Study on the Effect of Impermeable Anti-Cracking Agents and Fibers on the Performance of Panel Concrete

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Abstract. Concrete-faced rockfill dams (CFRDs) have become an important choice for dam construction worldwide due to their economy, construction simplicity and high adaptability to complex terrain. In this paper, the effects of impermeable anti-cracking agent, PVA fiber and cellulose fiber single admixture as well as compound admixture on the mechanical properties, deformation properties and durability properties of panel concrete were investigated. The results showed that: the enhancement of mechanical properties of panel concrete by fiber and impermeable anti-cracking agent was not obvious, the addition of fiber increased the early axial tensile strength; the addition of impermeable anti-cracking agent improved the cracking resistance, and the grade of cracking resistance was improved from Class II to Class I; the compounding of impermeable anti-cracking agent and fiber increased the drying shrinkage value; all specimens have a frost resistance grade of F200.

Keywords: Panel concrete, Impermeable anti-cracking agents, Fiber, Mechanical properties, Deformation properties, Durability properties.

1 INTRODUCTION

Concrete-faced rockfill dams (CFRDs) are swiftly developing as an vital dam type due to their strong points of low cost, relatively simple construction, and high adaptability to terrain and geological features[1]. Currently, the design and construction technology of CFRD has matured, with a maximum dam height of 200-300 m[2][3]. With advancement in materials science and engineering, new materials (e.g. high-performance concrete, fibre-reinforced materials, etc.) and innovative design concepts (e.g. more optimised panel structure design) are being applied to CFRDs to enhance the capacity and durability of dams. Concrete panels, as the main seepage control system in CFRDs, are prone to cracking due to deformation of rock piles, external temperature and humidity changes, and internal volume shrinkage in their thin and

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long strip structure (0.3-1.0 m thickness), which seriously affects the structural integrity and safe operation of dams[4][5]. Therefore, the safety and durability of panel concrete are crucial to ensure the structure integration and secure functioning of CFRD.

How to enhance the anti-cracking performances of panel concrete is the major focus of current research. The crack resistance of panel concrete can be effectively enhanced by incorporating a certain amount of fibers into the panel concrete. Chen et al[6] significantly improved the cracking resistance by incorporating 0.9% volume admixture of cellulose fibers in panel concrete, reduced the unit crack area by 88.1%, and significantly extended the initial cracking time. Wang et al[7] found that different fibers do not have the same effect on the enhancement of cracking resistance of panel concrete, polyvinyl alcohol fibers have better early cracking performance, but the later cracking performance of steel fibers is better, and the later cracking of carbon fibers has the expansion was the smallest. Li et al[8] similarly found that the incorporation of polyvinyl alcohol fibers effectively reduced the early shrinkage of panel concrete and inhibited the development of cracks.

Wang et al[9] used activated magnesium oxide up to 10% in order to remove premature shrinkage and improve early anti-cracking properties. With further increase in age, the pore structure of panel concrete gets better with age and there is no microcracking around the concrete containing the hydration products of magnesium oxide[10]. Wang et al[11] found that any increase in the volume rate of fly ash admixture from 0 to 40% significantly improves the resistance of panel concrete to plastic shrinkage cracking. Zhao et al[12] found that type II calcium sulfoaluminate-based expansion agent reduced the early shrinkage of panel concrete by 75.8% without cracking, 28 d dry shrinkage by 50.9%, and 42 d limiting shrinkage by 83.3%. Wu et al[13] used a combination of low-heat silicate cements, MgO-based expansion agents, and shrinkage-reducing admixtures to reduce the risk of cracking in concrete. Lv et al[14] found that single admixture of impermeable anti-cracking agent effectively enhanced the anti-cracking of concrete.

In this paper, polyvinyl alcohol (PVA) fibers and cellulose fibers as well as impermeable anti-cracking agent were selected to improve the cracking resistance of panel concrete by carrying out relevant panel concrete experimental studies, to grasp the effects of fibers and functional additives on its mechanical, deformation, and durability properties, and to reveal the roles of PVA fibers and cellulose fibers and impermeable anti-cracking agent for the anti-cracking of panel concrete, so as to provide theoretical research and engineering application with technical support for theoretical research and engineering application.

