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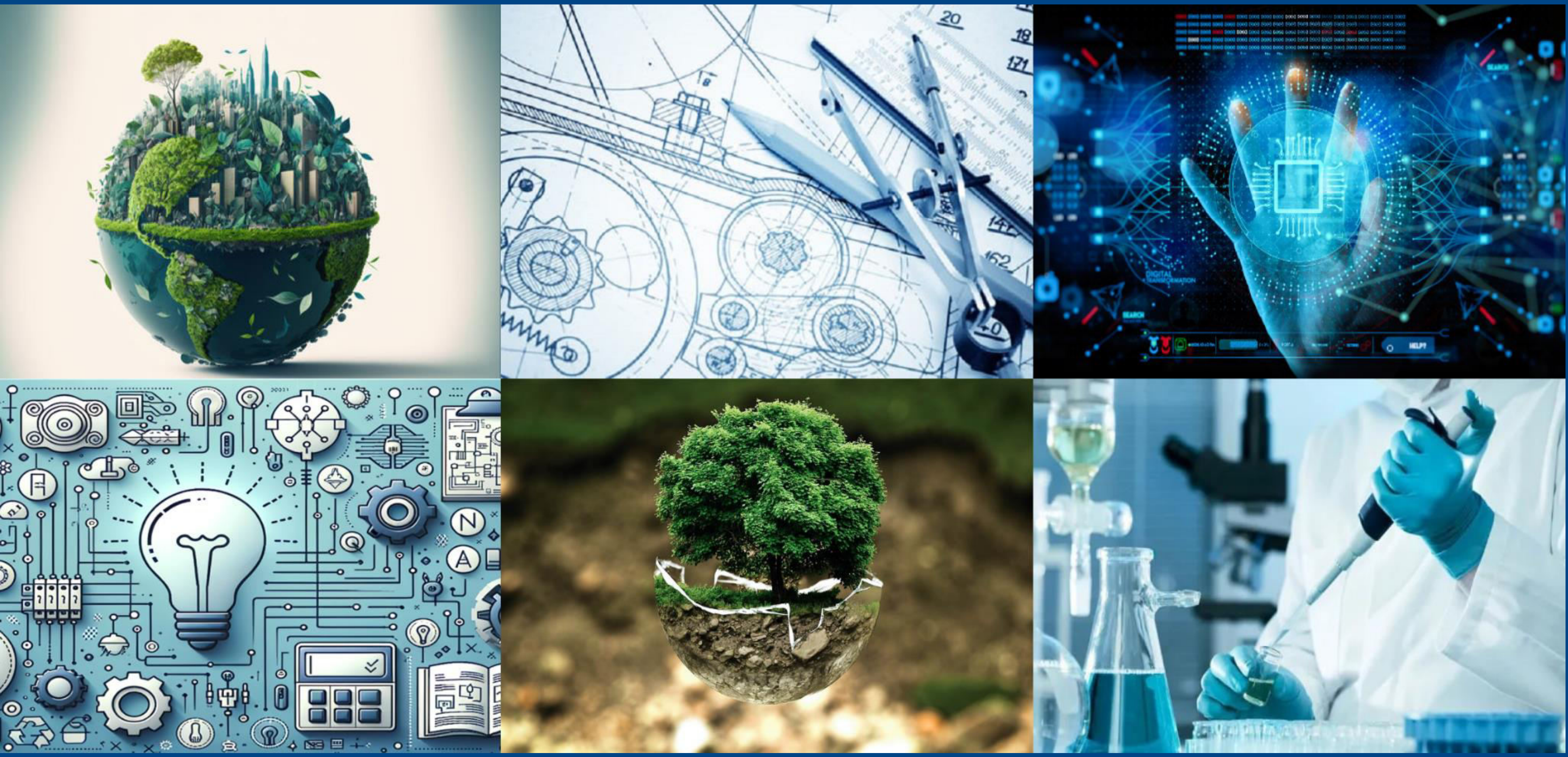

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Research Progress on Mechanical and Durability Properties of Basalt Fiber Reinforced Concrete

