iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 Issue: XII Month of publication: December 2025

DOI: https://doi.org/10.22214/ijraset.2025.76214

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue XII Dec 2025- Available at www.ijraset.com

Influence of Nano-Silica Incorporation on Concrete Toughness and Resilience

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Abstract: Concrete continues to serve as the primary construction material for modern infrastructure, forming the basis for buildings, bridges, pavements, and dams. Despite its versatility and strength, conventional concrete is prone to durability problems caused by environmental exposure, chemical deterioration, freeze–thaw cycles, and sustained mechanical loads. The emergence of nanotechnology has made it possible to improve the performance of cementitious materials through the inclusion of nano-silica, an ultrafine form of silicon dioxide. Owing to its exceptionally high surface area, Nano-silica occupies the microscopic pores within this cement system of matrix, creating a denser and more refined microstructure. Acting as a reactive pozzolan, it combines with calcium hydroxide to generate additional calcium silicate hydrate (C–S–H) gel—the phase primarily responsible for strength enhancement. This dual mechanism accelerates early hydration, reduces porosity, and significantly improves both mechanical properties and long-term durability. The present study evaluates the influence of nano-silica on various properties of concrete such as microstructural refinement, pore characteristics, compressive strength, hydration behavior, permeability, water absorption, and shrinkage. The results show that an optimal nano-silica dosage considerably enhances strength, compactness, and overall durability, while excessive additions may reduce workability and cause slight increases in early-age shrinkage. The findings offer valuable insights for designing with high-performance and durability of concretes capable of sustaining adverse mechanical and environmental surrounding conditions.
Keywords: Silica-Nano, Hydration Mechanism, Chloride-Penetration, Shrinkage Behavior, Performance Concrete

I. INTRODUCTION

The Cementitious Composite is one of the most extensively used materials in modern construction because it is economical, mouldable into diverse forms, and capable of sustaining heavy loads. It constitutes the foundation for today's infrastructure from high-rise buildings and bridges to road networks and dams—providing strength and long-term stability. However, conventional concrete is vulnerable to deterioration over time. Moisture infiltration, chloride attack, chemical reactions, and freeze–thaw cycles gradually weaken the matrix, leading to cracking, scaling, and overall loss of durability. Ensuring longer service life and minimizing maintenance costs have therefore become key priorities in contemporary structural engineering.

The advancement of nanotechnology has introduced new possibilities for enhancing cement-based composites. Among the many nanomaterials developed, nano-silica **(nS)** has attracted significant attention because of its high reactivity, ultrafine particle size, and excellent ability to refine the microstructure of hardened cement paste. With particle dimensions typically below 100 nm, nano-silica interacts rapidly with calcium hydroxide released during cement hydration to form additional calcium silicate hydrate (C–S–H) gel—the binding phase chiefly responsible for concrete strength. At the same time, its minute particles fill capillary pores, thereby reducing permeability and densifying the overall matrix.

These effects result in improved strength, resistance to aggressive agents, and enhanced durability. This paper investigates the impact of nano-silica on both the physical and mechanical characteristics of concrete. It analyzes changes in microstructure, compressive strength, hydration kinetics, and permeability to determine the optimum dosage range for practical applications. The research aims to provide clear guidance for engineers and material scientists seeking to design high-performance, sustainable concretes that can withstand demanding environmental and structural conditions.

II. RELATED WORK

A. An Overview of Nano-Silica and Its Influence on Cementitious Materials

The incorporation of nanoscale additives into cement-based composites has brought notable advancements in the manufacturing of concrete with superior performance. In these, Silica-nano a finely divided, amorphous form of the silicon dioxide has gained considerable attention for improving both mechanical strength and durability characteristics. According to Ji (2005), the enhances the interfacial transition zone (ITZ), leading to a denser microstructure with less porosity. Likewise, Gaitero at el, (2008) observed that the inclusion of silica nanoparticles mitigates calcium leaching, thereby promoting greater chemical stability and long-term durability of the material.

B. Microstructural Modifications and Pore Refinement

"Nano-silica contributes to microstructural enhancement through two complementary mechanisms: physical pore filling and chemical action reactivity. Because of its extremely high specific environmental area, nS particles occupy micro voids within the cement paste, while their pozzolanic activity promotes the generation of secondary **C–S–H gel** (Ranjan., 2024). confirmed that well-dispersed nano-silica improves particle packing density and minimizes pore interconnection. Conversely, inadequate dispersion may create agglomerates that form localized environmental weak zones, adversely affecting whole performance (Ghafari, Costa, and Júlio, 2014)".

