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Study of Replacement of Sand with Electroplating Waste Sludge (EWS) in Manufacturing of Concrete Paver Blocks Using Different Binder Systems

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Abstract: Electroplating waste sludge (EWS) is a hazardous industrial residue containing metal-bearing phases, while the growing demand for natural river sand creates a parallel resource-conservation challenge. This study evaluates processed EWS as a partial replacement of Zone II natural river sand in M40 concrete paver blocks manufactured with OPC 43 grade cement. Five mixes were investigated with 0, 5, 10, 15 and 20% sand replacement by mass. The experimental programme covered material characterization, dimensional tolerance, dry density, water absorption, compressive strength at 7, 14 and 28 days, 28-day splitting tensile strength, Böhme abrasion resistance, and heavy- metal leaching by Atomic Absorption Spectroscopy. A preliminary 50:50 EWS-waste-plastic thermal-fusion trial was also assessed. The 10% EWS mix achieved the highest 28-day compressive strength of 51.1 MPa, approximately 6.0% above the control, together with a splitting tensile strength of 4.05 MPa and water absorption of 4.88%. The 15% EWS mix retained a compressive strength of 42.8 MPa, water absorption of 5.65%, splitting tensile strength of 3.25 MPa and abrasion loss of 15,400 mm³/5,000 mm², and was identified in the source study as the maximum viable replacement level. At 20% replacement, strength and abrasion resistance decreased and water absorption increased to 6.72%. Leachate concentrations of Cr, Ni, Zn, Cu and Pb remained below the stated CPCB discharge limits up to 15% replacement, indicating effective immobilization in the hydrated cement matrix. The unformulated plastic-EWS thermal route produced a friable, non-cohesive material and was not carried forward. Overall, the results support low-to-moderate EWS utilization as a sand-conservation and hazardous-waste-management strategy for precast paver blocks.
Keywords: Electroplating waste sludge; fine aggregate replacement; paver blocks; M40 concrete; heavy-metal immobilization; sustainable construction.

I. INTRODUCTION

Concrete paver blocks are widely used in pedestrian areas, parking zones, city streets and other modular pavement systems because they combine load distribution, abrasion resistance, ease of maintenance and rapid replacement of damaged units. Their manufacture, however, consumes substantial quantities of natural river sand. Intensive sand extraction contributes to riverbank erosion, ecological disturbance and depletion of a finite construction resource. At the same time, electroplating and metal-finishing industries generate sludge during wastewater treatment. This electroplating waste sludge contains fine mineral matter and metal-bearing compounds and therefore requires controlled disposal.

The fine particle size of processed EWS creates a possible opportunity for use as a micro-filler and partial fine- aggregate substitute in cementitious products. Previous work has shown that electroplating residues can be solidified or immobilized in construction materials. Sgorlon et al. reported successful stabilization of electroplating waste in concrete paving blocks, while Hashim et al. demonstrated immobilization of metals in fired clay products containing electroplating sludge. More recently, Mojapelo et al. investigated wastewater sludge as partial fine-aggregate replacement and observed that higher sludge dosages can increase porosity and reduce mechanical performance. These findings point to the need for material-specific optimization rather than unrestricted replacement.

The present study therefore examines EWS as a partial replacement of natural river sand in OPC-bound M40 paver blocks at 0-20% replacement in 5% increments. The work evaluates structural, durability and environmental performance using the testing programme reported in the source thesis. A preliminary thermal route combining EWS and waste plastic granules was also explored to determine whether a non-hydraulic co-binder system could be feasible.

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II. MATERIALS AND METHODS

A. Constituent Materials and EWS Processing

OPC 43 grade cement conforming to IS 8112 was used as the sole hydraulic binder. Zone II natural river sand served as fine aggregate. Crushed granite aggregates of nominal sizes 12.5 mm and 20 mm were blended in a 60:40 proportion. Potable water and a polycarboxylate ether-based superplasticizer were used to maintain compaction at a water-cement ratio of 0.38. EWS was obtained from the effluent-treatment plant of a metal forging and casting facility in Ludhiana, Punjab. The as-received sludge contained approximately 50% moisture and was air-dried for 72 h, oven-dried at 105 ± 5°C to constant mass, pulverized, sieved through a 4.75 mm IS sieve and stored in moisture- resistant containers.

