Orthogonal Test Study on Hybrid Fiber Concrete

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Keywords: Impact and Wear-Resistant Concrete, Orthogonal Experiment, Variance Analysis, Fiber, Mechanical Property, Value Engineering.

Abstract: In order to improve the performance of hydraulic structure flow surface against high-speed sand-containing water flow impact and wear, an orthogonal test was designed to study the effects of three fiber dosage levels of polyvinyl alcohol fiber, polypropylene fiber and steel fiber on the compressive properties, splitting properties and impact and wear resistance of C35 impact and wear resistant concrete. Based on the concept of value engineering, the optimal fiber dosage was determined within the test range. The results show that adding the above three kinds of fibers to concrete will slightly reduce the compressive strength of concrete, but can significantly improve the splitting strength and impact and wear resistance of concrete. Among them, the PVA fiber dosage level has a significant effect on the splitting strength of concrete, and the PVA fiber and PP fiber dosage levels have a significant effect on the impact and wear resistance of concrete. Considering the performance and cost of concrete comprehensively, the impact and wear resistant concrete mix ratio of 1kg/m^{3}PVA fiber and 1kg/m^{3}PP fiber can achieve the best production efficiency.

1 INTRODUCTION

Since the 1970s, scholars have begun to conduct research on the abrasion resistance of hydraulic concrete (Deng and Wang, 2005; Deng et al., 2017). Some scholars have focused on the construction quality aspect, believing that strictly controlling the outlet temperature, placement temperature, and flatness of the abrasion-resistant concrete, along with subsequent temperature-reducing maintenance work, and minimizing the appearance defects of the concrete, are beneficial to flood discharge and energy dissipation of hydraulic structures (Wang et al., 2013).

In addition, incorporating suitable substances into the concrete can also effectively enhance its abrasion resistance (Wu et al., 2019), including fiber with high tensile properties such as steel fiber and polypropylene fiber, as well as admixtures such as silicon powder, abrasion-resistant agents, and HF fly ash, which can improve the strength or abrasive resistance of the concrete (Zu, 2010; Toiu Tanji et al., 1998; Parviz and Siavash, 1998). When studying the abrasion resistance of concrete, most scholars adopt the underwater steel ball method specified in the Test Code for Hydraulic Concrete (DL/T 5150-2017) . This method can well simulate the abrasion effect of bed load on the concrete surface. However, in many engineering research and development cases, experimental studies are often only conducted based on the influence of a single material on concrete performance (Dong et al., 2022; Huang et al., 2014). Few scholars have studied the influence

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Peng, M., Zhang, Q., Cao, H., Shi, X., Deng, C., Yu and F.
Orthogonal Test Study on Hybrid Fiber Concrete.
DOI: 10.5220/0013632000004671
In *Proceedings of the 7th International Conference on Environmental Science and Civil Engineering (ICESCE 2024)*, pages 241-247
ISBN: 978-989-758-764-1; ISSN: 3051-701X

law of mixing multiple substances on various concrete properties.

This paper selects steel fiber, polypropylene(PP) fiber, and polyvinyl alcohol (PVA) fiber as the research objects. By designing orthogonal tests, it studies the influence of hybrid fiber on the performance of abrasion-resistant concrete and further analyzes the significance between single substances and concrete strength indicators, aiming to find a mix proportion scheme that balances strength performance and economic benefits.

2 PROJECT OVERVIEW

The Fengdongzi Shipping Project on the Qujiang River is the "last link" in illuminating the development channel of the Qujiang River. The project mainly includes the construction of a new Class III navigation lock with effective dimensions of 200m×23m×4.2m; a new hydropower station with an installed capacity of 75 MW; and new water retaining and discharging structures, including 20 flood discharging and sand flushing gates, non-overflow dams, and joint dams on the left and right banks. Among them, the water conveyance corridors of the navigation lock, the floors of the flood discharging and sand flushing gates, gate piers, stilling basins, stilling piers, and power generation plants all require a 0.5m-thick layer of C35 abrasion-resistant concrete on the exposed structural surfaces to resist the damage caused by turbulent high-speed flows carrying sediment. High-quality abrasion-resistant layers can ensure the durability of the structures, extend their normal service life, and reduce the time and economic costs associated with subsequent damage inspection, repair, and reinforcement.