C. Influence on the Hydration Kinetics

During hydration, nano-silica functions as a nucleation site for C–S–H gel formation, thus accelerating the hydration process. Palla, Bhattacharyya, and Aggarwal (2012) observed a reduction in the dormant period and greater early-age heat evolution, leading to faster strength gain. Asgari et al. (2018) found that liquid-dispersed nano-silica improves hydration kinetics more effectively than dry powders. Wang, Li, and Liu (2015) corroborated this through calorimetric studies exhibiting higher heat evolution and a more compact microstructure within the first 24 hours of hydration.

D. Enhancement of Mechanical Properties

Numerous studies have verified that nano-silica enhances the compressive strength of concrete. Givi et al. (2010) reported strength increases of 15–25 % at early ages and 8–15 % at 28 days with 1–3 % nS addition. Jalal et al. (2012) demonstrated similar improvements in self-compacting concrete (SCC), noting that correct admixture dosage can maintain workability while maximizing strength. However, excessive nano-silica (> 3 %) may cause agglomeration and higher water demand, resulting in reduced performance (Chen @ et al. 2012).

E. Water Uptake and Permeation Characteristics

The durability of concrete largely depends on the penetration to water penetration. According to Givi et al. (2010), the inclusion of nano-silica can lower the water absorption coefficient by nearly 50%. Similarly, Chen et al. (2012) observed that optimum pore refinement occurs at comparatively lower nano-silica dosages, ranging from 0.25% to 0.85%. Furthermore, demonstrated that incorporating around 4% nano-silica reduces the chloride diffusion coefficient by approximately 17–20%, thereby enhancing corrosion resistance and extending the service life.

F. Chloride-ION Penetration and Corrosion Level Resistance

Chloride-induced corrosion represents one of the most persistent problems in reinforced concrete. Said et al. (2012) and Liu et al. (2019) confirmed that nano-silica decreases chloride permeability by refining pore networks and strengthening the ITZ. Optimal performance occurs at 2–3 % nS, offering notable resistance without impairing workability. Moreover, Ghale Noee and Nasiri Rajabli (2023) highlighted that nano-silica also enhances the environmental sustainability of SCC through enhanced resistance to fluid ingress and reduced.

G. Shrinkage - Dimensional Stability

Although nano-silica strengthens concrete, it may also influence shrinkage behavior. The documented up to a 94 % increase in early-age shrinkage with 1–1.5 % nS due to accelerated hydration and elevated water consumption. Nevertheless, long-term shrinkage stabilizes when appropriate curing conditions are applied.

H. Comprehensive Evaluation of Durability and Sustainability

Beyond physical durability, nano-silica contributes to sustainable construction by extending the service life of concrete and reducing maintenance demands. Its synergistic use with supplementary cementitious materials like as fly ash further enhances pozzolanic reactions, yielding denser and more durable matrices suitable for aggressive environments (Said et al., 2012; Fu et al., 2025; Ranjan et al., 2024)

Table 1: Summary of Related Work Findings

Author & Year	% nS Used	Study Focus	Key Findings	Remarks
Ji (2005)	3.8%	Water permeability	Reduced by 45%, denser ITZ	Established nS benefits
Gaitero et al. (2008)	6%	Calcium leaching	Reduced $Ca(OH)_2$ loss	Improved chemical durability
Givi et al. (2010)	1–3%	Strength & absorption	15–25% strength gain, 50% drop in absorption	Optimum at ~2%
Chen et al. (2012)	0.25–0.85%	Hydration & porosity	Fine dispersion yields densest matrix	Dispersion critical

III. DISCUSSION OF AXIMOS

A. Microstructure And Pore Structure

The internal microstructure of concrete plays a crucial role in determining its overall performance and long-term durability. Ordinary concrete typically exhibits a heterogeneous composition with numerous capillary pores and voids, “especially in an interfacial transition environmental zone (ITZ) between the aggregate and the cement paste”. These voids create pathways for moisture, chlorides, and other aggressive substances to infiltrate, leading to gradual deterioration over time.

Nano-silica substantially alters this microstructure due to its exceptionally fine particle size and strong pozzolanic reactivity. Acting simultaneously as a filler and as a reactive agent, nano-silica fills microvoids and chemically interacts with calcium hydroxide produced during cement hydration. This reaction leads to the formation of additional calcium silicate hydrate (C–S–H**)** gel, which refines the pore structure and strengthens the ITZ—the weakest zone in conventional concrete.

