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Study on Rigid Pavement Analysis and Design

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Abstract: Roads are of vital importance to make a nation rich and develop. A well-connected road network is required for industrial as well as civilization growth. This paper consists of a review on the methodologies followed in rigid pavement design. There are various methods of rigid pavement design. Rigid pavement design procedure explained in this paper.

I. INTRODUCTION

Roads make important contribution to economic development and growth of a nation. Roads are essential mode of transportation. Roads play vital role in urban, rural & industrial logistics. India has one of the largest road networks in the world. Recently, India bagged the record of per day construction of road. Broadly speaking, roads are of two types based on type of construction: Rigid & Flexible. Generally, rigid pavement are concrete road and flexible pavement are bituminous road. In this paper, we will discuss regarding the design methodology of Rigid Pavement.

II. TYPES OF CONCRETE PAVEMENT

As per IRC: 44-2008, minimum M40 grade of concrete (flexural strength 4.5 MPa) shall be used for construction of normal concrete pavements. For rural roads minimum M30 grade of concrete (flexural strength 3.8 MPa) is recommended to be used. For white topping, high performance concrete of grade M50 is recommended. In rigid pavement construction, following three pavement design types are commonly used -

1) *Jointed plain concrete pavement (JPCP)* - JPCP is cost effective concrete pavement as it do not contain reinforcement. Maximum transverse joint provided 5 m to 6.5 m. Dowel bars provided across transverse joint to cater vehicle load across slab and tie bars across longitudinal joints to develop aggregate interlocking between slabs.
2) *Jointed reinforced concrete pavement (JRCP)* - Welded wire fabric or, deformed bars are provided in JRCP throughout the slab in addition to dowel bars and tie bars in transverse and longitudinal joints respectively. Reinforcement of 0.15 % to 0.25 % of cross-sectional area is distributed in slab, which controls cracking in slab. In general steel bars are provided at middle of slab, which provides advantage in balancing positive and negative moments equally and slab permit to flex before crack. But sometimes in heavy traffic load steel bars are provided in both faces of slab. Thickness of JRCP is thinner. Joint spacing is allowed upto 9 m to 12 m. JRCP is the preferred concrete pavement by different road construction agencies where huge concentrated load is envisaged and quality of material and workmanship is doubted.
3) *Continuously reinforced concrete pavement (CRCP)* - A significant amount of longitudinal reinforcement (0.6 % to 0.8 %) is provided in CRCP. Though transverse reinforcement is not mandatory, but better to use transverse reinforcement in small amount to prevent cracks. High content of longitudinal reinforcement generates transverse cracks. Allowable limit of these transverse crack spacing is 0.9 m to 2.5 m. Longitudinal reinforcement holds these cracks tightly together. No contraction joint is provided in CRCP. Sometimes CRCP is used in airfield runways, high traffic highways, and urban routes for their suitability in high traffic loads.

Plate - 1 (Longitudinal and Transverse Reinforcement Arrangement in CRCP)

Other than above concrete roads are also classified as below –

a) *Pavement quality concrete road (PQC)* **-** As per IRC, for highway and airport runway, where heavy load is expected cement concrete made with large size aggregates poured over a dry lean concrete. Steel reinforcement conform to IS:432, IS:1139 and IS:1786, coated with epoxy paint to prevent corrosion to be provided as per design requirement. If steel mesh is used, it shall conform to IS:1566. Dowel bars conform to grade S-240 and tie bars conform to grade S-425 to be provided as per requirement. The maximum water cement ratio shall be 0.50. For power operated machine low slump (0 - 25) and 0.78 compacting factor for vibrator to be maintained. Recommended temperature during concreting is recommended between 5° C to 30° C.
b) *Pre-stressed concrete pavement (PSCP)* **-** In recent days PSCP is used specially in airport runway project as well as national highways for its high load bearing capacity. The greatest advantage of PSCP is minimum joint is required which is beneficial for aircraft landing and take-off in airport runway. A continuous length upto 120 m can be laid without any joint. 22 kg/sqcm and 3 kg/sqcm to 4 kg/sqcm are minimum pre-stress in longitudinal direction and transverse direction respectively. The pre-stressing cable should be 7 mm diameter with ultimate tensile strength 140 kg/sqcm to 170 kg/sqcm.

