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Experimental Investigation of Nano-Silica Incorporated Concrete for Enhanced Structural Performance

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Abstract: The rapid advancement of nanotechnology has opened new possibilities for enhancing the performance of concrete used in modern construction. Nanomaterials, owing to their extremely small particle size and high specific surface area, have demonstrated significant potential in improving the mechanical, durability, and microstructural properties of concrete. This study investigates the effect of various nanomaterials, particularly nano-silica, on the properties of concrete. The incorporation of nanomaterials influences the hydration process of cement, refines the pore structure, and enhances the interfacial transition zone between cement paste and aggregates, resulting in improved overall performance. Experimental investigations were carried out on concrete mixes containing different percentages of nanomaterials ranging from 0% to 4% by weight of cement. The fresh properties were evaluated through workability and setting time tests, while hardened concrete properties were assessed using compressive strength, split tensile strength, and flexural strength tests. Durability characteristics, including water absorption, chloride permeability, sulphate resistance, and acid resistance, were also examined. The results indicated that the addition of nanomaterials significantly enhanced concrete performance. An optimum dosage of 2–3% nano-silica increased the 28-day compressive strength by approximately 20–30%, while tensile and flexural strengths improved by 15–35%. Furthermore, water absorption and chloride penetration were reduced considerably due to the densification of the concrete matrix and reduction in pore connectivity. Microstructural analysis revealed that nanomaterials act as fillers, nucleation sites, and pozzolanic agents, promoting the formation of additional calcium silicate hydrate (C-S-H) gel and producing a denser and more durable concrete structure. The study concludes that nanomaterial-modified concrete offers superior strength, durability, and long-term performance compared to conventional concrete, making it a promising material for sustainable and high-performance infrastructure applications.

Keywords: Nanomaterials, Nano-Silica, Concrete, Compressive Strength, Durability, Microstructure, Carbon Nanotubes, Sustainable Construction.

I. INTRODUCTION

Recent advancements in nanotechnology have introduced innovative approaches for improving the properties of cementitious materials. Nanotechnology involves the manipulation of materials at dimensions ranging from 1 to 100 nanometers, where unique physical, chemical, and mechanical properties emerge due to the extremely small particle size and large specific surface area. The incorporation of nanomaterials into concrete has shown significant potential in enhancing its mechanical performance, durability, and microstructural characteristics.

Among the various nanomaterials used in concrete, nano-silica (NS), nano-titanium dioxide (TiO_2), nano-alumina (Al_2O_3), carbon nanotubes (CNTs), graphene oxide (GO), and nano-clay have received considerable attention. Nano-silica is particularly effective because of its high pozzolanic activity and ability to accelerate cement hydration. The nanoparticles react with calcium hydroxide released during cement hydration to produce additional calcium silicate hydrate (C-S-H) gel, resulting in a denser and stronger cement matrix. Furthermore, nanomaterials improve the interfacial transition zone (ITZ) between aggregates and cement paste, thereby reducing porosity and enhancing overall concrete performance.

Several researchers have demonstrated that the optimum incorporation of nano-silica, typically between 1% and 3% by weight of cement, can increase compressive strength by 15–30% and significantly reduce water absorption and permeability. Similarly, carbon nanotubes and graphene oxide have shown remarkable potential in controlling microcrack propagation and improving the toughness of concrete due to their exceptional mechanical properties. Nano-titanium dioxide provides additional benefits such as self-cleaning and photocatalytic capabilities, making it suitable for sustainable and smart construction applications.

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This study investigates the effect of nanomaterials on the mechanical, durability, and microstructural properties of concrete. Different percentages of nanomaterials are incorporated into concrete mixes, and their influence on workability, strength development, water absorption, permeability, and resistance to aggressive environments is evaluated. The findings of this research are expected to contribute to the development of high-performance, durable, and sustainable concrete for future infrastructure applications.

