ARTICLE IN PRESS

Engineering xxx (xxxx) xxx

Contents lists available at ScienceDirect

Engineering

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

Research
Civil Engineering—Feature Article

A Brief Review of Rock-Filled Concrete Dams and Prospects for Next-Generation Concrete Dam Construction Technology

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ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Rock-filled concrete dam
Pouring compactness
Effect of large rocks
Intelligent quality control
Unmanned dam construction

ABSTRACT

Over the past few decades, one of the most significant advances in dam construction has been the invention of the rock-filled concrete (RFC) dam, which is constructed by pouring high-performance self-compacting concrete (HSCC) to fill the voids in preplaced large rocks. The innovative use of large rocks in dam construction provides engineers with a material that requires less cement consumption and hydration heat while enhancing construction efficiency and environmental friendliness. However, two fundamental scientific issues related to RFC need to be addressed: namely, the pouring compactness and the effect of large rocks on the mechanical and physical properties of RFC. This article provides a timely review of fundamental research and innovations in the design, construction, and quality control of RFC dams. Prospects for next-generation concrete dams are discussed from the perspectives of environmental friendliness, intrinsic safety, and labor savings.

1. Introduction

Although dams have been constructed for thousands of years, dam engineers continuously strive to develop new technologies to improve the safety and economics of dam construction. The systematic development of various dam construction technologies has established a sound foundation for understanding dam behavior, allowing higher dams to be built and culminating in significantly improved levels of dam safety, especially in recent decades [1,2]. The development of the roller-compacted concrete dam and the conventionally vibrated concrete dam has proven successful, which has led to an increasing number of projects adopting gravity dam and arch dam configurations due to their benefits of safety and efficiency [3–5]. Nevertheless, an obvious challenge remains for concrete dams: temperature cracking. The rock-filled concrete (RFC) dam was invented by Jin and An [6] from Tsinghua University of China to address this key challenge. Conceptually, RFC is constructed by pouring high-performance self-compacting concrete (HSCC) into an assembly of large rocks. The use of large rocks provides many advantages, such as reducing the cement consumption, thereby substantially lowering the hydration thermal increase and shrinkage of the concrete. Consequently, no cooling pipes are needed as temperature-control measures. The employment of HSCC eliminates vibration or roller compaction in concrete placement, which simplifies the construction process. RFC dams are economically profitable due to their use of naturally available large rocks and simplified construction procedures [7]. The foundations suitable for conventional concrete gravity dams are generally acceptable for the construction of RFC dams as well. Statistics from practical dam projects demonstrate that the comprehensive unit price of an RFC dam is 10%–30% lower than that of a conventional concrete dam or roller-compacted concrete dam [8]. Liu et al. [9] conducted systematic research on the life-cycle assessment and environmental impact of RFC and conventional concrete. RFC reduces carbon dioxide (CO_2) emissions by 72% in material production, 25% in transportation, 51% in construction, and 15.6% in the operation and maintenance stage.

To date, more than 130 RFC dams have been constructed and more than 30 RFC dams are under construction in China. For example, the Baijia RFC double-curvature arch dam with a height of 69 m was initially impounded in September 2015 and has been operating for more than 7 years. Monitoring data demonstrate that it operates very well, evidenced by measured maximum

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https://doi.org/10.1016/j.eng.2023.09.020

Please cite this article as: F. Jin, D. Huang, M. Lino et al., A Brief Review of Rock-Filled Concrete Dams and Prospects for Next-Generation Concrete Dam Construction Technology, Engineering, https://doi.org/10.1016/j.eng.2023.09.020

displacements at the dam crest and bottom of 8.4 and 1.5 mm, respectively. Notably, the dam discharged a peak flood of 1600 $m^3 \cdot s^{-1}$ through the spillway on the crest on September 28, 2017.

