A Comprehensive Literature Review on the Elastic Modulus of Rock-filled Concrete

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ABSTRACT

Rock-Filled Concrete (RFC) is formed by pouring High-performance Self-Compacting Concrete (HSCC) into gaps between pre-placed rocks (that form a strong rock skeleton) in the formwork. An in-depth analysis of RFC's elastic modulus must focus on its static and elastic modulus behavior, strength characteristics, and sustainability aspects. Mesoscopic finite element modeling effectively incorporates pre-positioned rocks, Self-Compacting Concrete (SCC), and the Interfacial Transition Zone (ITZ) to correctly predict performance. RFC is a promising alternative to traditional construction methods, offering combined advantages for masonry and concrete techniques while reducing cement usage. Studies continue to examine the creep properties of reinforced fiber composites, with promising signs of their effectiveness in reducing hydration heat and concrete shrinkage. Subaquatic conservation agents enhance environmental stewardship in wet situations. The elastic modulus of rock-filled concrete increases logarithmically, mostly influenced by the rock-fill composition. It is crucial to study the shape, size, and rock-fill ratio of rocks in RFC that impact its stability, strength, and resistance to static and dynamic loads. Irregularly shaped rocks can enhance interlocking and mechanical properties, while a well-graded mix of sizes improves compaction and uniformity. Studying these properties enables engineers to optimize design and construction for durability and performance.

Keywords-rock-filled concrete; interfacial transition zone; elastic modulus; high-performance self-compacting concrete; dam

I. INTRODUCTION

Concrete is a composite material distinguished by intricate microstructures spanning numerous scales. On a smaller scale, it refers to the microstructure of the hydrate foam, which comprises water and air phases and needle-shaped hydrate phases. In engineering scale modeling, concrete is generally treated as an isotropic homogeneous continuum, called the macroscale [1]. The strategy is characterized by its computing efficiency due to avoiding material heterogeneity at smaller length scales. However, this approach limits the ability to investigate the relationships between structure and properties [2]. Depending on the perspective, explicit consideration of structural features can be incorporated while modeling at varied length scales, also known as the micro- and mesoscales. According to [3], a traditional methodology employs a multiple-scale approach in which the results of cement paste-scale models are homogenized to obtain characteristics for mortar-scale models. Similarly, the results from the mortar-scale models are homogenized to determine characteristics for concrete-scale models.

Rock-Filled Concrete (RFC) is a novel type of concrete construction invented in China in 2003. This method has been employed in various construction projects, most of which are water conservancy projects. Large rocks (larger than 300 mm) are placed in the design framework and the gaps are filled with High-performance Self-Compacted Concrete (HSCC). [4]. The SCC fills the spaces between the rock skeleton and hardens and bonds it, resulting in a complete RFC. In [5], RFC was compared with conventional concrete regarding filling capacity. This cutting-edge construction technology does not need vibration and uses less cement. RFC is more cost-effective, requires less hydration energy, and is more effective than traditional concrete for large-scale buildings. RFC is more cost-effective, requires less hydration energy, and is more effective than traditional concrete for large-scale constructions. HSCC is combined with large rocks to construct gravitational reservoirs and arch dams (Figure 1). The method combines the advantages of masonry and concrete while minimizing their disadvantages. It also minimizes the amount of cement used, the temperature increase caused by hydration heat, and concrete shrinkage [6]. SCC is employed to fill the voids within a pre-assembled arrangement of rock particles, hence leading to the formation of RFC. The RFC can be formed in two ways: General-type RFC construction and Riprap-type RFC construction [7]. This innovative kind of mass concrete exhibits unique characteristics. The excellent flowability of SCC enables gravity to rapidly fill the pores of a collection of large rocks with grain sizes larger than 300 mm. There is no maximum size limit for rock size because it depends upon transportation and placing facilities. When comparing RFC to conventional or roller-compacted concrete, it is clear that RFC provides significant benefits. These advantages derive from the lack of vibration or compaction needs during construction, which results in a shorter construction duration, less labor-intensive work, and lower cost [8].

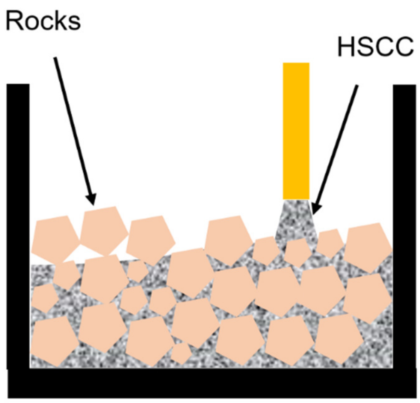

Fig. 1. Construction process and sketch map of rock-filled concrete.