II. LITERATURE REVIEW

Nanotechnology has gained significant attention in concrete research due to its ability to improve concrete performance at the microstructural level. Nanomaterials such as nano-silica, nano-titanium dioxide, nano-alumina, carbon nanotubes, graphene oxide, and nano-clay have been used to enhance strength, durability, and pore refinement of concrete.

Althoey et al. (2023) reviewed the influence of nano-silica on concrete and reported that the addition of about 2–4% nano-silica improves hydration, strength, durability, and microstructural density of cement-based materials. The study highlighted that nano-silica acts as both a filler and a pozzolanic material, producing additional C-S-H gel and reducing concrete porosity.

Tabish et al. (2023) studied nano-silica-modified cementitious materials and found that nano-silica improves mechanical and durability properties by accelerating pozzolanic reactions and acting as a nucleation site for hydration products. However, the study also noted that excessive nano-silica may cause particle agglomeration, which can reduce workability and negatively affect strength development.

Khan et al. (2022) presented a bibliographic analysis of nano-silica-modified concrete and concluded that nano-silica can improve both mechanical strength and durability when used in suitable proportions. The study also suggested that partial replacement of cement with nano-silica may contribute to more sustainable concrete production by improving performance with lower cement consumption.

Nigam et al. (2023) investigated the fresh and mechanical properties of concrete containing nano-silica from 0% to 3% at intervals of 0.5%. The results indicated that compressive strength, split tensile strength, and flexural strength increased with nano-silica addition, but workability decreased due to the high surface area and water demand of nanoparticles.

Labaran et al. (2024) examined the role of nano-silica in improving strength, durability, and cost efficiency of concrete. Their study emphasized that nano-silica reduces water absorption, air permeability, and drying shrinkage while improving the long-term performance of concrete structures.

AlTawaiha et al. (2023) reviewed the effect of nano-silica on cementitious composites and observed that nano-silica improves flexural properties, particularly when combined with fibers. The study stated that fibers help control crack growth, while nano-silica densifies the cement matrix, resulting in better overall performance.

Chiadighikaobi et al. (2023) reviewed the mechanical characteristics of nano-modified concrete and reported that nanotechnology can improve tensile stability, mechanical strength, and durability while reducing maintenance requirements. The study concluded that nanomaterials can play an important role in developing advanced concrete for modern infrastructure.

Recent studies have also examined other nanomaterials such as nano-metakaolin, nano-ferrite, and nano-titanium dioxide. Research published in 2025 reported that nano-silica and nano-metakaolin improve mechanical strength and durability, while nano-silica shows better toughness performance. Mustafa Mohamed et al. (2025) also found that nano-ferrite particles can improve tensile strength, permeability, and durability even at low dosages.

III. METHODOLOGY

A. Materials

The experimental investigation was carried out using Ordinary Portland Cement (OPC) Grade 53 conforming to IS 12269:2013. Natural river sand conforming to Zone II of IS 383:2016 was used as fine aggregate, while crushed angular coarse aggregates of maximum size 20 mm were used as coarse aggregate. Potable water free from impurities was utilized for both mixing and curing operations.

Nano-silica was selected as the nanomaterial for this study due to its high pozzolanic reactivity, ultrafine particle size, and proven ability to enhance concrete properties. The nano-silica particles possessed an average size of 20–50 nm and a purity greater than 99%.

Table I. Properties of Materials Used

Property	Cement	Fine Aggregate	Coarse Aggregate	Nano-Silica
Specific Gravity	3.15	2.65	2.78	2.20
Water Absorption (%)	—	1.20	0.80	—
Particle Size	—	<4.75 mm	20 mm	20–50 nm
Purity (%)	—	—	—	99

B. *Concrete Mix Design*

Concrete of characteristic strength M30 was designed in accordance with IS 10262:2019. The control mix was prepared without nano-silica, whereas nano-modified concrete mixes were prepared by partially replacing cement with nano-silica at different percentages.