With continuous technological advancement and maturity, an increasing number of high RFC dams have been completed, such as the Xiyuan (77 m high), Pingkeng (79.7 m high), Manping (77 m high), Maliuwan (75 m high), and Songlin (90 m high) RFC gravity dams, as well as the Baijia (69 m high), Shaqian (66 m high), and Niudongkou (64 m high) arch dams. In addition, the Yongfeng (83 m high) RFC arch dam is currently under construction. The practice of using RFC in high-altitude and cold areas also demonstrates its good durability, with examples such as the Manping high RFC dam on the Qinghai-Tibet Plateau. The Xiaolonggou RFC dam, which has a crest elevation of 3957 m, was completed in May 2023. Moreover, RFC was implemented in the reservoir dam for the 2022 Beijing Winter Olympics, to support the water supply for snowmaking for the alpine skiing events. In that project, the RFC pouring of a 58 m-high dam body was completed within only 140 days—a historically rapid construction for RFC dams. The state-of-the-art design and practice of RFC dams is well documented in a series of technical codes, including the *Technical Guide for Rock-Filled Concrete Dams* (NB/T 10077-2018) [10], *Construction Specification for Rock-Filled Concrete of Hydropower and Water Conservancy Engineering* (DL/T 5806-2020) [11], and the *Technical Code for Rock-Filled Concrete Arch Dams* (DB52/T 1545-2020) [12]. To date, RFC dams have been recognized by the international community, and RFC dam constructions are set to break ground in countries beyond China, such as Burundi and Angola.

It should be noted that Michel Lino was involved in the review of the International Commission on Large Dams (ICOLD) bulletin No. 190 *Cemented Material Dam: Design and Practice—Rock-Filled Concrete Dam* [13]. According to this bulletin, RFC dams are not only a type of cemented material dam (CMD) but are also basically concrete dams, whether gravity dams or arch dams. As a new construction technique, RFC dams are very efficient in terms of cost and timelines, according to Chinese experience. It is also an environmentally friendly technique, with low cement consumption and a reduced carbon footprint. The Chinese experience of more than 100 successful projects demonstrates that RFC is virtually a mature and safe dam-construction technique. ICOLD is supporting Chinese engineers' efforts and encouraging the development of RFC dams worldwide, along with the transfer of this efficient technology to designers and contractors all over the world. Further research and practice are being undertaken worldwide to consolidate the knowledge in view of the global dissemination of RFC dams.

The content covered in this article falls into five sections. The basic idea, development, and current state of the practice of RFC dams are introduced in the first section. Fundamental scientific issues of pouring compactness and the effect of large rocks, and how these influence the major principles of RFC, are presented in the section 2. Applications of these principles to the design and construction of RFC dams are presented in later sections: section 3 introduces innovations in the design and construction practice, where project-oriented insightful comments are provided. A sketch of the future of concrete dam construction from the viewpoint of the authors is shown in section 4. The last section concludes with insights gained from engineering practice, which will guide the development of innovative technology in the years to come.

2. Fundamental scientific issues of RFC: Pouring compactness and the effect of large rocks

The advantages of RFC come with concerns that need to be addressed, such as whether HSCC can thoroughly fill the voids among rocks—a concept known as pouring compactness—and the effects of the large rocks on the mechanical and physical properties of RFC, which is hereafter referred to as the "effect of large rocks" [8]. An illustrated diagram of research and scientific issues in the area of RFC is provided in Fig. 1.

2.1. Pouring compactness of RFC

Over the years, the pouring compactness of RFC has been comprehensively investigated with regard to the filling process of HSCC and the blocking mechanism of coarse aggregates in this filling process. A series of well-designed experiments were conducted to simulate HSCC flow in the rockfill by a collaborative research team from Northwestern University in the United States and Tsinghua University in China. Through these experiments, the effects of aggregate size and yield stress on the filling behavior of HSCC were determined [14]. Moreover, the porosities of the interfacial transition zone (ITZ) between the large rocks and HSCC have been examined using both backscatter electron and nanoindentation tests. The pouring compactness of the HSCC in the rockfill has a significant effect on the interface porosity after hardening. The better the filling is, the higher the interface porosity of the specimen after hardening, the narrower the ITZ zone, and the denser the microstructure in the RFC will be [15–18].