Table 1. Selected physical and chemical characteristics of materials

Material / property	Observed value	Relevant source standard
OPC 43 grade - specific gravity	3.15	IS 4031 / IS 8112
OPC 43 grade - 28-day strength	48.2 MPa	IS 4031 / IS 8112
River sand - grading / specific gravity	Zone II / 2.62	IS 383; IS 2386
River sand - water absorption	1.15%	IS 2386
Processed EWS - specific gravity	2.24	IS 2720
Processed EWS - matrix pH	5.3-5.6	IS 2720
Processed EWS - physical form	Fine powder, 100% passing 4.75 mm	Visual / sieve processing

X-ray fluorescence characterization of the EWS showed oxygen (42.64%), iron (16.53%), carbon (8.72%), calcium (8.70%) and silicon (5.34%) as major constituents. The principal regulated heavy-metal targets were chromium (2.72%), nickel (2.62%), zinc (0.97%), copper (0.39%) and lead (0.05%), which motivated the leaching assessment of hardened specimens.

B. Mix proportions and specimen preparation

The control mix was proportioned for M40 grade paver blocks. Natural sand was replaced by processed EWS at 0, 5, 10, 15 and 20% by mass, designated S0, S5, S10, S15 and S20 respectively. Cement, water and coarse aggregate contents were held constant, while the superplasticizer dosage increased as EWS content increased. Paver blocks measuring 200 mm × 100 mm × 80 mm were fabricated under vibro-hydraulic compaction and water cured.

Table 2. Mix proportions used in the experimental programme (kg/m³)

Component	S0	S5	S10	S15	S20
EWS replacement (%)	0	5	10	15	20
OPC 43 grade	425.0	425.0	425.0	425.0	425.0
Water	161.5	161.5	161.5	161.5	161.5
w/c ratio	0.38	0.38	0.38	0.38	0.38
River sand	710.0	674.5	639.0	603.5	568.0
Processed EWS	0.0	35.5	71.0	106.5	142.0
12.5 mm aggregate	730.0	730.0	730.0	730.0	730.0
20 mm aggregate	486.0	486.0	486.0	486.0	486.0
Superplasticizer	3.82	4.05	4.25	4.68	5.10

C. Testing Programme

The hardened paver blocks were assessed for dimensional tolerance, dry density, water absorption, compressive strength, splitting tensile strength and abrasion resistance. Compressive strength was measured at 7, 14 and 28 days, while the remaining principal hardened-property tests were evaluated at 28 days. Heavy-metal leaching was examined on crushed 28-day hardened matrix using an AAS-based procedure. The source thesis evaluated the results against IS 15658:2021 and CPCB discharge criteria. For consistency with the source experimental evaluation, the splitting-tensile acceptance value used in this paper is the 2.90 MPa criterion stated in the thesis testing matrix.

Table 3. Experimental testing matrix

Property	Age / specimen	Replicates	Acceptance criterion adopted in source
Dimensions and tolerances	Full block, 28 d	5 per mix	L/W ±2 mm; thickness ±3 mm
Compressive strength	Full block, 7/14/28 d	3 per age/mix	28-d target ≥40 MPa
Water absorption	Oven-dried full block, 28 d	3 per mix	Average ≤6.0%
Dry density	Oven-dried full block, 28 d	3 per mix	Reported as kg/m³
Splitting tensile strength	Full block, 28 d	3 per mix	≥2.90 MPa (as adopted in thesis)
Abrasion resistance	71×71 mm cut specimen, 28 d	3 per mix	≤18,000 mm³/5,000 mm²
Heavy-metal leaching	Crushed matrix, 28 d	Selected mixes	Within CPCB discharge limits

III. RESULTS AND DISCUSSION

A. Density and water absorption

Dry density decreased progressively from 2385 kg/m³ for S0 to 2260 kg/m³ for S20, consistent with the lower specific gravity of EWS (2.24) relative to river sand (2.62). Water absorption increased from 3.42% in the control to 6.72% at 20% replacement. S0-S15 remained below the 6.0% average absorption limit adopted in the thesis, whereas S20 exceeded it. The increase at higher EWS contents was attributed in the source study to the high surface area and porous chemical residues of the processed sludge, which increase water demand and capillary porosity.

