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Experimental Study and Analysis of Strength Properties and Sulfate Resistance of Self-Compacting Concrete Using Different Admixtures

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Abstract: The strength characteristics and sulfate resistance of self-compacting concrete (SCC) containing Class-F fly ash and metakaolin were investigated in an experimental study. Class-F fly ash and Metakaolin were added in varying proportions to the combinations, from 10% to 25%. The qualities were analyzed and discussed. These included the properties of both fresh concrete (slump flow, L-box, V funnel, and U-box) and hardened concrete (sulfate resistance and compressive strength). Class-F fly ash was used in self-compacting concrete (SCC) formulations, which showed 28-day compressive strengths between 30 and 40 MPa. The compressive strength decreased by 15.28% when cured in a MgSO4 solution as opposed to the control mix cured in water, with values ranging from 24 to 35 MPa. The compressive strength ranged from 34 to 54 MPa after curing in a MgSO4 solution, representing a 15.38% reduction from the control mix that was cured in water.
Keywords: Self-Compacting Concrete (SCC), Class-F fly ash (FA), Metakaolin (MK), Magnesium Sulfate (MgSO4), Ordinary Portland Cement (OPC)

I. INTRODUCTION

Cement-based materials are fundamental in construction and are expected to remain vital in the future, but they face challenges related to productivity, cost, quality, and environmental impact [1, 2, 3]. One promising advancement is self-compacting concrete (SCC), which naturally flows and consolidates under its weight, requiring no additional compaction [4]. SCC overcomes issues associated with traditional concrete, like the need for skilled labor, reinforcing bar arrangements, and pumping limitations due to its high fluidity and resistance to segregation [5]. The idea of self-compacting concrete (SCC) was first proposed by Professor Hajime Okamura in 1986, and a prototype was created by Professor Ozawa in Japan in 1988. Traditional vibrated concrete relies heavily on Ordinary Portland Cement (OPC), leading to increased costs and adverse environmental effects. OPC production generates significant CO2 emissions and kiln dust that can harm the environment and human health [6]. One solution is using industrial by-products like fly ash (FA) and Metakaolin (MK) as mineral admixtures to replace OPC in SCC [7]. Fly ash is a residue from coal combustion, On the other hand, kaolinite clay is heated to create metakaolin, an artificial pozzolana. This approach can reduce material costs and benefit the environment [3].

Despite some research on the effects of FA and MK on SCC properties [5, 6, 8], local acceptance of SCC has been limited, especially in regions with harsh environmental conditions [5]. SCC requires careful study due to its sensitivity to constituent properties, demanding high flow ability and segregation resistance. This study investigates the properties of SCC, comparing control concrete with mixtures that replace cement with fly ash and Metakaolin. The characteristics of freshly mixed concrete (slump flow, L-box, V-funnel and Ubox) and the characteristics of hardened concrete (sulfate resistance and compressive strength) are examined and compared. The SCC exhibited satisfactory slump flows of 600750mm, meeting EFNARC guidelines, with appropriate flow times. The L-box test ensured good resistance to segregation, and U-box measurements indicated proper flowability. All fresh properties aligned with European guidelines [9].

The remainder of the manuscript will discuss the methodology, experiments performed, and results.

II. METHODOLOGY AND EXPERIMENTAL PROGRAM

This section discusses the materials used in an experimental program for testing concrete samples in their plastic stage. The chapter also provides details about mix design and curing procedures. The experiment is centered on assessing the properties of self-compacting concrete both with and without the additional cementing materials of fly ash and metakaolin. The materials used include grade 53 of Ordinary Portland cement, fine aggregate (sand), and coarse aggregate.

The aggregates were appropriately sieved, washed, and dried. Drinking water quality was used for the concrete mix. An admixture called Amglen-N was used, conforming to relevant standards. Class F Fly Ash (FA) and Metakaolin (MK) were employed as

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mineral admixtures. The process of concrete mixing included the precise weighing of fine aggregates, coarse aggregates, water, cement, mineral admixture, and admixture. Hand mixing was carried out on a non-absorbing platform, starting with thoroughly mixin aggregates, followed by adding cement to achieve a uniform color. Water was added gradually, and casting was performed with different percentages (10%, 15%, 20%, and 25%) of Fly Ash and Metakaolin as replacements for cement. Every mix produced a total of 12 samples, comprising cubes designated for compressive strength assessments at both 7 and 28 days, as well as specimens for evaluating sulfate resistance.