During dam construction, a practical reference for evaluating the pouring compactness on site is desirable. This is achieved by reviewing extensive grating-box tests and numerical simulation data. When passing through narrow voids between packed rocks, large aggregates tend to jam the HSCC flow, which would cause poor compactness in the RFC. Both grating box tests and numerical investigations reveal that the size ratio of the coarse aggregates to the rocks is crucial for preventing such a jamming effect. Following this line of reasoning, an empirical relation has been proposed to evaluate the pouring compactness of RFC on site, based on the properties of the rocks and HSCC [8]:

$$I_A = \frac{MK(1-\varphi)}{s}\frac{\tau_0}{\rho g} \tag{1}$$

where I_A represents the gradient, which indicates the capacity of HSCC to fill the voids among the rockfill; φ is the volumetric ratio of rocks in the rockfill; τ_0 denotes the yield stress of HSCC; s is the characteristic length of the rocks (e.g., the average grain size of rocks); M and K denote the shape of rocks and their pattern of placement, g denotes the gravitational acceleration, and ρ represents density, respectively. Thus, the filling capacity of HSCC in the rockfill can be evaluated by two parts: the first part, $\frac{MK(1-\varphi)}{s}$, represents the filling resistance of the rockfill, and the second part, $\frac{\tau_0}{\rho g}$, denotes the property of HSCC. The relation in Eq. (1) provides a practical reference for the control criteria of rock grain size and HSCC workability during RFC dam construction.

2.2. Effects of large rocks on properties of RFC

Due to the large rocks, standard test methods for conventional concrete are not suitable for RFC, since an oversized RFC specimen at least three times greater than the grain size of the rocks (i.e., 300 mm) poses significant challenges in terms of testing capacity and costs. Therefore, unremitting efforts have been made in recent decades to develop appropriate laboratory and numerical methods for testing the strength and physical properties of RFC. Large RFC specimens with grain sizes of 300, 600, and 900 mm have been prepared and tested in terms of various properties, including static and dynamic compressive strength, tensile and shear strength, fracture energy, density, adiabatic thermal rise, coefficient of thermal expansion, creep, shrinkage, seepage resistance, frost resis-