2 TEST MATERIALS AND MIXING RATIOS

2.1 Raw Materials

The test site is from a hydropower station in Xinjiang, the raw materials are from the construction site, the cement is 42.5 medium-hot silicate cement produced by Xinjiang Tianshan Cement Co, Ltd, and the fly ash is adopted from Xinjiang Manas

Power Plant, the chemical composition of which is shown in Table 1.The artificial aggregates come from the project site, and in order to prevent the aggregate separation, the coarse aggregate adopts the second grade, the ratio of medium stone to small stone is 45:55. WHDF concrete impermeable anti-cracking agent was used in the test, and the performance of cement mixed with 2% WHDF concrete impermeable anti-cracking agent is shown in Table 2. Taian concrete with PVA fiber (TP) and Taian concrete with cellulose fiber (TC) were used for the fiber. Fibre indicators are shown in Table 3. AXT high-performance water reducing agent and AXSF air-entraining agent were used as additives.

2.2 Mix Ratio

In order to investigate the effects of impermeable anti-cracking agent and different fibers on the performance of panel concrete, the following six proportioning schemes were set up for testing, and at the same time, in order to ensure that the slump of panel concrete was controlled at 50-70 mm, the air content was controlled at 4.0-5.0%, and the water consumption per unit, the SP content and the AE content were adjusted appropriately. The test water-cement ratio was 0.47, in which the benchmark blank group (EMP) was set, 2% impermeable anti-cracking agent (IAA) was mixed alone, two kinds of fibers were mixed alone with 0.9 kg/m3 (TPF, TCF), and 2% WHDF impermeable anti-cracking agent and the compound mixing group of 0.9 kg/m3 fibers were set (COM1, COM2). The test mix ratios of panel concrete are shown in Table 4.

Table 1. Cement and fly ash chemical composition (%).

Materials	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Ignition loss
Cement	57.72	35.48	0.87	1.20	3.49	2.42	1.26
Fly ash	2.90	51.90	20.72	4.64	1.70	2.51	1.53

Table 2. 0% and 2% WHDF cement physical properties.

Type	Setting time (minute)		Flexural strength (MPa)			Compressive strength (MPa)		
	Initial setting time	Final setting time	3 days	7 days	28 days	3 days	7 days	28 days
0%WHDF	140	212	5.3	6.8	8.0	21.8	32.8	47.1
2%WHDF	180	315	5.4	6.9	7.9	22.0	33.9	47.1

Table 3. Quality indicators of fibers.

Type	Diameter (μm)	Density (g/cm^3)	Breaking Strength (MPa)	Elastic Modulus (GPa)
TP	30	1.3	1538	36
TC	19.5	1.2	780	8.2

Table 4. Quality indicators of fibers.

Type	W/B	WHDF (%)	TP (kg/m^3)	TC (kg/m^3)	SP (%)	AE (%)	Concrete quantity (kg/m^3)				
							Water	Cement	FA	Sand	Stone
EMP	0.47	\	\	\	0.80	0.0100	124	198	66	790	1267
IAA	0.47	2	\	\	0.80	0.0100	121	193	64	796	1276
TPF	0.47	\	0.9	\	0.85	0.0095	125	199	66	788	1264
COM1	0.47	2	0.9	\	0.85	0.0095	122	195	65	794	1273
TCF	0.47	\	\	0.9	0.80	0.0100	124	198	66	790	1267
COM2	0.47	2	\	0.9	0.85	0.0095	122	195	65	794	1273

2.3 Experiment Method

Mechanical property tests were conducted in accordance with SL/T 3520-2020 "Test code for hydraulic concrete"[15]. Cubic compressive strength and splitting tensile strength tests were conducted using cubic standard specimens with a side length of 150 mm; axial tensile strength ultimate tensile value was determined using a variable-section prismatic specimen with a central cross-section size of 100 mm × 100 mm and a pure tensile section of 220 mm; compressive modulus of elasticity was selected from a cylindrical specimen with a diameter of 150 mm and a height of 300 mm.

The deformation performance test was conducted in accordance with SL/T 3520-2020[15]. In order to observe the crack resistance of the panel concrete under the constrained state, the crack resistance of concrete was determined by the flat plate method, after molding, vibration and smoothing in the flat plate test mold, the cracking time, the number of cracks, the length and width of the cracks were recorded for the specimen; for the determination of the drying shrinkage value, a prismatic specimen with a diameter of 100 mm × 100 mm × 600 mm was selected, and the corresponding drying shrinkage values were determined at 3, 7, 14, 28, 60 and 90 days, respectively. The corresponding drying shrinkage values were determined at 3, 7, 14, 28, 60 and 90 days.

