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Experimental study on the creep behaviour of rock-filled concrete and self-compacting concrete

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HIGHLIGHTS

- Loading age did not significantly influence the creep of rock-filled concrete.
- Both creep and shrinkage of RFC were less than those of SCC.
- The creep ratio of RFC was related to the volumetric fraction of SCC.

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ABSTRACT

Rock-filled concrete (RFC) has become a widely used alternative for massive concrete engineering. Several studies have examined the creep behaviour of normal concrete. However, few studies have focused on the creep behaviour of RFC. In the present study, experimental compressive creep tests and shrinkage tests were performed on specimens with different loading ages with large-sized cylinders under identical laboratory conditions to investigate the creep properties of RFC and self-compacting concrete (SCC). The results showed that the loading age did not significantly influence the creep strain of RFC. Both the creep strain and shrinkage strain of RFC were less than those of SCC. The rock framework in the RFC significantly influenced its creep behaviour, and the creep ratio of RFC was related to the volumetric fraction of SCC. Furthermore, the creep models CEB-FIP and AIC209 were used to analyse the creep behaviour of RFC and SCC. These results can provide a theoretical and experimental basis for further practical engineering applications of RFC.

1. Introduction

At present, the most representative types of concrete dams are the normal concrete dams developed by the U.S. Bureau of Reclamation at the beginning of the twentieth century, and the roller compacted concrete (RCC) dams proposed by Prof. Raphael of the University of California in the 1970s. These concrete dams required mechanical vibratory or vibratory roller compaction and use cooling water pipes for temperature control. The method commonly used to reduce the heat of hydration and cost of mass concrete, especially dam concrete, is reducing the volume fraction of cement or using large-sized aggregates to increase the volume fraction of aggregates.

In 2005, a new construction method called rock-filled concrete (RFC) [1] was developed by combining the self-compacting ability of self-compacting concrete (SCC) and prepacked aggregate concrete. SCC, first developed in Japan in the late 1990s, was a major breakthrough in building construction owing to its good flowability, self-compacting ability, and segregation resistance compared to ordinary vibrated concrete [2]. The construction process for RFC has two main steps: filling the framework with large-sized rocks (aggregates larger than 300 mm), and then pouring fresh SCC into the interspace between rocks to produce an intact concrete structure. To verify the flowability of the SCC to the rock framework, a series of experiments were carried out and the corresponding mix design method for SCC was developed [3–8]. The thermal properties, mechanical properties, construction technology, and microstructure of RFC as well as the interfacial transition zone between rocks and SCC have previously been reported. These indicate that RFC exhibits several advantages such as simple construction technology, low unit price, low heat of hydration, ease of quality control, high construction efficiency, high volume stability, mechanized construction, and high construction speed [9–12]. This type of concrete has been successfully applied to 54 new dam

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projects, 8 dam reinforcement projects, 39 embankment projects, and several other massive concrete projects in China. The maximum height of dams under construction has reached 90 m [10,12]. RFC is especially suitable for massive concrete structures including those for hydropower, highways, bridges, and other industries with significant social and environmental benefits. Numerical models to evaluate the nonlinear seismic response and safety of rockfill dams have also been developed in recent years [13–16]. In investigations of the effects of rockfill material degradation on seismic response, all inclined-core rockfill dam models have shown that exceptionally strong shaking (0.7–1.0 g) does not reduce/threaten/affect structural safety [16].

As important basic performance indicators of concrete, shrinkage and creep affect the durability and crack resistance of concrete, especially the durability and internal force redistribution of massive concrete structures. A distinguishing characteristic of SCC is the high volume of paste. High paste volume has been shown to increase both the shrinkage and cracking of SCC [1]. Some researchers have attempted to replace cement with fly ash (FA). Current results indicate that SCC with higher FA content can reduce both drying and autogenous shrinkage, and using up to 60% FA as cement replacement can yield SCC with compressive strength as high as 40 MPa [17–20]. In addition, SCC delivers better long-term performance than conventional concrete in terms of creep strain [21,22]. Altoubat's [23] research showed that the addition of FA improves cracking resistance. RFC has an internal rock framework and negligible rock shrinkage and creep. Combined rock framework and SCC, those behaviour of RFC may be better than conventional concrete. However, there is a paucity of studies on the creep behaviour of RFC.

To further study the creep behaviour of RFC, clarify the creep relationship between RFC and SCC, and provide a basis for RFC design, experiments were conducted on the creep behaviour of RFC and SCC with high FA volume at different loading ages. The shrinkage performance of RFC and SCC under the same laboratory conditions was also studied to compare and correlate their behaviour. The effects of variations in saturation and curing on the creep behaviour of RFC and SCC are not covered in this study but will be considered in future research. The results of this study on the creep behaviour of RFC can serve as the basis for the design and engineering applications of RFC in dam construction.

2. Experimental program

2.1. Test specimens and manufacturing

Eleven large coupons were prepared and tested according to the relevant regulations stated in *GB/T50082-2009* [24]. The specimens were manufactured in the shape of a cylinder with a diameter of 350 mm and height of 700 mm. Five specimens were SCC coupons while the remaining six were RFC coupons. All RFC coupons were filled with SCC, which had the same mix proportion as the SCC coupons.