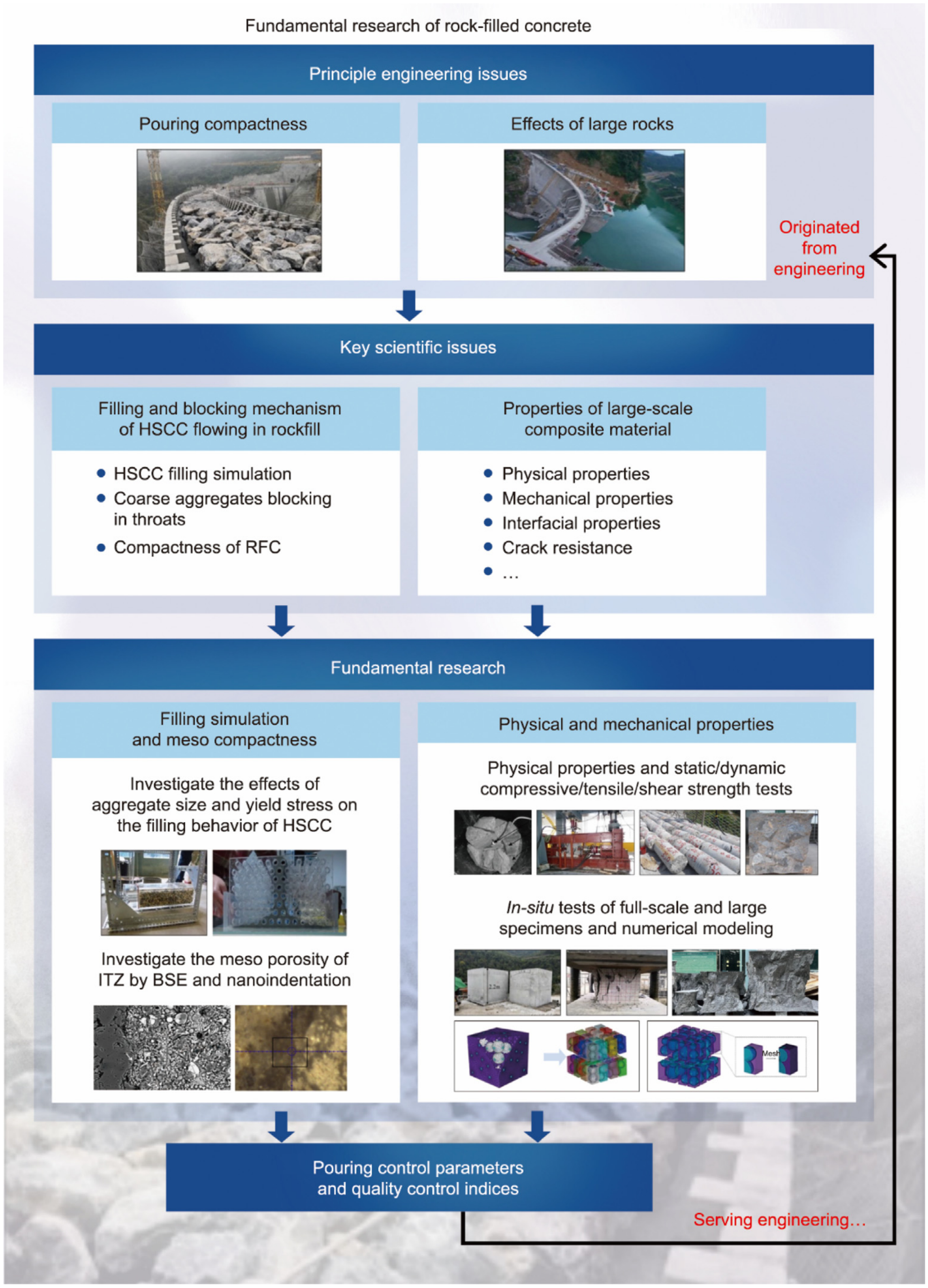

Fig. 1. Illustrated diagram of the fundamental research and key scientific issues of RFC. BSE: backscatter electron and ITZ: interfacial transition zone.

tance, and interface behaviors [15,16,19–25]. As RFC is a dam construction material, the seepage resistance of RFC has been measured not only in lab tests but also by water pressure tests in the dam body. Most onsite water pressure test results for RFC dam bodies are under 1 Lu (1 Lu indicates that when the pressure of the test section is 1 MPa, the pressure flow rate per meter of the test section is 1 L·min^{-1}). The seepage measurements of the bottom gallery of the Shaqian and Niudongkou RFC arch dams, which have dam heights greater than 60 m, are merely 0.325 L·s^{-1} and 0.26 L·s^{-1}, respectively.

To fully understand the effect of large rocks on RFC properties, two oversized 2.2 m cubes were cast on site and cut into large specimens to test their mechanical properties [26]. A significant number of qualified test data demonstrate that the compressive strength of RFC is always greater than that of HSCC, which establishes a solid foundation for determining the compressive strength of RFC using standard HSCC specimens for conservative and simple consideration. Aside from the compressive strength, the uniaxial and splitting tensile strengths have been studied via a series of companion tests. The relation between the splitting tensile strength and the compressive strength of RFC aligns well with that of conventional concrete. Based on the test results, the tensile strength of RFC can be determined to be 0.9 times the tensile strength of HSCC [10,11]. The shear strength at the lifts of RFC is rather high due to the interlocking effect of rocks exposed at the lift surface. The impacts of powders on the shear strength at the lift surface have been determined through tests, providing technical support for quality control standards for RFC [25]. To support the seismic design of RFC dams, a set of laboratory tests are also being carried out to understand their dynamic properties. It has been demonstrated that the "multipeak" behavior of a large RFC specimen is due to the ductility of the rockfill skeleton.

From a numerical perspective, a three-phase finite-element model that simulates rocks, HSCC, and the ITZ between them has been proposed [27]. Numerical simulations have shown that the model can adequately describe the mechanical behaviors of RFC specimens over multiple curing ages. The numerical simulation results align well with onsite experimental data, indicating that the method proposed in the study is validated for simulating the RFC behaviors for engineering applications. The Eshelby tensor inclusion theory is used to describe the effects of distributed large rocks, which allows for a realistic representation of the rock-skeleton structures in RFC. Thus, the equivalent elastic modulus over multiple curing ages could be determined. RFC has an initial modulus ($\sim$5 GPa) owing to the existence of the large rockfill skeleton. An empirical model for the estimation of the elastic modulus of RFC was thereafter developed based on the elastic properties of rock and HSCC, as well as the rockfill ratio [27].

