concrete, the compressive strength of concrete slightly increased with increasing dosage of PVA fiber but the change amplitude was very small. At the age of 90 day, when the dosages of PVA fiber were 0.8%, 0.9% and 1.0%, the compressive strengths of the concrete specimen were 55.0, 55.8 and 56.5 MPa, respectively. Compared to the dosage of 0.8%, the compressive strengths of the concrete specimen at the dosages of 0.9% and 1.0% increased by 1.45% and 2.73%, respectively, and thus the increase amplitudes were relatively small because the dosage of PVA fiber mixed in concrete was relatively low and the PVA fiber with stable physical and chemical properties in concrete would not modify the physical or chemical properties of concrete. In brief, doping a small amount of PVA fiber in concrete would not exert any substantial effect on the compressive strength of concrete.

According to Figure 7b, the splitting tensile strength of concrete increased with increasing dosage of PVA fiber. At the age of 7 day, when the dosages of PVA fiber were 0.8%, 0.9% and 1.0%, the splitting tensile strengths of the concrete specimen were 2.51, 2.59 and 2.65 MPa, respectively. Compared to the dosage of 0.8%, the splitting tensile strengths of the concrete specimen at the dosages of 0.9% and 1.0% increased by 3.19% and 5.58%, respectively. At the test age of 90 day, when the dosages of PVA fiber were 0.8%, 0.9% and 1.0%, the splitting tensile strengths of the concrete specimen were 3.65, 3.72 and

4.0 MPa, respectively. Compared to the dosage of 0.8%, the splitting tensile strengths of the concrete specimen at the dosages of 0.9% and 1.0% increased by 1.92% and 9.59%, respectively. This was because the splitting tensile strength of concrete was mainly embodied in its toughness and could reflect its ability to absorb energy in failure. After a small amount of PVA fiber was mixed in concrete, due to the fibrotic meshed structure of PVA fiber and its high bonding strength with concrete matrix, when stress was transmitted from the matrix to the PVA fiber, the latter would consume energy as a result of deformation and increase the load and macroscopic deformation of the concrete component upon initial cracking. Besides, as listed in Table 3, the PVA fiber used in the test was characterized by fine extensibility, high elastic modulus and high compressive strength, indicating that once concrete began to crack, PVA fiber would bridge the gap between the crack walls and prevent the rapid propagation of the crack. In addition, PVA would be pulled out or fractured only when stress exceeded the bonding strength between the PVA fiber and matrix or the tensile strength of PVA fiber. Thus, PVA fiber could significantly improve the fracture toughness and tensile strength of concrete.

In addition, as shown in Figure 7c, the anti-scouring and abrasion-resistant strength of concrete also slightly increased with increasing mixture of the PVA fiber. At the test age of 90 day, when the mixtures of PVA fiber were 0.8%, 0.9% and 1.0%, the anti-scouring and abrasion-resistant strengths of the concrete specimen were $11.09 \text{ h(g/cm}^2\text{)}^{-1}$, $11.48 \text{ h(g/cm}^2\text{)}^{-1}$ and $11.62 \text{ h(g/cm}^2\text{)}^{-1}$, respectively. Compared to the dosage of 0.8%, the anti-scouring and abrasion-resistant strengths of the concrete specimen at the dosages of 0.9% and 1.0% increased by 3.52% and 4.45%, respectively. This was because after doping a suitable amount of PVA fiber in concrete, when cement solidified, PVA fiber would present a 3D irregular distribution in cement paste, form a multi-directional supporting system, effectively improve the anti-scouring and abrasion-resistant performance of the concrete member and reduce the micro-cracks induced by the shrinkage of cement matrix. Under water flow scouring and abrasion by other forces, the concrete component would always fail for a crack, and the larger the crack, the easier the failure. In this case, doping PVA fiber could effectively reduce the formation of micro-cracks and other weak links in the concrete member and thus improve the anti-scouring and abrasion-resistant performance of concrete.