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ABSTRACT: To systematically review the research progress on the mechanical and durability properties of basalt fiber reinforced concrete (BFRC), this study summarizes recent experimental findings from three perspectives: mechanical properties, durability performance, and micro-mechanisms. The results indicate that the incorporation of basalt fibers significantly enhances the crack resistance and compressive toughness of concrete, and the improvement exhibits a “first increase and then decrease” trend with respect to fiber content and length. Under environmental conditions such as sulfate attack, chloride penetration, and freeze–thaw cycles, basalt fibers effectively reduce deterioration rates and improve durability by inhibiting crack propagation and refining pore structure. At the micro-scale, pore structure evolution, interfacial transition zone characteristics, and crack propagation behavior play critical roles in determining the macroscopic performance. Although considerable progress has been made in experimental techniques and mechanism analysis, challenges remain in understanding multi-field coupling mechanisms, establishing multi-scale correlations, and improving engineering applicability. Future studies should focus on performance evolution under complex environmental conditions and develop predictive models with strong practical applicability to promote the engineering application of BFRC.

KEYWORDS: Basalt fiber reinforced concrete; Mechanical properties; Durability; Damage evolution; Pore structure

I. INTRODUCTION

Concrete is one of the most widely used construction materials in civil engineering due to its abundant raw materials, relatively low cost, and excellent compressive strength. Nevertheless, it exhibits inherent limitations, including pronounced brittleness, low tensile strength, and a strong tendency to crack under mechanical and environmental actions. When exposed to harsh service environments—such as freeze–thaw cycles, sulfate attack, chloride ion penetration, carbonation, and elevated temperatures—these deficiencies become more pronounced, leading to progressive deterioration of material performance and posing potential risks to structural safety and long-term durability.

To address these challenges, the incorporation of fibers into concrete has been widely explored as an effective strategy to enhance its mechanical and durability properties. Among various fiber types, basalt fiber, as a novel inorganic material derived from natural basalt rock, has attracted increasing attention in recent years. It exhibits a combination of desirable characteristics, including high tensile strength, excellent chemical stability, resistance to corrosion and high temperatures, as well as environmental sustainability. The addition of basalt fibers into the concrete matrix has been demonstrated to effectively improve crack resistance, toughness, and overall durability, thereby enhancing the performance of concrete structures under complex service conditions.

Existing studies indicate that research on basalt fiber reinforced concrete (BFRC) has gradually evolved from an initial focus on basic mechanical properties toward a more comprehensive investigation encompassing durability performance and damage mechanisms [1]. In particular, recent advances in experimental techniques—such as nuclear magnetic resonance (NMR), digital image correlation (DIC), and scanning electron microscopy (SEM)—have enabled more in-depth characterization of the internal pore structure, crack propagation behavior, and interfacial properties of BFRC at multiple scales [2]. These developments have significantly improved the understanding of the relationship between microstructural evolution and macroscopic performance.

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Despite the growing body of research, a systematic synthesis of recent findings is still needed to clarify the current state of knowledge and identify key influencing factors and research gaps. Therefore, this study provides a comprehensive review of the mechanical properties, durability performance, and underlying micro-mechanisms of BFRC based on existing literature. The objective is to establish a clearer understanding of its performance characteristics and to offer a theoretical basis and reference for future research and engineering applications.

II. EFFECTS OF BASALT FIBER ON MECHANICAL PROPERTIES OF CONCRETE

The incorporation of basalt fibers into concrete has been demonstrated to effectively enhance its mechanical performance, particularly in terms of compressive strength, tensile strength, and overall toughness. Among these improvements, the enhancement of crack resistance and ductility is especially pronounced. Existing studies have shown that basalt fibers can effectively delay the initiation and propagation of microcracks, reduce the extent of damage localization, and significantly improve the compressive toughness of concrete [1]. From the perspective of energy evolution, the presence of fibers alters the failure process by reducing the rate of elastic energy release while increasing the energy storage capacity prior to peak stress. This energy dissipation mechanism contributes to improved deformation capacity and post-peak behavior, thereby enhancing the overall structural resilience of the material.

However, the reinforcing effect of basalt fibers is not linearly correlated with fiber content. Experimental results consistently indicate a non-monotonic relationship, characterized by an initial increase followed by a subsequent decrease in strength with increasing fiber dosage [3]. At relatively low to moderate fiber contents, fibers are well-dispersed within the matrix, enabling effective crack-bridging and stress transfer, which results in improved mechanical properties. In contrast, excessive fiber content tends to cause fiber agglomeration, increased porosity, and weak interfacial zones, ultimately leading to a deterioration in mechanical performance. Therefore, the optimization of fiber content is crucial to achieving the desired reinforcing effect.