It is of primary importance to understand the dynamic properties of RFC. Extensive laboratory tests have been conducted to investigate its dynamic failure mode, as well as the loading rate effect on the stress–strain behaviors. Large-scale triaxial-dynamic equipment has been used for this purpose. As per the requirement in the Chinese code [28], tests are conducted using a wide variety of RFC specimens: namely, 100, 150, and 300 mm cube specimens and 100 mm $\times$ 100 mm $\times$ 200 mm and 150 mm $\times$ 150 mm $\times$ 300 mm specimens. The influence of different strain rates (i.e., $10^{-5}\cdot s^{-1}$, $10^{-4}\cdot s^{-1}$ and $10^{-3}\cdot s^{-1}$) is considered. Various failure modes of cube specimens have been observed under dynamic loading at different strain rates. The presence of multiple peaks in the stress–strain relation clearly demonstrates that RFC has superior ductility under dynamic loading due to the existence of a rockfill skeleton.

3. Innovations in the design and construction of RFC dams

As one type of concrete dam, the design principles of RFC dams are similar to those of conventional concrete dams in terms of structural analysis methods and loads, flood discharge and energy dissipation, and foundation treatment. As some of the most important issues for concrete dams, the hydration temperature control and cracking resistance of RFC differ significantly from those of conventional concrete dams. The use of a large amount of large rocks reduces the cement consumption and hydration thermal rise, which results in the elimination of the need for cooling pipes. To study the flowing process of HSCC into the rockfill and the thermal exchange between HSCC and rocks, onsite measurements of the HSCC flowing process and temperature rise of HSCC are being conducted in practical RFC dam projects. The temperature field of the RFC dam and thermal stresses during the early ages of the RFC are simulated by three-dimensional (3D) finite-element models [29]. Technical innovations in RFC dams are summarized in Fig. 2.

3.1. Eliminating transverse joints and impervious zones in gravity dams

Based on monitoring data and numerical simulations of RFC dams, the Zunyi Survey and Design Institute of Water Conservancy and Hydropower pioneered the design of a wide-monolith gravity dam. The width of the monolith of the Datugai RFC gravity dam (41 m high) is greater than 130 m—much wider than the approximately 20 m of conventional concrete gravity dams. Furthermore, the Wanjiagou RFC gravity dam in Guizhou Province, which was designed by the same institute, is free of transverse joints and upstream impervious zones. This dam impounded the reservoir in April 2018, and no cracking or leakage has been observed since then in monitoring data and onsite inspections. Such a performance adequately demonstrates that it is feasible not to set an impervious layer when building a RFC dam with low to medium water heads, such that the dam can be cast in an integral section without transverse or longitudinal joints.

3.2. Development of RFC arch dams

It is well known that arch dams exhibit many advantages, such as small dam bodies and strong seismic overload capacity. An arch dam is a statically indeterminate structure with complex stresses and stricter requirements for dam-building materials. The development of the RFC arch dam dates back to the early 2010s, when the first RFC arch dam—the Mengshan single curvature arch dam with a height of 24.5 m in Shandong Province—was constructed. Another notable RFC arch dam, the Baijia double-curvature arch dam (69 m tall), was later designed by the Ankang Survey and Design Institute of Water Conservancy and Hydropower and was completed and established in 2016. The Baijia dam was the highest RFC arch dam at that time. The dam body is composed of RFC with a strength class of $C_{90}20$. The integrally poured HSCC impervious zone is set at the upstream face, and six conventional transverse joints are set at the RFC dam body. To date, more than 14 RFC arch dams have been completed or are under construction.

