



## Research on Rock-Filled Concrete Dams: a Review

---

Feng Jin, Hu Zhou and Duruo Huang

EasyChair preprints are intended for rapid dissemination of research results and are integrated with the rest of EasyChair.

August 25, 2018

## RESEARCH ON ROCK-FILLED CONCRETE DAMS: A REVIEW

Feng JIN \*, Hu ZHOU and Duruo HUANG†

\* Department of Hydraulic Engineering, Tsinghua University; Beijing, 100084, China  
 E-mail: jinfeng@tsinghua.edu.cn

**Keywords:** Rock-Filled Concrete, Dam, Workability, Property and Performance

**Abstract.** *Rock-Filled Concrete (RFC) is an innovative mass concrete technology. To date, RFC technology has been used to build a great number of gravity dams and arch dams. Since it was invented in 2003, many experimental and numerical research works have been conducted. During the construction process of RFC, an assembly of large rocks with more than 300 mm in grain size, called rockfill, can be cemented with a high-performance self-compacting concrete (HSCC). The RFC technology combines the advantages of masonry and concrete, in that it decreases cement consumption, lowers temperature rise of hydration heat, and reduces shrinkage of the concrete. This paper aims at acquainting readers with a timely review of state-of-the-art research on RFC technology, including (1) workability of HSCC and compactness of RFC, (2) thermal and mechanical properties of RFC, (3) structures of an RFC dam and (4) construction and quality control measurements.*

### 1 INTRODUCTION

Professors Jin and An in Tsinghua University invented Rock-Filled Concrete (RFC) in 2003. An assembly of large rocks, called rockfill, is cemented with a high-performance self-compacting concrete (HSCC) to build gravity dams and arch dams, as shown in Figure 1. The RFC technology combines the advantages of masonry and concrete, in that it frees vibration or roller compaction, decreases cement consumption, lowers temperature rise of hydration heat, reduces shrinkage of the concrete and has no use cooling pipes<sup>1</sup>. Since the first RFC dam was constructed in 2005, RFC technology has been successfully applied in more than 80 dam projects (including dam rehabilitation) in China, for dam heights between 30 m and 90 m. To date, based on the practice in China, building an RFC dam can reduce the construction cost by 10% to 30% when compared with a concrete dam or an RCC dam under the same condition.



Figure 1: construction process and sketch map of Rock-Filled Concrete

†Department of Hydraulic Engineering, Tsinghua University, Beijing, 100084, China

The first part of this paper introduces the research on the workability and the properties of RFC. Some new structures of an RFC dam and construction facilities are also presented. Some related research is reported at the end of this paper.

## 2 WORKABILITY OF HSCC AND COMPACTNESS OF RFC

In 2005, Jin et al. conducted a pilot experiment on the compactness of RFC. A sample with a dimension of 500 mm × 500 mm × 2000 mm was casted by pouring self-compacting concrete into pre-laid rocks at one end, as shown in Figure 2(a). The grain size of the rocks is 150mm to 200 mm. The maximum grain size of the coarse aggregates in SCC is 10mm. The slump flow of SCC reached 650 mm and V-funnel time was 20 s. Before pouring SCC, the initial void ratio between rocks is about 48%. The compressive strength of the RFC sample at the age of 7, 14 and 28 days measured by a resiliometer were 37.0MPa, 39.3MPa and 52.3MPa, respectively. Then the bending strength of this sample, which reached 2.08MPa, was tested. The failure section of the sample shown in Figure 2(b) illustrated that SCC is able to fill the voids among rocks fully. By visual inspection, there was no big pore. The section was smooth with a few large rocks fractured at this section, which indicates strong bonding between rocks and SCC.