Changes in hydration temperature can cause fractures in concrete due to alterations in its elastic modulus [9]. Using a preplaced rock foundation distributes stresses and imparts initial stiffness throughout the solidification process, leading to a unique development of the elastic modulus for RFC vs ordinary concrete. The wide dimensions of RFC have limited the scope of study on this material's elastic modulus over time, providing obstacles in conducting thorough studies. Instead, many smaller-scale studies were carried out, yielding empirical formulations that reveal a link between the elastic modulus of the hard RFC and its mechanical characteristics [10]. Reliable test results from full-scale RFC compression testing were recently acquired [11]. The precision of the finite element model is a critical requirement of the finite element technique for determining the dependability of the findings. Authors in [12, 13] created detailed mesoscopic finite element models to assess conventional concrete. These models consider aggregate grading, volume percentage, and the Interfacial Transition Zone (ITZ). However, reproducing the pre-existing rock skeleton is a considerable challenge in developing an accurate finite element model for the RFC procedure. Previous studies presented a variety of RFC models, but they could have been more effective in constructing the skeleton framework.

In 2008, authors in [14] constructed a two-dimensional, three-phase model to study the mechanical characteristics of RFC. However, this model omitted the skeletal structure, making it more equivalent to a model for conventional concrete than an accurate description of RFC, as proved in [15]. The homogenization method, which relies on the Eshelby tensor and average field theory is the most used method for predicting the effective elastic modulus of concrete materials [16]. The predicted outcomes frequently agree significantly with the empirical observations of hardened concrete. The anticipated results often correlate strongly with the corresponding empirical observations of hardened concrete. Nevertheless, the significant disparity in the elastic properties of the components renders conventional homogenization methods inadequate for early-age concrete [17]. In 2014, authors in [18] implemented a two-phase model in three dimensions, whereby rocks were pre-positioned. Nevertheless, the ITZ phase should have been addressed, and instead, the backdrop grid technique was employed, creating simulated zigzag contact surfaces between the rocks. In 2022, authors in [19] developed a three-dimensional finite element model to analyze the behavior of RFC. Additionally, they investigated the temporal evolution of the material's elastic modulus. Currently, mesoscopic finite element models cannot accurately represent the properties of RFC.

II. ROCK-FILLED CONCRETE CONSTRUCTION TECHNOLOGY

RFC denotes a novel form of mass concrete characterized by its superior structural integrity, high density, and reduced heat generation during hydration. The formation process of RFC involves filling gaps in the rock skeleton with the HSCC, which eliminates the need for vibration compaction [4]. This research sought to determine the capacity of SCC to penetrate a rock matrix. Studies show distinct characteristics in the thermal and mechanical properties, construction technology, and microstructure of RFC and the ITZ between rock and SCC. The usage of RFC provides several benefits. These benefits include simple building techniques, cost-effectiveness at the unit level, compatibility with low water temperatures, simplified quality management, expedited construction processes, increased stability for larger structures, mechanical construction capabilities, and accelerated implementation. The advantages above can be ascribed to the use of straightforward building techniques to develop RFC [9].

Authors in [20] reported dam components, except the dam's impermeable face plate upstream and the overflow deck, made of RFC with a strength grade of C15. Before beginning the pouring operation, a thorough inspection and evaluation of the quality of SCC is required. It is recommended that the slump value of SCC be maintained within the range of 250 to 280 mm [21]. The Slump Flow (SF) should be controlled within 630 to 750 mm, while the V-funnel (VF) should be regulated between 7 and 25 s. The rock size should be larger than 300 mm. The construction method used for the RFC is common, with each lift having a height of 1.8 to 2.0 m. RFC has the same 28-day standard full-strength schedule as normal vibrating concrete. However, in particular applications, RFC may demonstrate improved strength characteristics when evaluated over a period of 90 days. Authors in [22] discovered that pristine RFC lacks dirt and fractured rock. When running the model properly, the surface must be kept clean and uncomplicated, ensuring that the hardness and stability fulfill the criteria. The unloading track transfers rock blocks. Before installing large rocks into the formwork, a cleaning operation must be carried out to ensure the surface is within the specified silt accumulation limit. The blocks are then driven into the appropriate working area by bulldozers, where excavators or humans rearrange them to ease future compaction [7]. As depicted in Figure 2, SCC is produced on-site at a batching plant and transported to the designated area using concrete mixers. It is advisable to provide a curing period of 14 days for each RFC casting layer, with a recommended thickness range of 1.8-2.0 m. It is imperative to strictly adhere to the regulations outlined in the "Occupational Safety and Health Design Law for Water Resources and Hydropower Projects (GB 50706-2011)" as mandated by the Ministry of Water Resources of the People's Republic of China in 2012 during the dam-building process [23].

