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Study on the Reinforcement of South China Sea Island Resources and the Impact on Coral Sand Using Microbially Induced Calcification Technology

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Abstract: This paper aims to explore the application of Microbially Induced Calcification Process (MICP) in reinforcing South China Sea island resources and to analyze its impact factors on coral sand. Through literature review and field surveys, it firstly introduces the significance of South China Sea island resources and coral sand, as well as the principles and application methods of MICP technology. Subsequently, through field investigations and experimental design, the effectiveness of MICP technology in reinforcing these islands is assessed, and the changes in coral sand during the MICP process are analyzed. Further, factors affecting coral sand, including microbial activity, environmental conditions, and other factors, are discussed. The research findings indicate that MICP technology can effectively reinforce South China Sea islands and has a significant impact on coral sand, with microbial activity and environmental conditions being among the primary factors. This study provides an important reference for further exploration of the protection and utilization of South China Sea island resources and anticipates future research directions for MICP technology in this field.
Keywords: Microbially Induced Calcification Technology (MICP); South China Sea island resources; coral sand; impact factors; reinforcement effects.

I. INTRODUCTION

The South China Sea is one of the important maritime regions for China and the surrounding countries, possessing abundant reef resources, including various ecosystems like coral reefs. These reefs are not only habitats for marine life but also crucial components of the marine ecosystem, playing a significant role in maintaining marine biodiversity, ecological balance, and coastal protection. Additionally, the reef resources in the South China Sea support rich fisheries, providing essential support for the fishing economy and food security of the neighboring countries[1].

Coral sand, as a vital component of the reef ecosystem, forms the foundation of coral reefs and performs various ecological functions. Firstly, coral sand provides a solid foundation for coral reefs, maintaining the stability and diversity of coral growth. Secondly, coral sand plays an important filtering and protective role in the marine ecosystem, helping to maintain the cleanliness and transparency of seawater. Furthermore, coral sand serves as a habitat and food source for marine organisms, which is crucial for maintaining marine biodiversity and the balance of the food chain. However, in recent years, the reefs in the South China Sea have been facing increasingly severe natural and human threats, such as marine pollution, climate change, and overfishing, leading to the exacerbated destruction and loss of coral sand. Therefore, finding an effective method to protect and reinforce the reef resources in the South China Sea, especially coral sand, has become particularly important. Microbially Induced Calcite Precipitation (MICP) technology, a new geotechnical reinforcement method, has garnered attention due to its characteristics of not damaging the ecosystem and being environmentally friendly[2]. This study explores the application of MICP technology in reinforcing the reef resources in the South China Sea and its influencing factors on coral sand, which will help to effectively protect and utilize the reef resources, maintaining marine ecological balance and sustainable development.

This study aims to explore in depth the application of Microbially Induced Calcite Precipitation (MICP) technology in reinforcing the reef resources of the South China Sea and systematically analyze its impact on coral sand. The objectives include elucidating the practical application of MICP technology, such as its technical principles, construction methods, and reinforcement effects; evaluating the effectiveness of MICP in enhancing the stability and ecological functions of coral sand through a comprehensive analysis from both engineering and ecological perspectives; and analyzing the factors influencing changes in coral sand during the MICP process, including microbial activity, environmental conditions, and other potential factors. Achieving these objectives will provide a comprehensive understanding of MICP's application effects and impact mechanisms, offering scientific evidence and technical support for the protection and sustainable utilization of reef resources in the South China Sea.

Microbially Induced Calcite Precipitation (MICP) is an engineering technique that utilizes microorganisms to synthesize calcium carbonate ($CaCO_3$) through bioinduction. The process of MICP can be represented by the following reaction formula:

$$Ca^{2+} + CO_3^{2-} + H_2O \rightarrow CaCO_3 \downarrow$$

This process involves a microbially mediated carbonate precipitation reaction, where calcium ions (Ca^{2+}) and carbonate ions ($CO3^{2-}$) combine under suitable conditions to form solid calcium carbonate precipitates. These precipitates fill the pores in the soil or rock, thereby enhancing its strength and stability.

