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Synergistic Effects of Fly Ash and Metakaolin on the Performance of Sustainable Concrete

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Abstract: This study examines the development of environmentally sustainable concrete incorporating fly ash (FA) and metakaolin (MK). Concrete mixtures of grade M60 were produced with a fixed replacement of 20% FA to promote long-term matrix densification, alongside varying MK contents of 4%, 8%, 12%, and 16%. Mechanical properties, including compressive, split tensile, and flexural strengths, as well as durability characteristics such as sorptivity, water absorption, chloride permeability, and homogeneity, were assessed at curing ages of 7, 28, and 90 days. The results demonstrate that the mixture containing 20% FA and 12% MK delivered the most favourable performance among the SCM combinations, leading to improvements of approximately 24–28% in compressive strength, 21–25% in split tensile strength, and 22–24% in flexural strength relative to the control concrete. Life cycle assessment indicated notable reductions in global warming potential, ozone depletion potential and acidification offering substantial environmental benefits.
Keywords: Metakaolin, mechanical performance, chloride permeability, global warming potential

I. INTRODUCTION

The building and construction sector accounts for approximately 38% of global CO_2 emissions and nearly 35% of total energy consumption, largely driven by the increasing demand for infrastructure and the continued reliance on conventional construction materials [1]. With global concrete production exceeding 25 billion tonnes annually, the associated environmental burden has become a critical concern. One effective strategy to mitigate these impacts is the development of green concrete through the partial replacement of ordinary Portland cement (OPC) or natural aggregates with supplementary cementitious materials (SCMs), industrial by-products, or renewable resources, thereby reducing the overall environmental footprint [2].

A wide range of SCMs—including silica fume, fly ash (FA), metakaolin (MK), bottom ash, quarry dust, rice husk ash, and sugarcane bagasse ash—have been shown to enhance concrete performance through pozzolanic reactions, nucleation effects, and micro-filling mechanisms [3–7]. These processes refine the pore structure and promote the formation of C–S–H and C–A–(S)–H gels, resulting in improved strength and durability [8]. In addition to performance benefits, the use of SCMs contributes to environmental, economic, and social sustainability by reducing clinker consumption and conserving natural resources [9,10]. However, comprehensive studies focusing on durability-oriented optimization of SCM combinations remain limited [11].

Fly ash, a by-product of coal combustion in thermal power plants, is one of the most widely used SCMs in concrete [12]. Its partial replacement of cement reduces CO_2 emissions, manages industrial waste, lowers heat of hydration, and enhances long-term durability, although high replacement levels may adversely affect early-age strength [13–17]. Metakaolin, a thermally activated aluminosilicate derived from kaolinitic clays, is a highly reactive pozzolan known to significantly enhance both strength and durability of concrete [18–20]. Its fine particle size and high surface reactivity promote the formation of additional C–S–H and C–A–S–H gels through reactions with calcium hydroxide, leading to a denser microstructure and refined pore network [21–23]. Despite their individual benefits, the combined and synergistic effects of FA and MK in concrete remain insufficiently explored, particularly in relation to long-term performance.

Against this backdrop, the present study aims to develop sustainable concrete incorporating combined dosages of fly ash and metakaolin. The mechanical and durability properties of the developed concrete are systematically evaluated and analysed for M60 grade concrete, followed by life cycle analysis. The outcomes of this work provide valuable insights into the synergistic use of SCMs and recycled fibers, contributing to the advancement of durable and environmentally responsible concrete for sustainable construction applications.