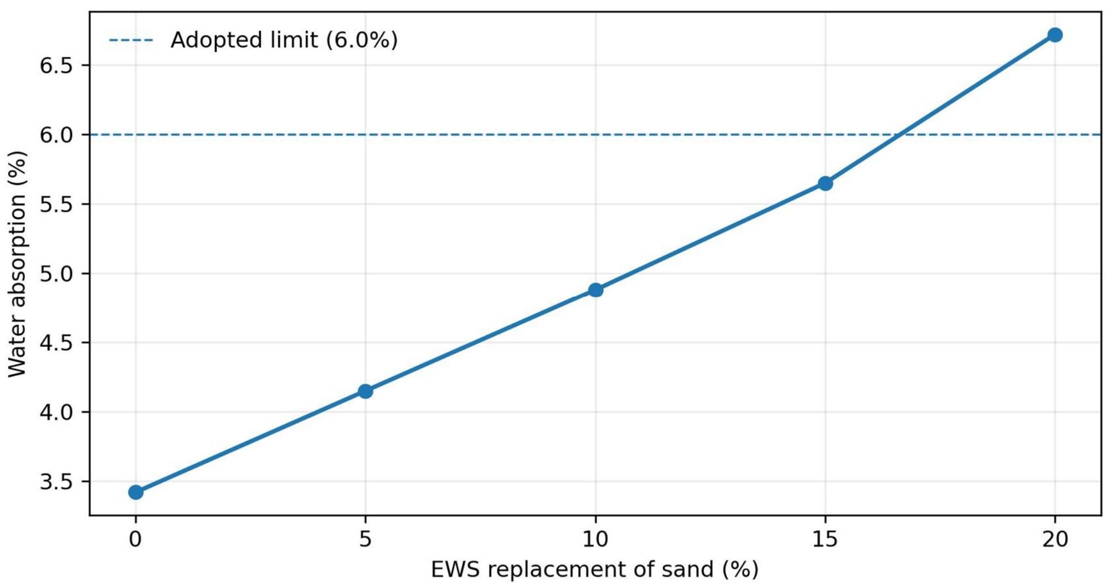

Figure 1. Effect of EWS replacement on 28-day water absorption

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Table 4. Summary of 28-day physical and mechanical performance

Mix	Density (kg/m³)	Water absorption (%)	Compressive strength (MPa)	Splitting tensile (MPa)	Abrasion loss (mm³/5,000 mm²)
S0	2385	3.42	48.2	3.85	11,250
S5	2360	4.15	49.5	3.92	11,800
S10	2335	4.88	51.1	4.05	12,650
S15	2305	5.65	42.8	3.25	15,400
S20	2260	6.72	35.6	2.68	18,900

B. *Compressive strength*

Compressive strength improved at low replacement levels and reached a maximum at S10. The 28-day strength increased from 48.2 MPa for S0 to 49.5 MPa for S5 and 51.1 MPa for S10, corresponding to a 6.02% increase over the control. The source study attributes this improvement to micro-filler action, improved particle packing and localized nucleation of hydration products. Beyond the optimum, strength decreased to 42.8 MPa at S15 and 35.6 MPa at S20. The decline at high replacement was associated with increased specific surface area, greater superplasticizer demand and a less favorable effective cementitious matrix around the fine sludge particles.