Experimental findings support this improvement. Ji (2005) reported that a 3.8 % nano-silica addition reduced water penetration depth by nearly 45 %, demonstrating a more compact and impermeable microstructure. Similarly, Gaitero et al. (2008) found significant reductions in calcium leaching with 6 % nano-silica, indicating improved chemical stability. Quercia et al. (2010) also observed that both colloidal and powdered nano-silica variants enhanced compactness and pore distribution, contributing to increased durability. Uniform dispersion is critical for achieving these benefits. Agglomeration of nanoparticles can result in weak regions within the matrix, negating the expected enhancements. To avoid this, methods such as ultrasonication, mechanical stirring, and aqueous pre-dispersion are often employed. When properly dispersed, nano-silica transforms porous and discontinuous concrete into a dense, homogeneous, and long-lasting material capable of withstanding aggressive conditions.

B. Compressive Strength

Compressive strength remains one of the most essential indicators of concrete quality, reflecting its ability to sustain load and maintain structural integrity. The inclusion of nano-silica has been shown to improve this property through two principal mechanisms: physical densification and accelerated pozzolanic reaction. The ultrafine nano-silica particles act as nucleation sites for hydration products, thereby expediting the formation of **C–S–H gel** and contributing to a denser and stronger matrix.

The degree of improvement depends heavily on several factors, including the dosage of nano-silica, the mix proportion, and the type of aggregate used. Studies on high-strength lightweight concrete indicate that when 3 % nano-silica was introduced, a slight reduction in compressive strength occurred as the proportion of lightweight aggregates increased. For example, 28-day strength values dropped from approximately 64.08 MPa to 54.08 MPa when lightweight aggregates replaced standard ones. This reduction is attributed to the lower intrinsic strength of lightweight aggregates and the potential decrease in hydration products during mixing.

Nevertheless, the early-age strength enhancement achieved through nano-silica addition is especially advantageous in precast concrete applications and other time-sensitive construction scenarios where rapid formwork removal or early loading is required. Proper dispersion and dosage optimization—typically within the range of 1–3 % by binder weight—are critical to maximizing strength gains. Beyond this range, excessive nano-silica can lead to particle agglomeration and increased water demand, reducing overall strength and workability. In short, careful mix design and controlled dispersion yield substantial improvements in both early and long-term compressive strength.

C. Fresh-State Properties of Concrete

The addition of silica – nano notably an effect the fresh properties of concrete, including workability, flowability, and setting behavior. Because of its extremely high specific surface area and strong water-absorption capacity, nano-silica tends to increase the overall water demand of the mix. As a result, the slump of concrete generally decreases while its viscosity increases. This phenomenon can be attributed to the nano-silica particles binding free water molecules, thereby limiting their availability for lubrication within the mixture.

Ghafari et al. (2014) reported a significant reduction in fluidity when nano-silica content increased, emphasizing the necessity for proper water and superplasticizer adjustments to maintain workable mixes. Interestingly, when the dispersion of nano-silica is adequately controlled, the material can exhibit a "ball-bearing effect," which slightly enhances flow characteristics. Jalal et al. (2012) Incorporating 2% nano-silica into self-compacting concrete maintained, and in some cases improved, its flow characteristics. improved by around 30 % in certain cases.

The interaction between nano-silica and recycled aggregates introduces additional complexity, as both materials absorb considerable amounts of water. Therefore, achieving an optimal balance between water content and admixture dosage is crucial for maintaining consistent quality. In general, a nano-silica dosage of up to 3 % by binder weight produces concrete with acceptable workability, provided that appropriate adjustments are made. With proper mix design, nano-silica can be effectively utilized in practical construction applications without compromising fresh-state performance.

D. Hydration Properties

The hydration process governs the strength development and long-term durability of concrete, as it directly influences the formation of its microstructure. Nano-silica significantly accelerates cement hydration by acting as a nucleation site for the precipitation of calcium silicate hydrate (C–S–H). In addition, its pozzolanic activity enables it to react with calcium hydroxide released during hydration, thereby enhancing the quality and density of hydration products.

