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Investigation of Biomineralization on the Strength, Durability Properties of Fiber-Based RAC

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Abstract: In concrete, recycling waste materials plays a crucial role in preserving natural resources, managing construction and demolition waste (CDW) and reducing environmental impact. Given the extensive use of aggregates in concrete, integrating recycled aggregates can significantly enhance the sustainability of construction practices. This study investigates an innovative approach to improving the mechanical strength and durability of recycled aggregate concrete (RAC) through biomineralization and fiber reinforcement. The novelty of this research lies in the synergistic use of basalt fibers (BF), polyvinyl alcohol (PVA) fibers, and bacterial self-healing mechanisms to enhance RAC performance. Experimental results indicate that fiber-reinforced RAC exhibits superior compressive and splitting tensile strength compared to conventional RAC with 50% or 100% recycled aggregate. Among the fiber types, basalt fibers consistently outperformed PVA fibers in enhancing mechanical properties. This study provides a novel strategy for optimizing RAC performance, making it a more viable and sustainable alternative for construction applications.
Keywords: RCA, PVA fiber, Basalt fiber, Mechanical properties, Microstructure, MICP.

I. INTRODUCTION

In modern era, the usage of concrete is the second widely used materials after water due to its desirable properties in construction, which enable the development of sustainable and durable structures. However, its continuous use poses a challenge due to the depletion of natural resources. The reconstruction of roads, buildings, and other structures produces a significant amount of construction and demolition (C&D) debris. Various innovative methods have been proposed for disposing of this waste, including its use in roadbeds and landfills. Additionally, research into environmentally sustainable solutions has gained traction [1]. The utilization of C&D waste in both structural and non-structural elements is increasingly recognized as a viable and sustainable alternative [2]. Nonetheless, investigations have demonstrated the difficulties linked to the incorporation of recycled aggregates (RA) in concrete. In comparison to natural aggregate concrete (NAC), the recycled aggregate concrete (RAC) has been found to show poorer properties particularly in terms of durability [3,4]. The incorporation of RA in varying proportions often results in reduced mechanical strength and durability due to its lower density and higher water absorption compared to natural aggregate (NA) [5]. Consequently, the large-scale adoption of RA in concrete has been limited by these deficiencies. Over the past decade, numerous researchers have explored different strategies to enhance the performance of RAC. These methods can be broadly categorized into three approaches: (1) Pretreatment of RA [6,7], (2) Addition of fibers [8–11], and (3) Incorporation of mineral admixtures into RAC [12–16]. Additionally, an emerging technique involves introducing bacteria into concrete to improve its properties, either independently or in combination with fibers. The drawbacks of RAC can be mitigated by incorporating reinforcing materials, with fibers being among the most commonly used due to their strength, cost-effectiveness, and toughness. Steel fiber has traditionally been the most widely used reinforcement; however, its high cost has led to the exploration of alternative fibers. Basalt fiber (BF), a silicate fiber, has shown significant potential due to its uniform dispersion in concrete and superior slurry retention compared to other fibers, which can substantially enhance RAC performance. Several researchers have investigated the integration of BF into RAC, reporting notable improvements in mechanical properties. Dong et al. [17] observed that BF enhanced the microstructure of the interfacial transition zone (ITZ) by accumulating on the surfaces of old mortar in RA. Chen et al. [18] studied the impact of BF on RAC across different curing ages and found that it effectively increased the initial strength.

Similarly, Ding et al. [19] analyzed the microstructure of basalt fiber-reinforced RAC and noted that the strong fiber-matrix bond, along with uniform fiber dispersion, reduced stress concentrations, delayed crack propagation, and improved resistance to carbonation.