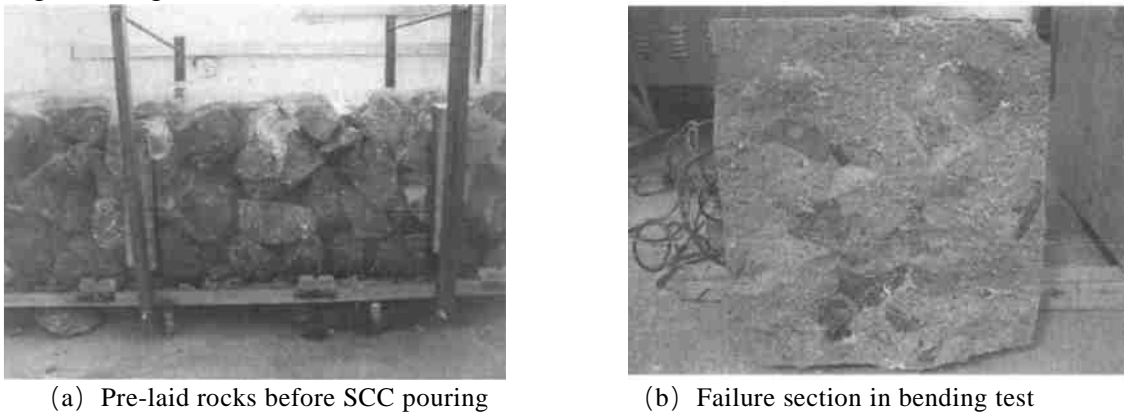


Figure 2: Pilot test of Rock-Filled Concrete

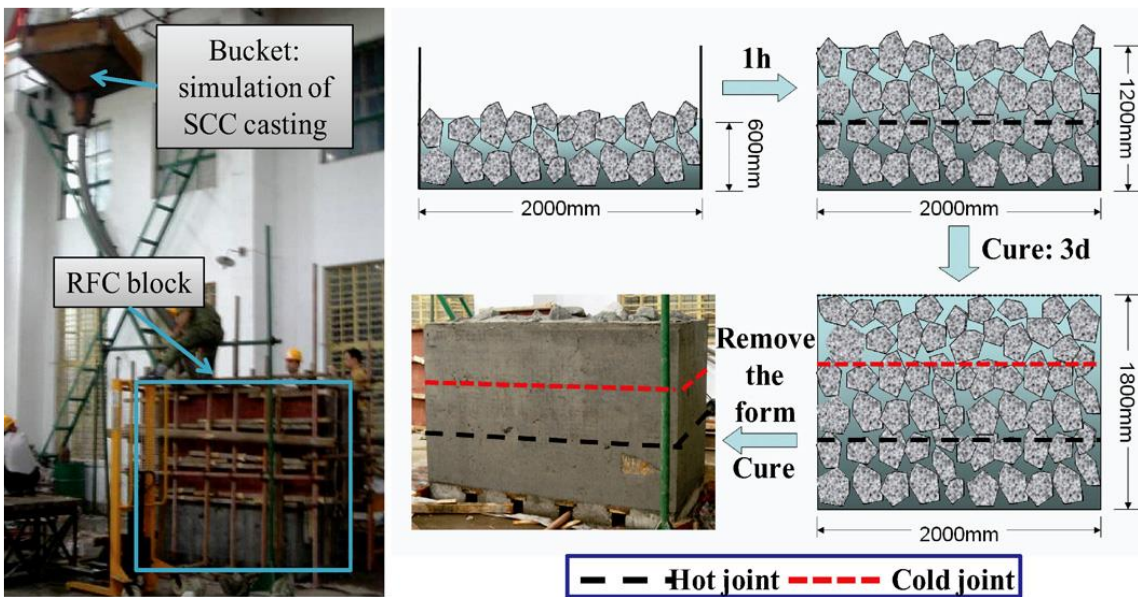


Figure 3: Rock-Filled Concrete test block

After the pilot experiment, a large RFC block with a dimension of  $1\text{m} \times 2\text{m} \times 1.8\text{m}$  was poured in the lab to study the mechanical properties and the construction process<sup>2</sup>, as shown in Figure 3. Three layers with a height of 300 mm of RFC were casted. The second layer was poured on the first layer only after 1 hour, yet the third one was poured 3 days later. The RFC block was cut into many small samples and permeability and strength tests were conducted. The test results demonstrated that the RFC has a higher compressive strength than the SCC. The joints between layers have good seepage resistance. These experiment results supported the construction of the first RFC dams.