2.4. Mix Design and Concrete Performance Test

As indicated by the test on dosage selection for fly ash, with increasing dosage of fly ash, the compressive strength, splitting tensile strength and anti-scouring and abrasion-resistant strength of concrete all decreased. With the growth of test age, due to the late-stage effect of fly ash, the concrete with a higher dosage of fly ash witnessed a faster strength increase; at the age of 90 day, the strengths of concrete at different dosages of fly ash were relatively close to each other. Given that the anti-scouring and abrasion-resistant concrete for Dagangshan Hydropower Station had a design age of 90 day, to fully utilize fly ash's advantage of faster strength increase in the late stage, it was recommended to use a dosage of 20% for fly ash. As indicated by the test on dosage selection for silica fume, with increasing dosage of silica fume, the compressive strength and anti-scouring and abrasion-resistant strength of concrete increased as well; when the dosage of silica fume increased by 2%, the compressive strength of concrete increased by approximately 5%. Meanwhile, with increasing dosage of silica fume, the dry shrinkage rates of concrete at different ages would increase as well; when the dosage of silica fume increased from 5% to 9%, the increase in the dry shrinkage rate of concrete was within 8%. To guarantee the compressive strength and anti-scouring and abrasion-resistant strength of concrete and reduce the probability of concrete cracking, it was recommended to use a dosage of 5% for silica fume. The performance test result on the concrete at different dosages of PVA fiber shows that when the dosage of PVA fiber increased from 0.8 kg/m^3 to 1.0 kg/m^3 , the compressive strength, splitting tensile strength, and anti-scouring and abrasion-resistant strength of concrete gradually increased, but the increase in amplitudes was not substantial [26–31]. The test adopted the dosage of 0.9 kg/m^3 recommended by the manufacturer for PVA fiber. After several times of field trial mixing

and optimal adjustment, the construction data listed in Table 7 were finally proposed for guiding field concrete casting.

Table 7. Construction mix proportion of spillway tunnel sidewall lining concrete (unit: kg/m³).

Strength Grade	Grade	Water-Binder Ratio	Sand Ratio/%	Binder Materials Content	Amount of Material in Each Cubic Meter of Concrete							
					Water	Cement	Sand	Stone	Fly Ash	Silicon Powder	Water Reducing Agent of JM-PCA	Air Entraining Agent of NOF-AE
C ₉₀ 50	Two	0.33	38	379	125	284	718	1172	76	19	3.411	0.015

Based on the basic mix proportions of fly ash and silica fume for concrete construction provided in Table 7, after field sampling, an indoor test was conducted on the concrete specimen's compressive strength, splitting tensile strength, elastic modulus, anti-scouring and abrasion-resistant strength, dry shrinkage deformation, adiabatic temperature rise and other performance parameters. The test results are listed in Table 8.

Table 8. Physical and mechanical parameters of spillway tunnel side wall lining concrete.

Strength Grade	Elastic Modulus/GPa		Compressive Strength/MPa		Split Tensile Strength/MPa		Abrasive Resistance/h(kg/m ²) ⁻¹		Volume Shrinkage Rate/(×10 ⁻⁶)						Thermal Insulated Temperature Rise/°C		
	28 day	90 day	7 day	28 day	90 day	7 day	28 day	90 day	28 day	90 day	3 day	7 day	14 day	28 day		60 day	90 day
C ₉₀ 50	26.9	28.7	34.0	51.7	60.0	2.51	3.52	3.81	6.52	7.96	-12	-71	-156	-253	-323	-359	41.8 × t/(2.278 + t)