Freeze was conducted in accordance with SL/T 3520-2020[15]. For the freez-thaw resistance test, the fast-freezing method was used, the specimen size was 100 mm × 100 mm × 400 mm, and aggregates with particle size larger than 30 mm were removed by wet sieving method before molding, and the number of freezing and thawing cycles was 50, 100, 150, and 200, and the mass loss and relative dynamic elasticity modulus of the specimens were determined after completing each test cycle.

3 RESULTS AND DISCUSSION

3.1 Effects of Anti-seepage and Anti-cracking Agents and Fibers on the Mechanical Properties of Panel Concrete

The test results of compressive strength and split tensile strength of concrete are shown in Table 5 and Table 6, and it is found that single mixing of PVA fibers and single mixing of cellulose fibers do not have much effect on the mechanical strength of concrete panels, the strength is slightly lower than that of the EMP group at the age of 7 d, and basically the same as that of the EMP group or even a little bit higher at the age of 28 d and 90 d, and the maximum of the compressive and split tensile strengths at the age of 90 d reaches 40.1 MPa The main reason is that the compressive and split tensile strength of concrete mainly depends on the adhesive strength of the interface between cement paste and aggregate, and the main role of fiber is to prevent or reduce the generation and development of internal cracks in concrete, and at the same time, due to the small amount of mixing, the enhancement of compressive strength and split tensile strength is not obvious[16]. The single admixture of WHDF impermeable anti-cracking agent reduces the early strength and increases the strength in the later stage by stimulating the activity of the mix and admixture in the cement-admixture composite cementitious system[17].

The test results of the axial tensile strength of concrete are shown in Table 7, It can be observed that the added fibers increase the axial tensile strength of concrete, but the compound fibers and impermeable anti-cracking agent do not have the role of enhancement, instead, there is also a decline in the PVA fibers are slightly better than the cellulose fibers. the maximum of up to 3.57 MPa at the age of 90 d, enhancement of about 5%, the fibers have a high modulus of elasticity and tensile strength, when subjected to tensile loading, the distribution of fibers along the tensile direction will restrict the tensile strength of the concrete. distribution of fibers in the tensile direction will limit the crack development, and this lifting effect is not obvious due to the small fiber admixture[18]. The ultimate tensile values and compressive modulus of elasticity of concrete are shown in Table 8 and Table 9, with an increase of about 30% at 28 d compared to 7 d, while the increase at 90 d compared to 7 d is smaller, generally only about 5%. The ultimate tensile value at 90 d of COM1 group with impermeable anti-cracking agent compounded with PVA fibers is the largest, reaching 120×10-6. The difference of compressive elastic modulus of each group is small, and it is basically around 26.8-28.5 GPa at 90 d.

Table 5. Concrete compressive strength results.

Type	Compressive strength (MPa)		
	7 days	28 days	90 days
EMP	19.5	33.1	39.8
IAA	16.0	32.8	39.3
TPF	19.0	34.9	40.1
COM1	15.5	32.8	38.9
TCF	19.3	32.7	39.2
COM2	15.7	32.4	39.1

Table 6. Concrete splitting tensile strength results.

Type	Splitting tensile strength (MPa)		
	7 days	28 days	90 days
EMP	1.43	2.13	2.48
IAA	1.16	2.08	2.46
TPF	1.22	2.27	2.55
COM1	1.02	2.08	2.53
TCF	1.24	2.09	2.48
COM2	1.19	2.01	2.50

Table 7. Concrete axial tensile strength results.

Type	Axial tensile strength (MPa)		
	7 days	28 days	90 days
EMP	1.93	3.08	3.40
IAA	2.03	3.05	3.47
TPF	2.13	3.37	3.57
COM1	2.00	3.00	3.35
TCF	2.14	3.30	3.31
COM2	2.15	3.10	3.27

Table 8. Concrete ultimate tensile value results.

Type	Ultimate tensile value ($\times 10^{-6}$)		
	7 days	28 days	90 days
EMP	76	95	103
IAA	69	104	113
TPF	83	110	116
COM1	75	110	120
TCF	75	101	102
COM2	72	105	110

Table 9. Concrete compressive elastic modulus results.