In the design of arch dams, it is necessary to accurately determine the temperature load in order to analyze the stress distribution of arch dams, optimize their shape, and ensure dam safety. The integrally poured RFC arch dam has been developed and is free of transverse or longitudinal joints and thus of closure grouting [30]. This simplified dam structure greatly shortens the construction period. From the practical standpoint of structural analysis, the placing temperature of RFC is determined based on the air temperature and placing temperature of HSCC. The closure temperature of the integrally poured arch is estimated by appropriately accounting for the RFC placement temperature, as well as the evolution of the elastic modulus and hydration thermal increase. A modified trial load method is thereafter proposed using this closure temperature, based on extensive onsite monitoring and a clear understanding of the RFC's hydration thermal increase process [31]. Aligned with the new design principle, comparative analyses of multiple engineering calculations were carried out—particularly thermal–stress analyses covering the entire construction-impounding-operation phases. A corresponding allowable tensile stress of 1.5–2 MPa was thereafter specified to limit potential cracking, and the important design issues have been documented in the *Technical Code for the RFC Arch Dam of Guizhou Province* [12].

3.3. Integral HSCC impervious zone and other integral-HSCC detailing

An impervious zone at the upstream face is usually arranged in a conservative design of an RFC dam. At the early stage of RFC development, an impervious zone made of conventional vibrating concrete was constructed prior to or after the RFC dam body. To further facilitate construction, an upstream impervious zone using HSCC, which was cast together with the dam body, was recommended for RFC dams. During the construction process, the difference between the HSCC zone and the RFC dam body is that no large rocks are preplaced in the HSCC zone. Systematic tests demonstrate that integral impervious zones significantly enhance the construction efficiency and improve the cohesion between impervious zones and dam bodies. To date, integral HSCC impervious zones have become an extensively used design practice. With

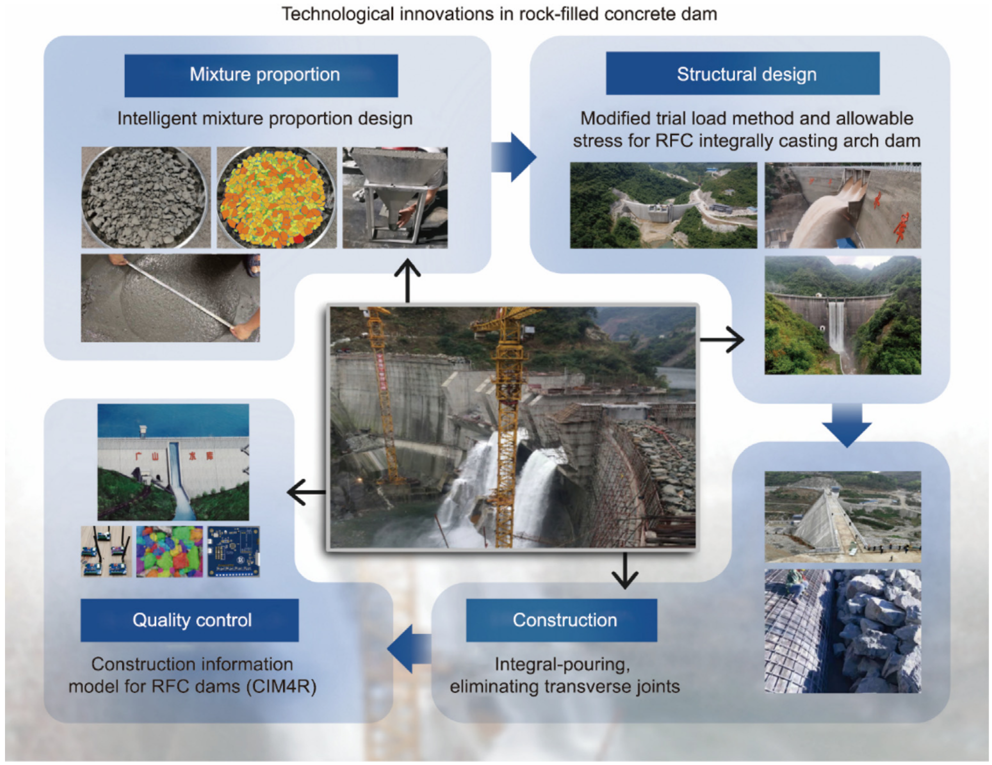

Fig. 2. Technical innovations in the RFC dams.

regard to dam detailing such as waterstops at transverse joints and galleries, integral HSCC casting technology can be employed. No large rocks are placed in the vicinity of the detailing; then, HSCC is cast together with the RFC dam body. The use of integral-HSCC detailing facilitates the construction of RFC dams.