3. Numerical Simulation of Temperature Field

3.1. Model, Parameters and Schemes

This numerical simulation of the temperature field of sidewall C₉₀50 concrete was performed by a 3D finite element method based on ANSYS [32]. The size of surrounding rock in the numerical model was roughly set at three times of the spillway tunnel diameter; the origin of the whole coordinate system was set at the bottom of the spillway tunnel (the direction from the upstream face to the downstream face as *y*-axis orientation; the horizontal direction perpendicular to the spillway tunnel axis as *x*-axis orientation; the upward vertical direction as *z*-axis orientation). The boundary conditions were selected as follows: the top and bottom and four sides of the surrounding rock served as the adiabatic boundaries; the construction placement section of the spillway tunnel played the role of solid–gas boundary, treated as a category-III boundary (the surface heat transfer coefficient between the boundary of the object and the surrounding fluid and the temperature of the surrounding fluid are specified). In mesh generation, hexahedral elements were adopted for surrounding rock and lining concrete, while pentahedral or tetrahedral elements were used locally as transition. The contact elements of zero thickness could be used for transmitting heat, compressive stress, shearing stress and so forth. The numerical model is shown in Figure 8. According to the site construction data and mix proportion optimization design, concrete performance test results at Dagangshan Hydropower Station and reference to similar engineering experience [33–35], the thermodynamic parameters of the C₉₀50 anti-scouring and abrasion-resistant concrete were used as listed in Table 9.

Table 9. Thermal parameters of abrasion resistance.

Strength Grade	Heat Conductivity Coefficient/kj(mh ² °C) ⁻¹	Specific Heat/kj(kg ² °C) ⁻¹	Linear Expansion Coefficient/(°C) ⁻¹	Thermal Conductivity/(m ² /h)	Exothermic Coefficient/(kj/mh ² °C)	Thermal Insulated Temperature Rise/°C	Poisson's Ratio	Elastic Modulus/GPa	
								28 day	90 day
C ₉₀ 50	6.36	0.93	8.0 × 10 ⁻⁶	0.0027	42	41.8 × t/(2.278 + t)	0.17	26.9	28.7

Figure 8. Meshes of simulated domains.

During casting of the sidewall C₉₀50 anti-scouring and abrasion-resistant concrete for the spillway tunnel, a pre-buried HDPE (High density polyethylene) plastic cooling water pipe was used for cooling purposes (inner diameter, 28 mm; wall thickness, 2.0 mm; thermal conductivity coefficient, 1.67 kJ/(mh °C)); it was laid in a uniform S-shaped mode, with a vertical laying interval of 1 m. During casting, it was buried inside the concrete (Figure 9). In general, cooling water has a throughput temperature T in the range of 12–17 °C, a throughput flow in the range of 1.5–1.8 m³/h and a throughput duration of no less than 7 day. The water flow should be continuous. In this numerical simulation, seven working conditions were introduced for comparison (i.e., absence of cooling water, throughput flow at 3.5 m³/h within 1–2 day after casting, throughput flow of 17 °C cooling water at 1.5 m³/h or 1.8 m³/h within 3–7 day and so forth); the change rules of the temperature field of C₉₀50 anti-scouring and abrasion-resistant concrete were obtained within a uniform simulation duration of 30 day.

Figure 9. Layout of the cooling pipes.

3.2. Analysis of Numerical Simulation Results

When analyzing the results from the numerical simulation of temperature control on the lining concrete for Dagangshan Spillway Tunnel, mainly the temperature change of the geometric center of the sidewall lining concrete was selected for a comparative analysis, and statistics were made on the highest temperature, the maximum temperature difference and other characteristic parameters of the point inside the concrete under various calculation conditions, as detailed in Table 10. Figure 10 shows the variation of the highest temperature over time inside the concrete at different cooling water temperatures and different throughput flows.

Table 10. Numerical simulation results of the highest temperature and maximum temperature difference of the sidewall lining concrete.

Schemes	Water Cooling					Casting Temperature/°C	Highest Temperature/°C	Maximum Temperature Difference/°C	
	The First Stage			The Second Stage					
	Temperature/°C	Flow/(m³/h)	Duration/day	Temperature/°C	Flow/(m³/h)				Duration/Day
1	/	/	/	/	/	17	50.22	27.95	
2	17	3.5	0~2	17	1.8	3~7	17	39.07	16.29
3	17	3.5	0~2	17	1.5	3~7	17	39.07	19.35
4	15	3.5	0~2	17	1.5	3~7	17	34.35	15.27
5	15	3.5	0~2	17	1.8	3~7	17	34.35	13.31
6	12	3.5	0~2	17	1.5	3~7	17	32.31	16.29
7	12	3.5	0~2	17	1.8	3~7	17	32.31	14.44

Figure 10. The maximum temperature duration curve of concrete under different schemes.