Type	Compressive elastic modulus (GPa)		
	7 days	28 days	90 days
EMP	20.5	26.0	27.5
IAA	20.2	25.0	28.3
TPF	21.2	25.5	27.0
COM1	20.2	26.3	26.8
TCF	20.7	25.9	27.8
COM2	19.8	25.2	27.1

3.2 Effects of Anti-seepage and Anti-cracking Agents and Fibers on the Deformation Properties of Panel Concrete

The results of concrete cracking resistance determined by plate test are shown in Table 10. The results show that the addition of anti-seepage and anti-cracking agent reduced the average cracked area by 90.7%, the number of cracks decreased by 70.7%, the cracked area per unit area decreased by 83.5%, and the cracking resistance grade was improved from Class II to Class I. Single-mixed PVA fibers and cellulose fibers also improved the anti-cracking grade, but PVA fibers were superior to cellulose fibers. There was no superposition effect of fiber and anti-seepage and anti-cracking agent compound doping, but it produced more fine cracks and increased the cracking area. The expansion properties of magnesium oxide in the anti-seepage and anti-cracking agent can efficiently prolong the expansion time, adjust the expansion rate, and compensate for the plastic shrinkage of concrete[9], the aluminum ions in dialuminum hydrogen phosphate and potassium aluminum sulfate form a complex network structure with the calcium ions and methyl silicate ions in the concrete, which improves the anti-cracking ability[19].

The results of drying shrinkage of concrete are shown in Figure 1, it can be found that the drying shrinkage grows faster in the first 14 days, and the change of drying shrinkage value in 60 and 90 days is very small, and the compound mixing of fibers and impermeable anti-cracking agents can not reduce the drying shrinkage value, which increases the drying shrinkage value in 14 and 90 days by about 12.6% compared to the blank group of EMP, respectively. Single-mixed impermeable anti-cracking agents and single-mixed fiber reduced the dry shrinkage value, of which the reduction effect of dry shrinkage of Taian concrete with PVA fiber was the most obvious, and all ages were lower than the blank group EMP group by 3%~6%. The bond between the fibers and the substrate inhibits the evolution of concrete shrinkage, and the fibers provide three dimensional stiffening of the structure to resist internal tensile forces and reduce drying shrinkage values[4][20].

Table 10. Concrete slab crack resistance test results.

Type	Cracking time (minute)	Average cracking area (mm^2)	Number of cracks per unit area ($number/mm^2$)	Crack area per unit area (mm^2/m^2)	Crack resistance level
EMP	455	23	2.8	71	II
IAA	402	2.1	5.6	11.7	I
TPF	315	4	8.3	32	I
COM1	339	4.9	16.7	80.9	II
TCF	223	12	8	99	II
COM2	307	6.2	15.1	94	II

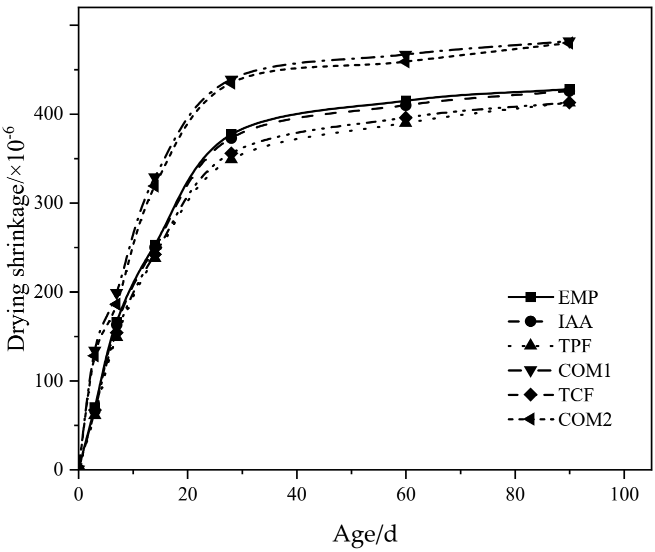

Fig. 1. Concrete drying shrinkage results.