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II. EXPERIMENTAL PROGRAM

A. Materials

This study examines the fresh and hardened properties of M60-grade concrete mixtures, comprising four fly ash–metakaolin (FA–MK) blended mixes and one control mix. The mix proportions for all mixtures are presented in Table 1. The concrete was designed in accordance with IS 10262:2019, aiming for a target compressive strength of 68 MPa. Ordinary Portland Cement (OPC), 53 grade was used as the primary binder. Class C fly ash, procured from a local ready-mix concrete (RMC) plant, and calcined clay (metakaolin) were incorporated as partial replacements for cement. The representative images of FA and MK are shown in Figure 1. The aggregate system consisted of crushed coarse aggregates of 20 mm and 12.5 mm sizes, combined with manufactured sand (Zone II, particles <4.75 mm). A sulphonated naphthalene-based superplasticizer (Conplast SP 430) was added to all mixes to achieve the specified workability.

Table 1 Mixture proportions of concrete mixtures in kg/m^3

Concrete type	C	FA	MK	FW	S	CA	SP
Mix (C)	492	-	-	187			
Mix (20%FA+4%MK)	374	98	20	--			
Mix (20%FA+8%MK)	354	98	40	--	621	1238	2.95
Mix (20%FA+12%MK)	334	98	60	--			
Mix (20%FA+16%MK)	314	98	80	--			

C- Cement, FA- Fly ash, MK- Metakaolin, FW- Freshwater, S- Sand, CA- Coarse aggregate, Mix (C) – Conventional mix.

(a) (b)

Figure 1 (a) Fly ash, (b) Metakaolin

B. Test Methods

The mechanical and durability performance of the mixtures was evaluated based on the specimen details provided in Table 2. Mechanical properties were determined through compressive strength, split tensile strength, and flexural strength tests. Durability characteristics were assessed using capillary water absorption and chloride permeability tests. For each test, three specimens were cast and tested to ensure the reliability and repeatability of the results.

Table 2 Specimen configuration of mechanical properties of concrete

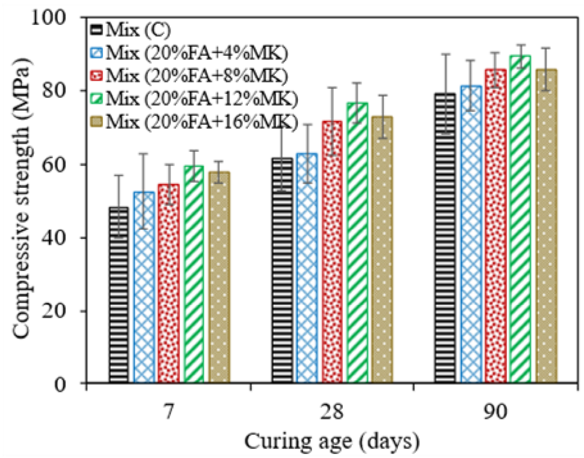
Test	Specification	Type of specimen	Specimen size (mm)
Compressive strength	IS-516: 1956	Cube	100×100×100
Split tensile strength	ASTM-C496	Cylinder	100×200
Flexural strength	IS 516: 2021	Beam	100×100×500
Capillary absorption	ASTM C1585	Disc	100×50
RCPT	ASTM C1202	Disc	100×50

III. RESULTS & DISCUSSIONS

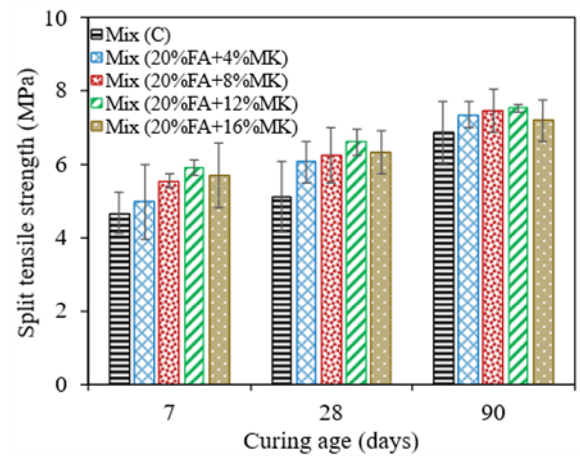
A. Mechanical properties of concrete mixtures

The mechanical performance of the binary blended concretes incorporating fly ash (FA) and metakaolin (MK) is shown in Figure 2. In comparison with the control mix, the FA–MK blends demonstrated significant improvements in strength, with the degree of enhancement increasing with curing age. The compressive strength increased by approximately 15–27%, while the split tensile and flexural strengths improved by 12–31% and 18–28%, respectively.

