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Experimental Investigation on Low Carbon Concrete

Bharat Gautam Dhuldhule[1], Krishna Ravindra Kharat[2], Hrutvik Ishwar Jamdar[3], Rushikesh Gangadhar Dude[4], Aditya Ambika Kale[5], Ganesh Ravindra Wagh[6]
Department of Civil Engineering, Imperial College of Engineering & Research, Pune, India

Abstract**: The construction industry is one of the largest contributors to global carbon dioxide (CO_2) emissions, primarily due to the production of Portland cement, a key ingredient in conventional concrete. This report explores the development and implementation of low carbon concrete as a sustainable alternative to traditional concrete, aiming to reduce its environmental impact. Low carbon concrete incorporates materials such as supplementary cementitious materials (SCMs), including fly ash, slag, and silica fume, as well as innovative technologies like geopolymer concrete and carbon capture and storage (CCS) techniques. These methods not only lower CO_2 emissions during production but can also improve the material's strength, durability, and overall performance. Despite the promising potential, the widespread adoption of low carbon concrete faces challenges, including economic barriers, material availability, and the need for industry-wide standardization. This report examines current trends, performance considerations, and future innovations in the field, with a focus on overcoming barriers and accelerating the transition to more sustainable construction practices. Ultimately, low carbon concrete represents a critical step toward reducing the carbon footprint of the built environment and supporting global sustainability goals.

I. INTRODUCTION

General: Low-carbon concrete is an innovative material aimed at reducing the environmental impact of traditional concrete production, which is responsible for a significant portion of global carbon dioxide (CO_2) emissions. Traditional concrete's main ingredient, cement, generates a high amount of CO_2 due to the energy-intensive calcination process in which limestone is heated to high temperatures. The production of one ton of cement releases approximately one ton of CO_2, contributing to nearly 8% of global CO_2 emissionsLow-carbon concrete seeks to reduce this impact by incorporating alternative binders, supplementary cementitious materials (SCMs), and other techniques that lower the carbon footprint without compromising structural integrity. Common SCMs include industrial by-products such as fly ash, slag, and silica fume, which replace a portion of cement in the concrete mix. Newer innovations include geopolymer concrete, which uses waste materials like fly ash and slag as the primary binder, eliminating the need for conventional cement entirely.The drive for low-carbon concrete is spurred by global goals to decarbonize construction and achieve net-zero emissions by mid-century. By reducing the CO_2 emissions associated with construction materials, low-carbon concrete not only supports these goals but also aligns with sustainable building practices, contributing to more eco-friendly cities and infrastructure. Low-carbon concrete offers a path forward for sustainable construction, addressing the dual challenge of maintaining structural performance while reducing the industry's environmental impact. With continued advancements and increased adoption, it has the potential.

A. Enviromental Impact Of Low Carbon Concrete

1) Reduction In Co2 Emission

Cement Replacement: Traditional Portland cement, the main binder in concrete, is responsible for most of concrete's carbon footprint, producing nearly 1 ton of CO_2 for every ton of cement made. Low-carbon concrete often uses supplementary cementitious materials (SCMs) like fly ash, slag, and natural pozzolans to replace a portion of the cement. These materials have a lower carbon footprint because they're often industrial by-products, thus reducing the demand for cement and its associated emissions.

Alternative Binders: Some low-carbon concretes, such as geopolymer concrete, replace cement entirely with alternative binders made from waste products like fly ash or ground granulated blast-furnace slag. This eliminates the need for cement, significantly reducing CO_2 emissions.

Carbon Capture: Some forms of low-carbon concrete incorporate technologies that capture CO_2 from the atmosphere or industrial sources and use it to cure concrete, sequestering carbon within the material itself.

Recycled Aggregates

Recycled Concrete Aggregate (RCA): Demolished concrete can be crushed and reused as aggregate in new concrete mixes, reducing the need for virgin aggregate and decreasing the carbon emissions associated with mining, processing, and transporting new materials.

Recycled Industrial By-Products: Waste products like slag from steel production and ceramic waste can be used as aggregates, reducing the demand for natural resources and supporting a circular economy in construction.

