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Effects of fly ash and crystalline additive on mechanical properties of two-graded roller compacted concrete in a high RCC arch dam

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HIGHLIGHTS

- Two-graded roller compacted concrete (RCC) can be used in RCC arch dams over 100 m.
- Two-graded RCC may contain high volumes of fly ash.
- Compressive and tensile strengths of two-graded RCC were studied.
- Ultimate tensile strain and modulus of elasticity of two-graded RCC were tested.
- Adding crystalline additive to the two-graded RCC may improve its performance.

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ABSTRACT

Two-graded roller compacted concrete (RCC) containing high volumes of fly ash has been widely used in anti-seepage structures of RCC dams in China. The crystalline additive as a self-healing addition is added to the grout enriched two-graded RCC to increase crack resistance. The effects of fly ash and crystalline additive on mechanical properties of two-graded RCC were investigated in this research. Tests were performed to measure plastic and hardened RCC properties. The results indicate that the vibrating compacted values and air contents of plastic RCC containing fly ash of up to 58% conform to the engineering requirements. As the fly ash content in RCC increases, the air content increases and the unit weight decreases. Adding crystalline additive to the concrete mixture has no apparent effect on the slumps of grout enriched two-graded RCC, but may increase the air content and reduce the unit weight. The cube compressive strength, splitting tensile strength, axial tensile strength, ultimate tensile strain, modulus of elasticity, and axial compressive strength of two-graded RCC all decrease with increasing amounts of fly ash content. At 90 days, the relations between these properties and two variables, fly ash to cementitious material ratio (F/CF) and water to cementitious material ratio (W/CF), between splitting tensile and cube compressive strengths, between axial tensile and cube compressive strengths, and between axial and splitting tensile strengths were analyzed. The values for these properties of two-graded RCC were lower than those of grout enriched two-graded RCC at the same age, F/CF and W/CF, and adding crystalline additive to the grout enriched two-graded RCC may produce higher values for these properties than that without crystalline additive in most cases. The results confirm the feasibility of using crystalline additive in two-graded RCC of high RCC arch dams.

1. Introduction

The development of roller compacted concrete (RCC) caused a major shift in the construction practice of mass concrete dams. In 1982, construction of the world's first all RCC structure, the Willow Creek Dam, was completed one year after the work was opened for bidding [1]. A RCC dam is constructed with the roller-compacted placement method in thin layers of dry lean concrete, composed of mixed sand aggregate and cement [2]. When the geological conditions allow, the arch dam is often the preferred dam type in the narrow valley whose width to height ratio is less than 3. By the end of the twentieth century, 11 concrete arch dams with height of more than 100 m had been built in China, and accounted for half of the total number of high concrete arch dams in the world

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[3]. Compared with the conventional concrete dam, the RCC dam has obvious advantages, such as fast construction, low construction cost and simple construction procedure [4]. The first RCC arch dam in China, Puding Dam with a height of 75 m, was built in 1994 [5]. It was the highest RCC arch dam in the world at that time. As of 2016, there are 192 RCC dams built or under construction in China, including 47 RCC arch dams such as the completed Sapai RCC arch dam with a height of 130 m. More RCC arch dams over 100 m will be built in China in the coming years [6].

The thickness to height ratio of RCC arch dams is much less than that of RCC gravity dams. For example, Zhaolaihe RCC arch dam in China, with a height of 107 m, has the thickness to height ratio of 0.17. With increased heights for RCC arch dams, the seepage under high hydraulic head becomes more problematic. In order to overcome this problem, an upstream impervious structure must be properly designed and constructed [7–9]. Various impervious structures have been used in RCC dams. A layer of conventional vibrated concrete, used as an impervious layer, has typically been poured on the upstream face of RCC dams [1,10,11]. In the USA, some RCC dams were constructed with waterproof membranes [12]. Polyvinyl chloride films were used in the Trigomil Dam in Mexico and the Copperfield Dam in Australia [13]. Two-graded RCC is used as the main anti-seepage materials and has been widely used in anti-seepage structures of RCC dams in China [14–17].