III. RELATIVE STIFFNESS OF CONCRETE SLAB

Sub-grade provides a certain amount of resistance against concrete slab deflection under load. In the other way, slab deflection is a direct measurement of the magnitude of sub-grade pressure under applied load on concrete slab. This characteristic of rigid pavement lead to a term known as “radius of relative stiffness”. Radius of relative stiffness can be deduced from Westergaard equation given as below -

$$l = \sqrt[4]{\frac{Eh^3}{12K(1-\mu^2\ )}}$$

where, l = Radius of Relative Stiffness,

E = Modulus of Elasticity of Concrete,
μ = Poisson’s Ratio of Concrete,
h = Thickness of Concrete slab,
K = Modulus of Sub-grade Reaction.

IV. GUIDING LOAD POSITIONS FOR DESIGNING OF RIGID PAVEMENT

Position of wheel of vehicle plays an important role on the intensity of stresses developed in concrete slab. There are three locations where the varying conditions of slab continuity exist: *interior*, *edge* and *corner*. These three locations are called as critical load position. Induced stresses are determined at these three locations for designing of rigid pavement.

V. RADIUS OF EQUIVALENT DISTRIBUTION OF PRESSURE

If the wheel load is concentrated on the interior part of the pavement, then only a small portion of the pavement is subjected to bending stress under that applied load. This equivalent radius of resisting section can be determined from Westergaard equation given as below -

$$b = \sqrt{1.6a^2 + h^2} - 0.675h \ if \ a < 1.724\,h\ , otherwise$$

$$b = a$$

where, b = Radius of equivalent distribution of pressure,

a = Equivalent radius of contact area of wheel load,

h = Thickness of Concrete slab.

VI. CALCULATION OF WHEEL LOAD STRESSES

Figure- 1 below shows the three critical wheel load positions on rigid pavement for determining (i) *Interior Stress* (σ_i), (ii) *Edge Stress* (σ_e) & (iii) *Corner Stress* (σ_c).

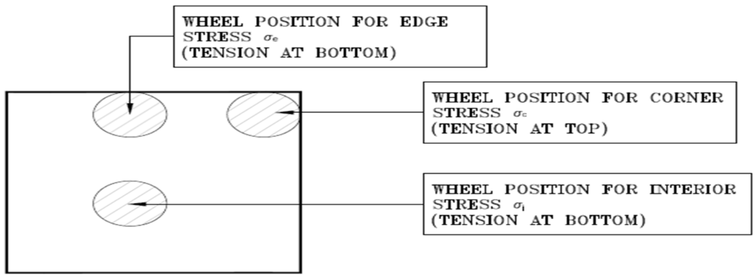

FIGURE-1

The slab is assumed to be homogeneous & have uniform elastic behavior. Vertical reaction from sub-grade is proportional to the deflection of slab.Westergaard established relationship for Interior Stress, Edge Stress & Corner Stress denoted by $\sigma_{i,}$ σ_e&σ_c respectively as below:

$$\sigma_i = \frac{0.316\,P}{h^2}\left[4\,\log_{10}\left(\frac{l}{b}\right) + 1.069\right]$$

$$\sigma_e = \frac{0.572\,P}{h^2}\left[4\,\log_{10}\left(\frac{l}{b}\right) + 0.359\right]$$

$$\sigma_c = \frac{3\,P}{h^2}\left[1 - \left(\frac{a\sqrt{2}}{l}\right)^{0.6}\right]$$

where,h = Thickness of Concrete slab,
P = Wheel Load,
a = Equivalent radius of contact area of wheel load,
l = Radius of Relative Stiffness,
b = Radius of equivalent distribution of pressure.

