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Design and Experimental Study of Steel Fiber Concrete Mix Ratio in Anchorage Area of Expansion Joints of Highway Bridges

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Abstract

Bridges in the highway are becoming more and more important, expansion joint anchorage area concrete in the vehicle impact load is prone to stress concentration, resulting in cracking, spalling, and damage, affecting the interface between the roadway and the bridge deck, hindering the normal operation of traffic. In order to study the working performance and force performance of steel fiber concrete, based on the raw material and performance requirements of steel fiber concrete in the anchorage area of expansion joints in actual bridge projects, the base mix ratio of steel fiber concrete is obtained with reference to the specification. Steel fiber admixture (SFD), sand rate (SR), and bone-cement ratio (BGR) were used as variable factors in orthogonal tests to investigate the effects of these three factors on the physical and mechanical properties of steel fiber concrete. The results showed that the "scaffolding" effect formed by steel fibers in the concrete mix reduced the collapse of the mix and increased the degree of expansion. Steel fiber has no significant effect on the compressive strength of concrete, and steel fiber significantly improves the flexural strength of concrete, with an increase of more than 19.42%. Under the premise that the working performance meets the requirements, the stress performance is relatively optimal for the test number GHT-5 proportion design, SR is 43%, SFD is 90, and BGR is 1.55.

Keywords

Steel fiber concrete; Proportion design; Workability; Force properties

1. Introduction

Bridges in the highway are in proportion more and more, according to the latest data statistics at present the national urban bridge has more than 86,000, and the dramatic increase in the number of bridges also makes the number of expansion joints more and more. Although the expansion joint is a subsidiary part of the bridge structure, it is in the local "discontinuous" section of the bridge deck structure, which is a weak part. With the traffic flow, vehicle load level increases, speeding, overloading, and violation of traffic rules continue to occur, the current society for the exercise of vehicle safety and smoothness requirements continue to improve, inevitably on the expansion joint and its anchorage area quality, durability, safety, long-term stability has more stringent requirements [1]. Because the expansion joint and its anchorage area is the last item of construction, often from the design, construction, maintenance, and repair, management does not get considerable attention, is easy to ignore weak links, and often repair, and replacement will bring additional economic losses and social impact [2].

Survey data show that concrete in the anchorage area of expansion joints is prone to stress concentration under vehicle impact loads, leading to cracking, spalling, and breakage, which is the most common form of damage to expansion joints. The elastic modulus difference between the expansion joint, asphalt paving layer, and concrete in the anchorage area is large, which is easy to leads to bond failure, and the concrete breakage will expose the anchorage reinforcement, trigger

corrosion, and lose the ability to bear the load with the steel girder, increase the risk of fracture of the center girder and side girder, and ultimately lead to the destruction of the expansion joint, affecting the articulation of the roadway and the bridge deck, and impeding the normal operation of the traffic [3]. Early damage to concrete in the anchorage zone is frequent and occurs mainly at the apex of the contact interface with asphalt paving and steel sections, followed by gradual expansion from the interface debonding in the direction of travel [4]. Warda [5] used Taguchi's design of experiments method to optimize the concrete mix ratio and investigated the optimum mix proportions of steel fiber concrete when its different properties are optimal respectively under the combined effect of influencing factors. Yu Jahuan [6] investigated the relationship between fiber, admixture, water and cement dosage, and concrete strength and compatibility respectively while keeping the water-cement ratio of concrete unchanged, so as to obtain better mechanical properties of steel fiber mixes.

2. Basic Properties of Raw Materials and Their Selection

In order to increase the ductility of concrete materials, the use of steel fiber concrete, cement, and mineral admixtures as the main cementitious materials, mixed with a certain proportion of sand, stone and steel fibers, and other aggregates, and add a certain quality of water and admixtures, through the mixing, vibration and maintenance of conventional mixing technology and processes, such as the gradual coagulation and hardening of the artificial mixed materials.

2.1 Cement

The manufacturer of Shanshui Dongyue brand ordinary silicate cement (P-O52.5) applied in this test is Shanshui Cement Group, and its chemical composition as well as mineral composition are shown in Table 1.

Table 1. Performance indicators of cement

Manufacturing location	Chemical composition (%)					Mineral composition (%)				
	SiO_2	CaO	MgO	Fe_2O_3	Al_2O_3	C_3S	C_2S	C_3A	C_4AF	SO_3
Henan	21.56	63.23	1.77	4.21	5.02	52.34	22.06	7.02	10.10	2.13

2.2 Silicon powder

Silicon powder mainly comes from the smelting of ferrosilicon alloy process in the chimney collection of incidental products, in which the active SiO_3 content of the material accounted for more than 98%, the particle size of silicon powder is mostly distributed in the range of 0.18-0.26um, the specific surface area of a great deal, about 15-25 m^2/g. The silicon powder is mainly used in the smelting of the ferrosilicon alloy process and is mainly used in the smelting of ferrosilicon alloy. The silicon powder used in this test is the silicon powder produced by Shandong Boken Co. The main components and performance indexes of the silicon powder are shown in Table 2.