Calorimetric analyses reveal that mixes containing nano-silica exhibit higher early heat evolution and a shortened dormant period compared to control samples. Palla et al. (2012) observed that the addition of approximately 2 % nano-silica reduced the dormant phase by nearly four hours, promoting faster early-age strength development. Likewise, Asgari et al. (2018) reported higher hydration rates for liquid-dispersed nano-silica than for its dry counterpart, highlighting the importance of dispersion medium and particle distribution. The consumption of free calcium hydroxide and the consequent formation of additional C–S–H gel result in a denser and more refined matrix, improving both the mechanical performance and durability of the hardened concrete. Overall, the presence of nano-silica enhances hydration kinetics, strengthens the interfacial transition zone, and reduces microstructural porosity, collectively contributing to longer-lasting concrete performance.

E. Water Absorption

The rate of water absorption serves as a vital indicator of concrete durability, as high absorption can increase susceptibility to freeze–thaw damage, chloride ingress, and chemical attack. Incorporating nano-silica markedly reduces water absorption by refining the pore structure and blocking capillary pathways. The nanoparticles fill voids within the cement matrix, making it more compact and less permeable to fluids. An observed that the inclusion of nano-silica reduced water absorption values from the 06.10% up to 05.21% after 28 and 90 days of curing. The corresponding coefficient declined markedly, from th3 3.05 up to 1.45 m^2/s, indicating that nano-silica effectively restricts water movement within the cement matrix. Similarly, Chen et al. (2012) reported that smaller dosages of nano-silica, typically ranging from 0.25% to 0.85%, yield optimal pore refinement owing to better particle dispersion and minimized agglomeration. A well-refined pore network not only restricts water uptake but also enhances resistance to environmental stresses, including carbonation and chemical degradation. Therefore, concrete containing nano-silica exhibits superior long-term performance and is particularly suitable for harsh environmental conditions such as coastal and cold regions. The reduction in water absorption highlights nano-silica's potential to produce concrete with improved impermeability and extended service life.

F. Chloride ION Penetration

Chloride penetration is one of the most critical factors affecting the durability of reinforced concrete, particularly in coastal environments and regions exposed to de-icing salts. Chloride ions can infiltrate the concrete matrix, reach the reinforcement, and initiate corrosion, leading to significant structural deterioration over time. The inclusion of nano-silica has been proven effective in mitigating this issue by refining the pore system and creating a denser, less permeable microstructure.

Research by Liu et al. (2019) demonstrated that the use of 4 % nano-silica in concrete, combined with a low water-to-cement ratio, reduced the chloride diffusion coefficient by nearly 17.95 % compared to control specimens. This enhancement is attributed to the densification of the very interfacial transition environmental zone and the overall reduction of pore connectivity. However, excessive nano-silica can lead to particle agglomeration, resulting in uneven mixing and reduced permeability resistance.

An optimal dosage—typically between 2 % and 3 % by binder weight—provides the best balance between chloride resistance and workability. Beyond this range, dispersion difficulties can counteract the benefits. When properly incorporated, nano-silica effectively extends the service life of reinforced concrete structures by providing superior protection against chloride-induced corrosion, thereby improving durability in aggressive marine and urban environments.

G. Shrinkage Properties

Although the addition of silica - nano improves several mechanical with durability characteristics of composite concrete, it can influence shrinkage behavior—particularly at early ages. Early-age shrinkage is primarily affected by the rate of hydration, water consumption, and internal temperature rise. The extremely fine particle size of nano-silica accelerates hydration reactions, often increasing water demand and leading to faster moisture loss, which contributes to higher initial shrinkage.

Wang et al. (2015) reported that the inclusion of 1.3 % nano-silica resulted in nearly a 94 % increase in early-age shrinkage compared with conventional concrete. This significant increase is largely due to rapid hydration kinetics and the high reactivity of the nano-silica particles.

However, the same study indicated that long-term shrinkage levels eventually stabilized and became comparable to those of standard mixes once hydration reached equilibrium.

To mitigate the potential risks associated with early shrinkage, it is essential to ensure proper curing practices, adequate moisture retention, and optimal nano-silica dosage. Controlled additions—typically below 1.5 % by binder weight—help maintain dimensional stability without compromising strength or durability. Thus, while nano-silica may initially accelerate shrinkage, its long-term effects remain manageable when appropriate mix design and curing measures are adopted.

H. Durability

The inclusion of nano-silica significantly enhances the durability of concrete by reducing its porosity, refining the microstructure, and strengthening the interfacial transition zone. These effects collectively minimize the pathways for water ingress, chloride ions, and other aggressive agents that cause degradation over time. The formation of additional **C–S–H gel** and the improved packing density of particles contribute to a denser, more resilient concrete matrix.