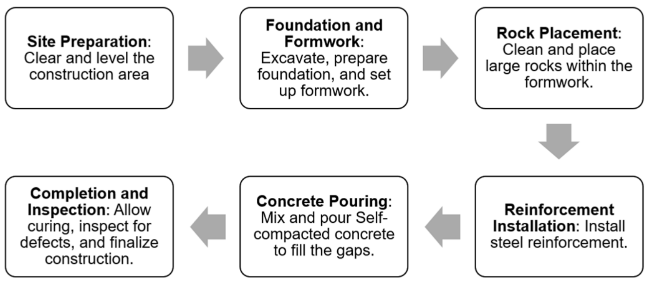

Fig. 2. Flowchart of RFC construction.

III. SUITABILITY OF ROCK FILLED CONCRETE

The invention of RFC can be attributed to Prof. Jin Feng and An Xuehui, who were awarded with the Chinese patent number ZL03102674.5 in 2003 for their pioneering work. RFC has been implemented in practical construction environments since 2005. It can be fabricated utilizing either the modular RFC construction technique (as described in Chinese Patent No. 200710100315.3) or the dump-type RFC construction method (as described in Chinese Patent No. 200710121791.3). Various experiments have been undertaken, encompassing evaluations of HSCC in terms of its capacity to fill gaps between rocks, compressive strength, and permeability [24].

The thermal parameters of RFC were examined in [25] encompassing the determination of constant heat gain, the coefficient of linear expansion, density, and permeability. It is crucial to clearly define the building specifications to effectively utilize the benefits offered by applications other than RFC hydraulic structures [26]. The uncertainty around the effects of stone on concrete's immediate and prolonged performance is attributed to the lack of consensus among experts in the field. One primary concern is the potential for brittle RFC failure due to the interplay between rock strength and the contact energy between rock and concrete [27].

In the last ten years, there have been significant advancements in computing capability and simulation models. The primary focus of research in this domain has predominantly revolved around examining failure features and behavioral patterns at the mesoscale. Authors in [28] adopted a two-dimensional multiscale approach, wherein the discrete elements of aggregates, mortar, and voids were assumed for engineering modeling. Authors in [29] utilized a circular-shaped discrete element to represent the aggregates in the simulation of the meso-structure. This enabled researchers to analyze the processes of concrete failure. A recent evaluation centered on the creation and distribution of rocks exhibited an escalating utilization of nonlinear finite element methodologies [30]. Authors in [31] employed a modeling approach to investigate the shape and distribution of rocks. The study incorporated randomly distributed shapes, encompassing circular, elliptical, and polyhedral elements. Numerical studies investigate the void effect on the compressive behavior of RFC. The void ratio is the main influencing factor, with a hyperbolic regression formula developed for uniaxial compressive strength. A critical threshold of 1.9% is set for the void ratio. When the void ratio exceeds 1.9%, the uniaxial compressive strength may be lower than the component HSCC, which is of great engineering significance. At the mesoscale, the proportion of HSCC increases and ITZ decreases as the void ratio increases from 0% to 5%. Stress concentration around the voids is observed quantitatively and qualitatively, with a 10%-15% higher damage proportion compared to models without voids [32].

Moreover, various models of irregular rock structures have been formulated. As an illustration, authors in [33, 34] examined the failure characteristics of high-strength concrete deploying the random aggregate technique and the Concrete Damage Plasticity (CDP) model. They employed a physical engine and a 3D random aggregate modeling technique. Some other studies applied the quadratic random clustering method on a lattice distribution to create a 3D random aggregation structure. The direct application of concrete's mechanical qualities and the analysis of its elements posed challenges in most of the mentioned above investigations.