To study the limit of filling ability of SCC in the rockfill body, an experimental apparatus was set up in the lab of Northwest University, USA<sup>3</sup>. The study investigated two of the most controversial issues regarding RFC—the filling performance of SCC and the large interface between SCC and rocks. The effects of different factors (aggregate size, yield stress, etc.) on the filling capacity of SCC and the properties of RFC were investigated based on filling rate, cross-section porosity, and interface microstructure. Two clogging mechanisms were summarized from literature and used to explain the experimental results. The findings indicate that the interface microstructure of RFC greatly depends on the filling performance of SCC, which is significantly affected by the size and condition of the large rocks. Therefore, the requirement for SCC in RFC, which is called high performance self-compacting concrete (HSCC) later, should be stricter in terms of workability and stability.

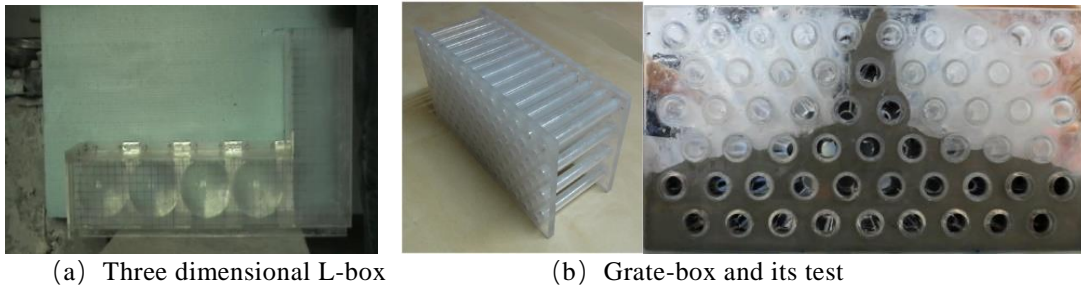


Figure 4: L-box and Grate-box test

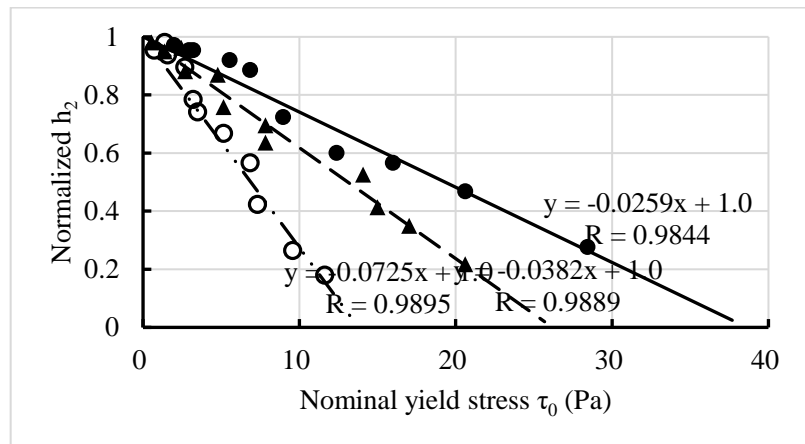


Figure 5: Results of Grate-box test

Two testing methods for filling capacity of HSCC into voids have been developed in Tsinghua University, China, as shown in Figure 4. The first one is 3-dimensional. Then, a simple one, called Grate-box<sup>4</sup>, was developed to substitute it. As shown in Figure 5, the results of Grate-box testing demonstrated that an indicator, normalized  $h_2$ , to evaluate the filling performance of different SCM can be found in the test, and its value linearly increases as the nominal yield stress ( $\bar{\tau}_0$ ) of SCM decreases. Another coefficient, which is called damping coefficient “ $\eta$ ” and calculated as shown in Table 1, can be employed as a more general indicator

of resistance ability to the filling movement of self-compacting cementing materials in the rockfill within the voids.

