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Microstructure of four-graded roller compacted concrete

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HIGHLIGHTS

- Concrete microstructure cannot be represented by paste microstructure.
- Characterize the microstructure of paste and ITZ by means of image analysis.
- Aggregate size and free water content affect four-graded RCC microstructure.

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ABSTRACT

This paper presents an experimental study on microstructure of four-graded RCC. Two temperatures of 20 °C and 40 °C were picked to represent interior and surface layers of four-graded RCC. The most used fly ash contents of 50% and 70% were selected, and two ages of 28 days and 56 days were tested. Three levels of paste, mortar and concrete were used to simulate different microstructural regions in four-graded RCC. 3D digital microscope experiment, micro-hardness test and back-scattered electron image analysis were carried out sequentially. It was found that four-graded RCC microstructure can be divided into three characteristic parts: bulk paste, interface transition zone around fine aggregate (ITZ-f) and interface transition zone around coarse aggregate (ITZ-c). By comparing the average wear width and depth, the strength and bonding ability of bulk paste was the highest, followed by ITZ-f and ITZ-c. Compared to the surface layer, the micro-mechanical strength of bulk paste and ITZ-f was higher in the interior layer, but that of ITZ-c was opposite. At early age, 50% fly ash content was more conducive to microstructure than 70%. The micro-hardness value of ITZ-c presented a decreasing trend with age and that of ITZ-f did not grow. In terms of product structure, $Ca(OH)_2$ content in ITZ-c gradually decreased from aggregate surface to paste part, and $Ca(OH)_2$ in ITZ-f had been partially converted to C-S-H gel. The proportions of hydration product and porosity were highest in ITZ-c, followed by ITZ-f, with bulk paste having the lowest. Microstructure of four-graded RCC was significantly affected by the combination of aggregate size and free water content on aggregate surface.

1. Introduction

Two- or three-graded roller compacted concrete (RCC) dam technology has been extensively used in gravity and arch dams. The maximum aggregate size is 40–80 mm. The application of four-graded concrete appears mainly in normal concrete projects, with its maximum aggregate size reaching 120–150 mm. Among few studies on four-graded RCC, the first demonstration and application took place in retaining structure of the Shatuo hydropower station in Wujiang, China [1].

Based on the results of various macroscopic performance experiments, it has been determined that, due to the increase in maximum aggregate size, not only basic water consumption of four-graded RCC is reduced by 8–10 kg/m^3 and just 70–72 kg/m^3 is needed, but the amount of bonding material is also reduced by 16–20 kg/m^3 compared to three-graded RCC [2]. Furthermore, when adjusting a sand ratio by 28%∼30% and a proper coarse aggregate mixture [3], compressive strength of four-graded RCC is not reduced, while tensile strength value, ultimate tensile value, autogenous volume deformation and compressive elastic modulus are almost the same, only shrinkage rate is reduced by 15%–25%. However, concrete adiabatic temperature rise decreases 2.2–2.5 °C at the age of 28 days, which is conductive to temperature control and crack prevention in mass concrete. Although impermeability

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and frost resistance are slightly lower at the age of 90 days, the performance still meets design requirements. In general, it has been proved that four-graded RCC exhibits superior conditions in terms of mechanical behavior, thermal performance and durability [4].

Nevertheless, the increase in aggregate size is both positive and negative, and depends on changes in paste and interface transition zone (ITZ) in RCC. As a result of poor cohesiveness of RCC mix during construction process, relatively less bonding materials cannot provide a sufficient aggregate package so that few large aggregate can be easily separated, leading to the generation of interior defects [5]. Therefore, the properties of paste and ITZ, as well as their bonding state at aggregate interface in four-graded RCC would inevitably differ from that of other graded concrete, while the microstructure formation and development would change accordingly. The study on microstructure of four-graded RCC also contributes to a deeper understanding of the relationship between structure and performance.

Generally, RCC system is extensively added with a large proportion of mineral admixtures to reduce adiabatic temperature rise and improve durability. Class F fly ash is the most commonly used mineral admixture, and more than 50% content of high-volume fly ash is mixed into four-graded RCC. The high-volume fly ash fills ITZ between coarse aggregate and mortar, reducing RCC pore radius and quantity. Owing to irregular porosity, RCC permeability is lower, while compressive strength and durability are improved [6,7]. Atis [8] and Mardani [9] studied the mechanical properties of high-volume fly ash RCC and found that the RCC exhibited a high compressive strength with 50% fly ash content and a moderate strength with 70%. Moreover, high-volume fly ash reduces cement equivalent; that is, water-cement (w/c) ratio is greatly increased when water-binder (w/b) ratio is constant, which will also result in a significant microstructure change. Thus, only reasonable content of fly ash can improve the durability of four-graded RCC.