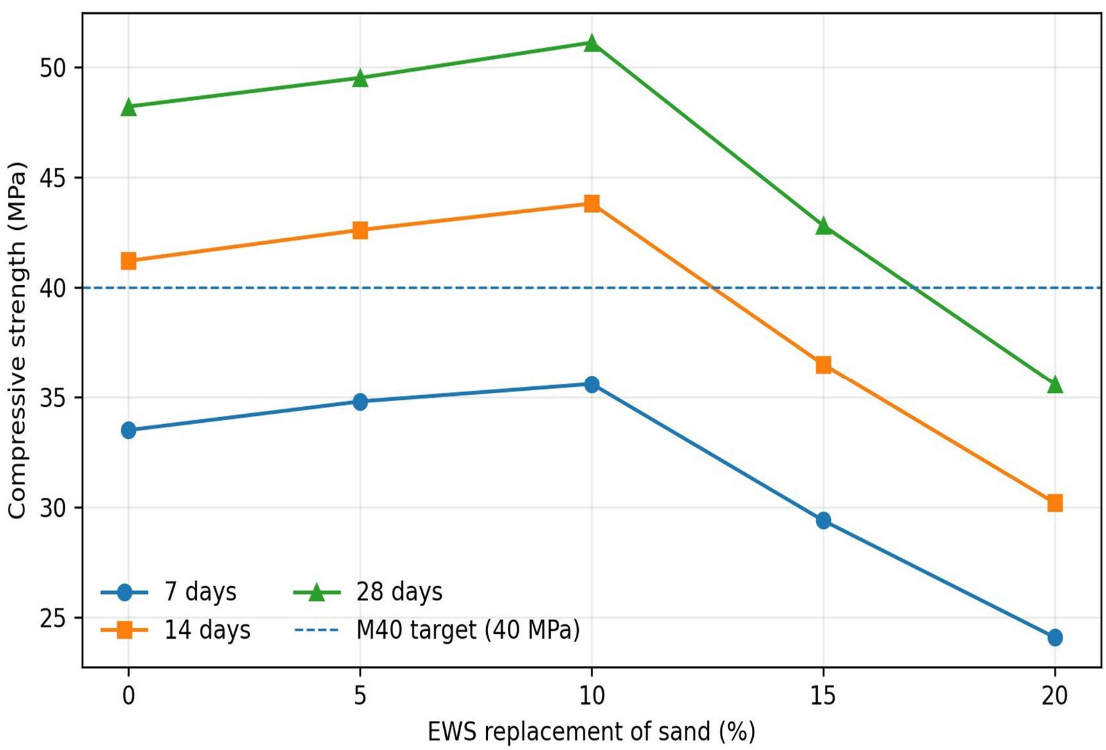

Figure 2. Compressive strength development with EWS replacement

C. *Splitting tensile strength and abrasion resistance*

Splitting tensile strength followed the same general trend as compressive strength, increasing from 3.85 MPa for S0 to a peak of 4.05 MPa for S10 before falling to 3.25 MPa at S15 and 2.68 MPa at S20. Under the 2.90 MPa criterion adopted in the thesis testing matrix, S0-S15 passed while S20 failed. Abrasion loss increased with EWS replacement, from 11,250 mm³/5,000 mm² for S0 to 18,900 mm³/5,000 mm² for S20. S0-S15 remained below the 18,000 mm³/5,000 mm² limit used in the source evaluation; S20 exceeded it.