IV. RESEARCH ON ELASTIC MODULUS STRENGTH OF ROCK FILLED CONCRETE AND CONVENTIONAL VIBRATING CONCRETE

The mechanical properties of concrete, specifically the modulus of elasticity and axial compressive strength, play a crucial role in determining concrete pathways' structural deformation and expansion [35]. The impact of concrete's modulus of elasticity and axial compressive strength on concrete tracks' structural deformation and expansion has been observed [36, 37]. Combining two distinct elements primarily determines the modulus of elasticity of concrete. The partial modulus of elasticity of each microscopic phase is one factor that influences concrete qualities. Other important aspects are the shape, size, and distribution of internal holes and cracks inside the material [38]. The overall strength of concrete is significantly influenced by these parameters. The presence of water within the small internal pores of damp concrete significantly increases the concrete's ability to block the flow of water when subjected to pressure. When exposed to compressive stresses, concrete structural components can withstand a specified pressure and the consequent deformation [39]. Water is displaced by air because water vapors exist within the pores. Air is more susceptible to compression and deformation than water when exposed to compressive stress, lowering resistance. As a result, the impact of the internal moisture content of concrete on its modulus of elasticity cannot be ignored [40].

According to one widely held view, the moisture content of concrete has no substantial influence on its modulus of elasticity. In 2022, authors in [40] discovered that the modulus of elasticity of impregnated concrete is 12 to 30% more than that of dry concrete. It was discovered that impregnated concrete exhibits greater values of Poisson's ratio and modulus of elasticity compared to dry concrete with equivalent volumes [41]. In [42], it was found that the modulus of elasticity of totally impregnated concrete exhibited a 30% increase compared to that of fully dry concrete. The modulus of elasticity of dry concrete exhibits a 15% reduction compared to impregnated concrete. A series of microscopic tests and theoretical studies obtained the elastic modulus and volume fraction of individual phases of hardened paste and the elastic modulus and thickness of the ITZ around the coarse aggregate. The results show that the incorporation of 10% silica fume (Table I) improves concrete's 28d axial compressive strength by 18.6% and the elastic modulus by 4.2% (Table II) [3].

TABLE I. MIX PROPORTION OF CONCRETE (kg/m^3)

Materials	Cement	Silica fume	Water	Fine aggregate	Coarse aggregate	Superplasticizer
SF0	500	0	175	600	1150	1.5
SF10	450	50	175	600	1150	2.5

TABLE II. 28-DAY COMPRESSIVE STRENGTH AND ELASTIC MODULUS OF CONCRETE

Findings	No.	Group 1	Group 2	Group 3	Avg.
Axial compressive strength (Mpa)	SF0	33.2	35.8	33.9	34.3
	SF10	41.2	38.9	44.1	41.4
Elastic modulus (GPa)	SF0	34.9	35.6	35.4	35.3
	SF10	36.5	36.8	37.1	36.8

Authors in [43] conducted a study that revealed that variations in hygroscopicity contributed to disparities in the modulus of elasticity. The study involved tests on the elastic modulus values at various water saturation levels (Table III, Figure 3), following the guidelines outlined in the People's Republic of China Industry Standard Test Code (SL 352-2006) for Hydraulic Concrete. The modulus of elasticity at various saturations was examined.

TABLE III. MIX PROPORTIONS AND MAIN PARAMETER OF CONCRETE

Strength Grade	Water/Cement Ratio	Mix Proportions (kg/m3)				
		Water	Cement	Medium Sand	Small Stone	Middle Stone
C15	0.65	158	243	729	709	709
C20	0.55	150	273	615	685	685
C30	0.42	165	391	581	646	646

In 2020, authors in [44] reported performing a full stress test on RFC in situ. This experiment was conducted while working on an RFC arch dam in Guizhou Province in southern China. The test was performed while building an RFC arch dam. In [45], it was observed that the aggregates had a sparse distribution and displayed a tendency to float inside the mortar. Once the full-scale cubic model has been validated, simulations may be conducted to determine the elastic modulus of the RFC using this model. During the early stages of development, the SCC (a specific component of concern) emerges as the sole component that has reached a state of development. The exponential model, initially presented in [46] was subsequently employed in [19], where three rock-fill ratios (50%, 55%, and 60%) were considered and their effect on the elastic modulus of RFC was studied (Figure 4).