3 OVERVIEW OF TESTING

3.1 Test Materials

3.1.1 Cement

42.5 low-heat Portland cement produced by Chongqing Xinjianan Building Materials Co., Ltd. was selected. Quality inspection was conducted on the Xinjianan cement, and the results of various performance tests are shown in Table 1. The test report indicates that the physical and mechanical parameters of this cement meet the technical requirements for P·LH 42.5 cement specified in Low-heat and Medium-heat Portland Cement (GB/T 200-2017).

3.1.2 Admixture

Class F, LevelII fly ash produced by Guodian Sheneng Huayingshan Power Generation Co., Ltd. was selected. Quality inspection was conducted on the Class II fly ash produced by this company. The test report indicates that the performance indicators of this fly ash meet the technical requirements for Class F II fly ash specified in Fly Ash for Use in Cement and Concrete (GB/T 1596-2017).

3.1.3 Fine

Aggregate Limestone machine-made sand produced by Huaxin Cement (Quxian) Co., Ltd. was selected.. The test results indicate that the technical indicators of the aggregate meet the requirements specified in Specification for Construction of Hydraulic Concrete (DL/T 5144-2015). The gradation meets the quality requirements for sand in Zone II specified in Sand for Construction (GB/T 14684-2022), and the gradation curve is shown in Figure 1.

3.1.4 Coarse

Aggregate Limestone graded crushed stone (5~20mm:16~31.5mm=6:4) produced by Hengyuan Mining Co., Ltd. in Dazhu County was selected. The technical indicators of the aggregate meet the requirements specified in the Specification for Concrete Construction of Water Transport Engineering (JTS 202-2011).

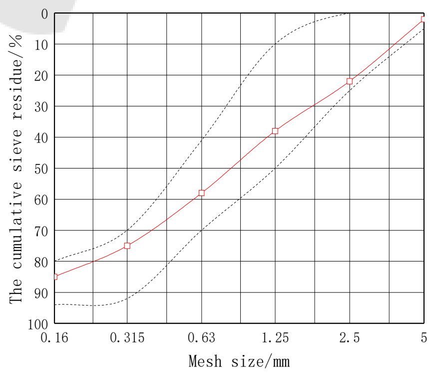

Figure 1: Gradation Curve of Machine-Made Sand.

3.1.5 Fiber

Three types of fiber were selected: PVA fiber, PP fiber, and steel fiber. Among them, PVA fiber and

PP fiber are monofilament, while steel fiber is shear-type. The specific physical properties are shown in Table 1.

Table 1: Physical Performance Test Results of Fiber.

Fiber variety	Length/mm	Fiber diameter /μm	Tensile strength/MPa	Elastic modulus/GPa	Elongation at break/%	Bending performance	Execution standards
PVA fiber	12	10~15	≥1450	35	4~8	-	GB/T 21120-2018
Fiber variety	12	20~45	≥450	3.5	＜30	-	GB/T 21120-2018
PVA fiber	32	0.7±0.2	≥600	-	-	≥3	JG/T 472-2015

3.1.6 Admixtures

Two types of admixtures were selected: impact-resistant and abrasion-resistant agent, and high-performance polycarboxylate superplasticizer. The water-reducing rate of the superplasticizer is 30.8%, with a pH value of 6.3.

3.2 Design Method for the Experiment

Intuitive analysis and analysis of variance play an important role in data analysis and statistics. When there are many independent variables, using this analysis method can greatly reduce the amount of experiments. This experiment uses visual analysis as a prerequisite for variance analysis. Through visual analysis, the impact of each factor on the indicator results is preliminarily judged, and further combined with variance analysis, the significance of the factor's impact on the results is determined, providing reference for the values of each factor.