VII. STRESSES DUE TO VARIATION OF TEMPERATURE

Temperature stresses are developed in rigid pavement due to variation of temperature in concrete slab. The variation in temperature is caused by (i) *daily variation* – it results in temperature variation across the thickness of slab & (ii) *seasonal variation* – it results in variation of overall slab temperature. The daily variation of temperature causes warping stress whereas seasonal variation of temperature causes frictional stress.

1) *Warping Stress* - Warping stresses developed at interior, edge & corner regions of slab are denoted by σt_i. σt_e&σt_crespectively. These stresses can be evaluated using below mentioned equations:

$$\sigma t_i = \frac{E\epsilon t}{2}\left(\frac{C_x + \mu C_y}{1-\mu^2}\right)$$

$$\sigma t_e = Max\left(\frac{C_x E\epsilon t}{2}, \frac{C_y E\epsilon t}{2}\right)$$

$$\sigma t_c = \frac{E\epsilon t}{3(1-\mu)}\sqrt{\frac{a}{l}}$$

where, E = Modulus of Elasticity of Concrete,

ϵ = Thermal Co-efficient of concrete per ^oC,

t = temperature difference between top & bottom of slab,

C_x&C_y = Co-efficient (L_x/l) in the desired direction & Co-efficient (L_y/l) perpendicular tothe desired direction,

μ = Poisson's Ratio of Concrete,

a = Equivalent radius of contact area of wheel load,

l = Radius of Relative Stiffness.

2) *Frictional Stress* - Frictional stress $\sigma_f$can be calculated using following equation:

$$\sigma_f = (WLf)/2$$

where, W = Unit weight of concrete per unit length of slab,

L = Length of slab,

f = Co-efficient of sub-grade friction, generally taken as 1.5

VIII. STRESS COMBINATION

The combined effects of different stresses are as below:

1) *Summer, Mid-day*: The critical stress at edge is given by $\sigma_{critical} = \sigma_e + \sigma_{te} - \sigma_f$
2) *Winter, Mid-day*: The critical stress at edge is given by $\sigma_{critical} = \sigma_e + \sigma_{te} + \sigma_f$
3) *Mid-night*: The critical stress at corner is given by $\sigma_{critical} = \sigma_c + \sigma_{tc}$

The combined stresses developed at edge and corner of slab should be less than the flexural strength of concrete slabfor defined grade of concrete.

IX. FATIGUE ANALYSIS

Generally, Fatigue Analysis are done in rigid pavement which are liable to heavy traffic movement (for traffic exceeding 150 Commercial Vehicles Per Day [CPVD]). For fatigue analysis, cumulative number of commercial traffic at the end of design period is given by the following formula:

$$N = A\ X \left(\frac{(1+r)^n - 1}{r}\right) X\ 365$$

where,A = Initial CPVD after completion of construction of road,

r = Rate of increase of traffic in decimal,

n = Design period in years,

N = Total number of cumulative commercial vehicles at the end of design period.

X. FATIGUE BEHAVIOUR OF RIGID PAVEMENT

Progressive fatigue damage occurs in form of micro-cracks in rigid pavement due to repetitive application of flexural stresses by vehicle loads. Stress Ratio (SR) is defined as the ratio between flexural stresses due to applied traffic load and the flexural strength of concrete. The relation between Fatigue Life (N_f) and Stress Ratio (SR) as per IRC:58-2002 is as follows:

N_f = Unlimited, for SR < 0.45;

$N_f = [4.2577/(SR-0.4325)]^{3.268}$, when $0.45 \leq SR \leq 0.55$

N_f = (0.9718- SR) / 0.0828, for SR > 0.55

Fatigue life of rigid pavement (N_f) should be greater than total number of cumulative commercial vehicles at the end of design period (N).

XI. DESIGN OF EXPANSION JOINTS

Expansion joints are provided in rigid pavement to facilitate movement due to expansion of slab for rise in temperature from construction temperature of road. Expansion joints are provided along the longitudinal direction of road.