The use of large amounts of mineral admixtures in RCC reduces both the adiabatic temperature rise of concrete and costs, and also improves durability. In China, Class F fly ash is the most common mineral admixture used in RCC dams. There have been various previous research reports on the development of structural and high-strength concretes containing large amounts of fly ash [18–23]. Malhotra et al. [24–26] studied the properties of concrete containing large amounts of fly ash. Siddique [27] carried out an experimental investigation on concrete containing large amounts of Class F fly ash with amounts of 40%, 45%, and 50% as replacement for cement. The experimental results showed that Class F fly ash can be suitably used up to 50% as replacement for cement in concrete for precast elements and reinforced cement concrete construction. Huang [28] explored a rational mix design method for concrete incorporating 20–80% fly ash as replacement for cement. The concrete mixtures incorporating low-LOI fly ash provided better mechanical properties than those of the corresponding mixtures incorporating high-LOI fly ash. It confirmed the feasibility that up to 80% of Class F fly ash as replacement for cement can be suitably applied in concrete by adopting a rational mixture proportion. Mardani-Aghabaglou et al. [29,30] studied the effect of high volume fly ash on mechanical properties of RCC and investigated mechanical properties and impact resistance of RCC containing polypropylene fiber. Fang et al. [31,32] reported properties of RCC for use in dams and presented eight regressive equations based on many experimental data of Chinese RCC projects. The high crack resistance RCC shows excellent anti-crack performance with elastic modulus reduced by 5% and ultimate tensile strain increased by 27% with higher strength. Liu [33] experimentally investigated the properties of RCC incorporating high volumes of fly ash. The test results indicated that keeping the same contents of cement and water, increasing the contents of fly ash in RCC could improve its properties including strength, deformation and durability. Similarly, keeping the same VC and contents of fly ash and increasing the maximum particle size of coarse aggregate could also improve the properties of RCC.

Intensive research has been done to study properties of concrete containing high volumes of fly ash. However, only a few reports [33] focused on mechanical properties of two-graded RCC containing high volumes of fly ash as the main anti-seepage materials in RCC dams. To inform the use of two-graded RCC containing high volumes of fly ash in building high RCC arch dams over 100 m, this paper presents the effects of incorporation of different proportions of fly ash on mechanical properties of two-graded RCC.

Crystalline additives contain substances, which react with cement constituents and form water insoluble pore/crack blocking deposits that increase the density of Calcium Silicate Hydrate (CSH), and are used to reduce concrete porosity and water permeability of concrete [34,35]. They can effectively serve as self-healing additions [36–39]. This research was also conducted to investigate the effects of crystalline additive on mechanical properties of grout enriched two-graded RCC to prevent longitudinal joints between the layers from forming, and further verified the feasibility of using crystalline additive in an upstream impervious structure of high RCC arch dams.

2. Experimental program

2.1. Materials

Ordinary Portland cement (P.O 42.5) was used. It conformed to the requirements of Chinese standard code GB 175-2007 [40]; the physical properties are given in Table 1. Class II fly ash was used in the investigation. The composition and physical properties of Class II fly ash used are given in Table 2. They met the requirements of Technical specification of fly ash as use in hydraulic concrete DL/T 5055-2007 [41]. The composition and physical properties of crystalline additive used in the mixture are presented in Table 3. Crushed stones of basalt were used for coarse aggregate and fine aggregate respectively. The fine aggregate used was manufactured sand with a nominal maximum size of 5 mm. The coarse aggregate used was the two-graded crushed stone of 5–20 mm and 20–40 mm in size, and the weight ratio of the two graded crushed stones was 1:1. Both aggregates were tested per "Code for testing aggregates of hydraulic concrete DL/T 5151-2014" and "Specifications for hydraulic concrete construction DL/T 5144-2001" [42,43]. The sieve analysis and physical properties of the manufactured sand are given in Table 4, and the physical properties of two-graded crushed stone are given in Table 5. Commercially available naphthalene-based retarding superplasticizer and air-entraining admixture were used.

2.2. Mixture proportions

Based on "Code for mix design of hydraulic concrete DLT 5330-2005" [44] and previous researches [11,32,45], two-graded RCC consists of five constituent materials (cement, mineral admixture,

Table 1
Physical properties of Portland cement.

Physical tests	Results obtained	Requirement GB 175-2007
Specific gravity	3.10	–
Mass (retained on 80 μm sieve) (%)	0.5	10 max
Specific surface area (m^2/kg)	350	300 min
Normal consistency (%)	26.0	–
Loss on ignition (%)	3.8	5.0 max
Vicat time of setting (min)		
Initial	120	45 min
Final	174	600 max
Compressive strength (MPa)		
3 days	25.8	17.0 min
28 days	48.0	42.5 min
Flexural strength (MPa)		
3 days	5.3	3.5 min
28 days	7.7	6.5 min