Experimental results from Said et al. (2012) revealed a marked reduction in chloride permeability when nano-silica was used at dosages around 6 %, demonstrating its capability to protect reinforced concrete against corrosion. Even smaller concentrations—ranging from 0.3 % to 0.9 %—were found to improve pore connectivity and long-term stability. When nano-silica is combined with supplementary cementitious materials such as fly ash or slag, further enhancements occur through secondary hydration reactions that produce additional binding compounds.

This synergy results in concrete that performs exceptionally well under harsh environmental conditions, such as marine exposure, chemical attack, or repeated freeze–thaw cycles. Overall, nano-silica contributes to the development of high-performance and sustainable concretes, characterized by longer service life, improved impermeability, and reduced maintenance needs. Its adoption aligns with the growing demand for durable, eco-efficient materials in modern infrastructure projects.

IV. KEY RESULTS AND DISCUSSION

The quantitative and qualitative effects of nano-silica on the key performance parameters of concrete are summarized below. The optimal dosage range of 1–3 % by binder weight consistently demonstrates substantial improvements in strength, durability, and microstructural refinement.

Excessive incorporation beyond this range tends to reduce workability and increase early-age shrinkage due to higher water demand and agglomeration of particles. Therefore, maintaining a controlled dosage and ensuring proper dispersion are crucial to balancing mechanical and durability properties.

Table 2: Summary of Nano-Silica Effects on Cementitious Composites

Property	Influence of Nano-Silica	Optimum Range (by wt. of binder)
Microstructure	Produces a denser matrix and refines pore distribution	2–3 %
Compressive Strength	Increases strength by about 10–25 % at 7 days and 8–15 % at 28 days	1–3 %
Workability	Reduces slump by approximately 10–30 %, which can be compensated using admixtures	≤ 3 %
Hydration Rate	Promotes faster hydration reactions and greater heat release	1–2 %
Water Absorption	Decreases by roughly 15–25 %, indicating reduced permeability	0.5–2 %
Chloride Penetration	Lowers chloride ingress by nearly 15–20 %	2–3 %
Early-Age Shrinkage	May increase up to 90 % initially but stabilizes over time	≤ 1.5 %
Overall Durability	Enhances long-term performance and resistance to degradation	1–3 %

A. Interpretation and Evaluation of Findings

Table 2 highlights that nano-silica substantially enhances concrete properties when applied in moderate amounts. Improvements in microstructural density, hydration rate, and compressive strength are most significant at dosages between 1 % and 3 %. The material effectively reduces water absorption and chloride permeability, leading to improved long-term durability. However, higher dosages may compromise workability and introduce early-age shrinkage. Thus, optimal performance can only be achieved through precise control of dosage, dispersion, and mix design.

V. CONCLUSION

The incorporation of nano-silica as an additive in cementitious composites has emerged as an effective strategy to enhance the mechanical strength, microstructural integrity, and durability of concrete. Its dual functionality—as a filler that reduces voids and as a reactive pozzolanic agent that generates additional C–S–H gel—leads to a denser, more compact matrix with superior resistance to environmental degradation. The optimal dosage, typically ranging between 1 % and 3 % by weight of binder, accelerates hydration, refines the pore structure, and strengthens the interfacial transition zone. These improvements contribute to higher compressive strength, reduced permeability, and enhanced long-term durability. However, overdosing can result in agglomeration, lower workability, and increased early-age shrinkage. Proper dispersion methods and adequate curing practices are therefore essential to fully realize the benefits of nano-silica incorporation. Overall, nano-silica represents a transformative material in the production of high-performance concrete, enabling improved sustainability, reduced maintenance costs, and extended service life of modern infrastructure. Its integration into concrete design marks a major advancement toward achieving durable, eco-efficient, and resilient construction materials suited for the challenges of contemporary engineering.

VI. ACKNOWLEDGMENT

Thank you to the publisher for their support in the publication of this research article. We are grateful for the resources and platform provided by the publisher, which have enabled us to share our findings with a wider audience. We appreciate the efforts of the editorial team in reviewing and editing our work, and we are thankful for the opportunity to contribute to the field of research through this publication.

A. Declaration

Author Contributions

Kirithika K: conceptualization, study designing, data collection, data analysis, interpreting the results.