Polyvinyl alcohol (PVA) fiber, a synthetic fiber with high elongation at break, has also been explored for RAC reinforcement [4,8]. Its superior bonding with cement mortar, attributed to its surface hydrophilicity, suggests that PVA incorporation could enhance RAC performance [20–22]. Studies have shown that PVA fibers improve both the strength and durability of concrete [23,24]. Additionally, they act as a bridge to prevent microcracks from propagating, thereby enhancing structural integrity. Zheng et al. [25] developed high-strength concrete using PVA fibers, which exhibited superior hardness, durability, and elastic modulus retention compared to conventional concrete. However, an rise in fiber content lead to in a slight decrease in compressive strength. In the case of PVA fiber-reinforced recycled aggregate pervious concrete (RAPC), uniform fiber distribution was crucial for optimizing performance. The fiber network acted as a “stirrup” within the RAC grid, effectively complementing other RAC components.

A relatively novel approach for improving RAC performance is bacterial-induced calcite precipitation (BICP), which remains underexplored. This bio-based technology has attracted significant interest from concrete researchers. Chahal et al. [26] demonstrated that incorporating Sporosarcina pasteurii bacteria into fly ash concrete led to a 22% increase in compressive strength after 28 days. Additionally, water absorption was reduced by a factor of four, and chloride permeability decreased fivefold. It is hypothesized that bacterial calcium carbonate ($CaCO_3$) precipitation helps fill voids and microcracks, thereby enhancing concrete properties. Andalib et al. [27] performed the tests of SEM, EDS and XRD analysis as well as the mechanical strength. These tests were identified the optimum bacterial concentration of bacteria used Bacillus megaterium bacteria (30×10^5 cfu/ml) for promoting calcite precipitation in concrete. Similarly, Achal et al. [28] found that bacterially induced $CaCO_3$ deposition reduced concrete porosity, improving resistance to water, chlorides, sulfates, and other aggressive agents. However, altering the water-to-cement (w/c) ratio to reduce porosity may have unintended consequences on workability, heat of hydration, and shrinkage. The addition of Bacillus megaterium to concrete increased its compressive strength by 22.5% and its tensile strength by 18.5% when compared to conventional concrete, according to research by Nain et al. [29].

To encourage the widespread use of RA in making concrete structures, further innovative strategies for improving RAC properties are essential. Despite the potential of recycled aggregate concrete (RAC) as an eco-friendly solution, its inferior mechanical properties and durability remain major concerns. This study addresses these challenges by integrating basalt fibers (BF), polyvinyl alcohol (PVA) fibers, and bacterial-induced calcite precipitation (BICP) to enhance RAC performance. The incorporation of fibers improves mechanical strength and crack resistance, while bacterial activity aids in self-healing and durability enhancement. By combining these innovative techniques, the study provides a comprehensive approach to optimizing RAC properties, making it a more viable option for sustainable construction. The findings contribute to advancing green construction practices and promoting the large-scale utilization of recycled aggregates in structural applications, ultimately reducing environmental impact and supporting circular economy principles in the construction industry.

II. EXPERIMENTAL OVERVIEW

A. Materials

Ordinary Portland cement (OPC) of grade 43, acquired from Ultratech Cement Ltd., was used in this study. The coarse aggregate consisted of crushed stone in sizes of 10 mm and 20 mm, used in accordance with IS 383:2016 [30]. Locally available river sand was employed, and its physical and mechanical properties were evaluated as per IS 2386:1963 Part 3 [31] and Part 4 [32]. RA were formed by manually crushing 20 mm and 10 mm concrete samples previously used in consultancy and laboratory testing. The old concrete pieces were processed to obtain recycled coarse aggregate (RCA). Achieving the same gradation characteristics for RCA as natural coarse aggregate (NCA) during the acquisition process is challenging. Therefore, aggregates of precise sizes were used to minimize the influence of varying physical characteristics between NCA and RCA on concrete properties. This approach allowed us to specifically evaluate the impact of the biomineralization method on the mechanical and durability properties of RAC. As shown in Figure 1, basalt fiber and PVA fiber, each with a length of 12 mm, were used, with specifications detailed in Table 1. The bacterium *Bacillus megaterium* (MTCC 9885), a urea-based strain naturally present in soil, was mixed in concrete mixes of this study and was bought from CSIR, Pune, Maharashtra, India.

