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Mechanical properties investigation of high-fluidity impermeable and anti-cracking concrete in high roller-compacted concrete dams

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HIGHLIGHTS

- A new type of SCC that can form an impervious layer in a RCC dam is proposed.
- Cement in SCC is partially replaced by equal amount of expansion agent to form HIAC.
- A large concrete specimen is fabricated through roller and self-compacting.
- Mechanical properties of the interface between HIAC and RCC are assessed.
- A favorably splitting strength is measured at the interface between HIAC and RCC.

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ABSTRACT

To solve the seepage problem of roller-compacted concrete (RCC) gravity dams, grout-enriched vibrated RCC (GEVR) and immersion vibrated RCC (IVRCC) have been widely used as the primary impervious materials. However, the vibration process required for these materials severely impedes the rapid construction of RCC dams. To reduce the construction disturbance on RCC impervious structures, we propose a new type of self-compacting concrete (SCC), namely, high-fluidity impermeable and anti-cracking concrete (HIAC). HIAC is formed by partially replacing cement with an equal amount of expansion agent and by adjusting the mixture proportions through trial testing. The comprehensive performance of HIAC was studied using tests on its compressive strength, elastic modulus, permeability and, in particular, the mechanical properties of the interface between HIAC and RCC, using a large roller-compacted specimen. The results indicated that HIAC meets the basic requirements of hydraulic concrete. The compressive strength reached 1.52 times the design strength, and the permeability grade of the HIAC was greater than W34. In addition, the interfacial properties between HIAC and RCC were favorable. Relative to RCC, higher splitting strength was measured at the interface of HIAC and RCC. Therefore, using HIAC as the impervious material instead of GEVR facilitates simpler, faster and higher-quality construction. These advantages signify that HIAC is a promising material in hydraulic engineering.

1. Introduction

Roller-compacted concrete (RCC) dam construction technology, which combines the advantages of normal concrete dams and the roller compaction technology of earth dams, has been widely used in hydraulic engineering. Currently, there are over 550 RCC dams have been built worldwide [1]. However, RCC dams are associated with serious engineering problems during the construction and operation periods. For example, the Willow Creek dam, Brazil's Kamala RCC dam and the Xibing arch dam in China have experienced severe seepage as a result of construction quality problems [2,3]. With the development of water resources and hydropower construction projects, the concept of seepage prevention and control for RCC dams is increasingly important during dam design. Engineering practice shows that the roller compacted layer surface is often the weak part and the main pathway for seepage. To solve the universal seepage problems of RCC dams, a variety of seepage control structures have been proposed in the engineering field, e.g., supplementing with specific impervious materials [4–6]. At present, the most widely used and effective way to prevent seepage is to set the impervious layer with grout enriched vibrated RCC (GEVR) or to apply vibration technology on the entire placing face with immersion vibrating RCC (IVRCC)

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[7] to reduce the permeability of the compacted layer surface. The vibration process required by these materials interferes with the rapid construction of an RCC dam, as the next layer cannot be poured until the process of slurry addition and vibration is completed. In addition, a mature mixture proportion design method to ensure the performance of GEVR (seepage and crack resistance) and the balance of construction quality (uniformity of GEVR) and the construction progress (vibration time) requires systematic and in-depth studies [4].

Self-compacting concrete (SCC), which was developed in Japan in the mid-1980s [8], is an innovative material that can fill all recesses, reinforcement spaces and voids. SCC could be compacted under its own weight with no segregation or bleeding and without any need for vibrating compaction during the placing process [9], thus improving the overall efficiency of concrete construction projects. Recently, this type of concrete has gained widespread use in many countries [10]. A series of experiments have been conducted on its long-term performance [11,12], fracture behavior [13,14], and behavior when prepared with recycled coarse aggregate [15,16], among other experiments. Researchers have predicted that over time, SCC will replace the use of vibrated concrete in many applications [17,18]. In hydraulic engineering, An et al. [19] developed rock-filled concrete (RFC), produced by filling the voids of rock blocks with SCC, and successfully used SCC in massive structures in China for the first time. Liu et al. [20] evaluated the environmental impact of RFC and found that RFC is more environmentally responsible relative to conventional concrete throughout the life cycle of dams.

However, the increase in the height of RCC dams will lead to greater requirements for an impervious material. The permeability varies with position in RFC [19], thus it is challenging to ensure that the permeability of a dam body containing this material meets the impermeability requirements of high gravity dams. The performance of SCC is typically customized to the engineering situation. Therefore, a new type of SCC, high-fluidity impermeable and anti-cracking concrete (HIAC), is proposed in this paper. HIAC was designed to replace GEVR as the upstream impervious material, and its mixture proportions were obtained through engineering tests on SCC [21,22]. There is hardly any observable interface between GEVR and RCC, so the interfacial properties between HIAC and RCC determines the potential for replacing GEVR with HIAC. The bond strength between repairing materials [23,24] and old concrete has been widely studied [25,26]. Zhang et al. [27] proposed using scattered gravel to improve the bond quality between SCC not poured simultaneously and investigated the bond strength through experiments and numerical simulation. Liu et al. [28] implemented compaction tests of RCC with a hand vibration roller, and presented a real-time monitoring system for RCC compaction quality control. However, few studies have investigated on the interfacial properties between SCC and RCC through roller compaction tests. Therefore, it is necessary to evaluate the bond quality between the dam body (RCC) and impervious layer (HIAC) through reasonable experiments, that consider the construction procedure of RCC dams.