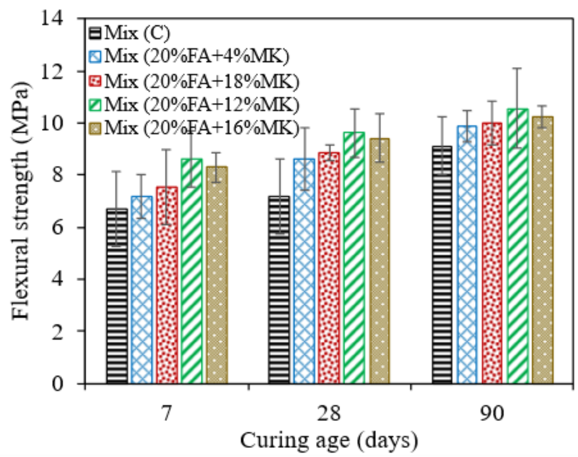
Among all the mixtures, the blend containing 20% FA and 12% MK consistently achieved the highest strength values at each curing age, indicating this proportion as the optimum combination. The observed improvement can be attributed to the synergistic interaction between the two supplementary cementitious materials. This complementary behaviour results in a denser and more refined microstructure, thereby improving overall mechanical performance. However, when the MK replacement level exceeded 12% (e.g., 20% FA + 16% MK), a slight reduction in strength was observed. This decline is likely due to excessive consumption of portlandite, leaving insufficient calcium hydroxide in the matrix to support further pozzolanic reactions.



(a) Compressive strength



(b) Split tensile strength



(c) Flexural strength

Figure 2 Mechanical properties of concrete mixtures

B. Capillary absorption of concrete mixtures

The sorptivity of all mixtures was measured at 7, 28, and 90 days, as presented in Figure 3, with water absorption quantified in terms of primary and secondary sorption rates. A consistent decrease in sorptivity was observed with increasing curing age, particularly between 28 and 90 days, indicating progressive microstructural refinement and pore densification, in line with earlier studies. At 7 days, the control mix exhibited 10–25% higher capillary absorption compared to the FA–MK blended mixtures, demonstrating the accelerated early hydration and pore refinement associated with metakaolin incorporation. As the MK content increased, sorptivity further declined at later ages relative to the control. Among all mixtures, the ternary blend containing 20% FA and 12% MK achieved the lowest absorption values, showing an overall reduction of approximately 16–21% across all curing ages, thereby indicating enhanced durability performance. However, when the MK content exceeded 12%, a slight increase in sorptivity was noted. This may be due to particle agglomeration at higher dosages and the reduced availability of portlandite for continued pozzolanic reactions, potentially leaving unreacted particles and microvoids within the matrix.