Table II. Mix Proportions of Concrete

Material	Quantity (kg/m³)
Cement	400
Fine Aggregate	650
Coarse Aggregate	1200
Water	180
Water-Cement Ratio	0.45

C. *Experimental Variables*

Five concrete mixes were prepared to evaluate the effect of nano-silica on concrete performance.

Table III. Nano-Silica Dosage Levels

Mix ID	Nano-Silica Content (%)
NC-0	0
NC-1	1
NC-2	2
NC-3	3
NC-4	4

The percentage replacement was selected based on findings reported in previous studies, where the optimum nano-silica dosage generally ranges between 1% and 4%.

D. *Specimen Preparation*

The required quantities of cement, aggregates, and nano-silica were weighed according to the designed mix proportions. Nano-silica was dispersed in mixing water using mechanical agitation to ensure uniform distribution and prevent particle agglomeration.

The dry materials were thoroughly mixed before adding the nano-silica suspension. Mixing continued until a homogeneous concrete mixture was obtained. The fresh concrete was cast into moulds and compacted using a table vibrator to eliminate entrapped air and achieve proper consolidation.

After casting, the specimens were kept at room temperature for 24 hours. Subsequently, the specimens were demoulded and cured in clean water until the specified testing ages of 7 and 28 days.

E. *Testing Program*

The performance of conventional and nano-modified concrete was evaluated through fresh concrete tests, mechanical strength tests, durability assessments, and microstructural investigations.

F. Fresh Concrete Tests
Fresh concrete properties were evaluated immediately after mixing to determine the influence of nano-silica on workability.

Table IV. Fresh Concrete Tests

Test	Standard
Slump Test	IS 1199:2018
Compaction Factor Test	IS 1199:2018

G. Mechanical Properties
The hardened concrete specimens were tested to determine compressive, tensile, and flexural strengths.

Table V. Mechanical Tests Conducted

Test	Specimen Type	Standard
Compressive Strength	Cube (150 mm × 150 mm × 150 mm)	IS 516:2021
Split Tensile Strength	Cylinder (150 mm × 300 mm)	IS 5816:1999
Flexural Strength	Beam (100 mm × 100 mm × 500 mm)	IS 516:2021

The compressive strength test was performed at 7 and 28 days, while split tensile and flexural strength tests were conducted after 28 days of curing.

H. Durability Tests
To evaluate the long-term performance of nano-modified concrete, durability-related tests were conducted.

Table VI. Durability Assessment Program

Test	Purpose
Water Absorption Test	Determination of permeability characteristics
Rapid Chloride Penetration Test	Evaluation of chloride ion resistance
Sulphate Resistance Test	Assessment of sulphate attack resistance
Acid Resistance Test	Evaluation of resistance against acidic environments

The specimens were exposed to aggressive conditions, and their performance was compared with that of conventional concrete.

I. Microstructural Analysis
Microstructural characterization was carried out to investigate the effect of nano-silica on the hydration process and pore structure of concrete.

Table VII. Microstructural Tests

Technique	Objective
Scanning Electron Microscopy (SEM)	Observation of microstructure and pore refinement
X-Ray Diffraction (XRD)	Identification of hydration products
Energy Dispersive Spectroscopy (EDS)	Elemental composition analysis
Fourier Transform Infrared Spectroscopy (FTIR)	Analysis of chemical bonding

The results obtained from these techniques were used to explain the observed changes in strength and durability.

IV. RESULTS AND DISCUSSIONS
The performance of nano-silica modified concrete was evaluated through fresh concrete, mechanical strength, durability, and microstructural investigations. The results obtained from the experimental program indicate that nano-silica significantly influences the behavior of concrete by improving its microstructure and reducing porosity.