In this paper, a 3000 mm × 700 mm × 300 mm specimen was fabricated by roller compacting (RCC) and unified pouring (HIAC). The splitting tensile strength test of the concrete specimens (sampled from a larger specimen) was implemented to investigate the interfacial properties between HIAC and RCC, and to evaluate the crack resistance performance. The basic performance of HIAC was also studied through tests on its compressive strength, elastic modulus and permeability. The results indicate that HIAC meets the basic requirements (i.e., strength and permeability) of hydraulic impervious concrete. In addition, HIAC has favorable interfacial properties with RCC, and the bond strength of the two materials is even stronger than that of RCC. Thus, HIAC is a suitable material to replace GEVR as the impervious material and can contribute to simpler, faster and higher-quality construction. These advantages signify that HIAC has potential use in hydraulic engineering.

2. Materials and methods

2.1. Materials

As an alternative impervious material for GEVR, HIAC must meet the basic performance requirements (i.e., seepage and crack resistance) of GEVR while also avoiding the disadvantages associated with GEVR. Therefore, the key requirements for the properties of HIAC are as follows:

(1) Convenient and high-speed construction without vibration;
(2) High bond strength with adjacent RCC and homogenization of the interface;
(3) Smooth, uniform surface after demolding and high construction quality;
(4) Self-stability and strong ability to adapt to deformation;
(5) Impervious capacity stronger than that of GEVR;
(6) Sufficient splitting resistance capacity to accommodate hydraulic fracture.

Portland cement P·O 42.5 was used as part of the cementitious material in the production of HIAC and RCC. The maximum diameter of the coarse aggregate was ≤20 mm, and the fine aggregate medium sand was hard and in good gradation [29]. In addition, the chosen admixtures were polycarboxylic acid superplasticizer water reducer, air-entraining foaming agent and expansion agent (UEA), developed by the China Academy of Building Research, whose main active ingredient is sulphoaluminate [30].

2.2. Mixture proportions

The key parameters of the mixture proportion of concrete are as follows: unit water consumption, water-to-binder ratio, fly ash content, sand ratio, aggregate gradation and admixtures. The first five parameters determine the basic mechanical properties and working performance of concrete. Admixtures greatly enhance the specific performance of concrete. SCC can compact under its own weight without any vibration during the placing process. Therefore, HIAC serves as a superior alternative to the SCC mixture proportion design method. Based on the mature engineering applications of SCC [21,22], as shown in Table 1, after considering the structure and function of an RCC dam, we developed the HIAC mixture design method, that is, replacing part of the cement with an equal amount of expansion agent and adjusting the component proportion to obtain concrete with optimal performance.

In this study, C25 strength grade HIAC was prepared. Firstly, the initial mixture proportion was calculated according to the Technical Specification for Application of Self-Compacting Concrete JGJT 283-2012. Secondly, the data of SCC (C25) were normalized, and the radar map of mixture proportions of SCC was acquired, as shown in Fig. 1. Different parameters determine different performance of SCC; thus, the specific design concepts of HIAC were as follows:

(1) Based on the mixture proportion of the local SCC of the hydraulic concrete dam, the advantages of strong contact with the other concrete are obtained.
(2) Considering the excellent anti-seepage performance of tunnel lining SCC, expansion agent is added, and the unit water consumption is increased.
(3) To improve the overall performance of HIAC and RCC, the fly ash content and sand ratio are adjusted close to that of RCC, to avoid an abrupt change in the material properties.
(4) A moderate silica fume is added, referring to the mixture proportions of the anti-cracking concrete wall.

According to the above method, after many test-mixing iterations, the mixture proportion of HIAC (C25) was obtained as shown in Table 2. And Fig. 2 shows the difference between the mixture proportions of the new material HIAC and the average mixture proportions of the most commonly used SCC in hydraulic engineering. Relative to SCC, an increase in the fly ash content leads to a decrease in the water-to-binder ratio. The unit water content of HIAC becomes higher leading to higher efficiency and a faster forming process. The addition of expansion agent can reduce permeability. HIAC can be considered a fully enhanced version of SCC that has been used in hydraulic engineering.

3. Experimental program

3.1. Experimental design

To verify the feasibility of the application, tests of HIAC were implemented as shown in Fig. 3. Basic performance tests were implemented to test physical and mechanical properties, and interfacial properties tests with a large rolling-compacted specimen were conducted to test the application performance of HIAC after roller compaction.