2) Optimized Mix Design

Low Cement Content Mixes: Concrete formulations can be optimized to use minimal cement while maintaining desired strength and durability. This often involves using SCMs or advanced admixtures to enhance performance.

Performance-Based Design: Rather than using prescriptive specifications (such as a set cement content), performance-based mix designs allow engineers to design concrete for specific strength, durability, and sustainability targets. This often leads to less cement usage and lower emissions.

Lightweight Concrete: Lightweight concrete uses alternative aggregates, like expanded clay or recycled plastics, to reduce density and cement requirements. This also reduces emissions related to transportation and handlin

3) Future Scope Of Low Carbon Concrete

Wider Adoption in Construction and Infrastructure Projects Growing Demand for Sustainable Construction:

With increasing awareness and regulatory pressure to reduce emissions, low-carbon concrete is expected to see expanded use in residential, commercial, and industrial construction. Governments, especially in Europe and North America, are implementing carbon reduction mandates for new buildings, pushing developers to adopt sustainable materials like low-carbon concrete.

Infrastructure and Mega Projects: Infrastructure projects, such as bridges, roads, and airports, are often large consumers of concrete. As governments pledge to reduce carbon emissions in public projects, low-carbon concrete could become a preferred material for these long-lasting structures, which will lead to significant reductions in embodied carbon.

Innovative Material Development and Research

Advances in Carbon Sequestration: New methods to capture and store CO_2 within concrete, such as carbonation curing and CO_2 injection, are being actively researched. In the future, these approaches could create concrete with a net-negative carbon footprint, where the material sequesters more CO_2 than is emitted during production.

Development of Novel Binders: Alternative binders, like geopolymers, magnesium-based cements, and bio-based binders, offer promising avenues to further reduce or even eliminate reliance on traditional Portland cement. Research will likely continue to refine these materials to improve their performance, durability, and cost-effectiveness.

4) Enhanced Lifecycle Assessment and Certification Standards

Lifecycle Assessment Tools: The development of advanced tools to accurately measure the lifecycle carbon footprint of building materials will make it easier for developers to choose low-carbon concrete. These tools will quantify not only embodied carbon but also long-term durability benefits and maintenance savings associated with low-carbon concrete.

Green Certification Programs: Building certification systems like LEED, BREEAM, and WELL are increasingly rewarding projects that use sustainable materials. Low-carbon concrete will likely become a key component of certified green buildings, enhancing market demand for this sustainable alternative.

Cost Reduction and Scaling of Low-Carbon Concrete Technologies

Scaling Production and Reducing Costs: As demand grows, the production of low-carbon concrete and its alternative binders is expected to scale up, leading to reduced costs and greater availability. Advances in production techniques, such as using renewable energy in cement plants and optimizing SCM processing, will make low-carbon concrete more accessible for a wide range of applications.

Economies of Scale for SCMs and Alternative Materials: As low-carbon concrete technologies mature, the cost of supplementary cementitious materials (SCMs) and alternative binders is expected to decrease. Increasing availability of SCMs, particularly in regions without ready access to industrial by-products like fly ash or slag, will help expand low-carbon concrete adoption.

Global Policy and Regulatory Support

Carbon Pricing and Emission Reduction Targets: Policies like carbon taxes and cap-and-trade systems put a financial cost on carbon emissions, incentivizing the use of low-carbon alternatives. As governments increase pressure on industries to cut emissions, low-carbon concrete could become a preferred material in regulated markets.

International Standards and Codes: Standards organizations such as ASTM, ISO, and local building codes are gradually developing guidelines for low-carbon concrete use. The establishment of universal standards will provide builders with clear specifications, ensuring safety, quality, and environmental impact are consistently addressed.