No.	Gap width (mm)	$h_{max}$ (mm)	Formula of fitting line	Absolute value of slope	$\eta$ /
				$\left  \frac{\eta}{\rho g b} \right $ (Pa-1)	
1	10	55.43	$y = -0.0259x + 1.0$	0.0259	56.0
2	8	55.71	$y = -0.0382x + 1.0$	0.0382	82.6
3	6	56.44	$y = -0.0725x + 1.0$	0.0725	156.8

Table 1: Calculation of the damping coefficient  $\eta$  of the different grate-box

Besides experimental studies, several numerical models have been developed to simulate the filling process of RFC, such as Distinct Element Method (DEM)<sup>5</sup>, Lattice Boltzmann Method (LBM)<sup>6,7</sup>, Smoothed Particle Hydrodynamics (SPH) method<sup>8</sup> and LBM-DEM hybrid model<sup>9</sup>. HSCC was modelled as a two-phase Bingham fluid in the last hybrid model, where coarse aggregates were simulated by DEM and mortar was considered to be Bingham fluid modelled by LBM. Based on this model, the filling process of HSCC into the voids and its clogging mechanism were investigated. The simulation results indicate that the key factor that controls blocking is the gap width to solid particle diameter ratio  $Ar$  in the case of single gap. The critical  $Ar$  is about 2.0, below which the risk of blocking increases sharply. As the volume fraction of solid particles increases, blocking becomes easier. However, the pressure gradient has little impact on the blocking status. In the multi-channel case, SCC is able to 'find' the wider gaps automatically. As a result, the flow divides into "main channel" and "tributary stream". The risk of blocking increases significantly as the number of narrow gaps increases. So, the number of small rocks must be controlled in the rockfill that could form more narrow gaps.

### 3 THERMAL AND MECHANICAL PROPERTIES OF RFC

As a new construction material, the thermal and mechanical properties of RFC have been tested<sup>10,11</sup>. These tests include adiabatic thermal rise, linear expansion coefficient<sup>12</sup>, density and the ratio of void<sup>13</sup>, compressive, tensile, bending and shear strength<sup>14</sup>, class of impermeability and frost resistance. The typical values of these properties of RFC are listed in Table 2.

Density	Linear expansion coefficient	Adiabatic thermal rise	Compressive strength	Shear strength of cold joint	Impermeability class
2500-2600 kg/m <sup>3</sup>	$7-10 \times 10^{-5}/^{\circ}\text{C}$	12-16 $^{\circ}\text{C}$	15-25MPa	$f' = 1.7$ $c' = 1.59\text{MPa}$	W4-W8

Table 2: Typical value of properties of RFC

Li and Xin conducted experiments on the performance of I- and I-II mix mode fracture of RFC beams. Tang et al.<sup>15</sup> proposed a multiphase mesostructured mechanics approach to study the fracture behavior of RFC. The failure pattern of RFC beam simulated by the approach



agrees well with experimental results, as shown in Figure 6. The big rocks can effectively prevent propagation of cracks in RFC.

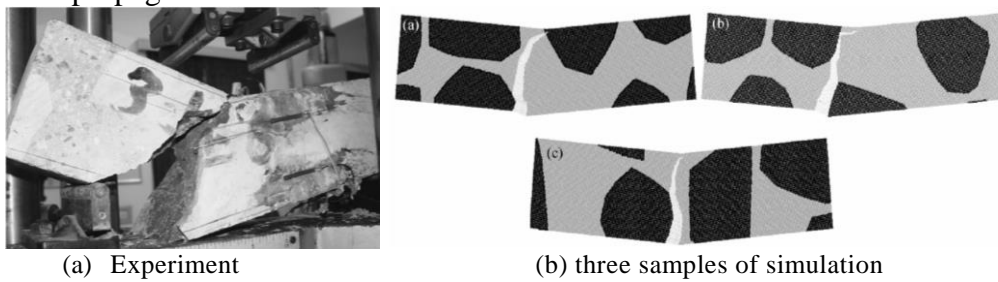


Figure 6: Failure pattern of four-point flexural beam by experiment test and numerical simulations

