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Rock-Filled Concrete: Materials, Properties and Quality Control for Indian Practice

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***Abstract*: Rock-filled concrete (RFC), developed in China by Prof. Feng Jin and his team, is mainly used for dams. Large rocks are placed first. High-performance self-compacting concrete (HSCC) is then poured from the top of the rock-filled lift and flows under its own weight into the spaces between them. This paper reviews how the materials act together and discusses rock, HSCC and composite properties, testing, quality control and validation with Indian materials. It also explains why HSCC requires performance beyond basic SCC test compliance. RFC has been used extensively in China for gravity and arch dams, with projects also reported outside China.**

***Keywords*: Concrete properties, Indian implementation, Quality control, Rock-filled concrete, Self-compacting concrete.**

1. Introduction

Rock-filled concrete (RFC) is a mass concrete that was developed in 2003 in China, mainly for dams. It is made in two stages. Large, sound rocks, generally 300 mm or larger, are placed inside the formwork to form a stable skeleton. HSCC is then poured from the top of the rock-filled lift and flows under its own weight through the interconnected spaces, without vibration. After hardening, both materials act as one monolithic composite having properties similar to conventional vibrated concrete. Unlike conventional concrete, the large rocks are placed separately at site rather than mixed at the batching plant. HSCC is a complete concrete containing cementitious powder, sand and coarse aggregate [1], [2].

As RFC was developed in China, it has been used there extensively. A July 2026 inventory, dominated by Chinese projects, lists 226 RFC gravity dams and 14 RFC arch dams higher than 15 m, together with seven strengthening works [3]. These include completed dams and projects under construction. Although China remains the principal centre of RFC practice and provides most of the available construction experience and material-performance data, published records also document RFC projects in Burundi, Pakistan, and Türkiye [1], [2].

During a technical visit to China, the author visited the Canlin, Matiao and Guangkeng gravity dams and directly observed RFC construction, including placement of the large-rock skeleton and pouring of HSCC from the top of the lift. The dams are 66.5 m, 69.0 m and 74.0 m high, respectively [3], [4]. These field observations inform the practical explanations; numerical values and acceptance guidance remain drawn from cited literature.

RFC performance depends on three linked parts: the rock skeleton, the HSCC filling the spaces, and the rock-concrete interface. If HSCC cannot reach every accessible space, hidden spaces may remain. Cube tests assess HSCC but cannot reveal such unfilled spaces; RFC quality must therefore combine concrete tests with a representative filling trial.

This technical review considers RFC from a concrete-material viewpoint: material selection, relevant properties, mix development, filling, testing and quality control. For Indian conditions, acceptance criteria need to come from trials with the proposed rock, sand, cementitious materials, admixtures and water.

2. Materials and Mix Requirements

A. Materials and their Functions

Fig. 1 shows the arrangement. Large rocks form the skeleton; HSCC fills the voids and bonds the mass. Reported rock content is commonly about 50 to 65 percent of RFC volume [1], [2], [5], but the workable proportion depends on rock size and shape, available voids, HSCC flow and travel distance. Table 1

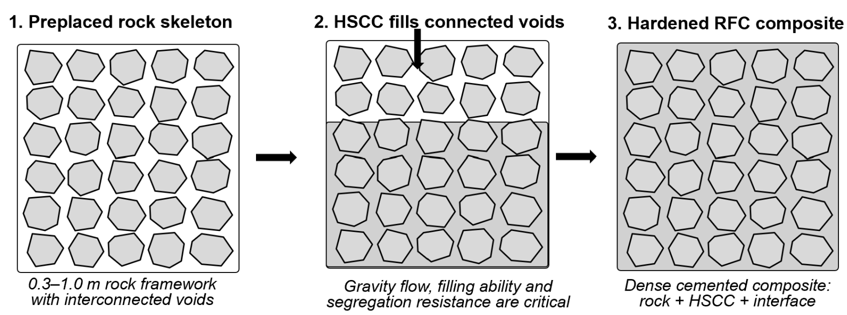

Fig. 1. Formation of rock-filled concrete from a preplaced rock skeleton and HSCC (based on [1], [2])

*Corresponding author: ramaner2003@gmail.com explains the role of each material.

1) Large-rock properties

Large rock replaces part of the concrete volume, carries load, forms the internal skeleton and defines passages for HSCC. ICOLD Bulletin 190 requires the use of sound, durable rock of adequate strength and excludes weak or thinly bedded materials such as shale and slate. As summarised in the Bulletin, Chinese practice evaluates rock in the saturated condition and generally requires a strength at least twice the specified RFC strength. Rock surfaces must be clean, as dust and clay can impair bond development, while excessive small fragments may obstruct the flow of HSCC [1].