3.4. Optimization of raw material and the intelligent mixture proportion design of HSCC

Fly ash, as a component of the HSCC mixture, is an important material that reduces hydration heat and improves the performance of HSCC. To date, the highest completed RFC gravity dam is the Songlin dam in Yunnan Province, with a height of 90 m. Due to the lack of fly ash near the dam site, limestone powder was used as a replacement in HSCC production. Through mixture proportion optimization for the HSCC, the performance of HSCC without fly ash can fully meet the design requirements, allowing HSCC without fly ash to be used in an RFC dam. This type of HSCC effectively reduced the pumping pressure and exhibited favorable segregation resistance in the construction of the Songlin RFC dam. It offers a technical, economic, and environmental solution for RFC construction in regions with sufficient limestone quarries.

A total of 114 sets of HSCC mixture proportion data from 88 RFC dam projects have been compiled and systematically analyzed. Based on these analysis results, an effective mixture proportion design software has been developed. The materials used in RFC dams are sourced to make optimal use of local materials. If there is a shortage of large rocks, the feasibility of using smaller rocks (e.g., with a grain size of 150 mm instead of 300 mm) should be investigated. Following this line of reasoning, smaller coarse aggregate is now used, although the requirements for higher HSCC flowability must be met. In some regions in Southwest China, only soft red sandstone can be found, the compressive strength of which may be less than 30 MPa—the requirement for the strength of large rocks. After demonstration by an onsite test, red sandstone was used in the Qiyi RFC dam. This employment of red sandstone made full use of local materials and reduced the construction costs.

3.5. Instrumentation and AI-based construction management

To determine the behavior of an RFC dam during the periods of construction, reservoir filling, and operation, measurements are made on the dam body to obtain behavior criteria values such as uplift pressure and seepage. Taking the instrumentation of the Baijia double-curvature RFC arch dam as an example, vibrating-wire piezometers and uplift pressure meters are installed to monitor the seepage pressure and hydraulic pressure at the dam base, respectively. A total of 73 resistance thermometers are distributed in several dam sections for temperature measurements, while a group of 27 electrical resistance strain gauges have been installed to form a comprehensive strain-monitoring system in the RFC dam. To further improve dam quality control, an artificial intelligence (AI)-based construction information model for RFC dams (CIM4R) was recently developed. A series of monitoring equipment and image-recognition technologies based on deep learning have been developed, which realize intelligent onsite monitoring at RFC dam sites. Intelligent onsite image recognition of rocks has also been developed, as the particle size is crucial in determining the compactness and quality of RFC. Based on CIM4R, a database center for RFC dam projects has been established; CIM4R efficiently integrates multisource and multilevel information, including raw material, machinery, personnel management, construction management, monitoring, and other data, into the information platform [32,33]. These AI-based construction-management technologies have been implemented in Guangshan, Yanggongyan, Shaqian, and other RFC dam projects. Precise quality control has been achieved, marking the beginning of a new age of intelligent construction management for RFC dams.

