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Influence of fly ash dosage over the compressive strength of rock-filled concrete

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Rock-filled concrete (RFC) is a new technology that has been promoted in water conservation and hydropower projects. The flow and compressive strength of the RFC can be improved by adding an appropriate amount of fly ash. In this article, various doses of fly ash are added to concrete, their effect on the compressive strength of concrete is tested, and the optimal dosage of fly ash is determined. The test results show that the strength of the RFC first increases and then decreases, rather than decreasing continuously, as the dose of fly ash increases. When the fly ash dosage reached 30 %, the RFC reached its maximum strength. When the dosage of fly ash was equal to or higher than 40 %, the strength of the RFC decreased to a certain extent. Based on engineering expertise, hardened RFC has optimum strength when the fly ash dosage is between 20 % and 40 %.
Keywords: fly ash dosage, dam, Rock-Filled Concrete (RFC), compressive strength.

Вплив дози летючої золи на міцність на стиск кам'яно-наповненого бетону. *Changchun Wu, Jianhua Zhu*

Кам'яно-наповнений бетон (RFC) — це нова технологія, яка була просунута у проектах з охорони водних ресурсів та гідроенергетики. Плинність і міцність на стиснення RFC можна підвищити, додавши відповідну кількість летучої золи. У цій статті в бетон додаються різні дози летючої золи, перевіряється їх вплив на міцність на стиснення бетону та визначається оптимальне дозування летючої золи. Результати випробувань показують, що міцність RFC спочатку збільшується, а потім знижується, а не безперервно знижується, зі збільшенням дози летючої золи. Коли дозування летючої золи досягло 30 %, RFC досяг максимальної міцності. Коли дозування леткої золи дорівнювало або вище 40 %, міцність RFC певною мірою знижувалася. Спираючись на інженерний досвід, загартований RFC має оптимальну міцність, коли дозування летючої золи становить від 20 % до 40 %.

1. Introduction

Based on high self-compacting concrete (HSCC), rock-filled concrete (RFC) is a new concrete construction technique that produces strong and dense concrete mass by filling the void spaces with HSCC in rockfill mass. This technique has been widely adopted in water conservancy and hydropower projects. The RFC is usually prepared in the following process: Firstly, rock blocks of a certain particle diameter are directly entered into the bunker, forming a rock-block mass with pores. Next, a special self-compacting concrete is poured to the upper part of the rock-block mass. Due to its high fluidity and segregation performance, the self-compacting concrete fills the pores between the rock blocks under the action of gravity. In this way, a complete, dense, and high-strength concrete is formed. The RFC preparation solely relies

Table 1. Performance parameters of fly ash

Parameter	Fineness, %	Water content, %	Water demand ratio, %	Ignition loss, %	28d strength activity index, %
Measured value	15.9	0.21	102	2.6	70.9
Required value in DL/T5055-2007	≤25.0	≤1.0	≤105	≤8.0	–

on the dead weight of self-compacting concrete to evenly fill up all construction spaces, eliminating the need for vibration. This significantly improves the construction efficiency.

Many domestic and foreign scholars demonstrated the effects of fly ash dosage on the performance of self-compacting concrete. For instance, Langley et al. [1] and Carette et al. [2] analyzed the influence of fly ash dosage on concrete. Through repeated tests, Sukumar et al. [3] presented the calculation formulas for strength of early age self-compacting concrete with a high volume of fly ash. Dong et al. [4] studied the effect of the high fly ash content on the compressive strength of concrete under various curing conditions.

Currently, there are not many studies on how fly ash dosage affects the RFC strength of reservoir dams. Based on the previous research results, this paper investigates the RFC mixture ratio of the reservoir dam, and experimentally analyzes the influence of different fly ash dosages on the compressive strength of an RFC dam. The results provide a reference for similar engineering practices.

2. Experimental

2.1 Raw materials

(1) The cement is Portland cement 42.5 (Conch).

(2) The coarse aggregates are sands and gravels of the size 5–35 mm. The fine aggregates are river sands collected from the dam site. The fineness modulus was tested as 2.72.

(3) The fly ash is of Grade II. The performance parameters of the fly ash are listed in Table 1.

(4) The rock blocks have a particle size of 150–220 mm, and a saturated compressive strength ≥45 MPa.

(5) The additive is a polycarboxylate superplasticizer.

(6) Tap water was directly used in our tests.

2.2 Specimen preparation

According to SL678-2014, the pouring of HSCC should be preceded by a testing of four indices: slump, slump expansion, V-funnel flow time, and self-compacting performance stability. Our test specimens met every requirement of SL678-2014: the slump fell within 260–280 mm, the slump expansion within 650–750 mm, the V-funnel flow time within 7–25 s, and the self-compacting performance stability 1h.

