CONCEPT AND PRACTICE OF HIGH PERFORMANCE CONCRETE FOR DAMS

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Abstract: Concept of high performance concrete and its application in buildings, roads, and so on has been discussed. Introduction has been made for the practice of high performance concrete for dams in China. Meaningful results have been achieved in Three Gorges Project, Jinghong Hydropower Station and Longjiang Hydropower Station. Methods of testing interface strength of different materials in concrete are proposed.

Key words: high performance concrete, dam, interface strength

1. High performance concrete

It has been nearly 20 years since the birth of the concept of high performance concrete (HPC). The application of HPC is still one of the most popular research topics on concrete material. HPC was firstly introduced at the meeting of the U.S. National Institute of Standards and Technology and the U.S. Concrete Association (ACI) in May 1990, and regarded as possessing some of the properties of homogeneous concrete. P.K.M ehta from the United States and P.C.A itcin from Canada think that high-performance concrete should be with high durability, not just with high strength. High durability should include high volume-stability, low permeability and high working-performance. Okamura from the University of Tokyo regards the concrete with the high-flow pattern, vibration-free and self-compacting as high-performance concrete. Wu Zhongwei, an academician of Chinese Academy of Engineering, believes that the low limitation of the HPC strength may extend to the middle-grade (30 MPa), on condition that it will not inflict any damage on the development and durability of the internal structure of concrete (pore structure, interfacial structure, hydration structure, etc.) [1].

HPC has already been widely used in the construction of high-rise buildings, bridges and roads. The features of the mixing proportion include the low ratio of water to cementitious material that is usually less than 0.40, the maximum diameter of aggregate being less than 40 mm, and the 28-day compressive strength of concrete being larger than 40MPa. Initially, some scholars believe that HPC must be a high-strength concrete. Therefore, dam concrete generally requiring the 90-day compressive strength of 15-30 MPa is obviously not a high-strength concrete, which obstructs the progress of understanding the relationship between high performance concrete and dam concrete. In recent years, with continuous deepening and enriching of the understanding of HPC, a rough idea of the implementation of high performance concrete for dams has been investigated. The research and development of high performance concrete for dams focuses on the durability requirement in terms of the characteristics of dam concrete (especially the low-heat requirement of massive concrete). HPC for dams does not require high-strength but long-durability. Simultaneously, due to mass-concrete dams, new types of admixtures should be developed for the saving of resource and cost on the premise of satisfying the design requirement in order to achieve the goal of "Green effect". The purpose of research and development of HPC is to neither abandon the present principle of concrete design nor replace cementing materials, but to improve the current level of concrete mixing by using high-quality cement, superplasticizer and admixtures, improving production technology, and scientifically matching raw materials, and hence enhance the concrete performances in the plastic, early and late hardening stages to satisfy the durability requirement of dam concrete[2]. Each specific project and the corresponding working-environment may have special requirements on certain performances of concrete but not on others. Therefore, it is not realistic to design such a concrete with excellent performances in all aspects.

2. Comparison between the mixing proportion in bid and that in construction of Three Gorges Dam concrete

The-second-phase concrete for the Three Gorges Project adopted artificial granite aggregate. The aggregate is of the coarse-grained and mosaic structure with a rough surface, resulting in high water consumption that is 30% larger than the consumption for natural aggregate of Yangtze River. The initial mixing proportion in bid made the concrete very high water-consuming, and hence increased the porosity of concrete, the amount of cementitious materials, and the shrinkage of concrete, which are disadvantageous to temperature control, volume stability, and concrete durability. The most important requirement of dam concrete performance is low hydration heat and high cracking resistance. However, the rise of hydration heat temperature of mass concrete is actually large while the strength of concrete (especially the tensile strength) is relatively low, which leads to a sharp conflict, particularly during the construction period when the development of concrete strength is in the early stage. To solve this problem, two measures are usually taken. The first is to reduce the rise of hydration heat temperature, which includes using low-heat cement, reducing the amount of cement, pre-cooling of aggregate, embedding cooling water pipes, etc. The second is to improve the concrete cracking resistance. The two measures require changing the traditional design concept of concrete mixing and using the design method of high performance concrete, which can fundamentally solve the above problem[3,4].