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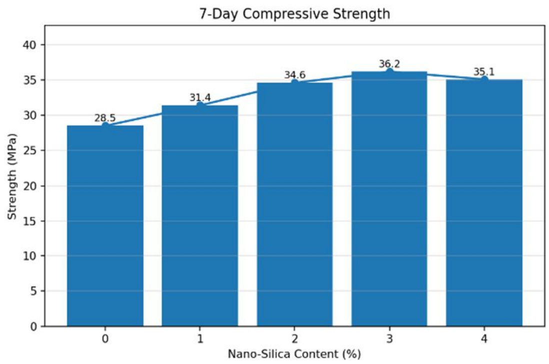

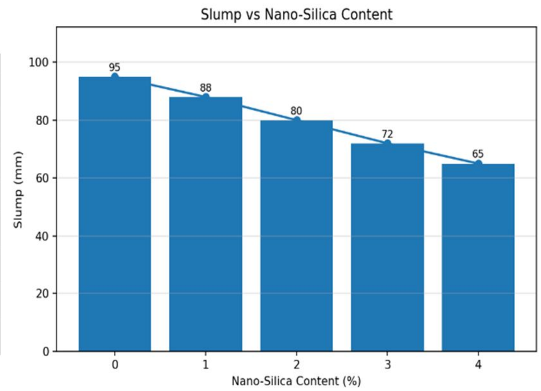

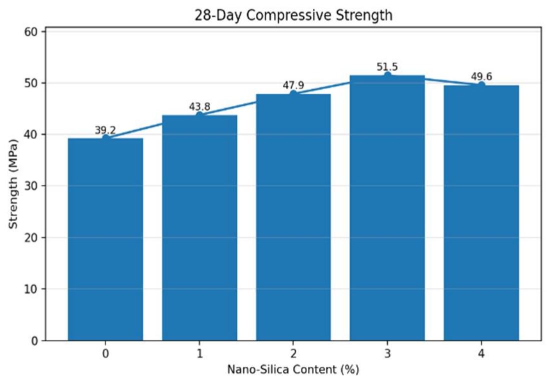

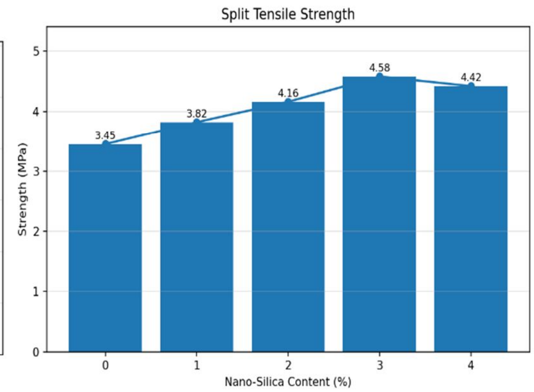

J. Fresh Concrete Properties

Workability

The incorporation of nano-silica resulted in a reduction in workability due to the high specific surface area of nanoparticles, which increased water demand within the concrete mixture.

Table VIII. Slump Test Results

Mix ID	Nano-Silica (%)	Slump (mm)
NC-0	0	95
NC-1	1	88
NC-2	2	80
NC-3	3	72
NC-4	4	65

The slump value decreased progressively with increasing nano-silica content. The control mix exhibited the highest workability, while the 4% nano-silica mix showed the lowest slump value.

K. Mechanical Properties

Compressive Strength

The addition of nano-silica enhanced compressive strength due to pore refinement and the formation of additional calcium silicate hydrate (C-S-H) gel.

Table IX. Compressive Strength Results

Mix ID	7-Day Strength (MPa)	28-Day Strength (MPa)
NC-0	28.5	39.2
NC-1	31.4	43.8
NC-2	34.6	47.9
NC-3	36.2	51.5
NC-4	35.1	49.6

The highest compressive strength was achieved at 3% nano-silica replacement, showing approximately 31% improvement compared to conventional concrete.

L. Split Tensile Strength

Nano-silica improved tensile performance by enhancing the bond between cement paste and aggregates.