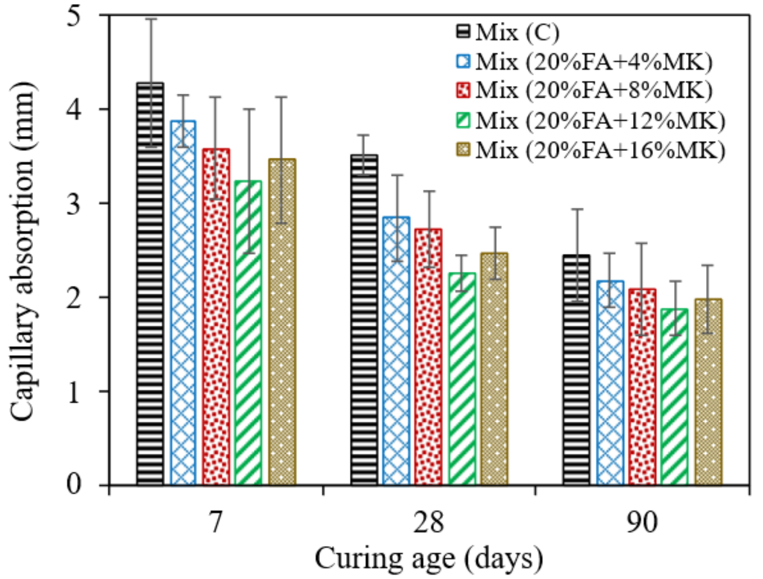


Figure 3 Capillary absorption of concrete mixtures

C. Chloride permeability (RCPT)

The chloride permeability of the concrete mixtures was assessed using the Rapid Chloride Penetration Test (RCPT) at curing ages of 7, 28, and 90 days, as shown in Figure 4. The total charge passed decreased consistently with increasing curing duration, reflecting a progressive refinement of the pore structure and a corresponding reduction in chloride ingress. The blended mixtures exhibited markedly lower permeability even at early ages, with reductions ranging from approximately 41–58% compared to the control mix. At later ages, the ternary blends demonstrated superior performance, with the mixture containing 20% FA and 12% MK recording the lowest RCPT values among all mixes. This enhanced resistance to chloride penetration can be attributed to the synergistic effects of metakaolin and fly ash. The fine particles and high reactivity of MK contribute to pore refinement and the blockage of chloride transport pathways, while the slower, sustained pozzolanic reaction of FA further decreases capillary porosity over time.