To stop or replenish water loss—which is necessary for the hydration process and, ultimately, the hardening of the concrete—the concrete specimens were cured.

Various tests were conducted on fresh concrete to evaluate specific properties, especially for Self-Compacting Concrete (SCC). SCC is distinct from conventional concrete, and its new properties are crucial for successful placement, focusing on passing ability, filling ability and segregation resistance [10].

1) *Slump Flow Test:* This test assesses the horizontal free flow of SCC without obstructions. It measures the diameter of the concrete circle, indicating filling ability. A higher slump flow value suggests better formwork-filling ability, with a minimum requirement of 650mm for SCC. It does not indicate the concrete's ability to pass between reinforcements without blocking.
2) *V Funnel Test:* This test determines concrete's filling ability (flowability) with a maximum aggregate size of 20mm. The equipment comprises a funnel with a V shape, and the duration taken for concrete to pass through is recorded. Prolonged flow times may indicate low deformability and elevated interparticle friction.
3) *L Box Test:* This test evaluates the concrete flow and its susceptibility to blocking by reinforcement. The apparatus is an 'L'-shaped box with a gate and vertical lengths of reinforcement. The ratio H2/H1 assesses passing ability, and T20 and T40 times indicate filling ability.
4) *U Box Test:* This test evaluates SCC's filling capacity using a vessel divided into two compartments. Reinforcing bars are installed at the gate. The difference in height between the two sections is measured to assess flow and passing ability
5) *Compression Testing Machine (CTM):* This examination is conducted on cubic specimens to assess compressive strength at various durations, usually at 7 and 28 days. It is advisable to conduct additional tests at ages like 56 days, 13 weeks, and one year. For early strength assessment, tests can be conducted at 24 and 72 hours.
6) *Sulfate Resistance Test:* This test assesses the concrete's resistance to sulfate attack by assessing compressive strength following a 7- and 28-day immersion of the cube in a 5% magnesium sulfate solution.

These tests help evaluate the essential properties of fresh and hardened concrete, with a focus on SCC and its unique characteristics and requirements.

III. RESULTS AND DISCUSSION

This section examines the variables investigated in control concrete and concrete that uses fly ash and metakaolin in place of cement to create self-compacting concrete. Comparisons between the various mixes are provided, along with a discussion of the parameters, which include Slump Flow, L-box, V-funnel and U-box for fresh concrete and Compressive Strength and Sulfate Resistance for hardened concrete.

A. *Fly Ash*

1) *Fresh Concrete Properties*

The study focused on evaluating the impact of adding fly ash to concrete as a cement replacement. Self-compacting concrete (SCC) with varying proportions of fly ash was tested for fresh concrete properties, including Slump flow, V-funnel flow times, L-box, and Ubox. The results, summarized in Table I, showed the following findings:

Mix	Slump	V-Funnel (Sec)	L-Box (H2/H1)	U-Box (H1 - H2)
CM	650	8.0	0.8	35
F10	670	7.7	0.78	25
F15	635	8.0	0.79	35
F20	605	8.3	0.77	40
F25	600	8.6	0.74	43

TABLE I: Fresh Concrete Properties (Fly ash)

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a) *Slump Flow:* All SCC mixes demonstrated acceptable slump flows falling within the range of 600-750mm, signifying good deformability. These values are considered appropriate for SCC, falling within the 6 to 12-second span suggested by EFNARC standards.

Mix	7 days	28 days
CM	30.83	40.44
F10	27.92	33.92
F15	26.1	32.80
F20	23.09	31.77
F25	20.03	29.56

TABLE II: Compressive Strength of SCC Mixes with FA (N/mm2)

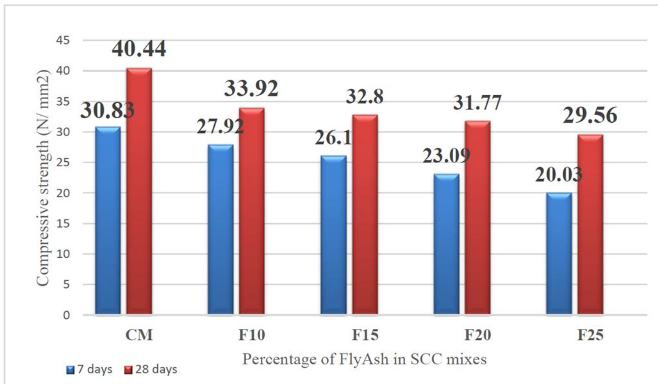

Fig. 1: Compressive Strength of SCC Mixes with FA

b) *V-Funnel Flow Times:* The V-funnel flow times for all SCC mixes ranged from 6 to 10 seconds. This range met the allowable flow time requirements.

c) *L-Box Test:* A maximum coarse aggregate size of 20 mm was used to prevent blocking. The space between reinforcement bars in the L-box test measured 35 mm. The L-box ratio H2/H1 for the mixes was approximately 0.8 or higher, in accordance with EFNARC standards.

d) *U-Box:* The variation in the height of concrete between the two compartments in the U-box test was within the range of 5 to 40 mm.