Dowel bars are provided in expansion joints of rigid pavement in order to effectively transfer load between two concrete slabs and to hold two slabs in same level. Dowel bars are rounded mild steel bars bonded with slab at one end and free to move at the other end. Load transfer capacity of dowel bar in shear, bending and bearing can be determined by using Bradbury's equation as below -

$$P_s = 0.785\, d^2 F_s$$

$$P_f = \frac{2\, d^3 F_f}{L_d + 8.8\delta}$$

$$P_b = \frac{F_b L_d^2\, d}{12.5\,(L_d + 1.5\delta)}$$

where, P_s = Load transfer capacity of single dowel bar in shear,

P_f = Load transfer capacity of single dowel bar in bending,

P_b = Load transfer capacity of single dowel bar in bearing,

d = Diameter of dowel bar,

L_d = Embedment length of dowel bar,

ð = Width of joint,

F_s = Permissible stress in shear for dowel bar,

F_f = Permissible stress in bending for dowel bar,

F_b = Permissible stress in bearing for dowel bar.

Figure- 2 below shows typical arrangement of expansion joint.

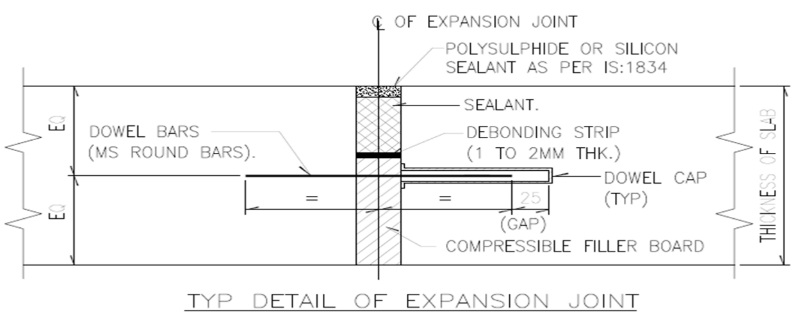

Figure - 2

XII. DESIGN OF CONTRACTION JOINTS

Contraction joints are provided in concrete pavement to allow for the contraction of slab due to fall in temperature below construction temperature of road. The design aspects for contraction joints are as below:

1) The movement of joint is resisted by sub-grade friction
2) Length of panel for contraction joint (L_c) can be determined using following equation -

$$L_c = \frac{2 \times 10^4 S_c}{W.f}$$

where, S_c = Allowable Tensile Stress of Cement Concrete,

W = Unit weight of Cement Concrete,

f = Co-efficient of sub-grade friction, generally taken as 1.5

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Figure- 3 below shows typical arrangement of contraction joint.

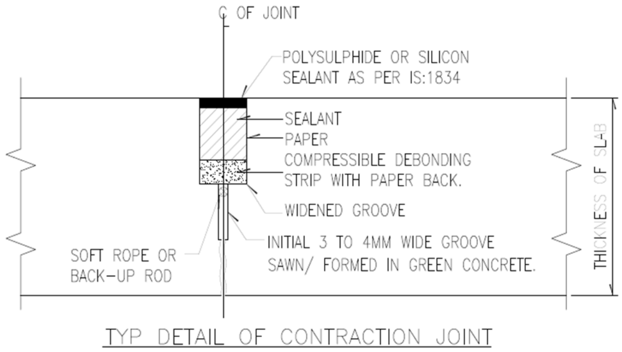

Figure - 3

XIII. DESIGN OF TIE-BARS

Tie bars are provided in rigid pavement, in order to tie two adjacent panels of slab together. Tie bars are not meant for transferring load from one panel of slab to another. So, tie bars need to be deformed bars or hooked so that they are firmly embedded in concrete member for their proper functionality. They are provided in longitudinal joints of concrete pavement. They are usually of smaller length & greater spacing than dowel bars.