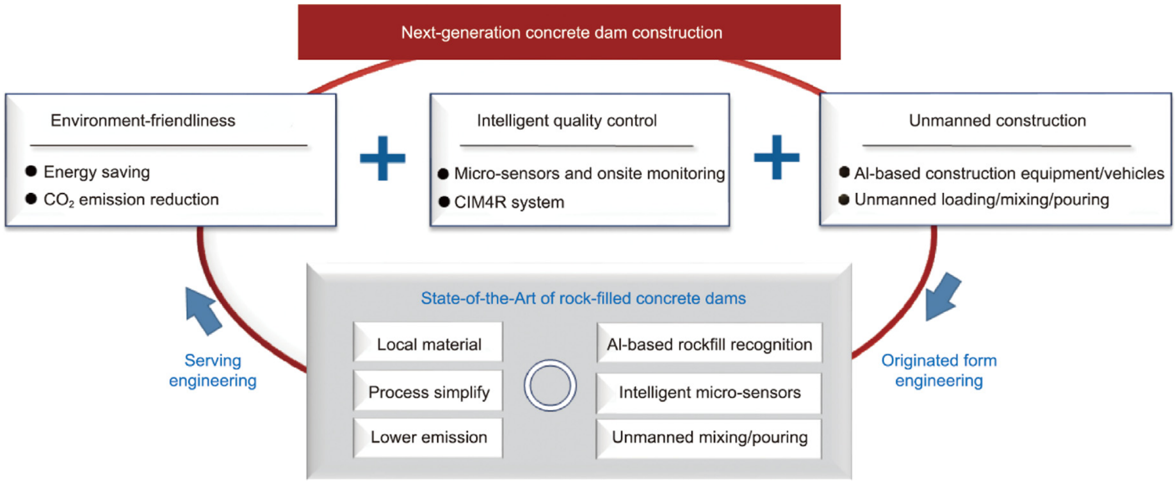

Fig. 3. Future directions in the construction of concrete dams.

4. Prospects for next-generation concrete dam construction technology

From our perspective, the basic characteristics of next-generation concrete dam buildings include environmental friendliness, intrinsic safety, and labor savings, which may require unmanned construction, as illustrated in Fig. 3. Given the crucial goals of energy conservation and emission reduction, the development of RFC has revolutionized construction technology, fulfilling these goals by eliminating vibration or roller compaction and making full use of local materials. As demands for intelligent dam quality control during construction necessitate new technologies, a team of researchers and engineers has been assembled to perform pioneering work in the design and applications of advanced sensing systems for intelligent RFC dam construction. For example, sensitive and robust instruments to measure the workability of HSCC need to be continuously researched and developed. Microsensors can then be assembled into dam structural elements, allowing the establishment of an intelligent dam construction information system. Sufficient data would provide a viable means to evaluate the quality over the entire construction phase of RFC dams.

Furthermore, intelligent or unmanned dam construction that adapts to the future labor market is a promising development direction, driving the further development of RFC technology to increase mechanical performance and the adoption of AI-based construction equipment and vehicles. Unmanned vehicles should be implemented to transport and place large rocks. Automatic mixing and pouring equipment for HSCC is currently under development. Environmental friendliness and intelligent concepts provide comprehensive and systematic solutions for the design of next-generation concrete dams. These concepts will find wide applications in future RFC dam construction.

5. Conclusions

Since its invention in 2003, RFC technology has been one of the nation's fastest-growing dam construction technologies. The employment of HSCC eliminates vibration or roller compaction in concrete placement, which simplifies the construction process while reducing the hydration thermal increase and shrinkage of concrete. To date, more than 130 RFC dams have been constructed and about 30 RFC dams are under construction in China. Based on the statistics of practical dam projects, the comprehensive unit price of an RFC dam is 10%–30% lower than that of a conventionally vibrated concrete or roller-compacted cement dam. Moreover, RFC reduces CO_2 emissions by 72% in material production, 25% in transportation, 51% in construction, and 15% in the operation and maintenance stages.

This article provides a timely review of the principles of RFC technology and innovation, as well as the application of these principles to the design and construction of RFC dams. State-of-the-art analyses of dam structure, laboratory testing, and onsite experiments are conducted to optimize the design of RFC. A comprehensive technical standard system for RFC dams covering construction materials, design, construction, and quality control has been established, including the ICOLD bulletin No. 190 *Cemented Material Dam: Design and Practice—Rock-filled Concrete Dam*, which was formally approved in 2022. It is believed that the emerging technologies of RFC are continually contributing to the long-term, sustainable, and environmentally friendly development of dam construction in China and countries beyond.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors are grateful for the support from the Key Program Grant (52039005) from National Natural Science Foundation of China and Grant (2022-KY-01) from State Key Laboratory of Hydroscience and Engineering.

Compliance with ethics guidelines

Feng Jin, Michel Lino, Duruo Huang, and Hu Zhou declare that they have no conflict of interest or financial conflicts to disclose.

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