Under dynamic loading conditions, basalt fibers also play a significant role in enhancing the mechanical response of concrete. It has been reported that, at a given strain rate, both the compressive strength and the dynamic increase factor (DIF) of basalt fiber reinforced concrete (BFRC) exhibit a similar non-monotonic trend with respect to fiber content and fiber length, reaching optimal performance at a fiber content of approximately 0.2% and a fiber length of 6 mm [4]. In addition, the inclusion of fibers contributes to a more uniform strain distribution within the material and effectively mitigates the development of localized damage zones during failure. This indicates that basalt fibers not only improve static mechanical properties but also enhance impact resistance and dynamic stability.

Fiber length is another key parameter governing the reinforcing efficiency of basalt fibers. Appropriate fiber length facilitates effective stress transfer and crack bridging, thereby significantly improving mechanical properties. However, excessively long fibers are prone to entanglement and agglomeration during mixing, which can negatively affect workability and reduce the uniformity of fiber distribution, ultimately diminishing the reinforcing effect [5]. On the other hand, some studies have reported that, under specific conditions, relatively longer fibers (e.g., 12 mm) may yield greater improvements in compressive and flexural properties [6]. These findings suggest that the optimal fiber length is not universal but depends on factors such as matrix composition, fiber dispersion conditions, and testing regimes.

In terms of interfacial properties, surface modification of basalt fibers has been proven to be an effective strategy for further enhancing mechanical performance. The use of coupling agents and nano-SiO_2 for fiber surface treatment can significantly improve the interfacial bonding between fibers and the cementitious matrix. This enhanced interfacial adhesion promotes more efficient stress transfer across the fiber–matrix interface and leads to notable improvements in strength and crack resistance [7]. Consequently, the interfacial transition zone (ITZ) plays a critical role in determining the overall reinforcing efficiency of basalt fibers.

Overall, the improvement in concrete performance due to basalt fiber incorporation can be attributed to a combination of mechanisms, including crack-bridging effects, stress redistribution, and interface strengthening. These mechanisms operate across multiple scales—from microstructural modifications at the pore and interface level to macroscopic improvements in strength, toughness, and deformation capacity—demonstrating a clear multi-scale reinforcing mechanism of basalt fiber reinforced concrete.

III. DURABILITY PERFORMANCE OF BASALT FIBER REINFORCED CONCRETE

The durability of basalt fiber reinforced concrete (BFRC) under complex environmental conditions has become a central topic in current research, particularly in relation to its long-term service performance in aggressive environments. Compared with ordinary concrete, BFRC exhibits enhanced resistance to various deterioration mechanisms, which can be attributed to the synergistic effects of fiber bridging, crack control, and microstructural refinement.

In sulfate environments, basalt fibers play a significant role in improving resistance to sulfate attack. Experimental studies indicate that the incorporation of fibers effectively delays the development of sulfate penetration depth and enhances the retention of mechanical strength during exposure [8]. This improvement is primarily associated with the ability of fibers to inhibit crack initiation and propagation, thereby reducing pathways for sulfate ions to penetrate into the matrix. Furthermore, it has been demonstrated that an optimal fiber content of approximately 0.2% can minimize mass loss and strength degradation under different sulfate exposure conditions [9]. This suggests that an appropriate fiber dosage is essential for achieving a balance between structural integrity and durability performance.

Under composite salt environments, which involve the combined action of multiple aggressive ions, deterioration mechanisms become more complex and severe. In such cases, basalt fibers still exhibit a beneficial effect in mitigating damage. It has been reported that chloride ions (Cl^-) can interact with sulfate ions (SO_4^{2-}), altering the morphology and distribution of corrosion products and thereby influencing the overall deterioration process [10]. Despite this complexity, the incorporation of basalt fibers can effectively reduce the rate of degradation, indicating their robustness under multi-ion coupled environments.

Freeze–thaw and salt–freeze conditions are among the most critical factors affecting concrete durability in cold and arid regions. Repeated freezing and thawing cycles induce internal stress due to ice formation, leading to microcracking and progressive damage accumulation. Research has shown that basalt fibers can significantly reduce mass loss, slow down the degradation of dynamic elastic modulus, and enhance frost resistance, with an optimal fiber content of approximately 0.15% [11]. The presence of fibers helps to restrain crack growth and maintain structural continuity during cyclic loading. Moreover, under combined salt–freeze conditions, fibers contribute to reducing porosity and refining pore size distribution, thereby mitigating internal damage and improving resistance to freeze–thaw deterioration [12]. These findings highlight the importance of microstructural stability in enhancing frost durability.