3.3 Concrete Mix Proportion

To systematically analyze the effects of different fiber types and dosages on the compressive strength, splitting tensile strength, and abrasion resistance of impact-resistant concrete, an L9(3^4) orthogonal experiment was designed using an orthogonal experimental design method with a four-factor, three-level table. The optimal fiber type and dosage level were determined through visual analysis and variance analysis. The experimental factors A, B, C, and D correspond to PVA fiber, PP fiber, steel fiber, and a control group, respectively. The three levels of factors A and B correspond to dosages of 0 kg/m^3, 0.5 kg/m^3, and 1 kg/m^3, respectively, while the three levels of factor C correspond to dosages of 0 kg/m^3, 5 kg/m^3, and 10 kg/m^3. For example, A2B1C3 represents a concrete mixture with 0.5 kg/m^3 of PVA fiber, 0 kg/m^3 of PP fiber, and 10 kg/m^3 of steel fiber. The specific mix proportions and mixture properties are shown in Table 2.

Table 2: Mix Proportion and Mix Performance of Concrete L9 (34) Orthogonal Test.

Type of fiber	Cement/kg/m^3	Fly ash/ kg/m^3	Water cement	sand ratio /%	Fine aggregate /kg/m^3	Coarse aggregate /kg/m^3	Water reducing agent/kg/m^3	Anti impact agent /kg/m^3	Slump /mm	air content /%
A1B1C1D1									165	3.1
A1B2C2D2									145	3.3
A1B3C3D3									135	3.4
A2B1C3D2									140	3.3
A2B2C3D1	340	60	0.40	40	732	1099	4.8	12	135	3.3
A2B3C1D2									130	3.4
A3B1C3D2									135	3.4
A3B2C1D3									130	3.4
A3B3C2D1									120	3.5

The results showed that adding fiber would reduce the slump of the mixture, while the air content showed an increasing trend. This is because fiber have a thickening effect and cannot be mixed evenly in concrete mixtures, especially fine PP fiber and PVA fiber, which tend to aggregate into clumps. Therefore, the fluidity of concrete will decrease, and fiber may be wrapped in air during the mixing process. As the fluidity of concrete decreases, internal air becomes more difficult to discharge, leading to an increase in the air content of concrete.

4 TEST RESULTS AND ANALYSIS

The compressive strength test and splitting tensile strength test were conducted according to the "Standard for Test Methods of Physical and Mechanical Properties of Concrete" (GB/T 50081-2019); the abrasion resistance test was carried out using the underwater steel ball method specified in the "Specification for Testing of Hydraulic Concrete" (DL/T 5150-2017). The results of the 28-day compressive strength, 28-day splitting tensile strength, and abrasion resistance of the concrete specimens are shown in Figure 2 (where 28d CS is compressive strength on the 28 day , 28d STS is splitting tensile strength on the 28 day, IARS is impact and abrasion resistance strength on the 28 day).

4.1 Compressive Strength

As seen in Figure 2, the addition of hybrid fiber may reduce the compressive strength of concrete, but the splitting tensile strength and abrasion resistance can be enhanced to a certain degree. To refine the impact of PVA fiber, PP fiber, and steel fiber on various performance indicator. From Table 3, it can be seen that, a visual analysis of the compressive strength results shows that the level corresponding to the maximum values of k1, k2, and k3 is A1B1C3. The range term R indicates: A > B > D (error) > C, suggesting that steel fiber have a minimal impact on the compressive strength of concrete. The compressive strength of fiber-reinforced abrasion-resistant concrete is primarily determined by the dosage levels of PVA fiber and PP fiber. Higher dosages of these two types of fiber result in lower compressive strength. This is because filamentous materials such as PVA and PP fiber cannot provide compressive capacity to concrete themselves. fiber distributed chaotically in the slurry can reduce the integrity of the specimens, and their external contours can become weak interfaces when the specimens are subjected to significant compressive loads, leading to damage first. Since the independent variables and dependent variables in this test are negatively correlated, further variance analysis is not conducted.

Table 3: Visual Analysis of Orthogonal Test Results for Compressive Strength.

Type of fiber/ Type of k	A	B	C	D	Compressive strength/MPa
A1B1C1D1	1[a]	1	1	1	45.2
A1B2C2D2	1	2	2	2	44.2
A1B3C3D3	1	3	3	3	43.1
A2B1C3D2	2	1	2	3	43.7
A2B2C3D1	2	2	3	1	43.4
A2B3C1D2	2	3	1	2	41.2
A3B1C3D2	3	1	3	2	42.4
A3B2C1D3	3	2	1	3	41.3
A3B3C2D1	3	3	2	1	40.9
k1[a]	**44.2**	**43.8**	42.6	43.2	-
k2	42.8	43.0	42.9	42.6	-
k3	41.5	41.7	**43.0**	42.7	-
R	2.6	2.0	0.4	0.6	-

[a]The number 1, 2, and 3 in the table represent dosage levels, and the rest number represent strengths in MPa.