Table 2. Performance indexes of silicon powder

Test items	SiO_2 (%)	K_2O (%)	Na_2O (%)	PH value	LOI	Moisture content	45-micron screen balance	Specific surface area	Densities (Kg/m^3)
test value	95.06	0.59	0.53	6.59	0.86	0.42	3	19	200-400 (940U) 600-700 (940D)

2.3 Slag powder

Active substances are also present in slag, but only under specific preconditions, and when it is mixed with water only, there is hardly any visible reaction. On the contrary, when it is stirred with calcium hydroxide solution, the hydration reaction is strong, and the higher the concentration of $Ca(OH)_2$ the more violent its hydration reaction. Therefore the source of alkaline excitation is defined by the process of slag's action with $Ca(OH)_2$. The raw materials used for alkaline excitation are lime and cement clinker. The slag micro powder used in this test is produced by Shandong Changshengyuan Co. and its chemical composition is shown in Table 3.

Table 3. Composition and content of slag micro powder (%)

SiO_2	Fe_2O_3	CaO	MgO	Al_2O_3	SO_3
33.98	1.85	38.74	6.93	14.68	2.01

2.4 Coarse aggregate

The coarse aggregate in the course of this test is selected from well-graded limestone crushed stone, most of the particle size control in the 5-25mm or so, the use of a sieve test to determine whether the particle gradation is good, weighing 7000g of coarse aggregate specimens, test results are shown in Table 4, to meet the specification requirements.

Table 4. Coarse aggregate sieve test results

Sieve size (mm)	Sieve allowance (g)			Subtotal sieve balance (%)	Cumulative sieve residue (%)	Specification (%)
	1	2	On average			
26.5	0.00	0.00	0.00	0	0	—
19	463.84	323.53	393.68	5.62	5.62	0-5
16	2809.54	3280.86	3045.20	43.50	49.13	20-50
9.5	2625.62	2336.72	2481.17	35.45	84.57	70-85
4.75	708.52	687.49	698.00	9.97	94.54	85-95
2.36	362.17	356.61	359.39	5.13	99.68	95-100
Sieve bottom quality (g)	30.31	14.80	22.55	—	—	—

2.5 Fine aggregate

The fine aggregate selected during this test is well-graded river sand, and the sieve test is used to determine whether it is well-graded or not, 500g of the fine aggregate specimen is weighed, and the test results are shown in Table 5.

Table 5. Results of fine aggregate sieving experiments

Sieve size (mm)	Sieve allowance (g)			Subtotal sieve balance (%)	Cumulative sieve residue (%)	Specification (%)
	1	2	Average			
9	0.00	0.00	0.00	0	0	—
4.75	9.98	14.28	12.13	2.43	2.43	0-10
2.36	37.37	31.71	34.54	6.91	9.33	0-25
1.18	62.75	69.65	66.20	13.24	22.58	10-50
0.6	164.62	159.33	161.98	32.40	54.97	41-70
0.3	139.78	145.05	142.42	28.48	83.46	70-92
0.15	77.97	69.11	73.55	14.71	98.16	90-100
Sieve bottom quality (g)	7.53	10.86	9.18	—	—	—

3. Mixing Ratio Design

3.1 Steel fiber concrete adaptation emphasis

Combined with a viaduct project in Zhengzhou City, a study was carried out to prepare C50 steel fiber concrete, the standard deviation of concrete strength was taken as 6.0, and the 95% guarantee rate, the strength of steel fiber concrete trial was:

$$f_{cu,o} = f_{cu,k} + 1.645\sigma = 50 + 1.645 \times 6 = 59.87 Mpa$$

3.2 Calculate the water-cement ratio

The actual project uses P.O52.5 cement to formulate C50 concrete, silica fume mixing 9%, mineral admixture mixing 18% of slag micro powder, so silica fume influence coefficient is taken as 1.0, slag micro powder influence coefficient is taken

as 0.95, so that the cementitious material 28d compressive strength of the cemented sand is.

$$f_b = \gamma_f \gamma_s f_{ce} = 1.0 \times 0.95 \times 52.5 = 49.875 Mpa$$

The coarse aggregate used is crushed stone and the regression coefficients are taken as $\alpha_a = 0.53$, $\alpha_b = 0.2$, the water-cement ratio of steel fiber concrete is.

$$\frac{W}{B} = \frac{\alpha_a f_b}{f_{cu,o} + \alpha_a \alpha_b f_b} = \frac{0.53 \times 49.875}{59.87 + 0.53 \times 0.2 \times 49.875} = 0.406$$

The obtained results do not comply with the "highway bridge and culvert construction technical specifications" [7] JTG / TF50-2020, needs to reduce the water glue ratio, so the water glue ratio is reduced to 0.32.