In chloride-rich environments, BFRC demonstrates improved resistance to ion penetration and corrosion-related degradation. Studies reveal that the chloride diffusion coefficient in BFRC is significantly lower than that of ordinary concrete, and the rate of strength degradation is correspondingly reduced [13]. This behavior can be attributed to the densification of the internal structure and the reduced connectivity of pores and microcracks, which together hinder the transport of chloride ions. As a result, the risk of reinforcement corrosion in reinforced concrete structures can be effectively mitigated.

With respect to carbonation, basalt fibers also contribute to enhancing durability. Carbonation, caused by the ingress of CO_2 into the concrete matrix, leads to changes in pore structure and a reduction in alkalinity, potentially affecting structural performance. Experimental results indicate that BFRC exhibits lower carbonation depth and porosity compared to ordinary concrete, along with a more stable evolution of tensile strength during carbonation processes [14]. This suggests that basalt fibers can delay carbonation progression by improving the compactness of the matrix. However, when supplementary cementitious materials such as phosphogypsum are introduced, the carbonation and permeability behavior becomes more complex due to changes in hydration products and pore structure [15]. This highlights the significant influence of composite material systems on durability performance and indicates that fiber–matrix interactions should be considered in multi-component systems.

In summary, the enhancement of durability in BFRC can be attributed to several key mechanisms. Basalt fibers refine the pore structure, reduce pore connectivity, and inhibit crack initiation and propagation, thereby limiting the ingress and transport of aggressive agents such as sulfate ions, chloride ions, and CO_2. These microstructural improvements collectively contribute to the superior durability performance of BFRC under various environmental conditions.

IV. DAMAGE EVOLUTION AND MICRO-MECHANISMS

With the continuous advancement of experimental techniques, research on basalt fiber reinforced concrete (BFRC) has progressively shifted from macroscopic performance evaluation to a deeper exploration of microstructural mechanisms. This transition enables a more comprehensive understanding of the intrinsic relationships between internal structural evolution and external mechanical behavior.

Under high-temperature conditions, BFRC undergoes significant microstructural alterations, particularly in terms of pore structure characteristics. Experimental results demonstrate that increasing temperature leads to a notable rise in porosity, accompanied by a reduction in fractal dimension, indicating a simplification of pore structure complexity. Meanwhile, both the density and width of internal cracks increase markedly. These microstructural degradations weaken the integrity of the cement matrix and ultimately result in a decline in mechanical properties such as compressive and tensile strength [2]. This suggests that thermal damage primarily manifests through pore expansion and crack coalescence, which jointly compromise the load-bearing capacity of the material.

Under dynamic loading conditions, the reinforcing effect of basalt fibers becomes more evident. Digital image correlation (DIC) analysis reveals that fibers play a crucial role in suppressing crack initiation and propagation. By bridging microcracks and redistributing localized stress, basalt fibers contribute to a more uniform strain field within the material. As a result, damage localization is mitigated, and the overall deformation capacity is enhanced. This effect is particularly pronounced under high strain rates, where the ability of fibers to delay crack instability significantly improves the dynamic performance of BFRC [4].

From the perspective of pore structure evolution, environmental actions such as carbonation and freeze–thaw cycles induce complex and time-dependent changes. During the early stages of carbonation, the formation of carbonation products can partially fill internal pores, leading to a temporary reduction in porosity and a corresponding increase in strength. However, as carbonation progresses, the accumulation of expansive products generates internal stresses, which in turn initiate microcracking and structural damage, resulting in a subsequent decline in mechanical performance [14]. Similarly, under salt–freeze conditions, repeated freeze–thaw cycles promote the development of internal pores and cracks. Nevertheless, the incorporation of basalt fibers effectively reduces porosity and refines pore size distribution, thereby inhibiting crack growth and enhancing resistance to environmental deterioration [12]. This highlights the critical role of fibers in regulating pore structure evolution under adverse conditions.

In summary, the performance of BFRC at the micro-scale is governed by the coupled effects of pore structure evolution, interfacial transition zone (ITZ) characteristics, and crack propagation behavior. The interaction among these factors determines the material's resistance to damage initiation and progression. Therefore, a multi-scale analytical framework that integrates pore structure, interfacial properties, and fracture mechanisms is essential for accurately characterizing the behavior of BFRC and guiding its optimized design and application.