Through comparing the temperature variation of the typical points in the sidewall C₉₀50 anti-scouring and abrasion-resistant concrete under different temperature control schemes, the following conclusions could be drawn:

(1) During the casting of sidewall C₉₀50 anti-scouring and abrasion-resistant concrete, the temperature inside the concrete roughly experienced two stages, i.e., hydration heat-induced temperature rise and temperature drop. In the initial stage of casting, because of the hydration heat action of cement, the temperature inside the concrete rose up abruptly and reached its peak roughly 2 day after casting. After that, on account of throughput cooling and other temperature control measures, the temperature inside the concrete began to drop. Considering that the peak temperature of concrete occurred roughly 2 day after casting, it was suggested that the early-stage throughput cooling be strengthened during construction to guarantee the cooling effect of concrete.

(2) As shown in Figure 10, under the same throughput flow conditions, throughput temperature declined from 17 to 12 °C, accompanied by the downward movement of the duration curve of the temperature inside the concrete; the peak temperature declined from 39.07 to 32.31 °C; the maximum temperature difference dropped from 19.35 to 14.44 °C, manifesting a good negative correlation. This suggested that throughput temperature was an important factor affecting the cooling effect of the cast concrete and that a relatively low throughput temperature should be adopted under suitable conditions during construction to enhance the cooling effect of concrete.

(3) According to Figure 10, under the same throughput temperature conditions, when throughput flow increased from 1.5 to 1.8 m³/h, the duration curve of the temperature inside concrete would correspondingly move downward, accompanied by the corresponding decrease in the maximum temperature difference. This suggested that throughput flow was another important factor affecting the cooling effect of the cast concrete and that there was an obvious positive correlation between such a cooling effect and the rate of the throughput flow, i.e., high throughput flow could more rapidly remove the hydration heat of concrete and create a quick cooling effect.

4. Analysis of Temperature Monitoring Data

The casting of sidewall C₉₀50 silica fume concrete lining was carried out by using a novel self-developed tunnel steel trolley. The trolley consists of a frame system, template system, vertical reciprocating lift system, automatic concrete spreading system, hydraulic running system, suspension system, shifting and jacking system, etc. When casting sidewall concrete, the vertical lift system of the trolley first lifts the stock bin with normal concrete to the predetermined height. After that, the electric hoist is enabled to drag the stock bin until it is right above the concrete spreader. Finally, both the concrete spreader and the stock bin are enabled so that the concrete spreader transports concrete to the inner side of the template and thus realizes the automatic casting of sidewall normal lining concrete. The field construction is shown in Figure 11.

Figure 11. Construction of spillway tunnel sidewall lining concrete.

Based on the performance test and numerical simulation results, in the construction of sidewall C₉₀50 silica fume concrete lining, the cooling measure of “early-throughput, high-flow and short-duration” was used for temperature control and crack prevention. In the view of the concentrated hydration heat and high heat production of C₉₀50 silica fume concrete in the early stage, it is suggested that the cooling measure of condition seven in the numerical simulation be adopted during construction to avoid excessively fast temperature rise of lining concrete. During the casting process and over 1–2 day after casting, 12 °C “high-flow and low-temperature” cooling water was guided in at a flow of approximately 3.5 m³/h. Within 3–7 day after casting, because of the template removal, with increasing radiating surface and reducing template constraints the temperature dropped abruptly. In contrast, the temperature inside the concrete still maintained a rising trend, resulting in a relatively large internal/external temperature difference. Under the action of expansion caused by heat and contraction caused by cold, tensile stress increased rapidly, making it susceptible to temperature cracking. To avoid excessively high peak temperature and excessively large internal/external temperature difference for lining concrete, during construction, 17 °C river water at a flow of 1.8 m³/h was guided in, and the 8# iron wire hooks with length of 20 cm were pre-buried at the top of the sidewall at intervals of 1 m; after sidewall demolding, the PVC (polyvinyl chloride) perforated pipes were hung on the pre-buried iron wire hooks and the water from a cooling water pipe was used to supply normal flowing water on the concrete surface for curing purposes. After 7 day, the temperature inside the concrete basically began to decrease over time. To avoid excessively fast cooling of concrete, cooling water should be suspended and surface flowing water alone could be sufficient for the cooling purpose.