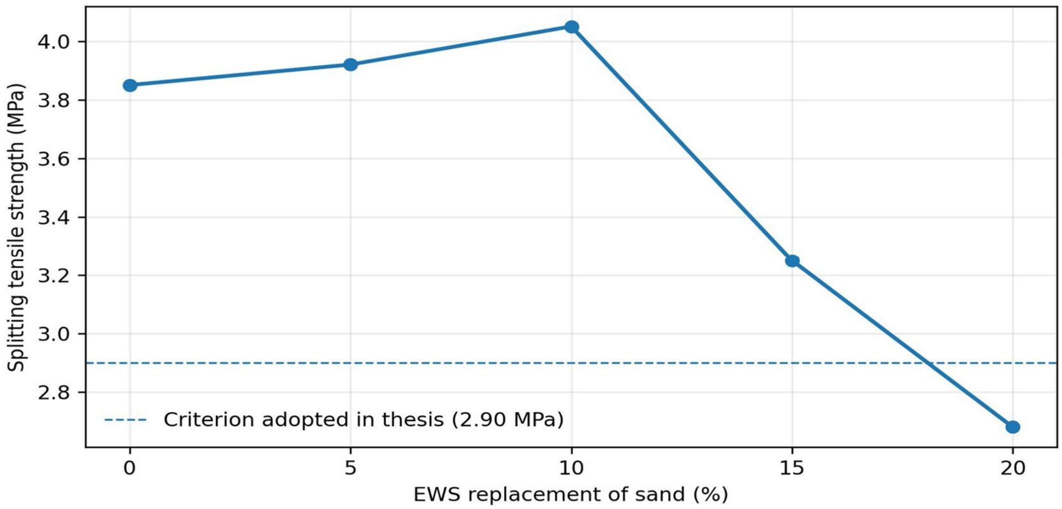

Figure 3. Splitting tensile strength at 28 days

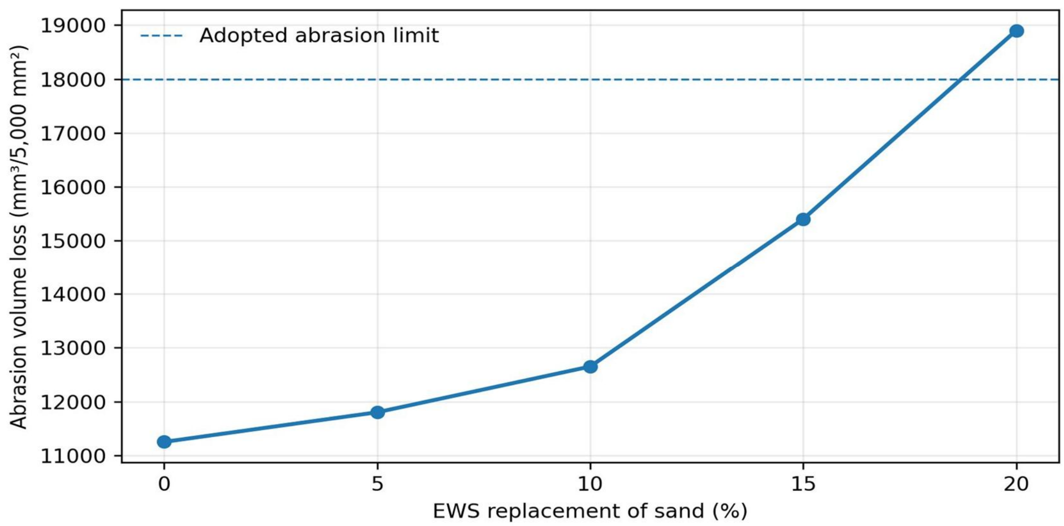

Figure 4. Böhme abrasion volume loss at 28 days

D. Heavy-metal leaching and environmental performance

Leachate concentrations increased as the EWS fraction increased, but all five target metals remained below the CPCB discharge limits through S15. At S15, Cr, Ni, Zn, Cu and Pb concentrations were 0.88, 0.95, 1.45, 0.32 and 0.04 mg/L respectively. The source study describes two complementary immobilization mechanisms: precipitation or chemical binding of metal species in the highly alkaline cementitious environment, and physical encapsulation within the hydrated C-S-H microstructure. Even at S20, the reported concentrations remained below the stated CPCB limits, although S20 was rejected on mechanical, absorption and abrasion performance grounds.

Table 5. Heavy-metal concentration in 28-day leachate (mg/L)

Metal	S5	S10	S15	S20	CPCB limit
Cr	0.12	0.35	0.88	1.82	2.0
Ni	0.18	0.42	0.95	2.15	3.0
Zn	0.35	0.78	1.45	2.80	5.0
Cu	0.08	0.15	0.32	0.65	3.0
Pb	0.01	0.02	0.04	0.08	0.1