Implementing Microbially Induced Calcite Precipitation (MICP) technology involves several key steps. First, suitable microbial strains, such as nitrate-reducing or urease-producing bacteria, are selected, cultivated, and activated to ensure high metabolic activity. An appropriate culture medium is then prepared, including essential carbon, nitrogen, phosphorus sources, and trace elements to support microbial growth and metabolism. Next, a calcium-rich solution, such as calcium chloride or calcium hydroxide, is injected into the soil or rock and mixed with the microbial culture, forming a calcium ion-containing solution. This solution is then injected into the target soil or rock, allowing it to permeate and fill the pores. During the solidification process, microbial metabolism produces alkaline by-products that react with calcium ions to form calcium carbonate (calcite). This calcite precipitates within the soil or rock pores, enhancing their mechanical properties and stability[3]. Through these steps, MICP technology effectively strengthens and stabilizes soils and rocks, offering a sustainable and efficient solution to geotechnical challenges.

In the context of the South China Sea reefs, the application of MICP technology requires careful consideration of the geotechnical characteristics and ecological environment. Therefore, during the processes of microbial cultivation, culture medium preparation, calcium source injection, and injection into the soil or rock, adjustments and optimizations should be made according to the specific properties and ecological conditions to ensure the effectiveness and environmental friendliness of the technology.

II. CURRENT APPLICATION STATUS OF MICP TECHNOLOGY IN MARINE ENGINEERING

Currently, MICP technology has been extensively studied in the solidification of siliceous sand. However, due to the fact that the main product of MICP is calcium carbonate, its application in the reinforcement of island reef scenarios holds even greater promise. Research on MICP reinforcement of calcareous sand in island reefs is also developing rapidly, primarily focusing on the following areas: (1) MICP reinforcement of calcareous formations and their mechanical properties; (2) MICP reinforcement of island reef foundations; (3) MICP reinforcement of island reef slopes; (4) theoretical modeling of MICP.

A. Reinforcement, Seepage Prevention, and Mechanical Properties of Calcareous Foundations

1) MICP Treatment of Calcareous Sand Columns.

Research on the reinforcement of calcareous sand columns using MICP technology was initially conducted by domestic research teams led by Fang. Fang et al. [4] utilized MICP grouting technology to cement a large number of standard calcareous sand column samples, identifying the influence of particle size and gradation on the solidification effects of MICP on calcareous sand. Guo et al. [5] studied the compressibility characteristics of island reef calcareous sand stabilized using MICP technology, revealing that the compression index of calcareous sand decreased by an average of about 0.1 after treatment. Khan et al. [6] performed microbial grouting on calcareous sand with a median particle size of 0.7 mm, achieving a strength of up to 20.2 MPa after 28 days. Liu et al. [7] conducted field microbial reinforcement experiments on artificially dredged calcareous sand foundations in island reefs. The results indicated that after 3 to 4 rounds of microbial reinforcement, the surface strength reached up to 20 MPa after 9 rounds, with a reinforcement depth of 70 cm and a maximum unconfined compressive strength of 821 kPa.

Some researchers, considering the high temperature and salinity of island reef environments, have studied the effects of seawater, temperature, pH, and other factors on the effectiveness of MICP reinforcement. Li et al. [8] used cementation solutions with five different urea-to-calcium ion concentration ratios to reinforce calcareous sand. Their results indicated that a higher urea-to-calcium chloride concentration ratio accelerated the microbial solidification reaction. However, an overly rapid reaction decreased the permeability of coral sand, reducing the number of possible solidification treatments. They recommended an optimal urea-to-calcium chloride concentration ratio of 1.00:1 to 1.2:1 in substrate solutions. Ou et al. [9] comprehensively analyzed the impact of solution salinity on the MICP reinforcement of calcareous sand, finding that the solidification effect was uneven, with better results in the upper layers compared to the lower ones. After solidification, the permeability coefficient decreased by an order of magnitude.

Currently, research on the effects of seawater environments on the MICP reinforcement of calcareous sand has not reached a consensus. Some scholars believe that the mildly alkaline environment of seawater enhances bacterial activity, leading to greater calcium carbonate deposition and better reinforcement effects. However, others argue that the difference in MICP reinforcement effectiveness between seawater and freshwater conditions is minimal.