Overall, the fresh concrete properties of all the SCC mixes conformed to the values recommended by European guidelines. According to the study, the fresh properties of the concrete did not suffer from the addition of fly ash as a substitute for cement, as they remained within acceptable ranges.

2) Compressive Strength

The research aimed to explore the influence of incorporating fly ash as a substitute for cement on the compressive strength of Self-Compacting Concrete (SCC). Cube specimens measuring 150 x 150 x 150 mm were created, with varying levels of fly ash replacement at 10%, 15%, 20%, and 25%. Compressive strength testing was conducted using a Compression Testing Machine (CTM) with a capacity of 1500 kN, and the specimens were subjected to a curing period of 7 and 28 days in water.

The results, as presented in Table II and Figure 1, showed the following findings: For the 10% fly ash replacement mix (F10), the compressive strength was 27.92 N/mm² at seven days and increased to 33.92 N/mm² at 28 days. As the percentage of fly ash replacement increased (F15, F20, F25), the compressive strength decreased from 27.93 N/mm² to 20.03 N/mm² at seven days and from 33.92 N/mm² to 29.56 N/mm² at 28 days.

The results indicate that higher levels of fly ash replacement reduced compressive strength for both the 7-day and 28-day testing periods, with the F10 mix showing the highest strength among the tested mixes.

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3) Sulfate Resistance

The study assessed the sulfate resistance of concrete using a 5% strength magnesium sulfate solution. Cube specimens measuring 150 x 150 x 150 mm were used, with different percentages of fly ash (10%, 15%, 20%, and 25%). After being removed from the casting molds, the specimens were immediately submerged in a magnesium sulfate solution and tested for compressive strength after and 28 days. The following observations were made based on the results, which are shown in Table III and Figure 2:

Mix	7 days	28 days
CM	28	34.22
F10	28	33.35
F15	26	32.15
F20	21	28.40
F25	18.25	24.60

TABLE III: Compressive Strength of SCC Mixes with FA after Immersed in MgSO4 (N/mm2)

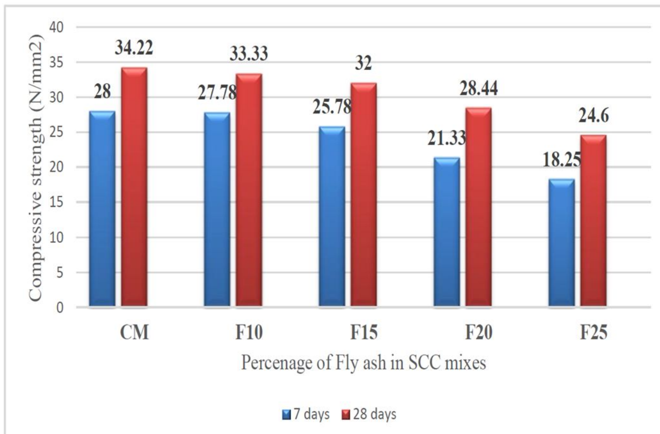

Fig. 2: Compressive Strength of SCC Mixes with Fly Ash after Immersed in Magnesium sulfate Solution.

When compared to specimens cured in water at the same ages, the specimens cured in the MgSO4 solution showed a decrease in compressive strength. The control mix, subjected to MgSO4 curing, exhibited a compressive strength of 28 N/mm², experiencing a loss of 9.17% at seven days and 34.22 N/mm² with a 15.38% loss at 28 days in contrast to the water-cured control mix.