II. LITERATURE REVIEW

1) Fadi Althoey,Ahmed Farouk Deifalla (2023): Researchers seek sustainable materials for eco-friendly cement and concrete to reduce CO2 emissions. This paper offers an extensive overview of the research conducted on concrete technology with minimal to zero-carbon emissions. This review paper reviews materials and technologies for lowering the construction industry's carbon footprint, focusing on alternative binders and supplementary cementitious materials (SCMs). Additionally, the paper explores the transformative potential of carbon capture and utilization technologies for sustainability. It also explored life cycle assessments, economic aspects, and financial implications of this technology. Overall, the review summarizes low-carbon concrete in the context of sustainable development and climate change mitigation. It has been found that substituting SCMs for cement reduces carbon emissions in concrete without compromising strength and durability. Materials such as slag, metakaolin, calcined clay, and limestone can replace clinker, eliminating CO2 emissions in cement production. This study highlights challenges, including market adoption and material availability, offering insights for successful implementation.
2) Danah Albuhairi,Luigi Di Sarno(2022): The sustainability of the construction industry is a priority in innovations made towards mitigating its notoriously high carbon emissions. Developments in low-carbon concrete technology are of peak interest today under the scrutiny of emerging policy pressures. Concrete is the external part of most structures vulnerable to permanent degradation and weathering, the possibility of an intrinsic restoration of its engineering properties promises unprecedented advancements towards structural resilience. Existing research in self-healing concrete (SHC) has often concerned the scope of material development and evaluation with inconclusive field testing, hindering its progress towards structural feasibility. This paper presents an overview of recent progress in SHC, and possible opportunities and challenges of popular healing systems are discussed. Moreover, trends are observed to investigate SHC's influence on the engineering properties of concrete, and future projections of SHC are suggested with identification of potential research needs
3) Don Wimpenny(2007): This paper summarises the results of the Low Carbon Concrete study conducted in 2007 on behalf of the UK Government Environment Agency (EA), CarbonReduction Fund. The objective of the study was to identify low CO2 alternatives to conventional concrete for use in EA infrastructure schemes, such as flood alleviation schemes. The prompt for the study was a newspaper article discussing low carbon alternatives concrete, including use of a bituminous binder from processing heavy fuel oils, which was claimed to have negative carbon emissions . At the outset, it was decided that the study should not focus on a single proprietary material but should review other alternatives to Portland cement binder. Concrete production accounts for approximately 5% of worldwide greenhouse gas emissions . Most of the embodied CO2 emissions in concrete derive from the Portland cement and the worldwide production of Portland cement accounts for approximately 3% of annual CO2 emissions
4) Antonella D'Alessandro,Claudia Fabiani,Anna Laura Pisello(2016): The article reviews the recent research contributions and future promising perspectives regarding innovation in concrete technologies for low-carbon applications in buildings. To this aim, an original classification of recent trends is presented for reducing the carbon footprint of concrete constructions by identifying three main research lines. The first one is related to the enhancement of physical and mechanical properties of concrete, the second one is related to resource efficiency and raw materials' saving and the third one concerns the role of smart concretes in building energy efficiency. Possible synergies between the three addressed main research lines are finally discussed.

III. METHODOLOGY

The methodology adopted for this project involved a systematic and structured approach to investigate the potential of Low Carbon Concrete (LCC) as a sustainable alternative to conventional concrete. The process began with an extensive literature survey, where various textbooks, research articles, and technical papers were reviewed to gain a deep understanding of the basic concepts, recent developments, and current trends in the field of low carbon construction materials. This step helped in identifying the research gaps and forming a strong foundation for the experimental investigation.

Following the literature review, the need for the research was clearly identified. With increasing global concerns about climate change and the construction sector's contribution to carbon emissions, the importance of developing eco-friendly construction materials became evident. The study aimed to explore viable substitutes for Ordinary Portland Cement (OPC) that could reduce the carbon footprint without compromising the performance of concrete.

Once the objectives were defined, the investigation stage commenced. This involved planning and designing the experiments to evaluate the mechanical and physical properties of concrete mixes prepared using low carbon materials. The selection of materials played a crucial role in this phase. Various supplementary cementitious materials (SCMs) such as fly ash, ground granulated blast furnace slag (GGBS), and silica fume were considered due to their pozzolanic properties and low environmental impact. Fine and coarse aggregates, along with water and admixtures (if required), were also selected based on standard specifications.