The first task of designing concrete mix for Three Gorges project was to investigate the HPC idea for dam concrete in order to improve cracking resistance, on the premise of suiting the level of construction technology, satisfying the design requirement and being economic. Accordingly, based on the design requirement of concrete and the characteristics of granite, raw materials were better chosen, and the first grade fly ash, superplasticizer, and air entraining agent were proposed to use in concrete. In addition, the technology of decreasing the ratio of water to cementitious materials and increasing the amount of fly ash was adopted for the optimization of concrete mix proportion.

Table 1 and Table 2 show the mixing proportions of concrete in bid and construction, and their corresponding performances and costs. It is indicated in Table 1 that after the optimization of concrete mix for construction, water consumption per cubic decreased 31 kg, cement consumption decreased nearly 40 kg, and water-cementitious materials ratio decreased from 0.60 to 0.50. This is due to great water-reducing effect of the use of fly ash, superplasticizers and air-entraining agent together. Meantime, air-entraining agent improves the freezing-and-thawing resistance of concrete significantly. The relative cracking resistance coefficient of concrete increased from 0.180 to 0.283, almost 60%. Each cubic concrete saved the cost of cementitious materials of 10 Yuan. Finally, the concrete of Three Gorges Project saved 200 million Yuan by optimization.

Table 1 Mixing proportions of concrete in bid and in construction

Types of mixing proportion	Aggregate grade	Types of fly ash	$\frac{W}{C+F}$	Fly ash ratio %	Sand ratio %	Quantity of materials per cubic meter（kg/m^3）						
						Water	Cement	Fly ash	Sand	Aggregate	Water reducer %	Air entraining agent 1/10000
In bid	4	II	0.60	20	28	115	154	38	582	1546	0.6%	0
In construction	4	I	0.50	35	27	84	109	59	584	1646	0.5%	6/10000

Table 2 performance and cost comparison of mixing proportion of concrete in bid and in construction

Technical parameter / Mixing proportion	Cement effect parameter MPa/kg	Heat to strength kJ/MPa	Elasticity Modulus to strength ×10^3	Relative crack resistance coefficient $K=\frac{S\times T}{D\times E}$	Total prices of cementitious materials and admixtures per cubic meter（Y/m^3）
In bid	0.183	1087.6	0.99	0.180	102
In construction	0.340	677.5	0.75	0.283	92

Where:S=tensile strength; T=ultimate tension value; D= dry shrinkage ratio; E=tension elasticity modulus.

3. HPC concept for dams without high quality materials

As for dam concrete, moderate heat Portland cement and fly ash are high quality materials, of which both are widely used for dam concrete. However, due to the huge volume of dam concrete, some construction sites, such as Jing hong and Jin Anqiao

Hydropower Stations, lack high quality fly ash. The transport cost of fly ash from a long-distance site is very high. The plan of using double admixtures, the ground slag and limestone powder, was developed for RCC and CVC of Jinghong Hydropower Station. This not only fully met the design requirement, but also saved cost with a significant economic effect. Longjiang hydro project lacked fly ash and moderate heat Portland cement. From the view of the project cost, long-distance transport of these materials was not quite advisable. After taking a full investigation，ordinary Portland cement, pozzolana and limestone surrounding the project within 70 kilometers were found and then used in dam concrete. By optimizing the mix of concrete, the concrete fully met the design requirement. The different plans of the mix proportion and the corresponding compressive strengths are shown in Table 3. The comparison of the costs of different plans is shown in Fig. 1.

Table 3 different plans for mixing proportion design and the results of compressive strength

Materials Plan	Quantity of materials per cubic meter（kg/m^3）					Compressive strength (90d)（MPa）	Design requirement
	PM	PO	P	L	F		
PM+F	134	0	0	0	45	39.2	$C_{90}30$
PM+P	138	0	46	0	0	37.3	
PM+L	134	0	0	45	0	37.8	
PO+P	0	155	52	0	0	36.5	
PO+L	0	158	0	40	0	38.2	

Where: PM=moderate heat cement; F=fly ash; P=pazzolana; L=limestone powder; PO=ordinary cement.