2) Dynamic Characteristics of MICP-Reinforced Marine Calcareous Sand

Under cyclic loads such as those from earthquakes and waves, the foundations of island reef calcareous sand are prone to liquefaction, leading to a loss of bearing capacity and potential damage to overlying structures. Based on microbial experiments, indoor cyclic triaxial tests, and model shaking table tests, Xiao [10] investigated the effects of MICP cementation degree, relative density, effective confining pressure, and dynamic stress amplitude on dynamic strength, dynamic pore pressure, and dynamic deformation. Xiao proposed a unified dynamic strength criterion and a novel unified pore pressure response model for MICP-reinforced calcareous sand. In practice, the enhancement of liquefaction resistance in MICP-reinforced calcareous sand primarily stems from the densification effect and cementation caused by the calcium carbonate produced during the MICP reaction. In the early stages of MICP reinforcement, the densification effect resulting from calcium carbonate filling the gaps between soil particles plays a significant role in improving liquefaction resistance. In the later stages of MICP reinforcement, the cementation effect formed by calcium carbonate between particles becomes the dominant factor in enhancing liquefaction resistance.

3) Compression and Breakage Deformation Characteristics of MICP-Reinforced Calcareous Sand

This section summarizes the characteristics of both single-particle compression breakage and overall compression deformation. Single-particle compression breakage is a crucial component of overall compression deformation, while the overall compression load characteristics determine the breakage patterns of individual particles. Shen et al. [11] conducted single-particle breakage tests on calcareous sand particles before and after MICP reinforcement, using both laboratory experiments and discrete element simulations. They explored the impact of MICP on the breakage behavior of calcareous sand particles based on Weibull distribution and electron microscopy scanning. The results showed that after MICP treatment, there was a significant formation of calcite on the surface of the calcareous sand particles, with the breakage pattern shifting from "multi-peak" to "single-peak." This shift was characterized by a reduction in localized cracks, with surface wear and direct through-cracks becoming more prominent.

Jiang [12] used in-situ bio-stimulation MICP to reinforce calcareous sand, finding that as the level of cementation increased, the compressibility of the samples significantly decreased. After compression, the proportion of fine and coarse particles in the in-situ bio-stimulated MICP-reinforced calcareous sand increased with the level of cementation.

4) Fiber-Modified MICP Reinforcement of Calcareous Sand

Yin [13] investigated the effects of fiber content on the mechanical performance and failure modes of calcareous sand through unconfined compressive tests and direct tensile tests. The addition of fibers increased the surface area available for bacterial colonization, thereby enhancing calcium carbonate deposition. This, in turn, improved the ductility and toughness of the samples, as reflected in a stepwise multi-peak stress-strain relationship. Lin et al. [15], using a dynamic triaxial system, studied the effects of MICP coupled with fiber reinforcement on the dynamic properties of solidified calcareous sand. They found that fibers enhanced the MICP process through a bridging effect. Zhao et al. [14] examined the influence of fiber type and content on the uniaxial compressive strength of MICP-reinforced calcareous sand. They discovered that each fiber type had an optimal fiber content. When the fiber content was below this optimal level, the connecting effect of the fibers was limited. Conversely, when the fiber content exceeded the optimal level, the fibers became unevenly distributed within the sand, leading to poor cementation and a reduction in sample strength.

The incorporation of fibers significantly improves the tensile strength of MICP-cemented calcareous sand. Zeng et al. [16] demonstrated that the presence of fibers increased the surface area for calcium carbonate deposition, mitigating the brittle failure typically seen in traditional microbially cemented sandy soils. This approach offers a promising strategy for island reef shore protection. By uniformly mixing fibers with island reef calcareous sand and applying MICP technology, sand stabilization and erosion resistance can be achieved. However, it is important to note that in island reef environments, mixing calcareous sand with fibers is time-consuming and labor-intensive, and achieving uniform mixing is challenging. Further research, tailored to practical engineering needs, is necessary to develop suitable construction methods and advance the application of microbial technology in island reef coastal protection.