The RFC specimens are of the size 600 mm (length) × 600 mm (width) × 1.500 mm (height). Referring to the relevant literature [5–12], the fly ash dosage of concrete dams is above 15 %. Therefore, the fly ash dosages were set as 20 %, 30 %, 40 %, 50 %, and 60 % for the mix ratios of our tests. Two specimens were prepared with each fly ash dosage, producing a total of 10 specimens. After standard curing, the rebound method was adopted to measure the 3d, 7d, 28d, and 90d compressive strengths of the specimens. The mean of each group was taken as the final measured strength.

During specimen preparation, the test silo was filled up with rock blocks (particle size: 150–220 mm). Then, the prepared HSCC was poured to the upper parts of the rock-block mass. Under the action of gravity, the HSCC automatically filled the pores of the rock-block mass, forming high self-compacting RFC specimens. Referring to *Technical Specification for Application of Self-Compacting Concrete* (JGJ/T283-2012), the mix ratios of our tests were designed (Table 2).

2.3. Compressive strength tests

Kovler et al. [13] demonstrated the high accuracy, safety, and reliability of testing the compressive strength of the RFC by the rebound method. According to the requirements of SL352-2020, this paper employs the rebound method to measure the compressive strength of each RFC specimen.

Test method

Following the standard curing method in SL352-2020, each specimen was cured to the required age at a temperature of (20±2)°C, and a relative humidity >95 %, before being tested. Once the specimen reached the curing age of 3d, 7d, 28d, or 90d, the appearance and size of the specimen were in-

Table 2. Mix ratios for HSCC tests

Specimen number	Fly ash dosage, %	Strength grade	Cementitious material, $kg{\cdot}m^{-3}$	Cement, $kg{\cdot}m^{-3}$	Fly ash, $kg{\cdot}m^{-3}$	Water, $kg{\cdot}m^{-3}$	Sand, $kg{\cdot}m^{-3}$	Pebble, $kg{\cdot}m^{-3}$	Water reducer, $kg{\cdot}m^{-3}$
1–2	20 %	C20	389	311.2	77.8	197	885	824	4.9
3–4	30 %	C20	408	285.6	122.4	197	881	808	5.4
5–6	40 %	C20	415	249.0	166.0	196	867	814	5.7
7–8	50 %	C20	453	226.5	226.5	196	852	793	6.2
9–10	60 %	C20	506	202.4	303.6	196	824	767	7.3

spected to see if the specimen is qualified for testing. If yes, the compressive strength of the specimen was measured using a heavy-duty concrete rebound hammer (rated kinetic energy: 24.9 J) and a 2.000 kN pressure testing machine. For each group of concrete specimens, the mean of the two measured values was treated as the compressive strength of that group.

Test steps

Step 1. Each 600 mm × 1.500 mm surface was divided into twelve 500 mm × 500 mm measuring zones along the height direction.

Step 2. A measuring zone was selected, and the loose materials and debris were removed from that zone, keeping the surface neat and clean.

Step 3. During the hammering, the axis of the rebound hammer was kept vertical to the test surface, and pressure was applied evenly at a slow rate. 16 points were selected in each measuring zone, according to the following principles: the points are distributed evenly in that zone, the points do not overlap any air hole or exposed coarse aggregate, and the interval between two points should be no shorter than 50 mm. Each measuring zone was hammered 16 times, once per point.

Step 4. After the rebound test, the carbonation depth was measured in 1/3 of the measuring zones. An electric percussion drill was used to open a hole (diameter: 20 mm; depth: 70 mm) in each measuring zone. The powder was removed from that hole, and dripped with 1.0 % phenolphthalein solution on the edge of the inner wall of the hole. Then, the carbonation depth L (the depth of the non-color change zone) of concrete was measured with a steel ruler (reading precision: 0.5 mm). The mean of the readings are taken, i.e., the carbonation depth of the concrete is estimated. If the depth is smaller than 0.4 mm, then the concrete is not carbonated.

Rebound data processing

Step 1. The three largest and three smallest values are removed from the 16 measured rebound values, and the mean of the remaining 10 rebound value is taken with an accuracy of 0.1 MPa.

Step 2. If the concrete structure/member is carbonated to a certain depth, the estimated RFC strength is modified by:

$$f_{ccN} = f_{ccNo} \times C, \quad (1)$$

where, f_{ccN} is the RFC strength revised by carbonation depth (MPa); f_{ccNo} is the RFC strengthestimated by the formula (MPa); C is the specified carbon depth correction value.

