Cement & Concrete Composites 54 (2014) 89–99

Contents lists available at ScienceDirect

Cement & Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

# Rock-filled concrete, the new norm of SCC in hydraulic engineering in China

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ARTICLE INFO

*Article history:*
Received 31 October 2013
Received in revised form 3 August 2014
Accepted 6 August 2014
Available online 22 August 2014

*Keywords:*
Rock-filled concrete
Self-compacting concrete
Workability
Mix design method
Integrated performance
Practical application

ABSTRACT

Rock-filled concrete (RFC) was developed in China in 2003 as an application of self-compacting concrete (SCC) that can then be used as "normal" concrete for massive concrete constructions. RFC is produced by filling the voids of rock blocks with SCC, which has good fluidity and segregation resistance. To guarantee the required workability of SCC, a mix design method for SCC based on its paste rheological characteristics was developed. The proposed method yielded practical benefits by saving on the amount of laboratory work, testing time, and raw materials. The integrated performance of RFC was studied by conducting tests on its compaction, compression strength, tensile strength, and permeability. Results indicated that RFC meets the requirements of hydraulic concrete. With two types of construction technology in practical application, RFC exhibits remarkable advantages, such as high construction efficiency, low cost, low heat of hydration, and low environmental load. These advantages contribute to a simpler construction management and an easier quality control, signifying that RFC is a promising technology in hydraulic engineering.



## 1. Introduction

Self-compacting concrete (SCC) is an innovative material that can flow through and fill the gaps of reinforcements or corners of molds without any need for vibrating compaction during the placing process, thus improving the overall efficiency of concrete construction projects [1,2]. SCC is widely used in various types of practical structures worldwide, except in massive concrete constructions in hydraulic engineering, because it has high cement content and releases more heat during hydration. These characteristics result in high cost, significant environmental impact, and difficulty in temperature control. Thus, we are making efforts to apply SCC in massive concrete constructions in hydraulic engineering, accompanying with lower costs and less environmental load.

Rock-filled concrete (RFC), a new type of concrete based on the technology of SCC, was developed for use in massive structures in China [3,4]. As shown in Fig. 1, RFC is a combination of SCC and rock; it is produced by filling SCC into the voids of rock blocks having a minimum size of 300 mm because of SCC's good fluidity and segregation resistance [5]. In the RFC mass, only 40–45% of the volume needs to be filled with SCC, which significantly reduces the total proportion of cement in a unit of RFC and highly improves the construction efficiency. RFC performs satisfactorily in reducing cost and heat of hydration because the unit cement content of RFC with a strength grade of C15 is only 80–90 kg/m$^3$ [4]. According to previous studies on the energy consumption and emissions during a dam's lifetime, i.e., material production, transportation, construction, and operation and maintenance stages, the total energy consumption is reduced by 55%, and approximately 64% of $CO_2$ emissions are saved when RFC is used instead of conventional concrete (Conv. C) [6,7]. Thus, RFC is more environmentally friendly than Conv. C.

RFC is based on the self-compactibility of SCC, which should flow into every void of the block mass purely by means of its own weight and without the need for vibrating compaction. This characteristic requires the high fluidity of SCC without aggregates segregation during placement. The production of SCC with excellent workability requires appropriate mix proportions [8,9]. However, to the best of our knowledge, existing mix design methods often require a significant number of time-consuming trial mixtures before an optimum is reached, a process that is not conducive to the costs and schedules of engineering projects [2]. Predicting concrete flow from its composition is still the paramount goal in SCC [10]. On the other hand, RFC is a two-phase material composed of rock and SCC, and thus, the integrated properties of RFC, such as

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http://dx.doi.org/10.1016/j.cemconcomp.2014.08.001
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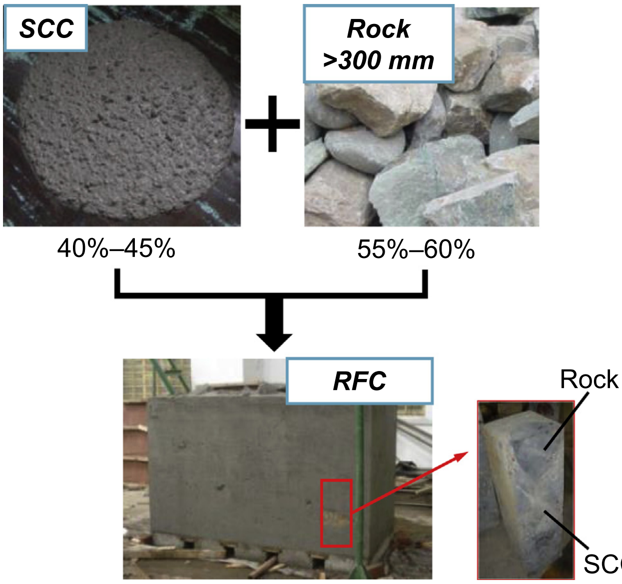



**Fig. 1.** Composite of RFC.

compactness, mechanical properties, and permeability need to be studied.