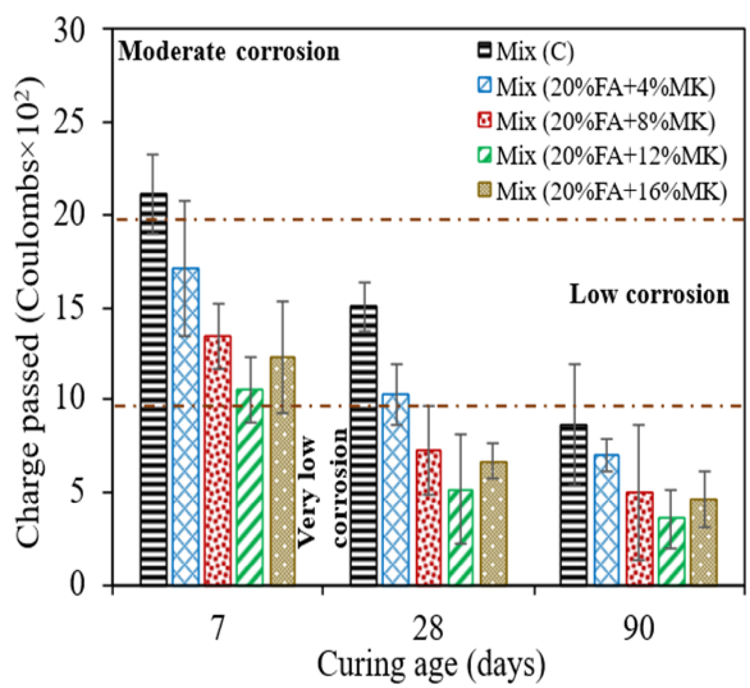


Figure 4 RCPT for various concrete mixtures

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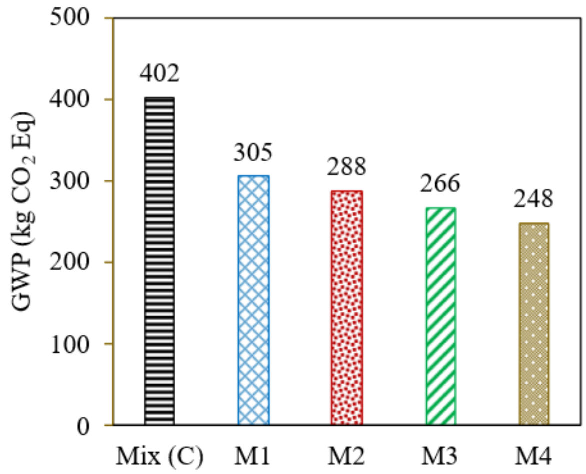
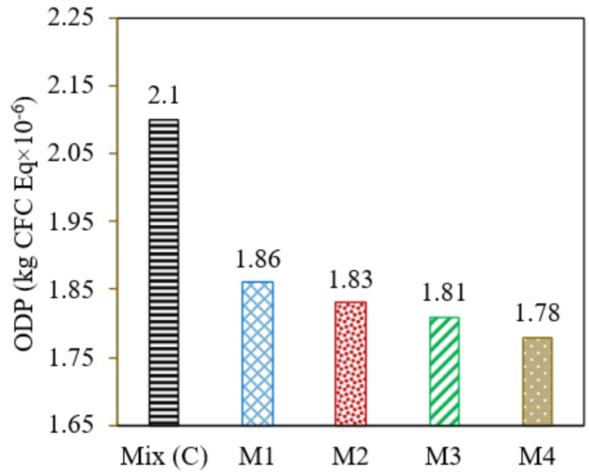
D. Life cycle analysis

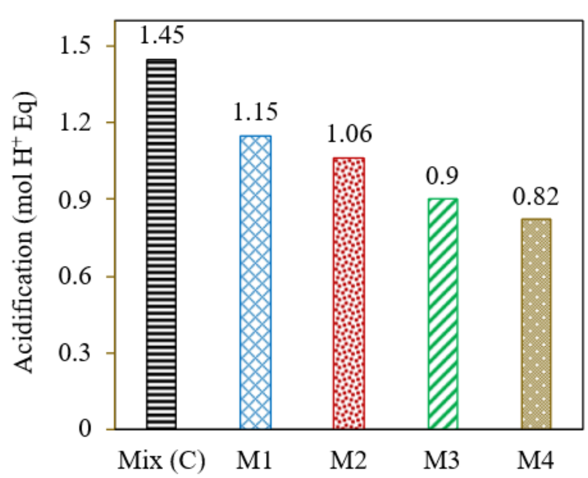
As anticipated, the partial replacement of cement with supplementary cementitious materials (SCMs) led to a marked reduction in Global Warming Potential (GWP). As illustrated in Figure 5, the percentage reduction in GWP increased progressively with higher silica fume (SF) content. The mixture containing 20% fly ash (FA) and 20% SF achieved the maximum reduction of approximately 36%. This significant improvement is primarily attributed to the high carbon footprint associated with cement production; therefore, reducing cement content through SCM substitution effectively lowers overall greenhouse gas emissions. A similar decreasing trend was observed for Ozone Depletion Potential (ODP), where the incorporation of SCMs resulted in reductions ranging from 11–15% across the various blended mixtures, as shown in Figure 5. Acidification potential also demonstrated substantial improvement with SCM substitution. The FA–SF blended concretes consistently recorded significantly lower acidification values compared to the control mix, with reductions between 21-42%, highlighting the environmental advantages of blended systems. The blended mixtures showed significant environmental benefits.



(a) Global warming potential



(b) Ozone depletion potential



(c) Acidification

Figure 5 Sustainability benefits of concrete mixtures

IV. CONCLUSIONS

Based on the experimental observations, the following conclusions are given below

1) Incorporation of FA and MK significantly improved compressive, tensile, and flexural strengths, with 20% FA + 12% MK identified as the optimum blend.
2) The synergistic pozzolanic action of MK and FA produced a denser microstructure, enhancing long-term performance.
3) Sorptivity decreased with curing age, and the 20% FA + 12% MK mix showed the lowest water absorption.

4) Chloride permeability was substantially reduced in blended mixes, indicating improved durability.
5) Cement replacement with SCMs significantly lowered GWP, ODP, and acidification impacts.
6) Overall, optimized FA–MK blends provide a sustainable and high-performance alternative to conventional concrete.