2) HSCC properties

HSCC is more than highly flowable concrete. It must move under its own weight through irregular voids between the rocks while maintaining a uniform distribution of coarse aggregate. This requires a balance of flowability, passing ability, viscosity, segregation resistance and workability retention throughout placement. ICOLD Bulletin 190 provides initial ranges for proportions and fresh-concrete tests; however, these must be validated with the proposed Indian materials, temperature, batching plant and placing distance [1].

IS 1199 (Part 6):2018 specifies Indian test methods for fresh SCC. Although useful as a baseline, compliance alone does not demonstrate effective RFC filling. HSCC must maintain flowability and stability during placement, pass through actual rock voids without blockage or segregation, and fully fill a representative full-scale rock arrangement. These aspects require project-specific verification trials [1], [6].

B. Why Filling Governs the Mix Design

In RFC, the most fluid HSCC mix is not necessarily the most reliable. HSCC needs enough paste and mortar to coat the rock and pass through the spaces, but also enough internal resistance, or viscosity, to remain uniform. If viscosity is too low, coarse aggregate may separate or water may rise, causing segregation or bleeding. Trials must balance powder content, water-to-powder ratio, superplasticizer dosage, aggregate grading and transport time.

Rock arrangement and HSCC grading must therefore be considered together. Small rock fragments can narrow a passage until coarse aggregate in the HSCC becomes trapped, creating a blockage. Filling tests should reproduce both the proposed rock arrangement and the expected flow distance [7]. For traceability, the mix-design record should state the percentage and size range of large rock, aggregate moisture, HSCC results at the mixer and at placement, and the time between mixing and placing.

Table 1
Materials used in RFC and their purpose [1], [2]

Material	What it does	What should be checked
Large rock	Forms the main load-carrying framework and replaces part of the concrete volume.	Rock type, strength, durability, shape, size range and clean surfaces free from mud and dust.
Cementitious powder in HSCC	Forms the paste that flows around the rock and binds the composite after hardening.	Cement and mineral additions, water-to-powder ratio, admixture compatibility and heat generation.
Sand and coarse aggregate in HSCC	Give body to HSCC while still allowing it to flow through the rock spaces.	Particle-size distribution, moisture, maximum aggregate size and risk of blockage.
Water and chemical admixture	Provide the required flow and help HSCC retain workability during transport and placement.	Water quality, correct dosage, mixing time, transport time and effect of temperature.

Table 2
Selected large-rock and HSCC references reported in ICOLD Bulletin 190

Property	What Bulletin 190 reports	How it should be used in India
Rock source and strength	Hard, sound quarry rock or durable boulders may be used. The reported Chinese practice requires saturated rock strength to be at least twice the specified RFC strength.	Test the actual source for rock type, strength, durability and the effect of water.
Rock size and cleanliness	A practical minimum rock size is 0.30 m. Rock size is normally about 10 to 15 times the largest aggregate in HSCC. Dust is limited to 0.2 percent, and clay-covered pieces are rejected.	Confirm by a filling trial because local rock shape and size distribution affect the available flow passages.
HSCC proportions	Starting ranges include 20 mm maximum coarse aggregate, coarse aggregate occupying 0.27 to 0.33 of the concrete volume, 170 to 200 kg/m^3 water, water-to-powder ratio of 0.80 to 1.15 by volume, and powder occupying 0.16 to 0.20 of the volume.	Use these values only to begin local trial mixes. Powder means cement and other very fine cementitious material.
HSCC flow and stability	Reported values include 260 to 280 mm slump, 650 to 750 mm slump-flow spread, 7 to 25 seconds through the V-funnel, and at least one hour of stable self-compacting behaviour.	Check that HSCC remains uniform and fills the intended rock arrangement over the full placing distance.

Note: Values independently compiled from ICOLD Bulletin 190 [1]. They are trial references, not proposed Indian acceptance limits.

Table 3
Fresh HSCC and filling checks [1], [2], [6], [7].