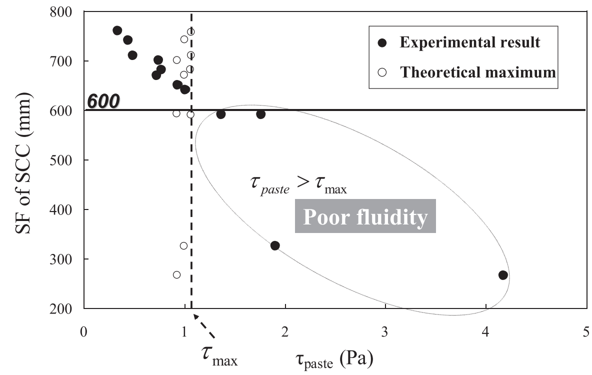
The present study developed a mix design method for SCC based on its paste rheological characteristics and investigated the integrated performance of RFC. We also proposed two types of RFC construction technology depending on the construction processes of SCC and rock, namely, general-type and riprap-type RFCs [3]. The successful applications and remarkable advantages of RFC construction technologies show that RFC is a promising material for use in massive concrete constructions in hydraulic engineering.

## 2. Experimental work

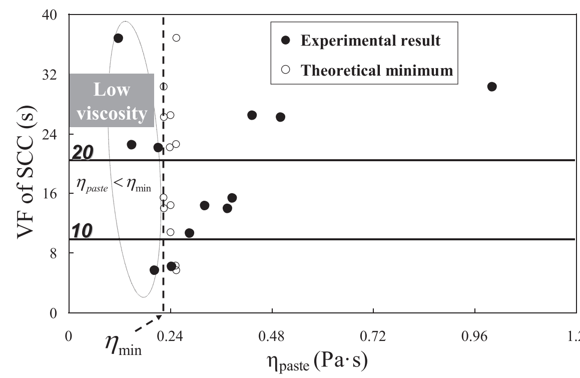
### *2.1. Mix design for SCC with excellent workability*

The key requirements for the basic SCC material are high fluidity without the segregation of aggregates during placement. Producing SCC with excellent workability requires appropriate mix proportions. To predict the workability of SCC from its composition and save on the amount of laboratory work, testing time, and raw materials, the fundamental principles involved in the physical phenomena of high fluidity and segregation resistance were investigated from a rheological point of view.

Previous studies showed that the behavior of fresh paste or mortar can be approximated using the Bingham model or the H–B model [11,12]. The two most important rheological characteristics in both models are yield stress $\tau$ and viscosity $\eta$. These characteristics respectively provide a measure of the shear required to initiate flow and a measure of the resistance to flow after the material begins to flow. Mortar characteristics are closely related to the workability of SCC because SCC can be considered as a two-phase material composed of gravel and the suspending mortar [13–16]. We established two mechanical models to analyze the influence of mortar rheological characteristics on the workability of SCC, i.e., high fluidity and segregation resistance. The high-fluidity model supposes that gravel particles must have the ability to move, and the upper gravel particle must overcome the sum of brace forces generated by the gravel particles below. A maximum for $\tau_{mortar}$ is required because brace force is determined by the yield stress of mortar [17]. However, the segregation resistance model assumes that the settlement of gravel particles as SCC flows follows Stokes law, and an inverse correlation exists between settlement velocity and mortar viscosity [18,19]. To prevent the gravel particle from sinking fast, which leads to segregation, a minimum for $\eta_{mortar}$ is required. In combination with existing empirical correlations between the rheological characteristics of mortar and paste [20–22], the criteria of the rheological characteristics of mortar can then be converted to those of paste, i.e., a maximum for $\tau_{paste}$ and a minimum for $\eta_{paste}$ are necessary to ensure the fluidity and segregation resistance of SCC respectively.




**(a)** Correlation between $\tau_{paste}$ and SF of SCC




**(b)** Correlation between $\eta_{paste}$ and VF of SCC

**Fig. 2.** Results of the paste rheological characteristics and the workability of SCC.

To validate the theoretical research, a series of SCCs and their equivalent pastes were prepared. Fig. 2 shows the experimental results and the theoretical thresholds. Fig. 2a indicates that when $\tau_{paste}$ exceeds the theoretical maximum value, the slump flow value (SF) of SCC is insufficient to reach 600 mm. Fig. 2b shows that when $\eta_{paste}$ is lower than the theoretical minimum, V-funnel time (VF) is shorter than 10 s or longer than 20 s, indicating a low viscosity and a high risk of segregation for the SCC. Only when $\tau_{paste}$ and $\eta_{paste}$ both satisfy the criteria proposed by our models can the excellent workability of SCC be achieved, i.e., SF $\geqslant$ 600 mm, VF = 10–20 s [23,24].

In summary, the experimental results of SCC workability measured by slump flow and V-funnel tests correspond very well with those predicted by the established model. Thus, a new mix design method for SCC based on the paste rheological characteristics is proposed (Fig. 3) [25]. First, the basic water–powder ratio of the powder material is tested to provide a reference for Vw/Vp [24]. A mini-slump flow test is then used to adjust the sp dosage. The final slump flow value (SF) and the time it takes for the paste to reach a prescribed spread 200 mm ($T_{200}$) are recorded and then converted to $\tau_{paste}$ and $\eta_{paste}$ according to [26,27]. In addition, the theoretical thresholds of $\tau_{paste}$ and $\eta_{paste}$ are given by Eqs. (1) and