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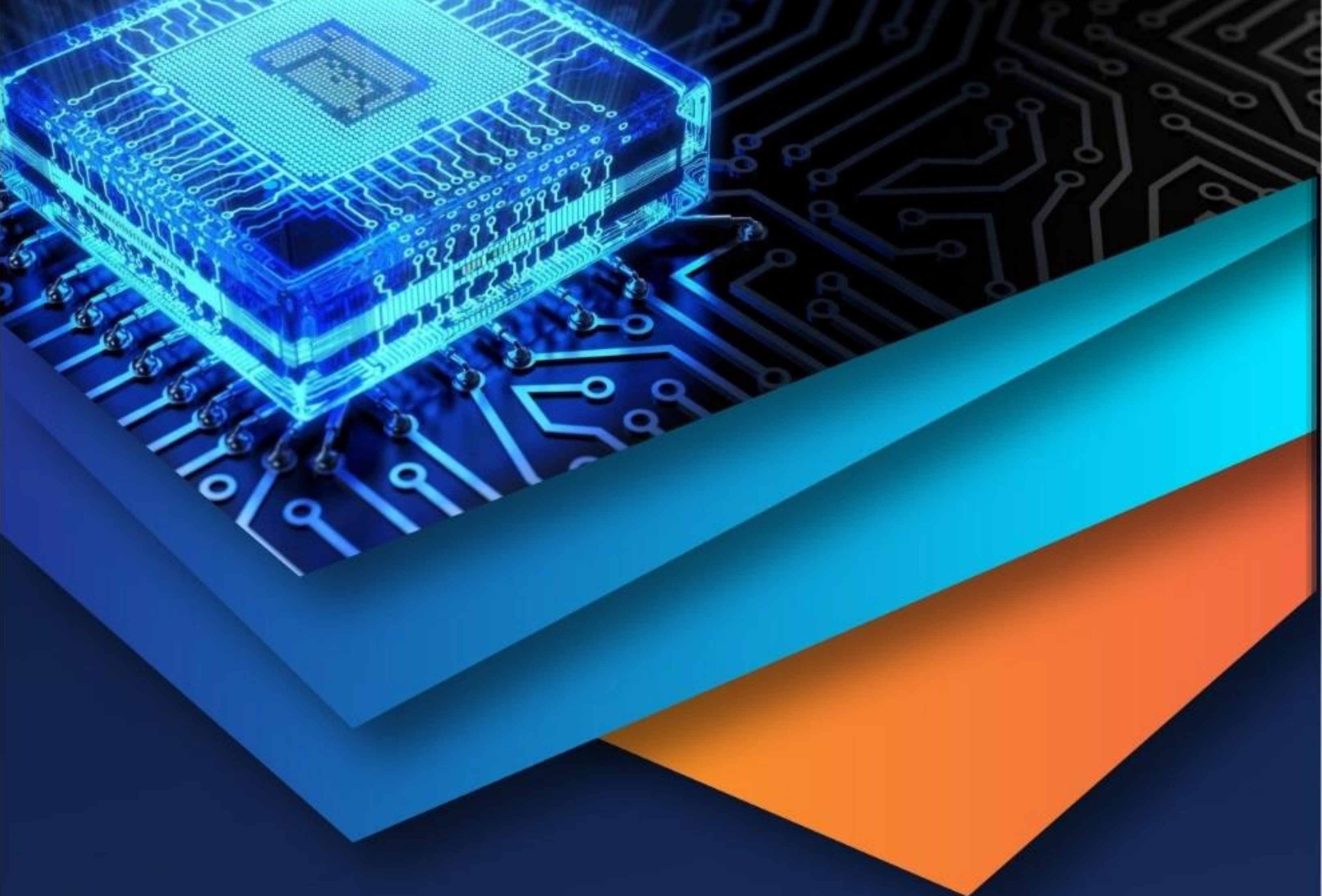

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