3.3 Calculating water consumption per unit

According to the sand used for the sand, the coarse aggregate maximum particle size of 20mm and construction collapse requirements for 180 ± 30 mm, this paper combined with the actual project, in the unadulterated additives when the water consumption was selected as 238 kg/m^3, mixed into the additives after the water consumption of 238 × (1-0.16) = 200 kg/m^3.

3.4 Amount of cementitious material per unit

The concrete cementing material used is：

$$m_{bo} = \frac{m_{wo}}{W/B} = \frac{200}{0.32} = 625 kg/m^3$$

Silicon powder dosage: $m_{go} = m_{bo} \times \beta_g = 625 \times 9\% = 56.25 kg/m^3$, fetch, 56 kg/m^3

Slag powder: $m_{fo} = m_{bo} \times \beta_f = 625 \times 18\% = 112.5 kg/m^3$, fetch, 113 kg/m^3

Amount of cement used: $m_{co} = m_{bo} - m_{fo} - m_{go} = 625 - 56.25 - 112.5 = 456.25 kg/m^3$, fetch, 456 kg/m^3

3.5 Calculate the amount of admixture

Based on an admixture dosage of 1.44 percent: $m_{ao} = m_{bo} \times \beta_a = 625 \times 1.44\% = 9 kg/m^3$

3.6 Calculate the amount of sand and stone

Calculate the amount of coarse and fine aggregates using the volumetric method:

$$\begin{cases} \dfrac{m_{co}}{\rho_s} + \dfrac{m_{ao}}{\rho_a} + \dfrac{m_{go}}{\rho_g} + \dfrac{m_{so}}{\rho_s} + \dfrac{m_{wo}}{\rho_w} + \rho_f + 0.01\alpha = 1 \\ \beta_s = \dfrac{m_{so}}{m_{so} + m_{go} + m_{fo}} \\ m_{fo} = 7850 \beta_f \end{cases} \tag{1}$$

Among others, m_{co}, m_{ao}, m_{go}, m_{so}, m_{wo}, m_{fo}—Respectively, the mass of cement, mineral powder, stone, sand, water, admixture, and steel fiber used in the unit volume of steel fiber concrete, kg/m^3;

ρ_c, ρ_a, ρ_g, ρ_s, ρ_w—cement density, mineral powder density, the apparent density of stone, the apparent density of sand, water density, and admixture density, respectively; kg/m^3; β_s—Sand rate of steel fiber concrete, %; ρ_f—Steel Fiber Volume Ratio, %; α—Air content of steel fiber concrete, α=1;

Orthogonal experimental design was adopted, due to the limitation of experimental conditions, the mixing amount of steel fiber (SFD/kgm^{-3}), sand rate (SR/%), and bone-cement ratio (BGR) were used as the variable factors of the orthogonal test to study the performance of these three factors on steel fiber concrete. Nine sets of test protocols for steel fiber concrete with different mix ratios were designed as shown in Table 6.

Table 6. Design of specimen mix ratio for each group of steel fiber concrete

Serial number	SR	SFD	BGR	Cement	Silicon powder	Slag powder	Sand	Stone in-scription	Water	Additive
GHT-0	43	0	1.55	456	56	113	394	522	200	9
GHT-1	40	60	1.45	456	56	113	343	454	200	9
GHT-2	40	90	1.55	456	56	113	366	460	200	9
GHT-3	40	120	1.65	456	56	113	390	465	200	9
GHT-4	43	60	1.45	456	56	113	368	428	200	9
GHT-5	43	90	1.55	456	56	113	394	432	200	9
GHT-6	43	120	1.65	456	56	113	419	436	200	9
GHT-7	46	60	1.45	456	56	113	394	403	200	9
GHT-8	46	90	1.55	456	56	113	421	405	200	9
GHT-9	46	120	1.65	456	56	113	449	407	200	9

4. Research on Physical and Mechanical Properties of Steel Fiber Concrete

4.1 Experimental methods

Forming and curing of concrete specimens: the specification referred to in the course of this test is the national standard "Standard for Test Methods of Mechanical Properties of Ordinary Concrete" [8] (GB/T 50081-2002). The concrete compressive strength test was carried out using cubic specimens with a side length of 100 mm. With a GZ-85-type cementitious sand vibrating table will be the specimen vibration mix molding 10min after its smearing, the test mold surface leveling covered with plastic film, placed at room temperature level ground 24h after demolding, demolding strictly in accordance with the sequence of the test block numbering, and immediately put the specimen into the water invasion and maintenance, as shown in Fig. 1, to reach the 3d, 7d and 28d, respectively, began to carry out the next test.

Figure 1. Curing of concrete specimens.