After finalizing the materials, suppliers were identified to procure them. The selection of suppliers was based on factors such as material quality, availability, and consistency. Once the materials were collected, laboratory tests were conducted to determine their physical and chemical properties. These tests included specific gravity, fineness, setting time for cementitious materials, and sieve analysis, water absorption, and impact value for aggregates. The water quality was also checked to ensure suitability for concrete mixing.

Based on the test results, appropriate mix designs were developed and concrete samples were cast and cured as per standard procedures. Various tests, such as compressive strength tests, were performed on hardened concrete specimens to assess the performance of the low carbon concrete mixes. The experimental data were then interpreted and analyzed to draw meaningful conclusions. Finally, the results were compared with those of conventional concrete to evaluate the effectiveness of using alternative materials in reducing carbon emissions while maintaining desirable strength and durability characteristics.

IV. THEROTICAL CONTENT

The various literatures have been referred from journals, procedding, books, various report,case study website etc.to understand the present status of project undertaken. From this literature, present work is formulated Impact on ordinary concrete on environment (carbon footprint) Carbon Emissions from Cement Production: Primary Contributor: Cement, the binding agent in concrete, accounts for 7–9% of global CO_2 emissions Producing 1 ton of cement releases approximately 1 ton of CO_2, High-temperature kilns: Limestone is heated to 1,450°C, primarily using fossil fuels like coal or natural gas . Chemical reaction (calcination): Limestone ($CaCO_3$) decomposes into lime (CaO), releasing CO_2 as a byproduct.

A. Broader Environmental Impacts

1) Resource Depletion: Sand and gravel, key aggregates in concrete, are over-extracted, threatening ecosystems and coastlines Global demand for concrete consumes 30 billion tons of aggregates annually, exacerbating resource scarcity Water Usage: Concrete production requires significant water for mixing and curing, straining freshwater suppliesAir Pollution: Cement manufacturing emits sulfur dioxide (SO_2) and nitrogen oxides (NO_x), contributing to smog and acid rain Waste Generation: Demolition waste from concrete often ends in landfills, with limited recycling efforts
2) Carbon footprint of the building: It is challenging to definitively pinpoint the carbon footprint of a building as it depends on numerous factors. The production of building materials consumes natural resources and energy, contributing to global warming. Population growth increases the demand for buildings, impacting greenhouse gas emissions.Cement production accounts for 3% of global CO2 emissions, primarily due to the decomposition of calcium carbonate. The high carbon footprint of building materials largely results from the type of energy used during production. In Poland, 77% of energy comes from coal, leading to high emissions.Energy-intensive buildings account for about 50% of resource extraction and use, and over 30% of waste in the EU. They consume 40% of energy and generate 36% of greenhouse gas emissions related to energy production. The construction sector is responsible for approximately 38% of global CO2 emissions, with 28% from building operations and 10% from the construction industry itself.

Buildings generate 70-80% of emissions during use and maintenance, while building materials account for one-third of the carbon footprint at the construction stage. Concrete and steel, primarily used in foundation slabs, contribute the most to these emissions.Challenges related to the embedded carbon footprint, particularly in the production of cement, steel, aluminum, and glass, are being addressed through new technologies and changes in production processes. Cement, responsible for 8% of global CO2 emissions, is becoming more eco-friendly through alternative fuels, increased use of mineral additives, and CCS (Carbon Capture and Storage) technologies.

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V. RESULTS

The mix design for M30 grade concrete was developed in accordance with IS 10262:2019, considering moderate environmental exposure and medium workability, which is suitable for general construction applications. The primary objective was to achieve a characteristic compressive strength of 30 MPa, with a target mean strength of 38.25 MPa, derived using the formula: $f'cm = f'ck + 1.65 \times S = 30 + (1.65 \times 5) = 38.25$ MPa,

where the standard deviation (S) was assumed as 5 MPa based on typical values for M30 mixes.