Table 1: Specifications of PVA and BF

Fiber type	Diameter (µm)	Specific weight (kg/m^3)	Tensile strength (MPa)	MOE (GPa)	Elongation (%)
PVA	12	1290	1680	41	7
BF	16	2600	2580	88.7	2.8

Figure 1: Pictures of PVA fiber and basalt fiber.

B. Mix Proportion and Test Program

The NCA concrete mix was designed according to IS 10262:2009 [33] and served as the reference concrete for this study. In RAC mixtures, NA was replaced to 50 and 100% with RCA to highlight the potential of recycled aggregates in concrete structures. Both bacterial and non-bacterial fiber-reinforced RAC mixtures were prepared to measure the effect of bacteria on the material's properties. The bacterial culture was mixed with calcium lactate and urea at a weight-to-volume ratio of 2%, followed by mixing with water for concrete preparation. Since RCA has a high-water absorption capacity, it was soaked in water for 24 hours. To prevent it from absorbing the mixing water and altering the water-cement (w/c) ratio, the RCA was subsequently dried in ambient conditions before being used in a saturated surface dry (SSD) condition.

C. Experiments

After the specimens were casted, they were cured according to standard procedures. In accordance with the requirements of IS 516:1959, the compressive strength test was conducted on 150 mm molded cubes after 7, 28, and 56 days [34]. Cylindrical specimens measuring 150 mm × 300 mm were cast for the split tensile strength test and tested as per IS 5816:1999 [35] at 7, 28, and 56 days. After the specimens were tested, SEM analysis was performed to examine the microstructure.

III. RESULT ANALYSIS AND DISCUSSIONS

A. Compressive Strength

The compressive strength of different mixtures is shown in Figure 2 which shows the effect of *Bacillus megaterium*. The incorporation of bacteria significantly enhanced strength, particularly when combined with PVA and basalt fibers. The reference concrete (RC) exhibited compressive strengths of 34.75 MPa, 42.34 MPa, and 45.53 MPa at 7, 28, and 56 days, respectively. However, the replacement of natural coarse aggregate (NCA) with 50% recycled coarse aggregate (RCA) resulted in a strength reduction to 28.1 MPa, 36.16 MPa, and 40.43 MPa at the same time intervals. A further reduction was observed in the 100% RCA mix, with compressive strengths dropping to 24.71 MPa, 35.34 MPa, and 39.86 MPa.

The inclusion of bacteria in fiber-reinforced RAC demonstrated a notable improvement in compressive strength. In PVA fiber-based RAC (50R0.2P), bacterial incorporation led to strength enhancements of 8.32%, 8.46%, and 11.33% at 7, 28, and 56 days, respectively. More pronounced strength gains were observed in basalt fiber (BF)-reinforced RAC, where bacterial addition resulted in increases of 20.56%, 16.46%, and 20.47% at 7, 28, and 56 days compared to the non-bacterial 50R mix. The primary reason for this improvement is the bacterial-induced calcium carbonate ($CaCO_3$) precipitation, which fills the pores within the concrete matrix, leading to densification and enhanced mechanical performance.

The incorporation of PVA fibers in RAC exhibited only marginal improvements in compressive strength when the fiber dosage was 0.2%, as shown in Figure 2. This limited enhancement can be attributed to the high cement mortar demand required to coat the fiber surface, which diminishes the compactness of RAC and leads to a weaker interfacial transition zone (ITZ) between the cement matrix and fibers.