Check	What it shows	How to verify it
Slump flow and its retention	The spread diameter shows how freely HSCC flows. Repeated testing shows how quickly workability is lost.	Measure at mixer discharge and again at placement; compare with the approved trial.
V-funnel flow time	The time taken to pass through the funnel indicates the mixture's viscosity and uniformity.	Use it with slump flow because a large spread alone does not prove a stable mix.
Resistance to segregation	Shows whether coarse aggregate remains evenly distributed instead of separating from mortar.	Use a recognised stability test and inspect cut surfaces of the trial placement.
Passing and blockage resistance	Shows whether HSCC can move through the narrowest spaces without aggregate becoming trapped.	Test with the proposed rock sizes and the longest expected flow distance.
Complete filling	Confirms that no unacceptable empty pockets remain inside the hardened RFC.	Cast a full-scale trial and inspect it by cutting, coring or another validated method.

3. Fresh HSCC and Filling Performance

While it is fresh, HSCC has one overriding task: to fill the rock skeleton without vibration or separation. To do this, it must flow far enough, remain uniform, pass through the available spaces without blockage and retain its workability until placement is complete. Table 3 explains the main checks and what each one tells the engineer.

Routine HSCC tests cannot show what happened inside the rock skeleton. A full-scale trial should reproduce the proposed rock, equipment, placing method, form size and flow distance. Cutting or coring after hardening can reveal the filling achieved. The trial should also represent delivery delay, temperature change and a short interruption.

Fresh-property control must continue throughout production. Adding water at site to recover lost flow changes the verified mix and should not be allowed. Repeated workability loss calls for checks on material temperature, moisture correction, admixture compatibility, mixing energy, transport time and the mix itself.

4. Properties of Hardened RFC

A. Strength, Stiffness and Rock-Concrete Bond

Once hardened, RFC consists of large rock pieces, hardened HSCC and a thin contact zone between them. HSCC strength alone cannot describe the strength of the composite. Rock strength and shape, rock content, the quality of the interface, placement, curing and specimen size all influence the result. Research also shows that the placing method can affect strength, water passage and small pores at the interface, while the rock skeleton changes the stiffness of the completed material [8], [9].

For this reason, equations developed for ordinary concrete should not be applied to RFC without verification. Strength and elastic modulus, a measure of stiffness, are best determined from specimens or cores large enough to contain several representative rock pieces. The sampling location and core direction also need to be recorded because a crack may pass through rock, HSCC and interface in different proportions.

Fracture energy is the energy needed to extend a crack. A 2024 numerical study used 400 N/m for RFC and 262 N/m for conventional vibrating concrete and predicted less RFC damage for the selected earthquake inputs [5]. The RFC value was inferred from tests and size-effect assumptions, not measured in a full dam, and is therefore not a general design value. It nevertheless suggests that Indian trials should examine whether large rocks and interface-controlled crack paths improve crack resistance.

B. Heat, Water-Tightness and Long-Term Movement

Replacing part of mass concrete with rock reduces the cementitious volume and may reduce heat generation. This benefit must be demonstrated because peak temperature also depends on materials, rock percentage, placing temperature, member size and curing. The coefficient of thermal expansion, which measures temperature-related size change, should be tested on RFC rather than HSCC alone [10]. The rock skeleton can also alter shrinkage and creep under sustained load [11].

Water-tightness similarly depends on complete filling and continuity across the rock-concrete interface; compressive strength by itself is not enough. Clean rock surfaces, stable HSCC, controlled placement and suitable curing all reduce the likelihood of porous interfaces and hidden voids. Table 4 lists the evidence needed before hardened-property targets are adopted in a project specification.

5. Quality Control of the Completed Composite

RFC quality control cannot be limited to concrete cube tests: these may confirm HSCC strength but not reveal hidden spaces. Control begins with materials and a full-scale trial, continues through batching, rock and HSCC placement and curing, and ends with checks on the composite. Table 5 follows this sequence.

A location-based record can link each placed volume to its rock source, HSCC batch, fresh-test results, placement time, weather, photographs and later core results. This traceability is valuable after hardening, when internal surfaces are hidden, but it does not replace inspection and testing.

6. Material Validation for Indian Use

Indian concrete practice already has well-established standards for materials and testing. IS 1199 (Part 6):2018 covers tests on fresh SCC, IS 383:2016 covers conventional aggregates, IS 10262:2019 addresses mix proportioning, and IS 516 (Part 1/Sec 1):2021 covers strength testing [6], [12]-[14]. They provide a sound starting point, but RFC needs additional checks because its rock pieces are far larger than conventional aggregate and are placed separately. The central construction question remains whether HSCC has completely filled the rock skeleton.