Ordinary Portland Cement (OPC) was used as the binder at a dosage of 400 kg/m³. The maximum size of coarse aggregate selected was 20 mm, and well-graded river sand was used as fine aggregate. Water content was fixed at 180 liters per cubic meter, suitable for medium workability requirements. The water-cement ratio was calculated as 0.45, which is within the acceptable limit for durability under moderate exposure conditions.

Using IS 10262 mix design guidelines, the aggregate proportions were estimated as:

Fine Aggregate (FA): 700 kg/m³

Coarse Aggregate (CA): 1200 kg/m³

Adjustments were made to account for the bulking of sand, considering an approximate 20% volume increase due to moisture. The final mix proportions by weight were established as:

Cement : Water : Fine Aggregate : Coarse Aggregate = 1 : 0.45 : 1.75 : 3.0

Carbon Footprint Analysis

A major focus of this investigation was to assess the environmental impact of the M30 mix in terms of carbon emissions. The embodied carbon values for each material were calculated as follows:

Cement: With 400 kg of cement per m³ and a known emission factor of 0.93 kg CO_2 per kg of cement, the total CO_2 emission from cement usage was calculated as:

$400 \times 0.93 = 372$ kg CO_2

Water: Considering the emission factor of 0.5 kg CO_2 per cubic meter, the emission for 180 liters (0.18 m³) of water used was:

$0.18 \times 0.5 = 0.09$ kg CO_2

Aggregates: For a combined total of 1900 kg of fine and coarse aggregates, and an emission factor of 0.03 kg CO_2 per kg, the total emissions were:

$1900 \times 0.03 = 57$ kg CO_2

Thus, the total carbon footprint per cubic meter of M30 concrete was calculated as:

372 kg CO_2 (cement) + 0.09 kg CO_2 (water) + 57 kg CO_2 (aggregates) = 429.09 kg CO_2

VI. DISCUSSION

From the analysis, it is evident that cement is the most significant contributor to the carbon footprint of concrete, accounting for approximately 87% of total emissions in the M30 mix. Aggregates, despite being used in larger quantities, contribute a relatively minor portion (around 13%) due to their lower emission factor. The impact of water is almost negligible. These results reinforce the importance of minimizing cement content or replacing a portion of it with supplementary cementitious materials (SCMs) such as fly ash or GGBS to achieve more sustainable and low-carbon concrete formulations in future investigations.

The experimental investigation conducted on the M30 concrete mix design highlights important insights into both the mechanical design parameters and the environmental impact associated with traditional concrete. The chosen M30 grade concrete is widely used in structural applications and offers a balanced combination of strength, durability, and workability suitable for moderately exposed environmental conditions.

A. *Mix Design Performance*

The mix design was developed based on IS 10262:2019 guidelines, targeting a characteristic compressive strength of 30 MPa and a target mean strength of 38.25 MPa. The water-cement ratio of 0.45 was selected based on durability requirements and desired workability for standard construction work. OPC (Ordinary Portland Cement) was used as the binder, with a dosage of 400 kg/m³. Fine and coarse aggregates were incorporated in the proportions of 700 kg/m³ and 1200 kg/m³ respectively, and the water content was kept at 180 liters per cubic meter.

The mix proportion obtained was:
Cement : Water : Fine Aggregate : Coarse Aggregate = 1 : 0.45 : 1.75 : 3.0
This proportion reflects a well-balanced design offering medium workability and structural adequacy. In practical terms, the mix is easy to place and compact while meeting the strength and durability criteria for a wide range of construction purposes. The design was also adjusted for bulking of sand, acknowledging the real-world condition of aggregate moisture, which plays a vital role in mix behavior and consistency.

B. Carbon Footprint Analysis

A crucial objective of this study was to assess the carbon emissions associated with conventional M30 concrete. The environmental performance was evaluated by calculating the embodied carbon emissions from each constituent material per cubic meter of concrete. The results show:

- Cement accounted for 372 kg CO_2, or approximately 87% of the total emissions.
- Aggregates (fine and coarse combined) contributed 57 kg CO_2, accounting for roughly 13%.
- Water had a negligible contribution of 0.09 kg CO_2.