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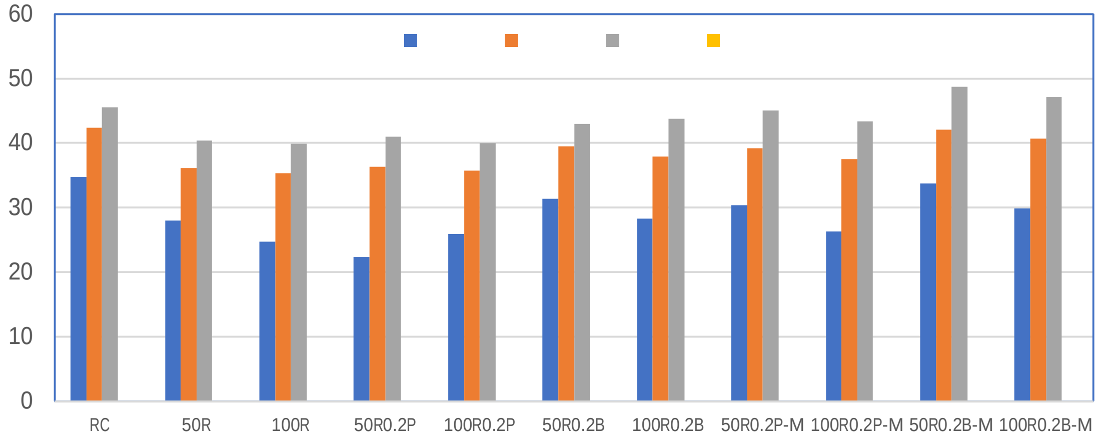

Figure 2: Results of compressive strength of fiber-based RAC with and without bacteria.

Conversely, the addition of basalt fiber (BF) in RAC resulted in a more significant strength increase compared to PVA fiber-based RAC. In specimens containing 50% RCA with 0.2% BF, compressive strengths improved to 31.34 MPa, 39.5 MPa, and 43 MPa compared to the 50R mix. Similarly, 100% RCA with 0.2% BF exhibited compressive strength enhancements to 28.32 MPa, 37.95 MPa, and 43.8 MPa relative to the 100R mix. This enhancement can be attributed to the higher elastic modulus of BF, which provides improved stress distribution and crack resistance in the concrete matrix. The proper dosage of BF contributes to increased compactness and a stronger ITZ, ultimately leading to superior mechanical performance in RAC.

B. Split Tensile Strength

The effect of fiber reinforcement and incorporation of bacteria on split tensile property shown in Figure 3. The replacement of natural coarse aggregate (NCA) with 50% recycled aggregate (RA) reduced the split strength by 17.17% at 28 days and 8.25% at 56 days, compared to the reference concrete. However, the mixing of basalt fiber (BF) in RAC caused in a notable enhancement, with tensile strength reaching 2.83 MPa at 7 days, 3.91 MPa at 28 days, and 4.53 MPa at 56 days, respectively, related to the 50R mix. Similarly, in specimens with 100% RCA and 0.2% BF, the split tensile strength increased to 2.41 MPa, 4.09 MPa, and 3.69 MPa at 7, 28, and 56 days, respectively, relative to the 100R mix.

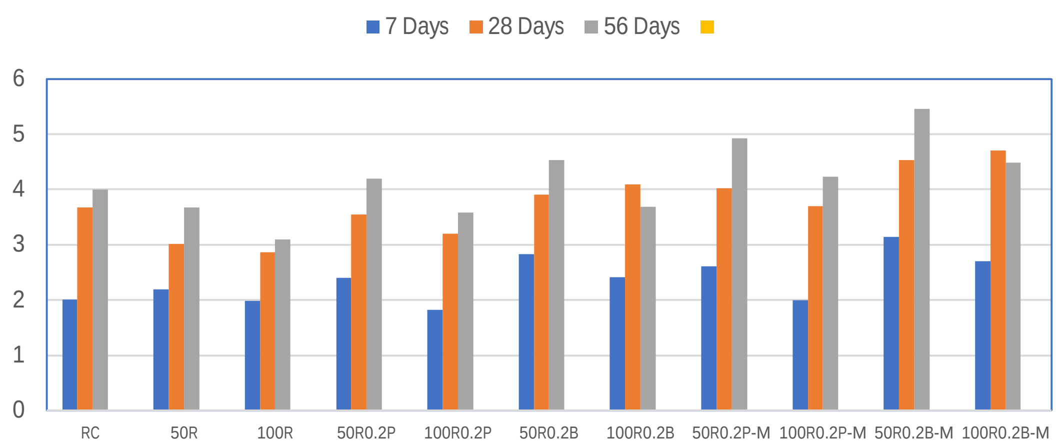

Figure 2: Split tensile strength of fiber-based RAC with and without bacteria.