Validation should begin with local rock, sand, cement, mineral additions, admixtures, water and expected site temperatures. Fig. 2 shows a suitable sequence. Meaningful

Table 4
Important properties of hardened RFC [2], [8]-[11]

Property	What can control the result	How it should be checked
Compressive and tensile strength	Cracking may pass through rock, HSCC or the interface.	Test representative large specimens and cores from different locations and curing conditions.
Elastic modulus (stiffness) and strain	The rock framework makes RFC respond differently from ordinary concrete.	Measure stiffness and deformation directly on representative RFC specimens.
Permeability (water passage) and filling	Water can pass through unfilled pockets or weak rock-concrete interfaces.	Inspect sawn trial sections and cores; carry out suitable water-pressure or permeability tests.
Heat and temperature change	Heat depends on the proposed cementitious materials, rock percentage and placing conditions.	Use laboratory heat tests and temperature sensors in a full-scale trial.
Shrinkage and creep	The rock framework restrains the surrounding HSCC and changes long-term movement.	Carry out project-specific tests where deformation or cracking is important.

Table 5
Quality-control structure for RFC [1], [2], [5]

Stage	What should be checked or recorded	Purpose
Source qualification	Rock-source identification, durability and cleanliness checks; HSCC constituent testing; trial mix records.	Whether the proposed materials are suitable for RFC trials.
Full-scale process trial	Rock placement, HSCC flow, filling compactness, cut surfaces or cores, curing and thermal observations.	Whether the selected mix and placement method can be approved for production.
Production control	Batching data, moisture correction, fresh tests, placement time, temperature, weather and lift photographs.	Whether each placed volume conforms to the approved process.
Post-hardening verification	Cores, density or defect mapping, strength and permeability checks, and review of nonconformances.	Whether the completed composite meets specified performance.
Traceable records	Link material source, batch, location and test results in one retrievable record.	Whether future inspection can interpret the concrete actually placed.

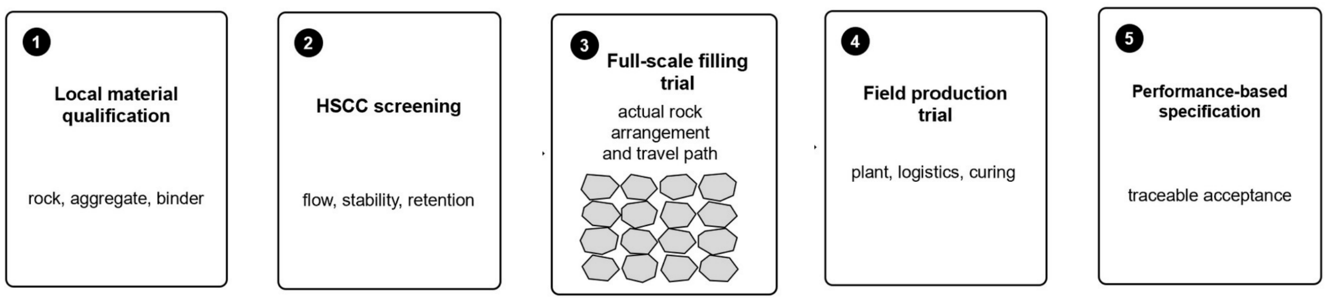

Fig. 2. Proposed India-focused material validation sequence before production-scale use of RFC

trials must use the rock, HSCC, batching plant and placing route proposed for the work.

An Indian specification should identify RFC-specific checks: rock quality and size, rock percentage, a full-scale filling trial, confirmation of complete filling, representative cores, temperature observations and traceable placement records. Acceptance values should come from trials with the proposed materials, not be copied from another climate or rock source. Indian laboratories should study filling with local rock and manufactured sand, interfaces, large-specimen properties, permeability, thermal behaviour and non-destructive testing.

7. Conclusion

RFC is a composite of a large-rock skeleton and HSCC. Performance depends on material quality, complete filling and a sound interface. HSCC tests alone cannot confirm these conditions, so approval should include a full-scale trial using the proposed rock and placing method.

Strength, stiffness, water-tightness, thermal response, shrinkage and creep should be measured on RFC, not inferred from HSCC. Representative specimens, cores and trials are needed because rock and interfaces affect the result. Any thermal benefit must also be demonstrated.

India needs dam construction for hydropower and water resources. RFC can save time and cost while offering a practical option for suitable dams. Adoption should follow local-material validation, full-scale trials, traceable records and acceptance based on measured performance.

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