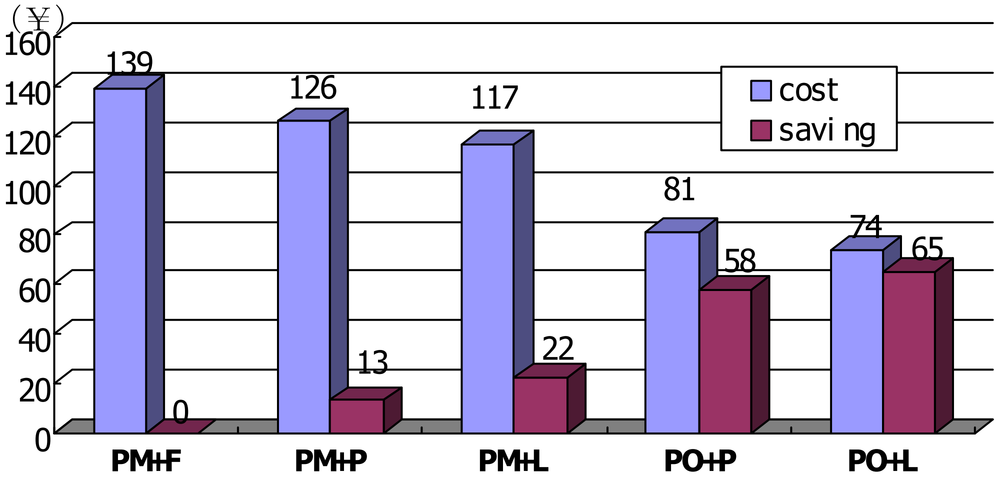

Fig.1 Comparison of costs of different plans

Table 3 indicates that the 90-day strength of each type of concrete meets the design requirement of $C_{90}30$. However, cementing material costs are significantly different. The cost analysis chart in Figure 1 shows that the cost of moderate heat Portland cement and fly ash plan is highest, while the cost of ordinary Portland cement and limestone powder plan is lowest. Longjiang hydro project needed the amount of 400,000 m^3 of the $C_{90}30$ concrete. The lowest cost plan could save 26 million Yuan, leading to "Green effect" of HPC.

4. Testing interface strength

The interfacial transition zone between coarse aggregate and cement mortar in concrete is a weak link and an uneven system in concrete, which can affect the macro-mechanical properties of the entire concrete structure. The non homogeneity of interfacial transitional zone is caused by the bleeding of internal structures at macro and micro levels. Interfacial strength directly affects the cracking resistance of concrete. For high-performance concrete, high strength of the interface is a key indicator. At home and abroad, testing methods for interfacial tensile strength of concrete entities are uncommon. The largest aggregate size of dam concrete ranges from 80 to 150 mm, and the interfacial zone between the aggregate at this level of size and mortar is largest. Therefore, the corresponding weak area is the largest, and the corresponding strength of the interface is the lowest. Testing the interfacial tensile strength of concrete helps to understand the constitutive relations in concrete, and promote the development of high-performance concrete for dams. The China Institute of Water Resources and Hydropower Research has established the equipment and the method for testing interfacial tensile strength of dam concrete. A test sample is firstly taken from the core of a dam concrete body, and then cut into small samples with interfaces by using the micro-precision cutting equipment. The small sample size can be chosen different, in terms of the size of aggregate. A core sample and corresponding small samples with interface after cutting are shown in Fig. 2 and 3, respectively. The tensile strength of interface and stress-strain curves are obtained by a small tensile testing facility with high-precision displacement sensors. These testing results can be used to compare interface effects and provide parameters for numerical analysis of the cracking resistance of concrete. Further, the microscopic slice with interface can be made. The improvement of the interface condition can be judged by electron microprobe and electron microprobe analysis of interfacial zone.

Fig.2 core samples with interface

Fig.3 cut samples with interface

Full scale concrete can be regarded as an anisotropic composite with three phases, including coarse aggregate, hardening cement mortar and the interface. By using the random aggregate distributing method, microcosmic concrete structure model (axial tensile) is established. With mechanical parameters of aggregate unit, cement mortar unit and interface unit, numerical methods can be used to simulate the cracking expansion process and the sample failure mode and quantitatively analyze the influence of interfacial strength on the concrete cracking resistance, in order to prove the high performance, particularly, the influence of interface strengthening on the concrete cracking resistance.

5. Conclusive remarks

Due to born contradictories among some performances themselves, it is unrealistic to require every performance to be excellent. On the premise of satisfying the project requirement, high performance concrete for dams can be achieved, with focusing on cracking resistance , durability, being economic, environment friendly and etc. by perfectly choosing raw materials and scientifically mixing different components based on the high performance concrete design concept. This paper is based on the research work lead by Prof. Zhen Yongyan and etc. in IWHR.

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