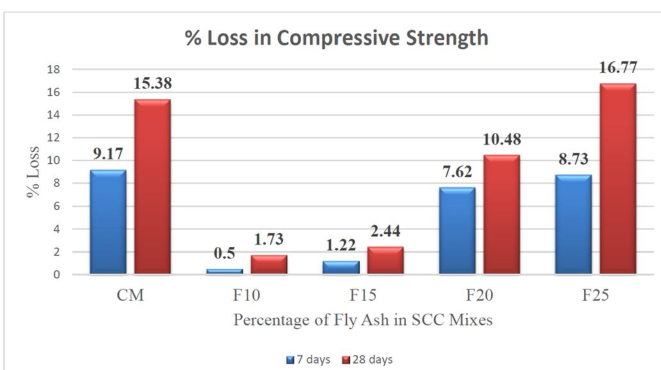

Fig. 3: Percentage Loss in Compressive Strength of SCC Mixes with FA after Immersed in MgSO4 Solution

Nevertheless, the reduction in compressive strength diminished with an increased substitution of cement with fly ash. Mix F15, F20, and F25 experienced loss percentages of 1.22%, 7.62%, and 8.73% at 7 days and 2.44%, 10.48%, and 16.77% at 28 days, respectively. The F10 mix had the best result, with a loss of only 0.5% at seven days and 1.73% at 28 days, making it the most suitable cement replacement with fly ash for maintaining sulfate resistance.

B. Metakaolin

In this section, the impact of substituting cement with Metakaolin in concrete is examined. Because of its high pozzolanic reactivity, metakaolin, a useful additive for cement and concrete, can enhance the performance of cementitious composites. It reacts with the calcium hydroxide generated by the hydration of Portland cement to produce additional cementitious products that change the structure of the concrete and improve its mechanical and durability properties.

1) Fresh Concrete Properties

The study examined the effects of using different amounts of metakaolin in place of cement on the initial characteristics of self-compacting concrete (SCC). Slump flow, V-funnel flow times, L-box findings, and U-box measurements were among the new characteristics that were evaluated for various SCC mixes that replaced metakaolin. As presented in Tabl IV, The outcomes indicate that all SCC mixes demonstrated satisfactory slump flows within the 600-700 mm range, indicating good deformability. These outcomes are in accordance with EFNARC standards, which deem flow times of 6-12 seconds suitable for SCC. The V-funnel flow times fell within the 6-12 seconds range, meeting the stipulated flow time criteria. The L-box ratios (H2/H1) were either at or above 0.8, complying with EFNARC standards, and the U-box exhibited variations in concrete height between two compartments ranging from 5 to 40 mm. In general, the fresh concrete properties closely aligned with the values recommended by European guidelines.

Mix	Slump	V-Funnel (Sec)	L-Box (H2/H1)	U-Box (H1 - H2)
CM	650	8.0	0.8	35
MK10	630	6.4	0.8	30
MK15	620	6.6	0.76	32
MK20	635	7.0	0.79	30
MK25	638	7.2	0.81	31

TABLE IV: Fresh Concrete Properties (Metakaolin)

2) Compressive Strength

The study investigated the impact of replacing cement with varying proportions of Metakaolin on compressive strength. Cubes measuring 150 x 150 x 150 mm were created, incorporating metakaolin at replacement percentages of 10%, 15%, 20%, and 25%. Subsequently, these specimens underwent curing in water and were subjected to testing at both 7 and 28 days.

The test results, shown in Table V and Figure 4, revealed the following findings:

Mix	7 days	28 days
CM	30.83	40.44
MK10	34.15	45.22
MK15	34.41	48.2
MK20	36.17	50.81
MK25	37.56	55.18

TABLE V: Average Compressive Strength of SCC Mixes with Metakaolin

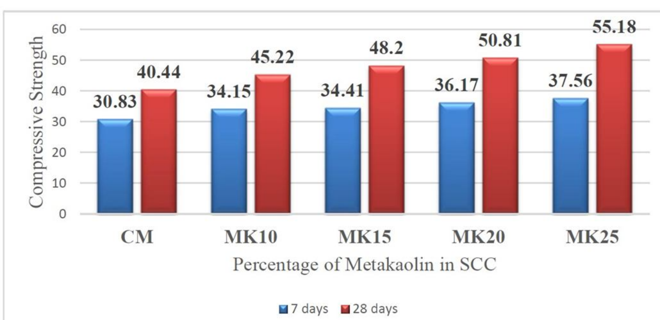

Fig. 4: Compressive Strength of SCC Mixes with Metakaolin

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Replacing 10% to 25% of the cement with Metakaolin resulted in better compressive strength in both short and long terms. Compared to the control mix,