Er. K. Sri Pranap: Conceptualization, study designing, data collection, writing manuscript

Ar. N. Debak: Data analysis, interpreting the results, writing manuscript, drafting final manuscript.

B. Conflict of Interest

The authors declare that they have no conflicts of interest related to the publication of this manuscript.

C. Declaration of Artificial Intelligence (AI)

Assistance Generative AI tools (Grammarly, ChatGPT) were used exclusively for grammar correction and language refinement. The authors confirm that no AI tool was used to generate, analyze, or interpret the research data or findings

D. Ethics Approval

Not applicable.

E. Funding

This research received no specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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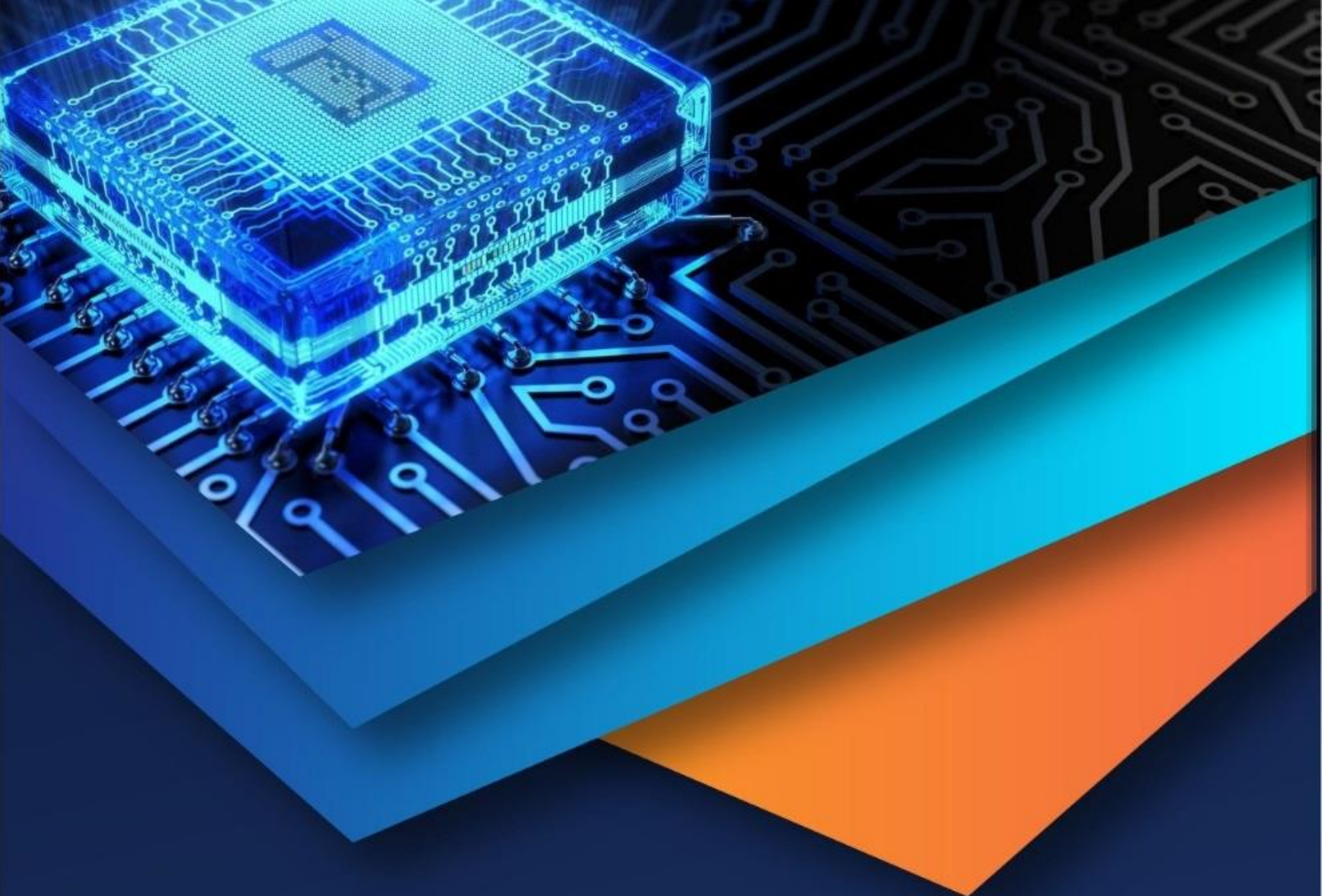

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