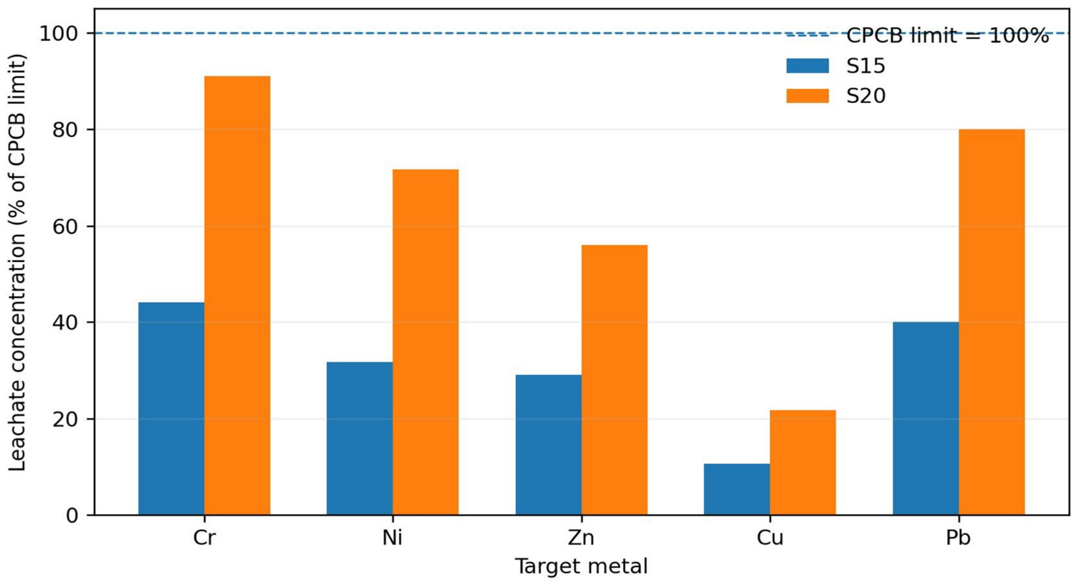

Figure 5. Leachate concentrations for S15 and S20 expressed as a percentage of CPCB limits

E. Preliminary waste-plastic/EWS thermal trial

A separate feasibility trial combined waste plastic granules of approximately 4 mm size with processed EWS in a 50:50 mass ratio and exposed the blend to 270°C for 24 h. The trial produced thermal degradation, charring, phase separation and a friable non-cohesive matrix. Because no durable structural bond was established, the plastic-EWS route was excluded from the hardened-property testing programme. Within the scope of the source study, OPC hydration and compaction therefore remained the viable route for EWS immobilization in paver blocks.

F. Optimum and practical replacement level

The experimental trends distinguish between a performance optimum and a maximum practical replacement level. S10 provided the best mechanical response, with the highest compressive and splitting tensile strengths. S15, although weaker than S10, was identified by the source study as the maximum viable replacement because it retained the adopted strength, absorption and abrasion criteria while replacing 106.5 kg/m³ of natural river sand. S20 was unsuitable for the intended M40 paver-block application because of reduced compressive and tensile strength, excessive water absorption and abrasion loss.

IV. CONCLUSIONS

1) Processed EWS can be incorporated as a partial replacement of natural river sand in OPC-bound M40 paver blocks, provided the replacement level is controlled.
2) A 10% replacement (S10) produced the best mechanical performance, with a 28-day compressive strength of 51.1 MPa and splitting tensile strength of 4.05 MPa.
3) The source study identified 15% EWS (S15) as the maximum viable replacement level. At this dosage, 28-day compressive strength was 42.8 MPa, water absorption 5.65%, splitting tensile strength 3.25 MPa and abrasion loss 15,400 mm³/5,000 mm².
4) At 20% replacement, compressive strength decreased to 35.6 MPa, water absorption increased to 6.72%, splitting tensile strength decreased to 2.68 MPa and abrasion loss increased to 18,900 mm³/5,000 mm²; the mix was therefore rejected for the target application.
5) AAS leaching results showed Cr, Ni, Zn, Cu and Pb below the stated CPCB discharge limits through the 15% replacement level, supporting effective immobilization of heavy metals in the hydrated cement matrix.
6) The preliminary 50:50 waste-plastic/EWS thermal-fusion route at 270°C did not develop structural cohesion and was not suitable as a load-bearing paver-block binder system in the investigated form.
7) At the maximum recommended 15% replacement, the mix conserves 106.5 kg of natural river sand per cubic metre of concrete while providing a controlled beneficial-use route for electroplating sludge.