B. Research on Island Reef Foundation Reinforcement

1) MICP Reinforcement of the Calcareous Sand-Pile Interface and Shear Band Characteristics

Due to the unique physical and mechanical properties of island reef calcareous sand, pile driving in such strata often disrupts the existing weakly cemented structure, leading to the "pile slipping" phenomenon. When the pile is subjected to loading, the significant particle breakage and damage to the cemented structure generally result in low side friction along the pile shaft in calcareous sand. The breakage of sand particles causes lateral contraction around the pile, while the destruction of the cemented structure leads to brittle fractures. These factors weaken the strength at the calcareous sand-pile interface and cause brittle failure, significantly reducing side friction and making it difficult for the pile foundation to meet design requirements.

In response to these challenges, an eco-friendly reinforcement technology for the calcareous sand-pile interface has been proposed. This includes the development of a multi-functional, visually monitored interface shear testing apparatus under multi-directional boundary conditions. The equipment is used to study the effects of factors such as cementing materials, degree of cementation, normal stress, and relative density on the shear behavior of the calcareous sand-steel interface.

2) Analysis of Pile Bearing Capacity Reinforced by MICP in Calcareous Sand

Lin et al. [17] were the first to propose using MICP to reinforce permeable concrete piles in sandy soil. They used a direct pouring method to sequentially inject the bacterial solution and cementation solution from the top of the pile. The results showed that the ultimate compressive load of the reinforced pile was 12,648 N, compared to 5,117 N for the unreinforced pile. Due to the effects of MICP, a model pile with a diameter of 76 mm developed an inverted cone-shaped cemented body, with an influence range of up to 229 mm and a cemented body at the pile tip with a diameter of 170 mm. This significantly improved the uplift load-displacement response, with the ultimate uplift load of the reinforced pile being 4.2 times that of the unreinforced pile.

For pile foundations in calcareous sand, Xiao et al. [18] used a post-grouting method to reinforce pile foundations in calcareous sand strata. By pre-installing grouting pipes inside the pile, the bacterial solution and cementation solution were pumped separately into the bearing layer. It was found that after MICP treatment, the ultimate compressive load of the model pile was 4.4 times that of the unreinforced pile. The pile tip formed an inverted cone-shaped cemented body, significantly optimizing the vertical load transfer mechanism.

While existing results indicate that MICP-reinforced piles can improve load-bearing behavior and significantly enhance ultimate bearing capacity, the focus of reinforcement varies depending on the grouting method. Post-grouting at the pile tip primarily forms a cemented body at the tip, greatly enhancing end bearing capacity with relatively less contribution to side friction.

3) Single Pile Foundation MICP Anti-Scour Test

For addressing local scour, two main protective strategies are commonly employed: (1) Reducing the erosive force of downflow and horseshoe vortices, which includes methods such as altering the pile cross-section shape, installing protective collars around the pile, adding slots to the pile shaft, or enlarging the base diameter—this is known as active protection. (2) Enhancing the erosion resistance of the bed sand, typically through measures like stone placement or bedding layers to protect the bed sand—this is referred to as passive protection. Following the passive protection approach, Tao et al. [19] pioneered MICP-reinforced model pile anti-scour tests, which showed no erosion around the model pile after MICP treatment. Montoya et al. [20] developed a casing MICP grouting system to reinforce the seabed around single piles in shallow water environments. Their study combined shear wave velocity, permeability characteristics, cementation content, and static cone penetration tests to reveal the mechanisms and effectiveness of MICP reinforcement. Using a large cross-section wave and flow flume system, further research was conducted on the anti-scour performance of large-diameter single piles reinforced with MICP. This was compared with traditional stone-throwing protection methods. The deposition of calcium carbonate in the seabed served to cement the seabed sand, encapsulate it, and fill seabed pores. The formation of an inverted cone-shaped cemented body resisted the impact of downflow, weakened the scour effects of horseshoe and wake vortices, and significantly reduced the scour depth around the single pile.