Step 3. The estimated RFC strength is determined. For the 10 measuring zones of each RFC specimen, the estimated strength of each zone is computed based on the mean strength and strength difference:

$$f_{C',e} = m_{fccN} - 1.645a, \quad (2)$$

where, $f_{C',e}$ is the estimated RFC strength; m_{fccN} is the mean strength of each measuring zone of the specimen; a is the strength difference of RFC strength.

3. Results and discussion

3.1 Test results

Taking fly ash dosage as the variable, the compressive strengths of the 10 RFC specimens were measured by the rebound method, revealing the compressive strengths of the RFC with different fly ash dosages at different ages (Table 3).

3.2 Data analysis

Based on the data in Table 3, the influence of fly ash dosage over RFC compressive strength, and that of age over RFC compressive strength are plotted in Fig. 1 and 2.

As shown in Fig. 1: (1) The RFC strength was relatively low after 3d and 7d. This is because the fly ash for 3d and 7d mainly fill the pores physically without participating in hydration. The concrete strength

Table 3. Compressive strengths of the RFC with different fly ash dosages at different ages

Specimen number	Fly ash dosage, %	Compressive strength, MPa			
		3d	7d	28d	90d
1–2	20 %	13.4	15.5	25.6	35.1
3–4	30 %	14.2	16.7	27.2	38.6
5–6	40 %	13.1	15.2	24.5	35.4
7–8	50 %	10.2	12.5	22.6	31.1
9–10	60 %	8.1	10.4	20.5	25.6

mainly depends on the hydration of cement. The addition of fly ash can disperse the cement particles, such that the cement is hydrated more sufficiently. Therefore, the early strength of concrete depends on the water-cement ratio.

(2) The early strength of the RFC first increased and then decreased, rather than drop continuously, with the growing dosage of fly ash. According to the data in Table 3, the strengths of the RFC specimens at any age reached a maximum at a fly ash dosage of 30 %. The reason is that the addition of fly ash significantly improves the working performance of the RFC. The RFC performs the best under this dosage of fly ash. In this case, the self-compacting concrete can fully fill the pores of rock blocks, resulting in a high density, a good uniformity, and the highest strength.

(3) The RFC strength at the fly ash dosage of 40 % was slightly lower than that at the fly ash dosage of 30 %. Further increase of the fly ash dosage did not improve the working performance of the RFC, but reduced the early strength.

As shown in Fig. 2, all RFC samples with different fly ash dosages showed an increase in compressive strength with age. At 3d and 7d, none of them reached the standard strength of C20 concrete. But all of them achieved the standard strength at 28d. After 90d, all specimens realized the strength of C30 concrete, except the specimen mixed with 60 % of fly ash. The results show that the fly ash dosage has a negative effect on the early strength of the RFC, but the negative effect weakens with the growth of the age. Similar to that of ordinary concrete, the RFC?s compressive strength exhibited a growing trend. Hence, the dam strength can be assured by adding a proper amount of fly ash into the RFC.

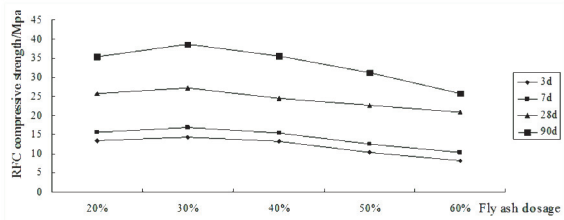

Fig. 1. Influence of the fly ash dosage on RFC compressive strength.

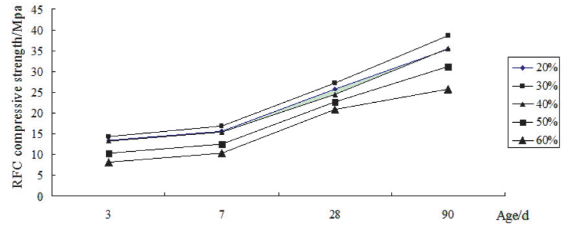

Fig. 2. Influence of age on RFC compressive strength.

4. Conclusions

The fly ash dosage affects the early strength of the RFC. The strength of the RFC first increased and then decreased, with the growing dosage of fly ash. The strengths of the RFC specimens at any age reached maximum at the fly ash dosage was 30 %. The further increase of the fly ash dosage slightly reduced the compressive strength of the RFC. However, the RFC strength gradually increased with the growth of the age. Therefore, the fly ash dosage should be controlled, if the RFC needs to have a high early strength.

The RFC achieved the best performance at the fly ash dosage of 30 %. In this case, the self-compacting concrete can effectively fill the pores of rock blocks, resulting in a high density. But our tests did not provide the RFC strengths at the fly ash dosages of 20–30 % and 30–40 %. Based on the experience of other concrete dam projects, the authors held that the hardened RFC can achieve the optimal strength, when the fly ash dosage is between 20 % and 40 %.

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