#### 4 NEW STRUCTURES OF RFC DAMS

Over the past years, Chinese engineers invent some new structures to improve the construction efficiency and safety of the RFC dams. To overcome potential weakness of the layer, an integrated impermeable layer is placed on the upstream face of the RFC dam body, as illustrated in Figure 7. For example, Baijia RFC double curvature arch dam with a height of 69 m employed this new type of impermeable layer structure.



Figure 7: Structure, photo of integrated impermeable layer and Baijia RFC arch dam (H = 69 m)

Figure 8 shows structure of the transverse joints and waterstops in RFC dams. Near the vicinity of these structures, there are only HSCC without rocks. Similar structure for galleries is also employed in RFC dams, as shown in Figure 9.

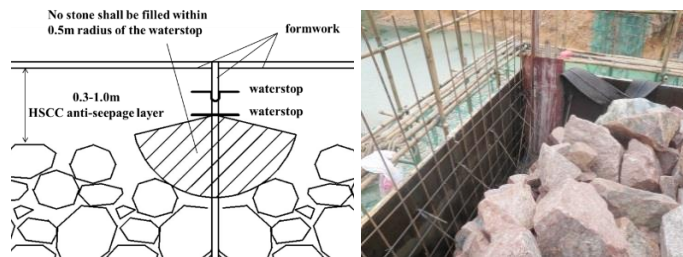


Figure 8: Structure and photo of transverse joint

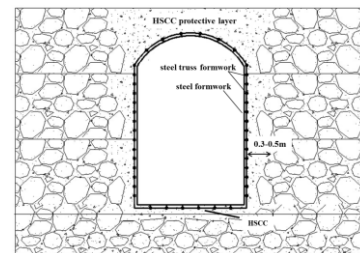


Figure 9: Structure of galleries

#### 5 CONSTRUCTION FACILITIES

During the construction process of RFC dams, some new facilities and equipment have been invented to improve efficiency and quality, such as rail sieve for rock bull screen, rock wash platform and grille bucket for rock loading, as shown in Figure 10.



Figure 10: Some new facilities and equipment for RFC construction

## 6 OTHER RELATED RESEARCH

Huang et al. <sup>16</sup> studied the environmental impact of RFC construction and concluded that RFC has a better environmentally friendly grade than conventional mass concrete and roller-compacted concrete. Liu et al. <sup>17</sup> evaluated the environmental loads in the lifetime of concrete dams by a hybrid life-cycle assessment (LCA) model. The results indicate that RFC reduces greenhouse gas emissions by approximately 64% and energy consumption by approximately 55% compared with conventional concrete. With regard to each life cycle stage, RFC reduces CO<sub>2</sub> emissions by 72% in material production, 25% in transportation, 51% in construction, and 15.6% in operation and maintenance.

## 7 SUMMARY

This paper reviews state-of-the-art research on RFC dams, which can be categorized as (1) Workability of HSCC and compactness of RFC, (2) Thermal and mechanical properties of RFC, (3) Structures of an RFC dam and (4) Construction and quality control measurements. The research demonstrates that RFC has good properties for dam construction and is an environmentally friendly construction technology. To date, the Chinese Standard “Technical Guideline for Cemented Material Dams” has been issued<sup>18</sup>, and another two technical guidelines are under preparation.

## ACKNOWLEDGEMENTS

The authors thank the National Natural Science Foundation of China (Grant No. 51239006), and the National 863 Technology Research and Development Program of China (No. 2012AA06A112) for their financial support. Many researchers who involved in RFC technology are gratefully acknowledged for their contribution.