The total carbon footprint for 1 m^3 of M30 concrete was calculated to be 429.09 kg CO_2.

C. Interpretation and Implications

The findings clearly indicate that cement is the dominant source of carbon emissions in traditional concrete. Despite being a relatively small proportion of the total concrete mix by weight, the carbon intensity of OPC is significantly higher than other components. This underscores the importance of targeting cement content when aiming to reduce the carbon footprint of concrete.
On the other hand, aggregates and water—although used in large quantities—have much lower emission factors and therefore contribute far less to the overall environmental impact. Nevertheless, optimizing aggregate sources and water usage can further reduce emissions, especially in large-scale projects.
The implications of these results are significant in the context of sustainable construction. In order to transition to low carbon concrete, there is a pressing need to partially or fully replace OPC with supplementary cementitious materials (SCMs) like fly ash, ground granulated blast furnace slag (GGBS), metakaolin, or silica fume. These materials not only lower the carbon footprint but can also enhance long-term durability and reduce heat of hydration in large pours.
Furthermore, the use of locally sourced aggregates and recycled water can contribute additional reductions in environmental impact. Consideration should also be given to optimizing mix design through performance-based specifications rather than prescriptive approaches, which often lead to overdesign and unnecessary cement usage.

D. Conclusion of Discussion

The M30 conventional mix design fulfills the structural and workability requirements for general construction; however, it comes with a substantial environmental cost. The carbon footprint analysis reveals that traditional OPC-based concrete is carbon-intensive, primarily due to the high emissions associated with cement production. These findings validate the motivation behind exploring low carbon concrete alternatives, where material substitution, efficient mix design, and sustainable sourcing play a pivotal role. Future work in this project will include designing alternative mixes using SCMs and comparing their performance—both mechanical and environmental—to the benchmark M30 concrete discussed here.

VII. CONCLUSION

The present study on "Experimental Investigation on Low Carbon Concrete" was carried out with the primary objective of analyzing the conventional M30 grade concrete in terms of its mix design characteristics and associated carbon footprint. The project involved a methodical approach beginning with an extensive literature review, followed by a standard M30 concrete mix design based on IS 10262:2019, and concluded with a carbon emissions assessment to identify the environmental impact of each component in the concrete mix.
The mix design adopted in this study achieved a target mean strength of 38.25 MPa, ensuring that the concrete satisfies both structural integrity and serviceability criteria. The proportions used—400 kg of OPC, 180 liters of water, 700 kg of fine aggregate, and 1200 kg of coarse aggregate per cubic meter—resulted in a balanced and workable concrete mix suitable for medium exposure conditions commonly encountered in construction.

However, the environmental evaluation revealed a significant finding: the cement component alone contributed to nearly 87% of the total carbon footprint, resulting in approximately 372 kg of CO_2 emissions per m^3 of concrete. Combined with minor emissions from aggregates and water, the total carbon footprint of M30 conventional concrete was found to be approximately 429.09 kg CO_2 per cubic meter. This underscores the fact that even though traditional concrete is effective from a performance standpoint, it poses a substantial environmental burden, primarily due to the high emissions involved in the production of Ordinary Portland Cement.

These findings emphasize the urgent need for sustainable alternatives in the construction industry. The high carbon intensity of OPC makes it imperative to adopt greener materials, such as supplementary cementitious materials (SCMs) like fly ash, GGBS, silica fume, and other industrial by-products, which offer the potential to reduce CO_2 emissions without compromising mechanical properties. Additionally, innovative practices such as recycled aggregates, performance-based mix design optimization, and water-efficient construction techniques can further enhance the sustainability of concrete.

In conclusion, this study highlights that while conventional M30 concrete fulfills structural requirements, its environmental impact is substantial. The outcomes of this investigation serve as a benchmark for future research aimed at developing and testing low carbon concrete alternatives, which not only meet strength and durability standards but also significantly reduce the carbon footprint of construction practices. Moving forward, the project can be extended to include experimental trials of concrete mixes incorporating SCMs, recycled aggregates, or carbon-capturing additives to achieve the dual goals of performance efficiency and environmental responsibility.