C. Research on the Reinforcement of Island Reef Slopes Using MICP

The Microbially Induced Calcite Precipitation (MICP) technology offers significant advantages over traditional slope reinforcement methods, particularly for island reef stabilization. The MICP process involves injecting a bacterial culture along with urea and calcium chloride solutions into the soil. The bacteria hydrolyze the urea, producing ammonia and carbon dioxide, which then react with calcium ions to form calcium carbonate. This calcite precipitates within the soil, binding the soil particles together, thereby significantly enhancing the soil's shear strength and stiffness. One of the primary advantages of MICP is its ability to improve soil properties without the use of synthetic materials or significant alterations to the natural environment. The calcite precipitation mimics natural processes, making MICP a more environmentally friendly solution that integrates seamlessly with existing ecosystems. Additionally, MICP has the potential to reduce the carbon footprint associated with traditional construction methods, aligning with global sustainability goals. MICP can be directly applied to the surface of island reef slopes to stabilize loose and erodible sediments. This surface treatment forms a hardened crust of calcite-bound sand that resists erosion caused by wave action and rainfall. The application process typically involves spraying bacterial and cementation solutions onto the slope surface, allowing the calcite to precipitate and bond the sand particles together. This method is particularly effective for stabilizing shallow slopes and preventing surface erosion, which is a common issue in island reef environments. For more substantial slope stabilization, MICP can be applied subsurface, where the bacterial solution is injected into the soil to form calcite bonds deeper within the slope. This approach not only stabilizes the surface but also enhances the overall strength and cohesion of the slope material, making it more resistant to large-scale movements such as landslides or slumping. Subsurface MICP treatment is especially beneficial for steeper slopes or areas with a history of slope failure, providing a more comprehensive reinforcement solution.

The toe of a slope is particularly vulnerable to erosion as it is often exposed to the most intense wave action. MICP can be used to reinforce the toe of island reef slopes, reducing the likelihood of undercutting and slope failure. By injecting bacterial and cementation solutions at the toe of the slope, a strong calcite-cemented zone can be created to resist the erosive forces of waves and currents. This approach is particularly effective when combined with other protective measures, such as the use of boulders or artificial reefs, to further dissipate wave energy and protect the slope. In some cases, MICP can be combined with vegetation to enhance slope stability. The roots of vegetation work in conjunction with the calcite bonds formed by MICP to provide additional reinforcement and reduce the potential for surface erosion. This integrated approach not only stabilizes the slope but also promotes the growth of native vegetation, further enhancing the ecological value of the island reef. The combination of MICP and vegetation offers a holistic solution that addresses both the geotechnical and ecological aspects of slope reinforcement. One of the primary challenges is the scalability and uniformity of MICP for large-scale slope stabilization projects. Achieving uniform calcite precipitation over extensive areas can be difficult, especially in heterogeneous soils or complex slope geometries. Inconsistent treatment may result in weak zones within the slope, reducing the overall effectiveness of the reinforcement. Another issue to consider is the environmental impact of MICP, particularly the potential effects of by-products such as ammonia from urea hydrolysis on local water quality. Careful management and optimization of the MICP process are necessary to minimize these impacts and ensure that the benefits of the technology outweigh any potential environmental risks. The durability of MICP-treated slopes in harsh marine environments is also a critical factor. Although calcite is naturally resistant to erosion, the long-term performance of MICP-treated slopes under continuous wave action, tidal fluctuations, and biofouling requires further investigation. Understanding the long-term stability and maintenance needs of MICP treatments is essential for their successful application in coastal settings. Finally, the cost and feasibility of large-scale MICP applications need careful evaluation. While MICP offers potential cost savings compared to traditional methods, the initial setup, monitoring, and possible need for repeated treatments could offset these savings. Additionally, practical challenges such as the availability of suitable bacterial cultures and the logistics of large-scale solution injection must be addressed.

D. Effects of Marine Environmental Characteristics on MICP Process

1) Salinity

Salinity is a key factor affecting the MICP process in marine environments. High salinity can significantly impact bacterial growth and metabolic activity, thereby affecting the efficiency of the MICP reaction. Under high salinity conditions, the metabolic rate of bacteria may decrease, and the rate of urea hydrolysis may slow down, leading to a reduction in calcium carbonate precipitation. To ensure the effectiveness of the MICP process in high salinity marine environments, it is necessary to select bacteria strains that can adapt to high salinity and optimize reaction conditions to ensure proper precipitation and reinforcement.