Area of tie-bars required per unit length of slab is given as below:

$$A_s x\, S_s = b \; x \; h \; x \; W \; x \; f$$

$$A_s = \frac{bhWf}{100S_s}$$

where, A_s = Area of Tie-bars required per unit length of slab,

S_s = Allowable Working Tensile Stress of steel reinforcement,

b = Width of panel,

h = Thickness of panel,

W = Unit weight of concrete,

f = Co-efficient of sub-grade friction, generally taken as 1.5.

Length of tie-bar required can be determined using following equation –

$$L_t = \frac{dS_s}{2S_b}$$

where, L_t = Length of Tie-bars required,

d = Diameter of Tie-bars,

S_s = Allowable Working Tensile Stress of steel reinforcement,

S_b = Allowable Bond Stress of steel reinforcement.

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XIV. DESIGN EXAMPLE OF RIGID PAVEMENT

Compressive strength of concrete, F_{ck} = 25 N/mm^2
Flexural strength of concrete, $S_c = 0.7\sqrt{F_{ck}}$ = 35 kg/cm^2
Elastic Modulus of concrete, E = 300000 kg/cm^2
Unit weight of concrete, W = 0.0024 kg/cm^3
Poission's ratio, μ = 0.15
Co-efficient of thermal expansion of concrete, α = $0.00001/^0C$
Tyre pressure, q = 8 kg/cm^2
Spacing of contraction joint = 400 cm
Width of slab, L = 400 cm
Type of sub-grade = soil
Co-efficient of sub-grade friction, f = 1.5
CBR value = 3
Temperature differential, t = 22
Load safety factor = 1.2
C/C distance of two tyres in dual wheel assembly, S = 182 cm
Thickness of slab, h = 30 cm
Wheel load in kg, P = 5000 kg
Design life of pavement = 20 years
Modulus of sub-grade reaction, K = 3.46 $kg/cm^2/cm$ (As per Table 3.2 of IRC: SP: 62-2014)
Radius of relative stiffness, $l = \sqrt[4]{Eh^3 / 12K(1-\mu^2)}$ = 118.86 cm
Radius of wheel load distribution per wheel
$a = ((0.8521\ P / q\Pi) + S / \Pi\ (P / 0.5227q)^{0.5})^{0.5}$ = 46.63 cm
a/h = 1.55 < 1.724
Equivalent radius of resisting section,
$b = (\sqrt{1.6a^2 + h^2}) - 0.675\ h$ = 45.92 cm
Value of Equivalent radius of resisting section, b = 45.92 cm
Westergaard relation for the stress
$\sigma_{interior} = 0.316\ P / h^2\ (4 \log_{10} (l/b) + 1.069)$ = 4.78 kg/cm^2
$\sigma_{edge} = 0.572\ P / h^2\ (4 \log_{10} (l/b) + 0.359)$ = 6.39 kg/cm^2
$\sigma_{corner} = 3P / h^2\ (1 - (a\sqrt{2} / l)^{0.6})$ = 4.96 kg/cm^2
L_x/I = 3.37
Cx = 0.27 (From Figure-2 of IRC:58-2002)
L_y/I = 3.37
Cy = 0.27 (From Figure-2 of IRC:58-2002)

Warping stress at interior, $\sigma t_i = E\alpha t*0.5*((Cx+\mu Cy) / (1-\mu^2))$ = 10.60 kg/cm^2

Warping stress at edge, $\sigma t_e = Max\{(CxE\alpha t)/2, (CyE\alpha t)/2\}$ = 9.01 kg/cm^2

Warping stress at corner, $\sigma t_c = E\alpha t*(a/I)^{\wedge}0.5*(3(1-\mu)$ = 16.21 kg/cm^2

Frictional stress = σ_f = (WLf)/2 = 0.72 kg/cm^2

Summer Mid-day, Critical stress at edge = $\sigma_{edge} + \sigma t_e - \sigma_f$ = 14.68 kg/cm^2<35 kg/cm^2 (Hence Safe)