Figure 2. Collapse test.

The reference basis of the test is the specification GB/T50081-2019 “Standard for Test Methods of Physical and Mechanical Properties of Concrete” [9], as shown in Figure 2. Collapse and extension test, the concrete mixture in accordance with the specification requirements into the collapse barrel, in turn, measure the collapse and the mixture of the highest point of the vertebrae between the straight-line distance and the mixture to expand the maximum diameter of the expansion surface and the maximum diameter of the diameter of the perpendicular direction of the diameter of the arithmetic average as the concrete collapse and extension of the value of the value of the collapse, in which the difference between the two values of the collapse value shall not be greater than 20mm, the expansion of two diameters difference shall not be more than 50mm, the measurement value is accurate to 1mm, the results should be revised to 5 mm.

Figure 3. Macrostructure of concrete specimens.

Figure 4. Three-point flexural test.

Axial compressive test and three-point flexural, 24h de-molded and placed in a standard curing room to 28d age. Axial compressive strength test, the specimen is molded as a 100mm × 100mm × 100mm rectangular specimen, determination of the concrete compressive strength of the instrument used in the NYL-2000 hydraulic concrete pressure tester, the destruction of the macro-structure of the concrete specimen as shown in Figure 3; three-point flexural test, the specimen is molded as a 100mm × 100mm × 400mm rectangular specimen, using the DBZ-300 in electronic universal testing machine DIG2000, as shown in Figure 4.

4.2 Physical and mechanical properties research

The worthwhile formula for calculating the compressive strength of concrete from the test data is as follows:

$$f_{cu} = \frac{F}{A} \tag{2}$$

Calculate the three-point flexural strength of steel fiber concrete specimens according to Equation 3, and continue loading until the concrete specimen is completely destroyed to obtain the load-one-deflection curve of three-point flexural concrete. The arithmetic mean of the load values measured for three specimens at the same deflection was taken as the load value of the group of specimens, and the results were accurate to 0.01 MPa.

$$f_f = \frac{3Fl}{2bh^2} \tag{3}$$

The working performance and force performance of each group of tests are specifically shown in Table 7.

Table 7. Table of physical and mechanical properties for each group of tests

Test number	Work performance		Force performance			
	Degree of collapse	Extensibil-ity	Compressive strength			Flexural strength
			3d	7d	28d	
GHT-0	189	625	36.72	50.66	68.43	8.96
GHT-1	226	761	39.90	51.67	67.86	9.60
GHT-2	174	636	38.03	52.37	65.60	10.04
GHT-3	210	647	35.26	53.54	68.15	9.71
GHT-4	254	706	38.58	49.44	65.24	10.04
GHT-5	214	711	40.17	53.28	68.27	10.37
GHT-6	228	641	33.71	51.87	70.95	9.49
GHT-7	259	684	37.99	50.71	65.65	10.04
GHT-8	199	608	35.58	46.01	60.30	10.37
GHT-9	180	582	29.89	48.94	64.70	10.70

As shown in Table 7, the working properties of steel fiber concrete, the degree of collapse shows a tendency to increase and then decrease with the increase of sand rate, and shows a tendency to decrease with the increase of steel fiber admixture and aggregate ratio. The degree of collapse decreases with the increase of sand rate and shows a tendency to decrease and then increase with the increase of steel fiber admixture and aggregate ratio. The “scaffolding” effect formed by steel fibers in the concrete mix reduces the caving degree of the mix and increases the degree of expansion. The force properties of steel fiber concrete, and steel fiber for concrete compressive strength have no significant effect. Steel fiber significantly improves the flexural strength of concrete, flexural strength with the increase of sand rate shows the trend of increasing and then decreasing, with the increase of steel fiber mixing and aggregate ratio shows the trend of increasing and then decreasing the enhancement of more than 19.42%. Under the premise that the working performance meets the requirements, the stress performance is relatively optimal for the test number GHT-5 proportion design, SR is 43%, SFD is 90, and BGR is 1.55.

5. Conclusion

In order to study the working and force properties of steel fiber concrete, the base mix ratio of steel fiber concrete is obtained with reference to the specification on the basis of the raw material and performance requirements of steel fiber concrete in the anchorage area of expansion joints in actual bridge projects. SFD, SR, and BGR were used as orthogonal test variable factors to study the influence of these three factors on the physical and mechanical properties of steel fiber concrete. The results showed that the “scaffolding” effect formed by steel fibers in the concrete mix reduced the collapse of the mix and increased the extension. The steel fiber has no significant effect on the compressive strength of concrete, and the steel fiber significantly improves the flexural strength of concrete by more than 19.42%. Under the premise that the working performance meets the requirements, the stress performance is relatively optimal for the mix design of test number GHT-5, with a sand rate of 43%, steel fiber dosage of 90, and a bone-cement ratio of 1.55.

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