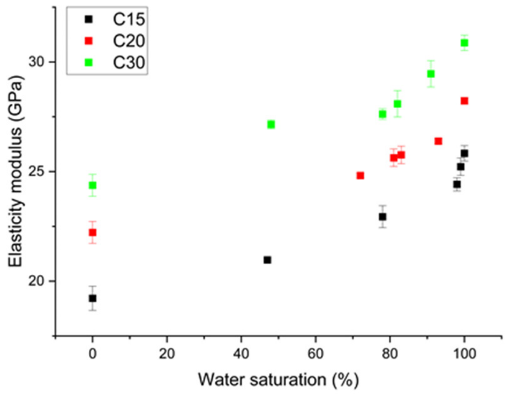

Fig. 3. Elasticity modulus with different saturation.

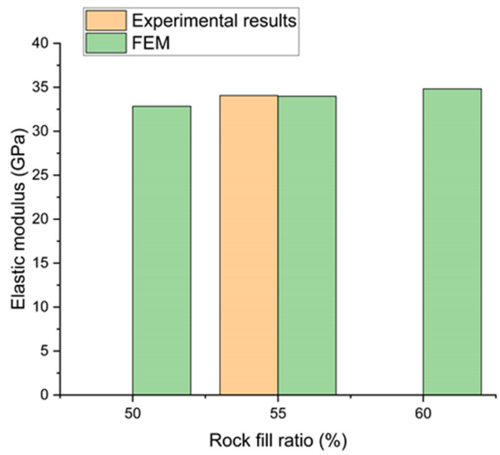

Fig. 4. Rock fill ratio effect on elastic modulus.

The ITZ was also found to be a thin layer encompassing the whole aggregate and having relatively poor strength qualities. The concrete scale, distinguished by its massive semi-continuum length scale and distinct, recognized characteristics, has sparked substantial interest in the modeling community. At the medium scale, concrete is often considered a two-phase composite comprising aggregate and mortar. However, it can also be viewed as a three-phase composite by incorporating ITZs between the aggregate and the mortar [47]. More recently, a four-phase composite model has been proposed, which includes inherent defects like voids and pores [48].

Developing intermediate structural models that integrate concrete heterogeneities requires substantially fewer processing resources than multiscale models. According to [49], structural models offer a practical technique for studying the phenomena of concrete deterioration and fracture. The ITZ was formed by the arrangement of anhydrous cement granules ranging in size from submicron to 100 mm, as opposed to the substantially larger aggregate particles. The presence of varied grain sizes in each aggregate causes the production of small barriers, disrupting the equal dispersion of cement grains and resulting in the wall effect. The ITZ microstructure can be improved by adjusting the particle size distribution of the cementitious material. This change eventually causes a reduction in porosity and the formation of a gradient in the water-to-cement ratio (w/c). Typically, the goal is reached by employing a mineral additive such as silica fume, metakaolin, or siliceous fly ash, all of which include particles much smaller than the size of the cement particles.

Authors in [50] found that the major heterogeneity in porosity occurs within a 15–20 mm region surrounding aggregates. This heterogeneity tends to lessen over time as hydrates infiltrate the pores. Previous research has shown that the ITZ strength affects the mechanical characteristics of concrete. Authors in [48] conducted experimental investigations while authors in [51] employed numerical simulations. These investigations jointly show that traditional two-phase models are no longer suitable due to the significant impact of the considerably reduced ITZ strength on concrete behavior. While this approximation reduces computing costs, it still needs to be determined to precisely determine the influence of the true thickness of the ITZ on concrete behavior. Authors in [52] presented an analytical solution that provides a link between macroscopic pressures applied on concrete, micro-tractions at the aggregate surface, and three-dimensional stress states inside the ITZ, resulting in the development of a two-step multiscale approach for computing ITZ stresses.

Several studies use the Discrete Element Method (DEM) to simulate the behavior of concrete materials. This technique simulates ITZs utilizing contact components offered beam or spring connections as suggested in [53]. Both approaches possess their own set of benefits and drawbacks. In all scenarios, elucidating the precise impact of ITZ thickness is unattainable. The ITZ is formed within the AEM, or alkali-activated material, as a layer consisting of wedge components that are 50 mm thick and surround the entire surface. The AEM method takes into account the precise thickness of the ITZ. Nevertheless, it is important to note that this particular procedure has just been substantiated for models based on images [54].