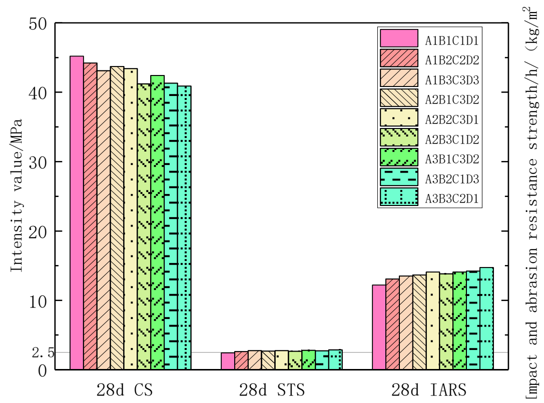

Figure 2: Concrete Strength Properties.

4.2 Splitting Tensile Strength

The results are presented in Table 4. The levels corresponding to the maximum values of k1, k2, and k3 are A3B3C3. The range term R indicates that the primary factors influencing the splitting tensile strength of concrete are PVA fibers, steel fibers, and PP fibers, in the order of A > C > B > D (error). In the experiment, the range of the error series objectively exists. To accurately determine whether there is a significant correlation between various factors and the splitting tensile strength of concrete, it is necessary to further conduct variance analysis based on the results of this intuitive analysis. This will clarify the relationship between the treatment effect and the random error. If the treatment effect dominates, then the level of that treatment effect should be adopted.

The variance analysis of the splitting tensile strength data is shown in Table 5. it is found that the sum of squares of deviations for factors A, B, and C is greater than the error term D, so the error term does not need to be combined. In this F-distribution, the P-value for factor A is less than 0.05, while the P-values for factors B and C are both greater than 0.05, indicating that factor A has a significant correlation with the splitting tensile strength of concrete, while factors B and C are relatively insensitive. This phenomenon can be explained by the advantages of PVA fiber over steel fiber in terms of quantity and specific surface area when comparing the same mass. Literature records show that uniformly distributing 0.9 kg/m³ of monofilament fiber in concrete results in over 20 fiber per cm³ of concrete (Xiang et al., 2010). These fiber can bond fully with the concrete slurry, forming a uniform and chaotic support system that effectively helps concrete resist external tensile stresses.

Table 4: Visual Analysis of Orthogonal Test for Splitting Tensile Strength.

Type of fiber/ Type of k	A	B	C	D	Splitting Tensile strength/MPa
A1B1C1D1	1	1	1	1	2.43
A1B2C2D2	1	2	2	2	2.62
A1B3C3D3	1	3	3	3	2.74
A2B1C3D2	2	1	2	3	2.69
A2B2C3D1	2	2	3	1	2.76
A2B3C1D2	2	3	1	2	2.66
A3B1C3D2	3	1	3	2	2.79
A3B2C1D3	3	2	1	3	2.73
A3B3C2D1	3	3	2	1	2.85
k1	2.60	2.64	2.61	2.68	-
k2	2.70	2.70	2.72	2.69	-
k3	**2.79**	**2.75**	**2.76**	2.72	-
R	0.19	0.11	0.16	0.04	-

Table 5: Variance Analysis of Orthogonal Test for Splitting Tensile Strength (α=0.05).

Variance source	Sum of squared deviations	Free degree	Mean square	F value	P value	Significance
A	0.056	2	0.028	21.641	0.044	√
B	0.019	2	0.010	7.45	0.118	×
C	0.039	2	0.020	15.10	0.062	×
D	0.003	2	0.001	-	-	-

k3 are A3B3C3. The range R indicates: A > B > C > D (blank error). The primary factors influencing the splitting tensile strength of concrete are PVA fibers, PP fibers, and steel fibers, respectively. The ranges of these factor columns are all greater than the error term D. The results are shown in Table 7.