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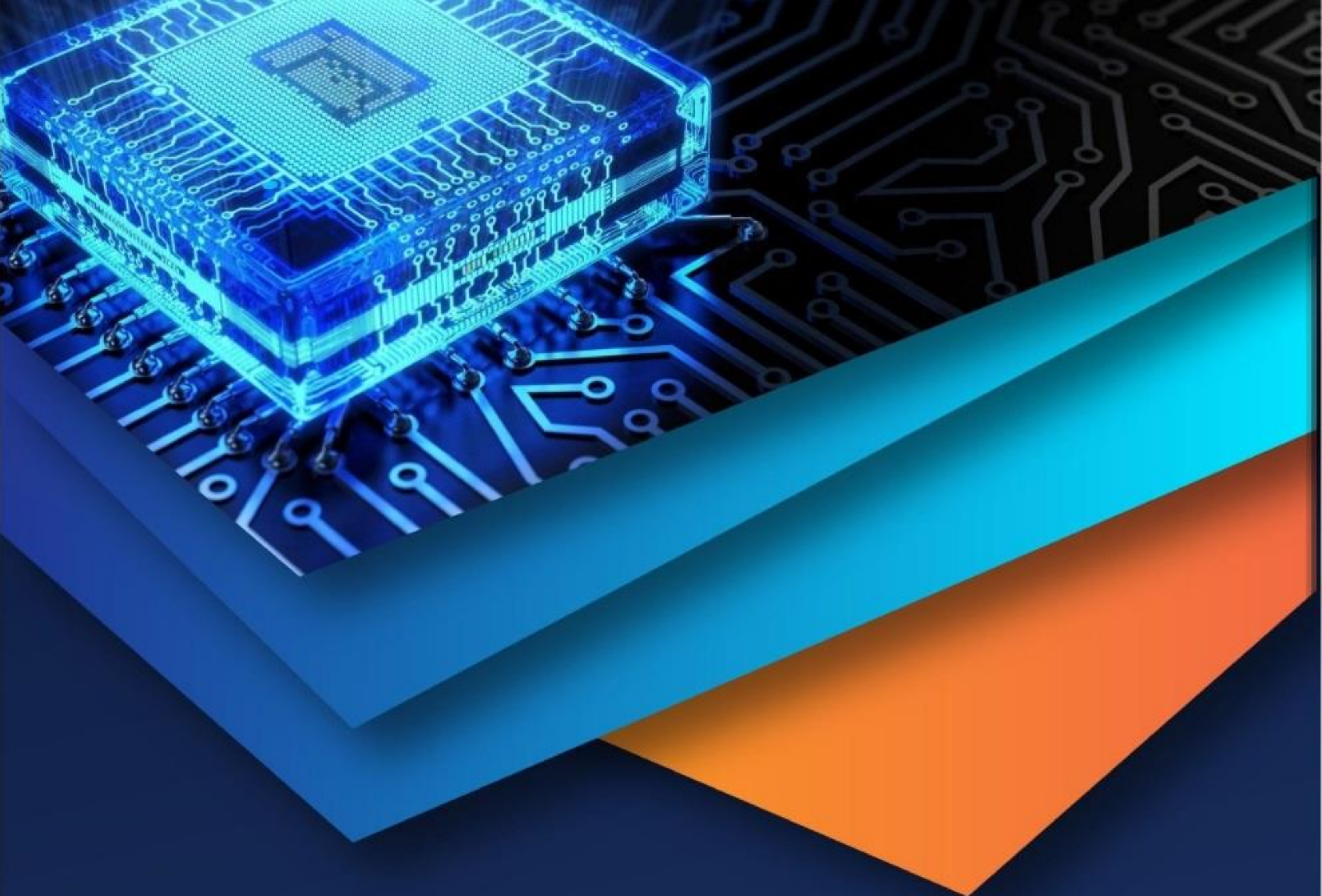

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