The incorporation of fibers and bacteria in RAC led to a gradual increase in tensile strength. In particular, PVA fiber combined with bacterial activity in 50% RA mixtures resulted in a maximum tensile strength increase of 19.18% at 7 days, 33.11% at 28 days, and 34% at 56 days, compared to the 50R mix. A more pronounced improvement was observed in 100% RCA specimens with PVA fiber and bacteria, where tensile strength increased by 29.37% at 28 days and 36.45% at 56 days, respectively, related to the 100R mix.

Furthermore, the combination of bacteria and basalt fiber in 100% RAC demonstrated an increase in tensile strength by 11% at 7 days, 12.68% at 28 days, and 20.30% at 56 days, respectively, related to the 100R mix. The enhancement in tensile strength can be attributed to bacterial-induced calcium $CaCO_3$ precipitation, which fills voids and microcracks in the concrete matrix, leading to improved density and better stress distribution.

C. SEM Image Analysis

The instrumental analytical approach for examining microstructural reaction and performance, illustrated in Fig. 4 (a)–(e), was employed to ascertain the structural behaviour of concrete. Using a concrete fragment that was approximately 5 mm in size, experimental research of scanning electron microscopy (SEM) was carried out to predict the precipitation of calcium carbonate ($CaCO_3$), the creation of a CSH gel, the identification of calcite, and a modified form of gypsum.