V. STATIC BEHAVIOR OF ROCK-FILLED MATERIALS

Authors in [55] proposed a comprehensive framework to analyze the plastic behavior of coarse-grained materials, considering particle fracture's influence on the critical state behavior. Authors in [56, 57] introduced a revised framework for the overall plasticity of sand. The present model considers the precise determination of the pressure-dependent critical void ratio and elucidates the response of sand under varying densities and confining pressures. In [57], a variant of the generalized plasticity model was employed to replicate the mechanical characteristics of cementitious sand reinforced with fibers. The investigations above have proven to be highly valuable in elucidating the mechanical characteristics of materials with a coarse-grained structure through applying a comprehensive plasticity model.

The model proposed in [58] presents challenges in accurately predicting a linear increase in deflection stress with axial strain during the initial phases of the triaxial test. The stress experienced by the rock burial material during dam construction and water storage deviates from the theoretical stress path anticipated for such material. Authors in [59] established a clear relationship between the stress route during the filling and retention of dams and the deformation parameters of rock landfill materials. When contemplating the application of the generalized plasticity model to rock backfill materials, it is usual to utilize established models, such as the uniform generalized plasticity model [60, 61] as well as the elastomer model that takes into account particle fracture [15]. The plasticity model proposed in [62] is also incorporated into the same framework. Each of the three models above possesses its distinct methodology for calculating the elastic modulus, and all three are frequently employed in predicting rock material behavior.

VI. DISCUSSION AND CONCLUSION

To summarize, our research provides a thorough comprehension of the development of the elastic modulus of RFC in its early phases. The evolution of this phenomenon has a logarithmic pattern, mainly influenced by an initial effective elastic modulus inside the pre-existing rock structure. The elastic modulus of RFC is significantly influenced by both the quantity and form of the rock fill. Furthermore, additional research is required to investigate the impact of the rocks' morphology on our understanding of the elastic modulus of RFC. RFC consist of large rocks so the shape, size, and rock-fill ratio of the rocks impact its stability, strength, and resistance to static and dynamic loads. Irregularly shaped rocks can enhance interlocking and mechanical properties, while a well-graded mix of sizes improves compaction and uniformity. Studying these properties enables engineers to optimize design and construction for durability and performance.

In the first stages of RFC's development, the predetermined rock framework substantially affects the material's elastic modulus. Currently, the characteristics of the existing rock structure significantly influence the total rigidity of RFC. Nevertheless, as the RFC advances and experiences structural modifications, the impact of the pre-existing rock framework decreases, resulting in a less pronounced influence on the material's elastic modulus throughout subsequent phases. The importance of the initial condition and composition of the rock framework in influencing the mechanical characteristics of RFC, especially in its early development, is emphasized.

In order to efficiently achieve technical standards, it is crucial to perform more basic research on the mechanical characteristics of RFC at the mesoscale level. An analysis of how a pre-existing rock skeleton affects the thermophysical characteristics of RFC, including compressive strength, tensile strength, fracture initiation, and propagation, might yield significant information.

Our study concludes with an intricate relationship between many parameters that influence the growth of RFC's elastic modulus. This emphasizes the need for more research to improve our knowledge and use of this promising material in different engineering applications.

VII. RECOMMENDATIONS

This analysis clearly provides a direction for future research efforts focused on fully understanding the long-term behavior of RFC. Additional research is needed to examine the effects of drying, post-hardening contraction, and freeze-thaw resistance, particularly in relation to greater dimensions. These factors are essential for guaranteeing concrete buildings' long-lasting endurance and optimal functionality over prolonged durations.

Furthermore, there is an urgent requirement for a more extensive investigation into the elasticity modulus and possible design alterations of RFC. Through a thorough exploration of these factors, researchers may create groundbreaking solutions that improve the overall efficiency and suitability of RFC in many engineering scenarios. Investigating the impact of rock shape and size on the elastic modulus reveals that irregularly shaped rocks with larger sizes tend to enhance stiffness in RFC. Moreover, understanding the dynamic properties of RFC, including natural frequency and damping ratio, is crucial for designing structures resilient to dynamic loading conditions such as seismic events. Experimental techniques such as resonant frequency analysis and impact testing can provide valuable insights into the material's dynamic behavior, aiding in the optimization of engineering applications.

This study highlights the significance of continuous research endeavors in bridging crucial knowledge gaps regarding the behavior of concrete and driving progress in materials science and engineering. By prioritizing these areas of investigation, we may lay the groundwork for advancing more durable and environmentally friendly concrete buildings in the future.

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