2) Temperature

Temperature variations in the marine environment also significantly impact the MICP process. Temperature affects bacterial activity, the rate of urea hydrolysis, and the formation of calcium carbonate precipitation. At high temperatures, bacterial metabolic rates and urea hydrolysis rates generally increase, but excessively high temperatures may cause bacterial death or inhibit their activity. Conversely, lower temperatures can slow down the reaction rate. Therefore, it is necessary to adjust the parameters of the MICP process under different temperature conditions to maintain optimal reinforcement effects.

3) Waves and Tides

Waves and tides in marine environments have a significant impact on the effectiveness of MICP reinforcement. Strong waves and tidal movements can lead to the washing away of applied bacterial solutions and cementing agents, thereby reducing the effectiveness of the MICP process.

To address this challenge, barriers or other protective measures can be employed during construction to minimize the interference of waves and tides with the MICP process, thereby enhancing the stability of the reinforcement effects.

4) Biofouling

Biofouling in marine environments, such as corals, seaweeds, and shellfish, can negatively impact the MICP process. These organisms can alter the distribution of sediments and lead to uneven precipitation of calcium carbonate. Therefore, when designing and implementing MICP processes, it is important to consider the effects of biofouling and take measures to reduce its interference, such as selecting appropriate construction times and locations and applying protective coatings.

5) Bacterial Selection and Cultivation

Selecting bacterial strains that are well-suited to marine environments is crucial for ensuring the effectiveness of the MICP process. Commonly used strains, such as Sporosarcina pasteurii, may require adaptation or optimization of cultivation conditions to thrive in marine settings. Additionally, controlling contamination during the bacterial cultivation process is essential to maintain bacterial activity and the overall effectiveness of MICP.

6) Solution Mixing and Injection

The ratio of solutions (such as the concentration of urea and calcium chloride) and the method of injection are critical factors affecting the reinforcement effectiveness of the MICP process. In marine environments, it is necessary to adjust the solution ratios based on specific salinity and temperature conditions and to optimize the injection method to ensure uniform and effective distribution in the target area. The choice of injection technique—whether spraying, infusion, or direct injection—can also impact the efficiency of the MICP process.

7) Reaction Control and Monitoring

Implementing MICP in marine environments requires stringent control and monitoring of the reaction process. Key factors such as bacterial activity, solution concentration, and precipitation rates must be monitored in real-time to adjust construction parameters and processes. Modern sensing technologies and real-time monitoring systems provide valuable data support, facilitating the optimization of the MICP process and ensuring its effectiveness in varying marine conditions.

III. CONCLUSIONS

The South China Sea, with its rich and diverse reef ecosystems, including coral reefs, plays a crucial role in marine biodiversity, ecological balance, and coastal protection. These reefs are vital for sustaining marine life, supporting fisheries, and contributing to regional food security. Coral sand, a fundamental component of these reefs, provides structural stability for coral growth, filters seawater, and serves as a habitat and food source for marine organisms. Recent challenges such as marine pollution, climate change, and overfishing have led to the degradation and loss of coral sand in the South China Sea. Addressing this issue is critical for the conservation and sustainable management of reef resources. Microbially Induced Calcite Precipitation (MICP) technology, a novel and environmentally friendly approach, offers a promising solution for reinforcing coral sand and protecting reef ecosystems.

This study explores the application of MICP technology in the South China Sea, focusing on its potential to enhance the stability and ecological functions of coral sand. MICP involves using microorganisms to produce calcium carbonate, which strengthens and stabilizes soil or rock formations. The study outlines the key steps of MICP, including microbial cultivation, solution preparation, and injection, and emphasizes the need for adjustments based on local environmental conditions.

Current research indicates that MICP technology has shown promising results in reinforcing calcareous sands and improving their mechanical properties.

It has been applied to various marine engineering scenarios, such as reinforcing island reef foundations and slopes, and addressing issues like liquefaction resistance and scour protection. The incorporation of fibers and the use of different grouting methods have further enhanced the effectiveness of MICP in these contexts.

However, the application of MICP in marine environments presents several challenges. Factors such as salinity, temperature, waves, tides, and biofouling can impact the efficiency of the process. Effective bacterial strain selection, solution mixing, and real-time monitoring are essential for optimizing MICP performance and ensuring environmental compatibility.