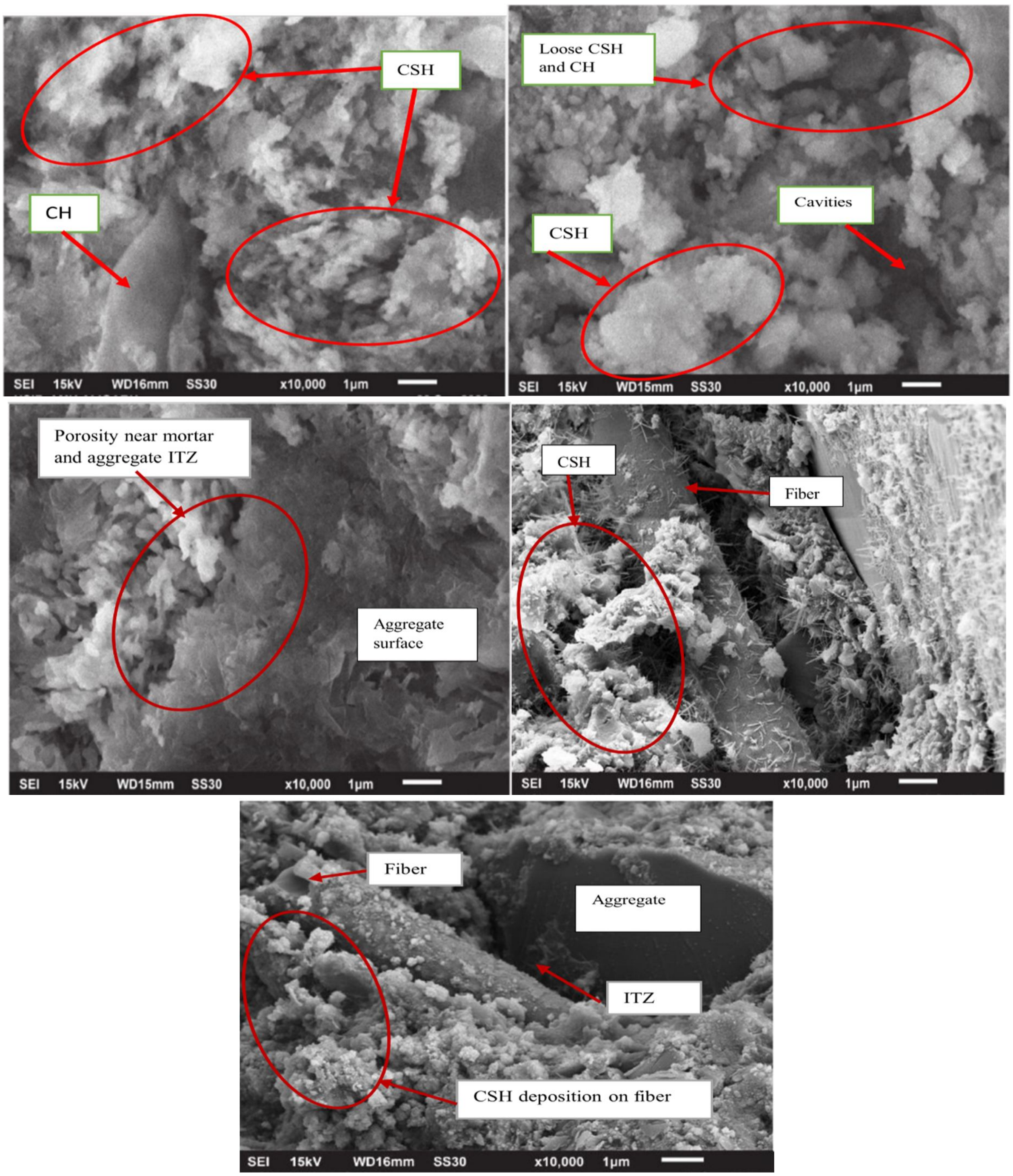

Figure 4 (a)-(e): SEM images of specimens made of fiber-based RAC with and without bacteria.

The C-S-H gel may be seen in the microscope of the control concrete that is displayed in Figure 4(a), which shows that the concrete includes C-H crystals. Within the SEM micrograph of mix R50 that is illustrated in Figure 4(b), it can make out the voids, in addition to loose C-S-H gel and C-H crystals. Similarly, the scanning electron microscope (SEM) micrograph shown in Figure 4(c) of mix R100 demonstrates that even while the creation of C-S-H gel is apparent on the aggregate mortar interface, a loose structure is generated as a result of the presence of tiny voids. This loose structure is responsible for the porosity that is present in RCA concrete. The reason for this is that RCA concrete has inferior qualities in terms of both its strength and its durability. Crystals of $CaCO_3$ that are similar to those shown in Figure 4(e) have also been observed in the plate shape. Earlier observations [36–38] have also indicated the presence of these microstructure traits that were detailed above. These are the bacterial $CaCO_3$ crystals that have the potential to produce a thick microstructure in RCA concrete, which would result in improved strength and durability.

IV. CONCLUSION

Through extensive testing and analysis, the compressive strength, split tensile strength, and microstructural properties of fiber-reinforced recycled aggregate concrete (RAC) were thoroughly investigated. Based on the research findings, the following conclusions were drawn:

1) The incorporation of PVA fiber had a minor effect on compressive strength, likely due to reduced compactness and increased interfacial transition zone (ITZ) formation between the cement mortar and PVA fibers. In contrast, basalt fiber (BF) significantly improved compressive strength, with a 9.24% increase in 50R0.2B and a 7.39% increase in 100R0.2B at 28 days.
2) The inclusion of bacteria proved to be highly effective in enhancing the strength of RAC. The compressive strength of fiber-reinforced bacterial concrete increased by 8.5% in 50R0.2P and 16.5% in 50R0.2B at 28 days compared to the 50R mix.
3) The split tensile strength of 100R0.2P exhibited significant improvements of 29.37% and 36.45% at 28 and 56 days, respectively. A similar enhancement was observed in the 100R0.2B mix, with tensile strength increases of 11%, 12.68%, and 20.30% compared to the 100R mix.
4) SEM analysis revealed that conventional RAC contains loose calcium hydroxide (CH) crystals and voids, leading to a weaker microstructure. However, the addition of fibers not only reduced these voids but also facilitated the development of additional calcium silicate hydrate (CSH) gel. This improvement in microstructural integrity enhanced ITZ properties, with BF incorporation further strengthening the mechanical and durability characteristics of RAC.