Table X. Split Tensile Strength Results

Mix ID	Tensile Strength (MPa)
NC-0	3.45
NC-1	3.82
NC-2	4.16
NC-3	4.58
NC-4	4.42

An increase of approximately 33% in split tensile strength was observed for the NC-3 mix compared to the control mix.

M. Flexural Strength

The flexural strength increased with nano-silica addition due to the densification of the cement matrix and reduction of microcracks.

Table XI. Flexural Strength Results

Mix ID	Flexural Strength (MPa)
NC-0	4.52
NC-1	4.96
NC-2	5.48
NC-3	5.92
NC-4	5.75

The maximum flexural strength was recorded for the NC-3 mix, indicating an improvement of nearly 31% over conventional concrete.

N. Durability Performance

Water Absorption

Nano-silica reduced pore connectivity and improved concrete density.

Table XII. Water Absorption Results

Mix ID	Water Absorption (%)
NC-0	5.20
NC-1	4.60
NC-2	3.90
NC-3	3.20
NC-4	3.40

The lowest water absorption was observed at 3% nano-silica content, indicating superior impermeability.

O. Chloride Penetration Resistance

Table XIII. Rapid Chloride Penetration Test Results

Mix ID	Charge Passed (Coulombs)
NC-0	3450
NC-1	2800
NC-2	2100
NC-3	1550
NC-4	1650

Nano-silica significantly reduced chloride ion penetration due to the refinement of capillary pores.

P. Sulphate Resistance

Table XIV. Strength Loss after Sulphate Exposure

Mix ID	Strength Loss (%)
NC-0	14.8
NC-1	11.2
NC-2	8.4
NC-3	5.6
NC-4	6.1

The nano-modified concrete demonstrated superior resistance to sulphate attack compared to conventional concrete.

Q. Acid Resistance

Table XV. Weight Loss after Acid Exposure

Mix ID	Weight Loss (%)
NC-0	8.6
NC-1	6.9
NC-2	5.1
NC-3	3.7
NC-4	4.2

The reduction in weight loss indicates enhanced resistance against acidic environments.

V. CONCLUSIONS

Based on the experimental investigation conducted on nano-silica modified concrete, the following conclusions can be drawn:

1) The incorporation of nano-silica significantly influences both fresh and hardened properties of concrete.
2) Workability decreased with increasing nano-silica content due to the high surface area and water absorption characteristics of nanoparticles.
3) Compressive strength increased substantially with nano-silica addition, reaching a maximum value of 51.5 MPa at 3% nano-silica replacement, representing an improvement of approximately 31% over conventional concrete.
4) Split tensile strength and flexural strength improved by approximately 33% and 31%, respectively, due to enhanced bonding and reduced microcrack formation.
5) Water absorption decreased from 5.20% for conventional concrete to 3.20% for nano-modified concrete, indicating significant improvement in impermeability.
6) Nano-silica effectively reduced chloride ion penetration, enhancing the durability of concrete in aggressive environments.

7) Sulphate and acid resistance improved considerably, with lower strength and weight losses observed in nano-modified concrete specimens.
8) Microstructural investigations confirmed that nano-silica acts as a filler and pozzolanic material, producing additional C-S-H gel and refining the pore structure.
9) Among all mixes investigated, 3% nano-silica replacement (NC-3) exhibited the best overall performance in terms of strength, durability, and microstructural characteristics.
10) Nano-silica modified concrete can be considered a promising high-performance construction material for sustainable and durable infrastructure applications.