Silica fume concrete is susceptible to early-stage plastic cracking; when the concrete surface is observed to turn white or the surface water evaporation rate was >0.5 kg/(m³h), a wind shield should be used for screening and spraying should be used to maintain a necessary humidity level on the concrete surface. In low-temperature seasons or in the case of a sudden drop in air temperature,

the demolding time should be properly postponed; in particular, demolding should be avoided in cold evenings, otherwise concrete may crack due to a large internal/external temperature difference. After demolding of fresh concrete, the transverse joint plane should be immediately covered with thermal insulation materials.

In the process of concrete casting, resistance thermometers were buried inside the concrete for real-time monitoring of concrete temperature. To be specific, for the concrete of each placement section, thermometers were buried alternatively on the left/right side and arranged at the centers of the placement sections and 4–5 m in height from the bottom plate (~60 cm from the concrete surface), as shown in Figure 12. In the first three days, the measurement interval of fresh concrete was less than 8 h and could be increased to 12h afterwards and the measurement duration lasted for no less than 28 day. The sidewall was buried with a total of 127 thermometers, 122 of which performed well until the end of the monitoring work, with a survival rate of 96.1%. The temperature monitoring results are listed in Table 11.

Figure 12. Layout of embedded temperature monitoring instrument.

Table 11. Temperature monitoring results of spillway side wall.

Stake Number/m	Number of Resistive Thermometer	Highest Temperature/°C	Average Maximum Temperature/°C	Permissible Maximum Temperature/°C	Analysis of Temperature Control Effect	
					Qualified Numbers	Pass Rate/%
0+000.00~0+120.00 m	14	36.7	32.05	36	13	92.86
0+120.00~1+037.71 m	110	35.8	33.60	34	101	91.82
1+037.71~1+075.50 m	3	33.65	33.47	36	3	100

According to the relevant standards, the maximum permissible temperature inside concrete is 34 °C and the maximum temperature difference is 25 °C. As listed in Table 9, the average highest temperatures of the concrete measured in the sidewall's transition section from 0 + 000.00 - 0 + 120.00 m, standard section from 0 + 120.00 to 1 + 037.71 m and transition section from 1 + 037.71 to 1 + 075.50 m were 32.05, 33.60 and 33.47 °C, respectively, slightly higher than those calculated under working condition seven from the numerical simulation but all within the permissible range. The measured peak temperature was reached roughly 2 day after casting, similar to the calculation results, as shown in Figure 13. To sum up, the change rules of the temperature field obtained through numerical simulation were relatively consistent with the measured results, and the overall temperature control monitoring of the sidewall lining concrete had a qualification rate of >91%, suggesting that the temperature control and crack prevention measures proposed in this study were satisfactory for controlling the temperature.

Figure 13. Temperature variation curve of concrete at typical side wall stake number.