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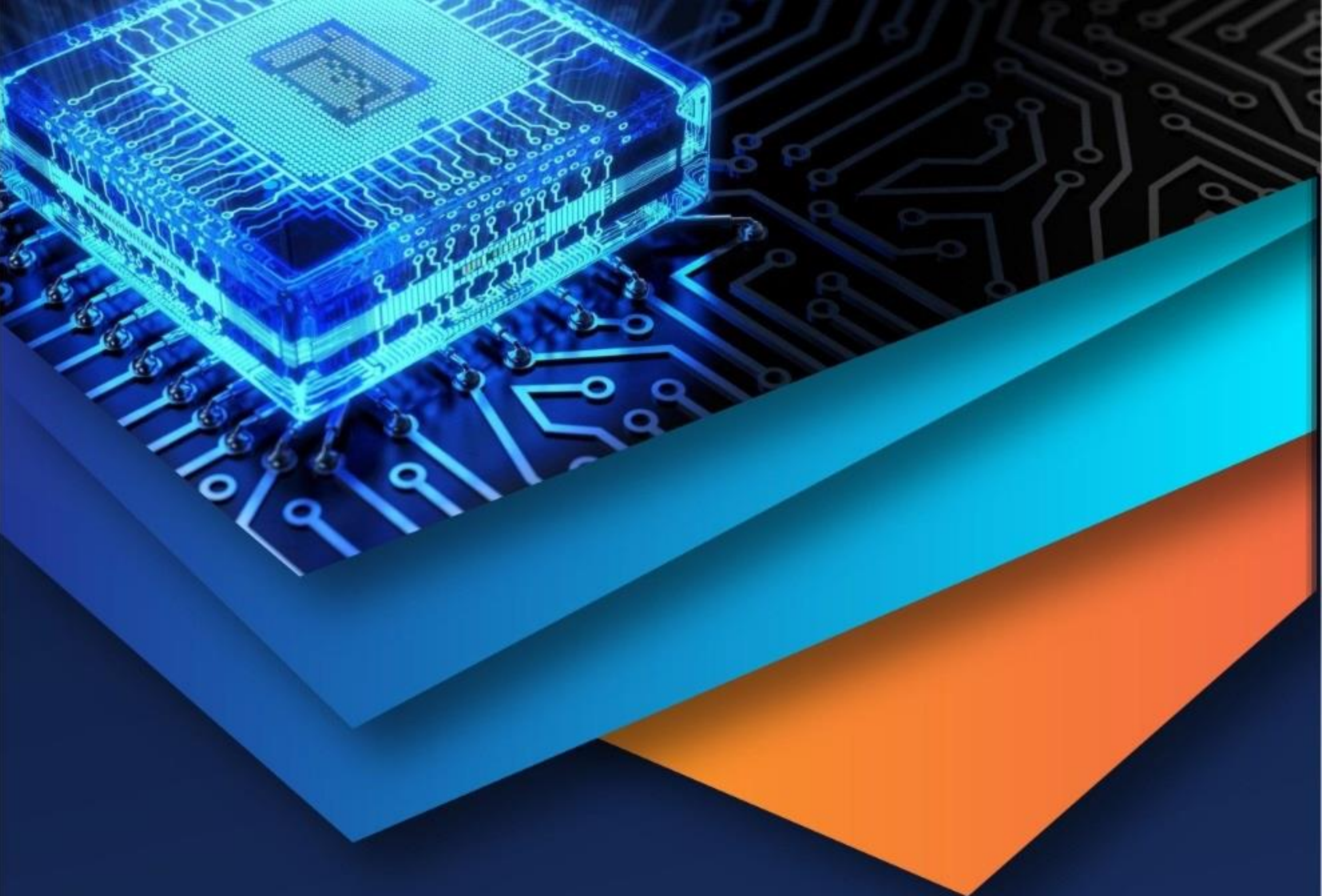

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