Two different loading ages (i.e. 7 d and 28 d) were considered to investigate the effects of loading age on the creep behaviour of RFC. The creep behaviour of SCC was tested to investigate the relationship between RFC and SCC at loading age of 28 d. The shrinkage experiments on RFC and SCC were simultaneously conducted. The mechanical properties of RFC and SCC were also obtained by measuring their elastic modulus.

Table 1 summarizes the details of all the specimens. The abbreviations SCC and RFC mean self-compacting concrete and rock-filled concrete, respectively. The three numbers (1, 2, and 3) denote the number of coupons in a group. The 7 d and 28 d denote the loading ages of 7 days and 28 days, respectively, and 'S' represents the shrinkage test.

The slump and slump flow (SF) of the SCC were tested prior to casting. As shown in Fig. 1, the SF of SCC is 720 mm. While making SCC coupons, SCC was directly poured into the cylinder template; no vibration was applied during or after casting. RFC coupons were cast layer by layer. The complete casting process can be divided into three steps (Fig. 2a–h). First, cast SCC with a thickness of 30 mm into the steel template (Fig. 2a). Then, rocks with a maximum diameter of 70–150 mm were piled into the steel template to create a tight framework with a height of approximately 250 mm (Fig. 2b). Next, SCC was slowly poured into the rock formwork, and rocks approximately 50 mm high were left exposed on surface of SCC so that these will

Table 1
Details of the test specimens.

Specimen ID	Dimension [diameter × height]	Type of test
SCC-1	350 mm × 700 mm	Elastic modulus test
SCC-2		
SCC-3		
RFC-1		Elastic modulus test
RFC-2		
RFC-3		
RFC-7d	350 mm × 700 mm	7 d creep test
RFC-28d		28 d creep test
SCC-28d		28 d creep test
RFC-S		Shrinkage test
SCC-S		Shrinkage test

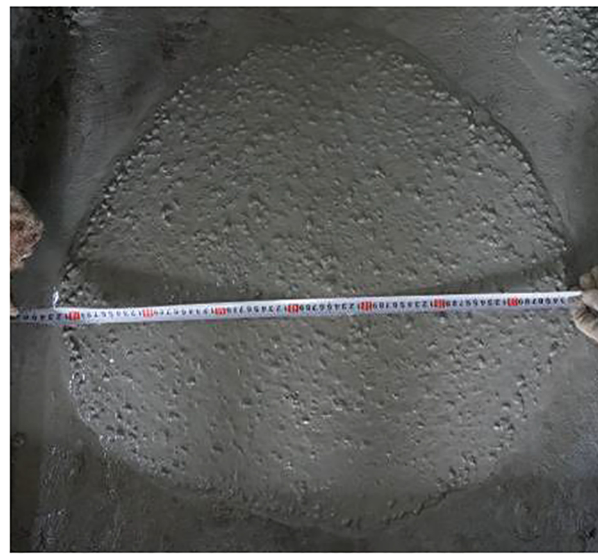

Fig. 1. Slump flow of SCC.

overlap with the next layer (Fig. 2c and e). In order to ensure that the SCC adequately fills the stone gaps, a rubber hammer was used to knock on the steel template while casting. The specimens were covered for curing after casting, and the top surfaces were press polished within 1 h. Additionally, the steel templates were unwrapped and the coupons were cured with water after 24 h.

2.2. Materials and mix proportion

The maximum and average particle size of stones in RFC specimens are 150 mm and 100 mm, respectively. It should be mentioned that in actual projects, the RFC contains rocks with sizes larger than 300 mm. The usual maximum size of rocks is approximately 1000 mm [10]; however, the size limit owing to laboratory conditions was set as 150 mm. Thus, the effects of rock size and laboratory temperature and humidity were not considered as parameters in this test, but will be studied in future work.

The average compressive strength and elastic modulus of rocks were determined as 72.9 MPa and 67.9 GPa, respectively, based on the testing method of SL264-2001 [25]. The size of the rocks is significantly smaller than that in actual projects; the space in the rock framework is also relatively narrow. Thus, the SCC cast in this experiment requires high fluidity and high slump-loss retardation. The mix proportion of C20 SCC was designed according to the design method stated in the *Technical Specification for Application of Self-compacting Concrete* [4] and the design idea of SCC with high volume fraction of FA [17–20]. In addition, the mixing test of SCC with desirable properties was successfully performed. The materials used in SCC production were ordinary Portland cement (grade P.O. 42.5), FA (grade II), polycarboxylate superplasticizer (PS), medium-sized sand with fineness modulus of 2.48, and pebbles with maximum particle size of 10 mm. The mix proportion of SCC is given in Table 2. The measured compressive strengths of SCC at different ages listed in Table 3 were obtained by averaging the values for three 150 mm × 150 mm × 150 mm test cubes. It is worth noting that, the compressive stress of SCC with high FA volume continuously increased after 28 d of curing, and remained steady after 180 d. In addition, the ratio of rocks (stone content) in RFC specimens were determined via tests and are listed in Table 4.