It is well known that conditions such as temperature and age greatly affect development of concrete microstructure in RCC dams [10,11]. Malkawi [12] studied the temperature control of a certain RCC dam and found that maximum peak temperature of the dam reached 43 °C when laboratory RCC temperature was increased to 26 °C. Noorzaei [13] discussed the division of RCC dam temperature distribution into 10 stages, where upper and bottom temperatures of the dam were higher than 40 °C. Therefore, temperature differences may exist between interior and surface layer of four-graded RCC, which cannot be ignored.

Fortunately, various scholars have been concerned with RCC microstructure, and have used certain mature test methods to study the phenomenon. Gao [14] used an optical microscope to observe RCC air porosity and calculated the interval factor of pores in order to characterise its frost resistance. Omran [15], Hoang [16] and Chi [17] all made use of a scanning electron microscope (SEM) to observe hydration products of paste and ITZ in RCC systems with different mineral admixtures. From the SEM chart, amorphous calcium silicate hydrate (C-S-H) gel, needle-like ettringite (AFt) crystals and portlandite ($Ca(OH)_2$) can be found in specimens [18]. Nonetheless, studies on microstructure of four-graded RCC have not been reported in detail. In experimental testing and image analysis of micron scale specimens, some RCC microstructure studies are based on paste microstructure representing concrete microstructure, which reduces the difficulty and costs of experiment, but leads to deficient understanding of the overall RCC microstructural characteristics.

Recently, certain researchers including ourselves proposed a solution to a key problem of differences among paste, mortar and concrete by defining and measuring them [3,19], therefore, in this study, different microstructural regions in four-graded RCC were simulated in three levels, from neat paste, to mortar, to concrete. Following this, microstructural morphology, micro-mechanical strength and product composition of paste and ITZ could be characterized by a variety of micro-test methods and analysis tools in order to identify microstructure differences under different conditions. Thereafter, the relationship between macro-performance and micro-mechanism of four-graded RCC could be established to provide effective theoretical support for future engineering design.

2 Experiment

2.1. Raw materials and mixture proportions

The raw materials used in this research include 42.5 ordinary Portland cement with specific surface area of 380 m^2/kg and density of 3130 kg/m^3, class F fly ash with fineness of 18.2%, crushed limestone processed on site as coarse and fine aggregate, laboratory tap water, naphthalene based superplasticizer (SP) and ionic resin based air entraining agent (AE). Table 1 displays the chemical composition of cement and fly ash.

Table 2 shows the physical property of aggregate. Coarse aggregate consisted of small gravel (5–20 mm), medium gravel (20–40 mm), large gravel (40–80 mm) and extra-large gravel (80–120 mm). Fine aggregate was further processed by crushing coarse aggregate and fineness modulus of fine aggregate was 2.79. However, the grain shape of aggregate was poor and flaky, a mass of aggregate could carry a certain amount of free water after reaching the saturated surface-dry condition. After applying the wet sieve method to remove large and extra-large aggregates, only small and medium coarse aggregates were obtained for experimental test, the maximum size of which was 40 mm.

Table 3 lists the laboratory RCC mixture design, which refers to Chinese standard DL/T 5330 [20]. The w/b ratio of four-graded RCC was selected to be 0.53, which is equivalent to the engineering RCC mixture design of Shatuo hydropower station. Vibrating compacted (VC) value and air content are 3–5 s and 3.5%–4.5%, respectively. The proportion of medium and small coarse aggregate is

Table 2
Physical property of aggregate.

Aggregate type	Saturated surface-dry condition	
	Density (kg/m^3)	Water absorption (%)
Fine aggregate	2630	2.2
Small coarse aggregate (5–20 mm)	2690	0.68
Medium coarse aggregate (20–40 mm)	2690	0.63

Table 1
Chemical composition of cement and fly ash.

Materials	Chemical composition (%)									
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	Loss	Sum	Other
Cement	20.47	4.51	4.28	60.58	4.14	0.52	0.23	3.26	0.87	98.86	1.14
Fly ash	55.41	25.29	6.68	2.10	2.59	1.38	0.42	0.30	4.67	98.84	1.16