Both the calculation and monitoring results indicated that concrete temperature generally would reach a peak level 2 day after casting and that the placing temperature of concrete exerted an obvious effect on its final highest temperature. Therefore, strictly controlling the placing temperature of concrete during construction is necessary. During the numerical simulation, the temperature of concrete was assumed to be 17 °C during casting; however, in the course of actual construction, the casting temperature was subjected to changes and fluctuations due to multiple factors. In the view of this, efforts should be made during construction for thermal insulation during concrete transport, e.g., improving the transport system and increasing the transport efficiency. Furthermore, concrete casting during high-temperature should be avoided. In addition, it is also necessary to adopt spraying and other measures to keep placement sections in the moisturized state and reduce their ambient temperature. The maximum thickness the cast layers should also be properly controlled. In the numerical simulation, surface spraying cooling or other measures are not considered and this might be the reason that the highest temperature of concrete calculated at the age of 30 day was slightly higher than those of the monitoring results. In short, the assumptions made for the numerical simulation and the uncertain factors existing in the field construction gave rise to some differences between the calculation and field monitoring. However, they followed similar change trends over time and the results provided important implications for selection of rational engineering measures for temperature control.

5. Conclusions

Due to the characteristics of high water head, high velocity, large discharge and complex shape, as well as the erosion of sediment and frequent use, there are bound to be higher requirements for the material performance, pouring construction technology and temperature control of concrete for the large-scale spillway tunnel. In order to meet the requirements of erosion resistance and wear resistance of the spillway tunnel, C₉₀50 silica fume concrete is used for the lining of the side wall and bottom plate of the tunnel. The hydration heat is concentrated and it is easy to produce temperature cracks. Therefore, strict comprehensive temperature control measures should be taken during construction to avoid concrete cracking due to a large temperature difference between inside and outside. The above-mentioned concrete anti-erosion and wear resistance and temperature control and crack prevention are two major problems faced by large-scale spillway tunnel projects and they are closely related and mutually affected. Therefore, the anti-scouring and abrasion resistance and temperature control of C₉₀50 silica fume concrete were studied.

(1) The doping of fly ash, silica fume, PVA fiber and other auxiliary cementing materials indicated that (a) fly ash with a dosage of 20% could reduce water consumption and micro-cracks via its “morphological effect”; (b) silica fume with a dosage of 5% could improve the early strength of cement concrete and make up for the strength loss caused by the fly ash; (c) PVA fiber with the dosage of

0.9 kg/m³ could enhance the concrete durability. The doping of these three additives can increase both the strength and abrasion resistance of concrete.

(2) The peak temperature of concrete occurred roughly 2 day after casting. Properly strengthening the early-stage throughput, increasing throughput flow and decreasing cooling water temperature could achieve a satisfactory cooling effect. This study proposed a new temperature control and crack prevention measure, i.e., the “early-throughput, high-flow and short-duration” cooling strategy, which proved to be effective in reducing the maximum temperature rise inside the concrete. In the casting process, within 1–2 day after casting, cooling water at roughly 12 °C was guided in at a flow of approximately 3.5 m³/h; within 3–7 day after casting, river water at roughly 17 °C was guided in at a flow of approximately 1.8 m³/h; 7 day later, using surface flowing water alone for curing could achieve the cooling effect. The field temperature monitoring data indicated that the temperature of the sidewall lining concrete had a qualification rate of >91%, suggesting that the temperature control and crack prevention measures can effectively reduce the maximum temperature rise inside the concrete and achieve a satisfactory temperature control effect.

(3) Through comprehensively utilizing the optimal mix proportion design, complex-curved novel template, self-propelled steel trolley, throughput cooling and other quality control measures, this paper guaranteed the construction quality of anti-scouring and abrasion-resistant concrete for the spillway tunnel and the fine shape control, smooth and flat surface and satisfactory crack control of cast concrete. The Dagangshan Spillway Tunnel began to take part in the flood discharge of the Dagangshan Reservoir in flood seasons in July 2015; at the end of 2015, its cumulative flood discharge duration reached 1784 h; at the end of December 2016, the cumulative running hours of the spillway tunnel reached 2690 h. Its annual average service frequency exceeded 2000 h/a, the highest among the same-type hydropower stations in China. According to the results of the inspection over the spillway tunnel after two years of frequent use, the concrete surface was as smooth as a mirror, without any obvious scouring trace, pot hole or crack failure.

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