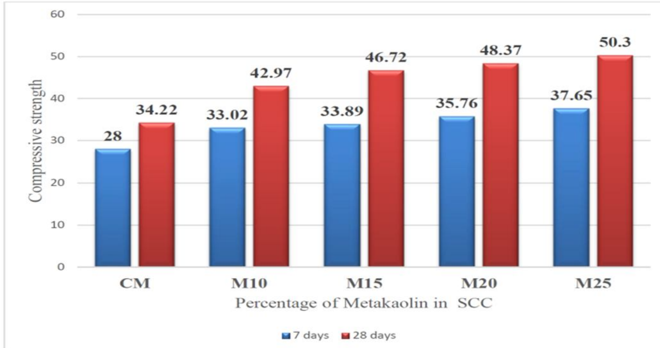

Fig. 5: Compressive Strength of SCC Mixes with Metakaolin (MK) after Immersed in MgSO4 Solution

the compressive strength of metakaolin concrete at 28 days increased by 10.57% to 26.71% with metakaolin percentages ranging from 10% to 25%, respectively. Compressive strength for MK10 concrete was 34.15 N/mm² at seven days and 45.22 N/mm² at 28 days. For MK25 concrete, compressive strength was 37.56 N/mm² at seven days and 55.18 N/mm² at 28 days. The results demonstrated that the inclusion of Metakaolin in concrete positively affected its compressive strength, with higher replacement percentages yielding significant strength improvements at short- and long-term intervals.

3) Sulfate Resistance

A 5% strength magnesium sulfate (MgSO4) solution was used to assess the sulfate resistance of concrete. Cube specimens measuring 150 x 150 x 150 mm were employed, with varying percentages of Metakaolin. The samples were immersed in the MgSO4 solution immediately after removal from the casting molds and were subjected to tests for compressive strength and splitting tensile strength at 7 and 28 days.The results, as presented in Table VI, revealed the following findings:

Mix	7 days	28 days
CM	28	34.22
MK10	31.39	40
MK15	32.89	44.72
MK20	34.76	48.37
M25	37.05	53.30

TABLE VI: Compressive Strength of SCC Mixes with Metakaolin (MK) after Immersed in MgSO4 Solution (N/mm2)

Specimens cured in the MgSO4 solution exhibited a decrease in compressive strength compared to those cured in water at the same ages. The control mixture, when cured in the MgSO4 solution, exhibited a compressive strength of 28 N/mm² with a reduction of 9.17% at seven days and 34.22 N/mm² with a decrease of 15.38% at 28 days, in contrast to the control mix that was water-cured. Replacing cement with Metakaolin resulted in a reduction in the loss of compressive strength. As more and more cement is substituted with metakaolin, ranging from 10% to 25%, the loss decreased from 8.1% to 1.35% at seven days and from 11.5% to 3.4%

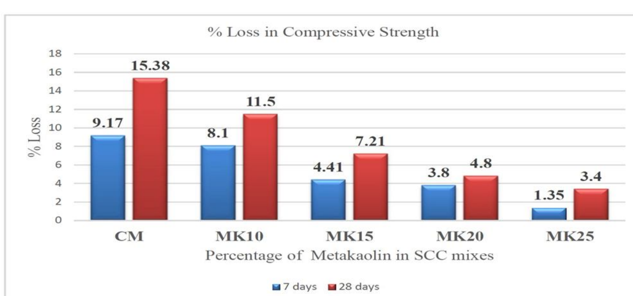

Fig. 6: Percentage Loss in Compressive Strength of SCC Mixes with Metakaolin (MK) after Immersed in MgSO4 Solution

at 28 days, as depicted in Figure 5. The M25 mix showed the best results for cement replacement with Metakaolin for maintaining sulfate resistance, with a compressive strength of 37.05 N/mm² (1.35% loss) at seven days and 53.30 N/mm² (3.4% loss) at 28 days.

IV. CONCLUSIONS

The experimental study evaluated self-compacting concrete's strength properties and sulfate resistance (SCC) when incorporating fly ash and Metakaolin as mineral admixtures. These admixtures were introduced at different replacement levels, including 10%, 15%, 20%, and 25%. Here are the key conclusions drawn from the test results:

For Fly Ash SCC:

SCC mixes can be effectively formulated with fly ash replacement levels of up to 25%, and all the fresh concrete properties, including slump flow, V-funnel, L-Box, and U-Box, adhere to EFNARC guidelines. A rise in the fly ash percentage replacing cement (F10, F15, F20, F25) results in a decline in compressive strength. When concrete specimens undergo curing in a magnesium sulfate solution, there is a decrease in strength properties compared to water curing. Nevertheless, this decline in strength properties is alleviated, reducing by up to 1.73% when fly ash is introduced as a cement replacement.