V. MAIN CHARACTERISTICS AND EXISTING LIMITATIONS

A comprehensive synthesis of the existing literature reveals several noteworthy trends in the research on basalt fiber reinforced concrete (BFRC).

First, the scope of research has gradually evolved from focusing solely on basic mechanical properties toward a more integrated investigation encompassing durability performance and multi-field coupling effects. Early studies primarily emphasized strength enhancement, whereas recent work increasingly considers the long-term performance of BFRC under complex service environments, such as combined chemical attack, freeze–thaw cycles, and thermal loading. This shift reflects a growing recognition that the engineering performance of BFRC cannot be fully characterized by isolated mechanical indicators alone.

Second, research methodologies have become increasingly diversified and sophisticated. The application of advanced characterization techniques—including nuclear magnetic resonance (NMR), scanning electron microscopy (SEM), and digital image correlation (DIC)—has significantly enhanced the ability to analyze internal damage evolution, pore structure distribution, and crack propagation behavior. These techniques enable a transition from traditional macroscopic testing toward a more refined understanding of the internal structural mechanisms governing material performance.

Third, some studies have attempted to establish predictive models for strength degradation, durability evolution, and damage accumulation, indicating a gradual shift from empirical observation to theoretical modeling and quantitative analysis [8]. These efforts provide a preliminary foundation for performance prediction and structural design, although their applicability remains constrained by specific experimental conditions.

Despite these advancements, several limitations remain and warrant further attention.
(1) There is still no unified consensus regarding the optimal fiber content and fiber length. The reported optimal values vary considerably depending on mix design, testing conditions, and performance indicators, highlighting the lack of a generalized design framework.
(2) Investigations into multi-factor coupling effects remain insufficient. Most existing studies focus on single environmental factors or simplified conditions, whereas real engineering environments typically involve the interaction of multiple physical, chemical, and mechanical processes.
(3) The multi-scale relationships between microstructural characteristics and macroscopic performance have not yet been fully established. Although microstructural analyses provide valuable insights, a systematic linkage across scales—from pore structure and interfacial transition zones to global mechanical behavior—is still lacking.
(4) The engineering applicability and practical validation of current research outcomes require further improvement. Many findings are derived from controlled laboratory experiments, and their direct applicability to large-scale engineering structures under real service conditions remains to be verified.
Overall, while significant progress has been made in understanding the behavior of BFRC, further research is needed to bridge the gap between experimental findings, theoretical modeling, and engineering application.

VI. CONCLUSIONS AND FUTURE PERSPECTIVES

Basalt fibers have demonstrated significant potential in enhancing the crack resistance, toughness, and durability of concrete. Their incorporation effectively alters the failure characteristics of the material, transforming brittle fracture behavior into a more ductile response. This improvement is primarily attributed to the crack-bridging effect of fibers, which delays crack initiation and propagation, as well as to their ability to optimize the internal pore structure and improve the integrity of the matrix.

However, the strengthening and toughening effects of basalt fibers are not unconditional. Their effectiveness is highly dependent on key parameters such as fiber content, length, dispersion, and interfacial bonding with the cement matrix, as well as on the surrounding environmental conditions. Inappropriate fiber dosage or poor dispersion may lead to defects such as fiber agglomeration and increased porosity, which can offset the beneficial effects. Therefore, achieving a balanced and optimized fiber configuration remains a critical issue in practical applications.

From a durability perspective, basalt fibers contribute to improved resistance against various environmental actions by suppressing crack development and reducing the connectivity of pore networks. This, in turn, limits the ingress and transport of harmful agents, thereby slowing down the deterioration process and enhancing the long-term performance of concrete structures. Nevertheless, the behavior of basalt fiber reinforced concrete under complex service environments is still not fully understood.

Future research should place greater emphasis on the following aspects. First, it is necessary to investigate the long-term performance of basalt fiber reinforced concrete under multi-field coupling conditions, such as the combined effects of mechanical loading, temperature variation, moisture, and chemical erosion. Such studies are essential for accurately evaluating its service behavior in real engineering environments. Second, further efforts are required to establish multi-scale analytical frameworks that can effectively link microstructural features—such as pore structure, interfacial transition zones, and crack evolution—with macroscopic mechanical and durability performance. This will contribute to a deeper understanding of the underlying mechanisms governing material behavior. Third, the development of reliable and practical predictive models should be strengthened, with particular attention to their applicability and robustness in engineering practice. These models should be capable of integrating experimental data and theoretical analysis to support performance evaluation and design optimization.