3.3 Effects of Anti-seepage and Anti-cracking Agents and Fibers on the Frost Resistance of Panel Concrete

The results of the frost resistance tests are shown in Figure 2 and Table 11, and it is found that the concrete mass loss of all schemes is less than 5% and the relative modulus of elasticity is more than 60%, which meets the design indexes of frost resistance of F200. The relative modulus of elasticity of the panel concrete of different schemes is close to each other; the concrete with added fibers has the most obvious improvement with the mass loss of less than 1% after 200 freeze-thaw cycles. The air-entraining agent added in the mix design introduces tiny air bubbles (20-50 μm) in the interior of the concrete, and the average spacing of the bubbles is controlled to be within 200 μm, which provides tiny cavities for the freezing and expansion of water, slows down the freezing and expansion force as well as the capillary water infiltration pressure during freezing and thawing, and improves the freezing performance[21]. The modulus of elasticity of the fiber has the characteristic of increasing with decreasing temperature, and when cooling, the modulus of elasticity gradually increases, which can offset the expansion force due to water freezing to a certain extent; when warming, the modulus of elasticity becomes smaller, which reduces the volume deformation caused by expansion[22].

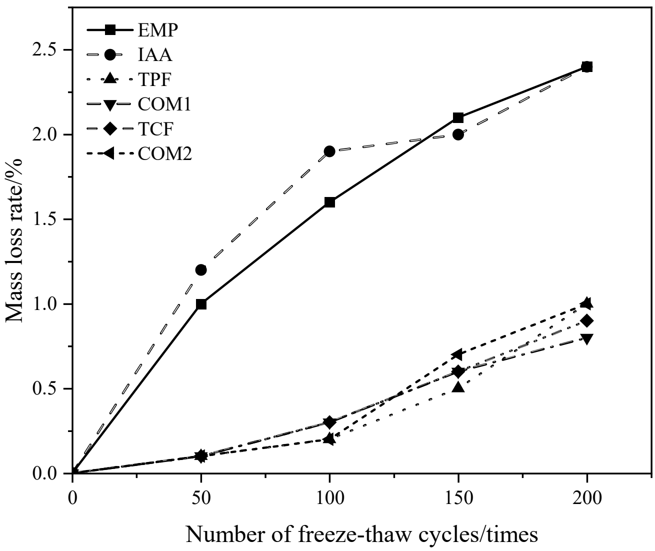

Fig. 2. Mass loss results of concrete under different freeze-thaw cycles.

Table 11. Relative dynamic elastic modulus results of concrete under different freeze-thaw cycles.

Type	Number of freeze-thaw cycles				
	0	50	100	150	200
EMP	100	99	95	93	91
IAA	100	99	94	92	90
TPF	100	98	95	93	90
COM1	100	98	95	92	91
TCF	100	98	95	93	91
COM2	100	98	96	93	91

4 CONCLUSION

In this study, we have made a series of useful findings by analysing the effects of impermeable crack-resistant agents, polyvinyl alcohol (PVA) fibers and cellulose fibers alone and in their combination, on the mechanical properties, deformation properties and durability of concrete for CFRDs panels. These findings have important practical implications for the design and construction of CFRDs: (1). despite the limited effect of fibers and impermeable crack arresters in increasing the compressive strength of the panel concrete, the addition of fibers significantly enhanced the early axial tensile strength, reaching a maximum of 3.57 MPa at 90 days. this suggests that the incorporation of fibrous materials into the design of CFRDs can be an effective way of enhancing the tensile properties of the structure in the early stages, thereby enhancing the total reservoir stability of the dam. (2). impermeable anti-cracking agents have an aggressive improvement on improving the early cracking properties of concrete and can significantly increase the cracking resistance class of concrete. This finding emphasises the importance of incorporating impermeable anti-cracking agents into the design of CFRDs panel concrete to enhance its resilience to environmental changes and prolong its service life. (3). The introduction of fibers not only improved the freeze-thaw resistance of the panel concrete, but also ensured that the mass loss was less than 1%, which is essential for improving the durability of CFRDs in cold regions. Therefore, the inclusion of fibers in the formulation of panel concrete can significantly enhance the durability and reliability of CFRDs.

In summary, the findings of this study give precious reference information for the design and construction of CFRDs. The performance and durability of CFRDs can be effectively enhanced through the rational application of fibers and impermeable anti-cracking agents in panel concrete. These findings not only help to guide current engineering practice, but also provide new ideas and directions for future related research and engineering applications.

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