4.3 Impact and Abrasion Resistance Strength

A visual analysis was conducted on the results of the abrasion resistance and impact strength, and the findings are presented in Table 6. The levels corresponding to the maximum values of k1, k2, and

Table 6: Visual Analysis of Orthogonal Test for Impact and Wear Resistance Strength.

Type of fiber/ Type of k	A	B	C	D	Impact and Abrasion Resistance Strength/(h/(kg/m^2))
A1B1C1D1	1	1	1	1	12.20
A1B2C2D2	1	2	2	2	13.09
A1B3C3D3	1	3	3	3	13.50
A2B1C3D2	2	1	2	3	13.66
A2B2C3D1	2	2	3	1	14.07
A2B3C1D2	2	3	1	2	13.83
A3B1C3D2	3	1	3	2	14.07
A3B2C1D3	3	2	1	3	14.23
A3B3C2D1	3	3	2	1	14.72
k1	12.93	13.31	13.42	13.66	-
k2	13.85	13.80	13.83	13.66	-
k3	**14.34**	**14.02**	**13.88**	13.80	-
R	1.41	0.70	0.46	0.14	-

Table 7: Variance Analysis of Orthogonal Test for Impact and Wear Resistance Strength (α=0.05).

Variance source	Sum of squared deviations	Free degree	Mean square	F value	P value	Significance
A	3.075	2	1.538	83.6800	0.012	√
B	0.782	2	0.391	21.2800	0.045	√
C	0.381	2	0.190	10.3600	0.088	×
D	0.037	2	0.018	-	-	-

The P-values for factors A and B are less than 0.05, indicating a significant correlation with the abrasion resistance and impact strength of concrete, while factor C shows insensitivity. Randomly distributed fibers can serve as bridging elements within the concrete matrix, aiding in effectively bearing and dispersing the abrasive energy from high-speed bedload, thereby hindering the propagation of abrasive cracks. Even when part of the matrix experiences minor damage, the fibers can restrain the fragments and reduce the deterioration rate. Therefore, consider reducing the level of factor C based on the A3B3C3 mix ratio.

The market prices of polyvinyl alcohol (PVA) fibers, polypropylene (PP) fibers, and steel fibers are approximately 12 yuan/kg, 7 yuan/kg, and 4 yuan/kg, respectively. Further tests on the relevant properties of A3B1C1 and A3B3C1 were conducted: their abrasion resistance and impact strengths are 13.78 h/(kg/m²) and 14.42 h/(kg/m²), respectively, and their splitting tensile strengths are 2.71 MPa and 2.77 MPa, respectively. Based on the value engineering concept, V = F/C (where V is value, F is function, and C is cost), when replacing A3B3C2 with A3B1C1 and A3B3C1, the abrasion resistance and impact functions of the materials decrease by approximately 6.4% and 2.0%, respectively, while the costs decrease by approximately 9.4% and 8.0%. This results in an increase in engineering value by approximately 2.2% and 6.5%, respectively. The splitting tensile strength of the materials decrease by approximately 4.9% and 2.8%, respectively, leading to an increase in engineering value by approximately 5.0% and 5.7%, respectively. Therefore, consider eliminating steel fibers while retaining a PP fiber dosage of 1.0 kg/m³ and incorporating 1.0 kg/m³ of PVA fibers.

5 CONCLUSION

Through the above experimental analysis and demonstration, the following conclusions can be drawn:

(1) Fiber have a thickening effect and are easily aggregated into clusters when added to concrete mixtures, reducing the fluidity of the mixture. fiber are prone to carry air into the mixture during the mixing process, increasing the air content of the mixture.

(2) Weak filamentous substances such as PVA fiber and PP fiber cannot provide compressive strength for the interior of concrete, and are prone to forming weak interfaces during the compression process, which deteriorates the compressive performance of concrete. PVA fiber, PP fiber, and steel fiber can effectively enhance the splitting tensile strength and impact and wear resistance of concrete.There is a significant correlation between the PVA fiber content level and the impact and wear resistance, as well as the splitting tensile performance, with the most obvious gain effect.

(3) Adding 1kg/m³ PVA fiber and 1kg/m³ PP fiber to the C35 impact resistant and wear-resistant concrete results in relatively high functional and economic advantages, making it a preferred mix ratio.

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