Overall, advancing research in these directions will not only deepen the understanding of basalt fiber reinforced concrete but also facilitate its wider and more reliable application in engineering practice, particularly in structures exposed to complex and harsh service conditions.

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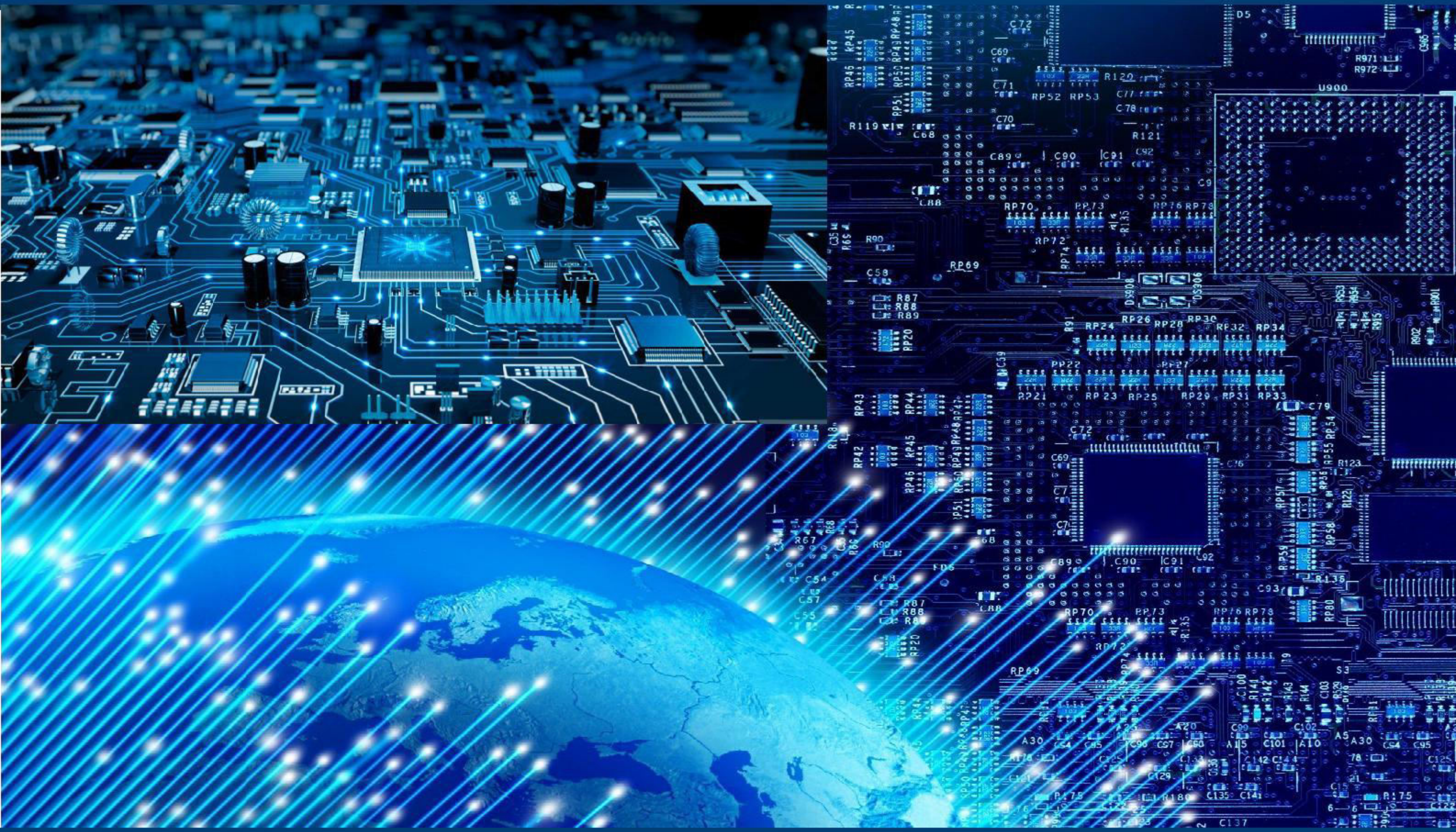

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