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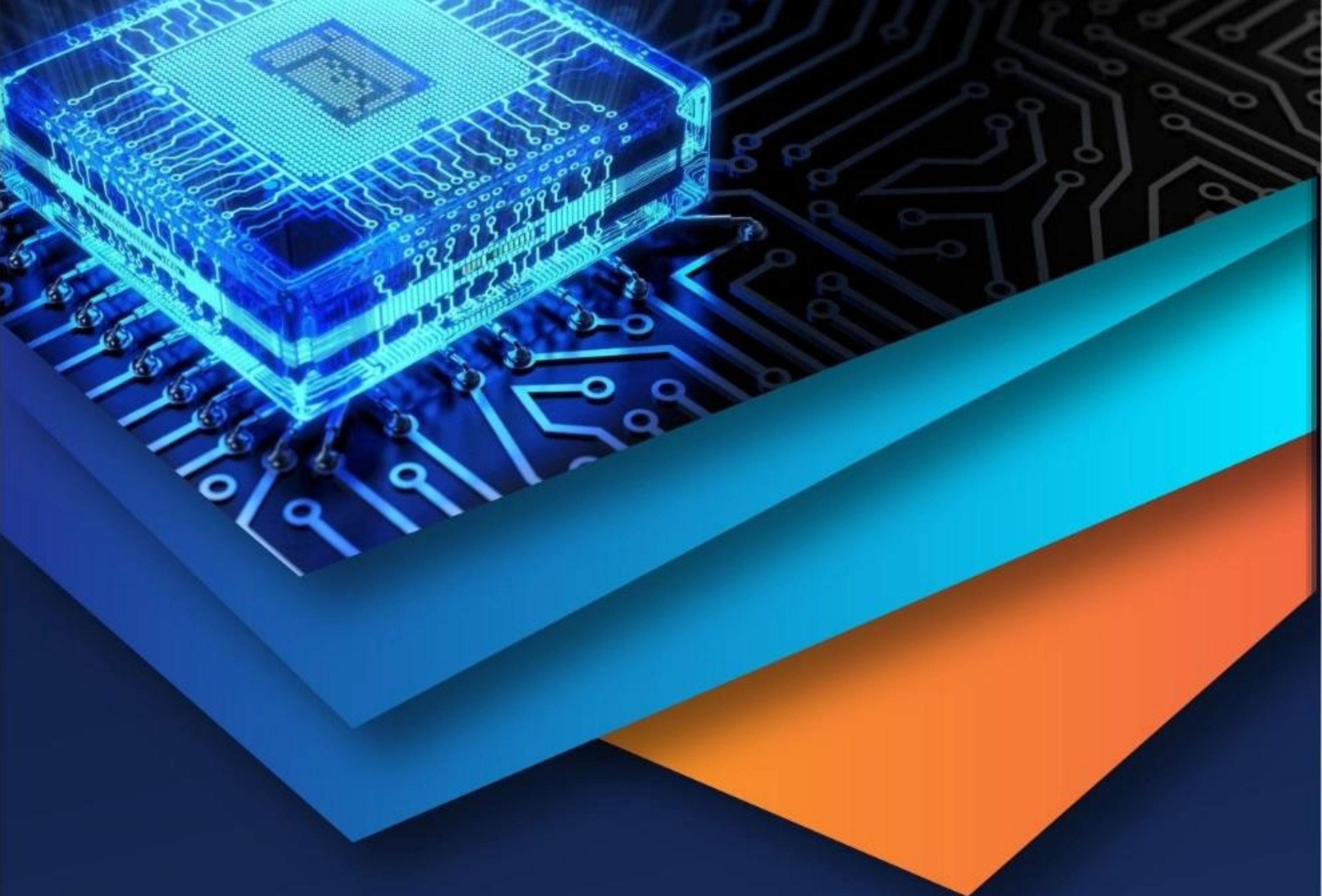

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