## REFERENCES

- [1] ICOLD, *Bulletin on Rock-Filled Concrete Dam*, (Under preparing and to be published), 2019
- [2] M. Huang, X. An, H. Zhou and F. JIN, *Rock-fill concrete, a new type of concrete*, Tailor Made Concrete Structures, Walraven & Stoelhorst (eds), Taylor & Francis Group, London, ISBN 978-0-415-47535-8, pp1047-1049, 2008.
- [3] Y. Xie, D. J. Corr, M. Chaouche, F. Jin and S. P. Shah, *Experimental study of filling capacity of self-compacting concrete and its influence on the properties of rock-filled concrete*, Cement and Concrete Research, Vol. 56, pp121-128, 2014.
- [4] Y. Wang, F. Jin, J. Pan, Y. Xie and B. Wang, *Grating-box test: A testing method for filling performance evaluation of self-compacting mortar in granular packs*, Under review

- [5] J. Zheng, X. An and M. Huang, *GPU-based parallel algorithm for particle contact detection and its application in self-compacting concrete flow simulations*, Computers and Structures, Vol. 112-113, pp 193–204, 2012.
- [6] L. Qiu and Y. Han, *3D Simulation of Self-Compacting Concrete Flow Based on MRT-LBM*, Advances in Materials Science and Engineering, Article ID 5436020, 2018.
- [7] S. Chen, C. Zhang, Y. Feng, Q. Sun and F. Jin, *Three dimensional simulations of Bingham plastic flows with the multiplerelaxation-time lattice Boltzmann model*, Engineering applications of computational fluid mechanics, Vol. 10, No. 1, pp 346-358, 2016.
- [8] L. Qiu, *Three dimensional GPU-based SPH modelling of self-compacting concrete flows*, 3<sup>rd</sup> International symposium on Design, Performance, and use of self-consolidating concrete, Xiamen, China, 2014.
- [9] S. Chen, C. Zhang, F. Jin and Q. Sun, *Lattice Boltzmann-Discrete Element Modelling Simulation of SCC flowing process for Rock-Filled Concrete*, Computer Modeling in Engineering and Science, 2018.
- [10] M. Huang, X. An, H. Zhou and F. Jin, *Rock-Filled Concrete – development, investigations and applications*, International water and dam construction, April, pp 20-24, 2008.
- [11] X. An, Q. Wu, F. Jin, M. Huang, H. Zhou, C. Chen and C. Liu, *Rock-filled concrete, the new norm of SCC in hydraulic engineering in China*, Cement & Concrete Composites, Vol. 54, pp 89-99, 2014.
- [12] J. Wang, S. Wang and F. Jin, *Measurement and Evaluation of the Thermal Expansion Coefficient of Rock-filled Concrete*, Journal of Testing and Evaluation, Vol. 41, No. 6, 20120293, 2013.
- [13] J. Liu, *The Research and Application of Dam Construction Technology of Rock-Filled Concrete*, Applied Mechanics and Materials, Vol. 438-439, pp 1347-1350, 2013.
- [14] S. He, J. Lin and H. Zhou, *Experimental studies on shear properties of cold joints of Rock-filled Concrete*, International Conference on Electric Technology & Civil Engineering, pp 2191-2195, 2011.
- [15] X. Tang, C. Zhang and J. Shi, *A multiphase mesostructure mechanics approach to the study of the fracture damage behavior of concrete*, Science in China Series E: Technological Sciences, Vol. 51, Supp II, pp 8-24, 2008.
- [16] M. Huang, H. Zhou, X. An and F. Jin, *The environmental impact assessment of rock-filled concrete technology in dam construction*, Hydropower 2006, pp 1188-1197, 2006.
- [17] C. Liu, C. Ahn, X. An and S. Lee, *Life-Cycle Assessment of Concrete Dam Construction: Comparison of Environmental Impact of Rock-Filled and Conventional Concrete*, J. Constr. Eng. Manage., Vol. 139, A4013009, 2013.
- [18] Ministry of Water Resources of the People's Republic of China, *Technical guideline for cemented material dams*, SL678, 2014.