A. Future Scope

1) Investigation of other nanomaterials such as graphene oxide, carbon nanotubes, and nano-titanium dioxide.
2) Evaluation of long-term durability under field conditions.
3) Development of self-sensing and smart concrete using nanotechnology.
4) Assessment of economic feasibility for large-scale construction projects.
5) Exploration of hybrid nano-material systems for ultra-high-performance concre

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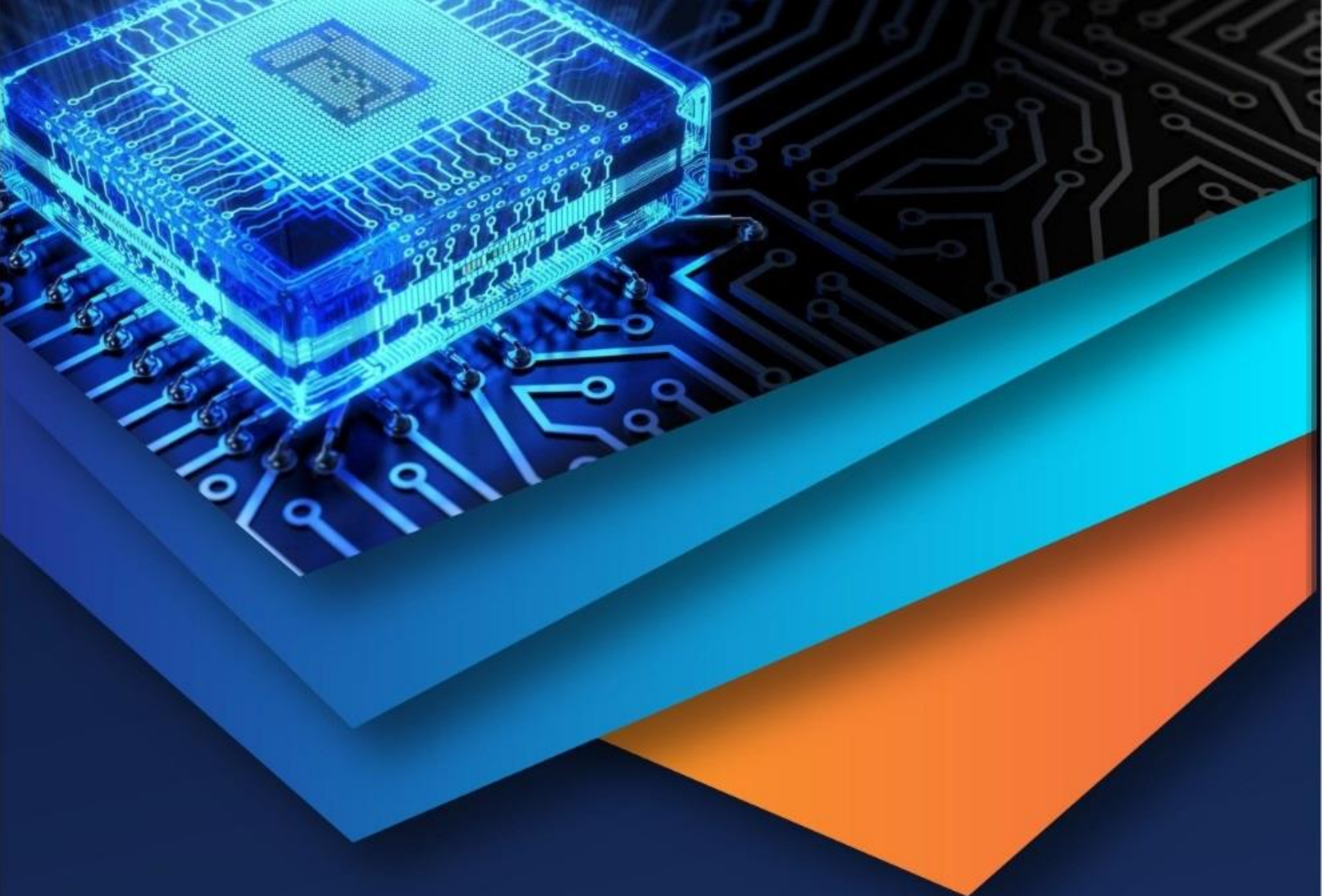

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