For Metakaolin SCC:

SCC incorporating Metakaolin exhibits satisfactory workability, with properties falling within the EFNARC guideline range. The concrete's compressive strength increases by up to 26% as the cement replacement level with Metakaolin rises from 10% to 25%, compared to the control mix. This increase is attributed to the pozzolanic properties of Metakaolin, which react with free lime (calcium hydroxide) in cement to produce additional cementitious compounds. The inclusion of Metakaolin as a cement replacement enhances the sulfate resistance of the concrete. With the replacement percentage reaching 25%, the loss in strength parameters decreases by up to 3.4% compared to the control mix.

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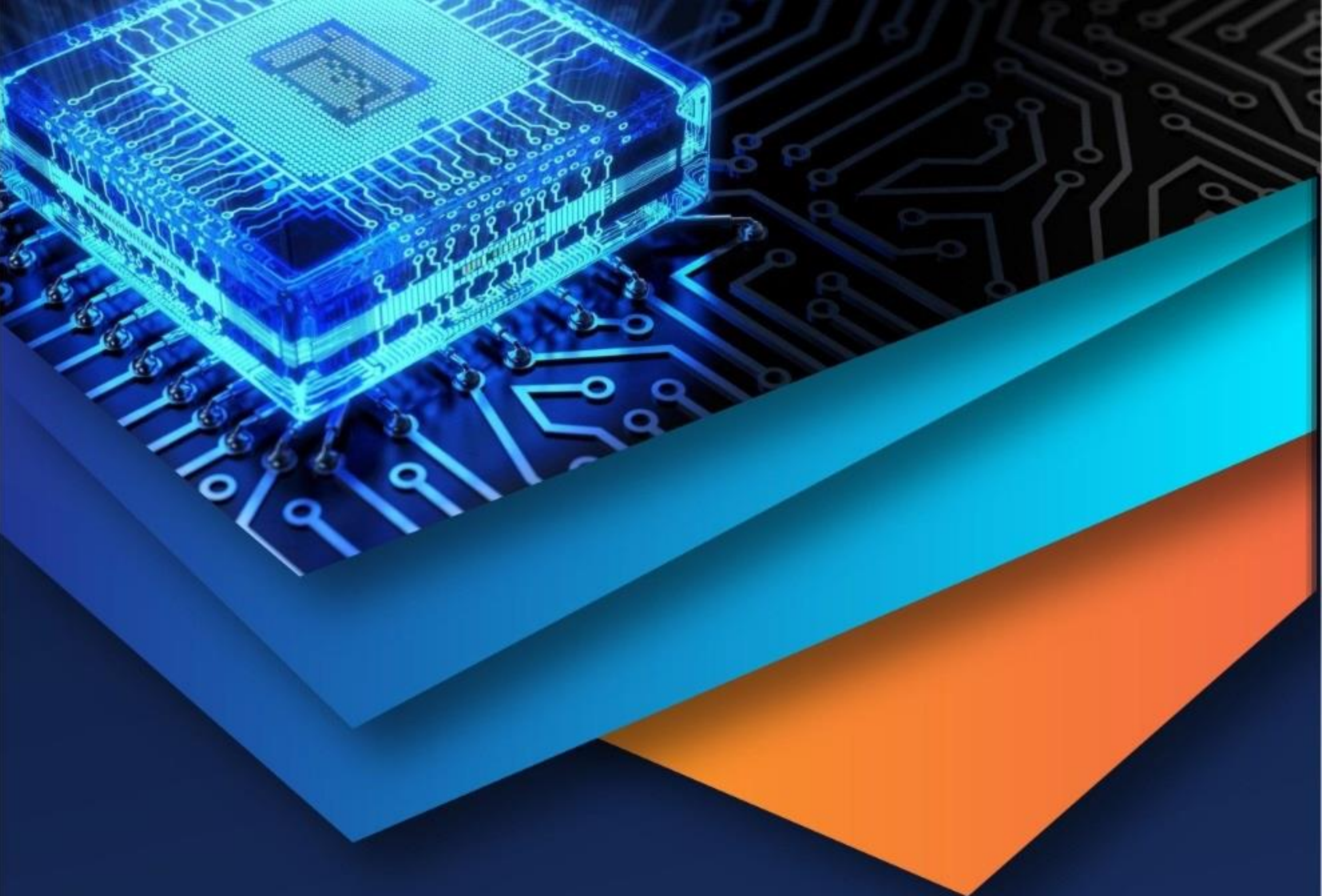

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