In conclusion, MICP technology represents a valuable tool for the protection and reinforcement of coral sand in the South China Sea. By integrating MICP with existing conservation efforts and addressing the technological and environmental challenges, it is possible to enhance the resilience of reef ecosystems, support marine biodiversity, and promote sustainable development in this critical maritime region.

A. Data Availability Statement

All data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

B. Acknowledgments

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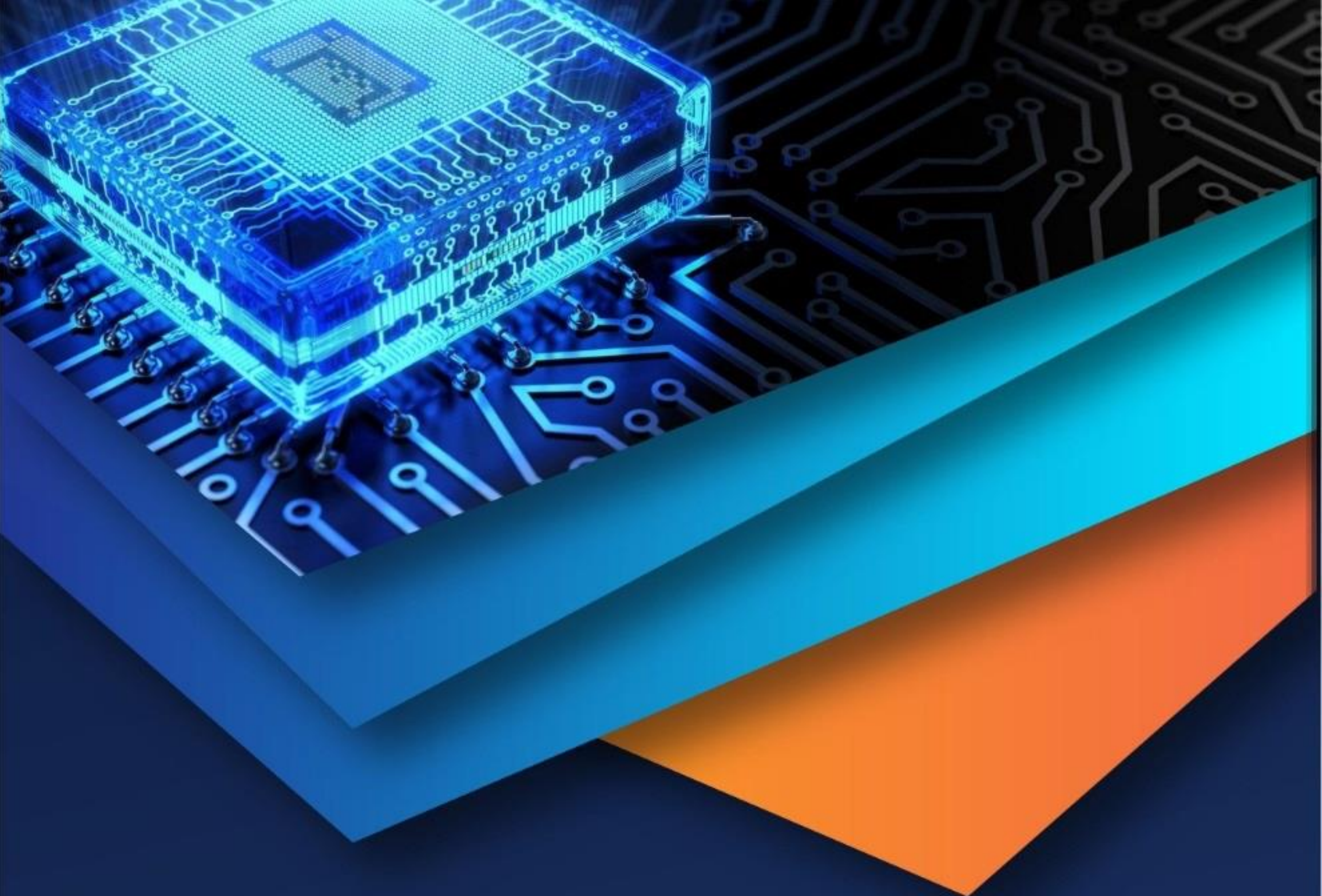

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