Winter Mid-day, Critical stress at edge = $\sigma_{edge} + \sigma t_e + \sigma_f$= 16.12 kg/cm^2<35 kg/cm^2 (Hence Safe)

Mid-night, Critical stress at corner = $\sigma_{corner} + \sigma t_c$ = 21.17 kg/cm^2<35 kg/cm^2 (Hence Safe)

Stress ratio SR, = (edge stress / flexural stress of concrete) = 0.18 <0.45, Concrete can sustain infinite no. of repetition

A. Design of Tie-bar

Width of panel, b = 300 cm
Co-efficient of sub-grade friction, f = 1.5
Density of concrete, W = 2400 kg/m^3
Allowable tensile stress in deformed bars (IRC: 21-2000), S_s = 2000 kg/m^2
Allowable bond stress in deformed bars (IRC: 21-2000), S_b = 24.6 kg/m^2
Diameter of tie-bar,d = 12 mm
(Ast) / meter width of joint to resist the friction force at slab bottom
$A_s = \frac{bhWf}{100S_s}$= 16.2 mm^2/m
Spacing of tie-bar = 6977.78 cm
Length of tie-bar = $L_t = \frac{dS_s}{2S_b}$= 48.78 cm
As per Table no 9 of IRC:58-2002, for slab thickness 30 cm max spacing for 12 mm diameter bar will be 60 cm and minimum length will be 64 cm.

B. Design of Dowel bar

Diameter of dowel bar, d = 20 mm
Joint width, □ = 2 cm
Permissible shear in dowel bar (F_s) = 1000 kg/cm^2
Permissible bending in dowel bar (F_f) = 1400 kg/cm^2
Permissible bearing in dowel bar (F_b) = 100 kg/cm^2

$L_d = 5d\sqrt{\frac{F_f(L_d+1.5\delta)}{F_b(L_d+8.8\delta)}}$ [Eq.29.14, P-29.5, Mathew & Krishna Rao]

L_d= 31.3 cm

Length of dowel bar (L_d + d) = 33.3 cm

Providing length of dowel bar = 35 cm

Actual L_d = 33 cm

From Bradbury's analysis:

Load carrying capacity of single dowel in shear (P_s) –

$P_s = 0.785\, d^2\, F_s$[Eq. 29.11, P-29.5, Mathew & Krishna Rao]
P_s = 3140 kg
Load carrying capacity of single dowel in bending (P_f) –
$P_f = \frac{2\, d^3 F_f}{L_d+8.8\delta}$[Eq. 29.12, P-29.5, Mathew & Krishna Rao]
P_f = 442.69 kg
Load carrying capacity of single dowel in bearing (P_b) -

$P_b = \frac{F_b L_d^2\, d}{12.5(L_d+1.5\delta)}$[Eq. 29.13, P-29.5, Mathew & Krishna Rao]
P_b = 484 kg
Maximum Wheel Load, P = 5000 kg
Assuming load capacity of dowel bar = 40% of maximum wheel load
Load transfer capacity of dowel bar (maximum of) –
$(0.4P)/P_s$ = 0.637
$(0.4P)/P_f$ = 4.518
$(0.4P)/P_b$ = 4.132

Hence, load carrying capacity factor of dowel bar =	4.518
Radius of relative stiffness, I =	118.86 cm
Effective distance of load transfer (1.8I) =	213.94 cm
Spacing of dowel bar =	25 cm
No. of dowel bars in effective load transfer distance =	9
Actual capacity =	4.793 > 4.518 (Hence OK)

Therefore, provide 20mm dia. Dowel bars of length 35cm@25cm spacing center to center.

XV. CONCLUSION

Rigid pavement performs very satisfactorily under heavy load & it minimizes maintenance cost. Proper design & drainage arrangement can substantially increase the usable life of road & reduces maintenance cost. There is scope for research work in this domain to optimize the design and construction of rigid pavement.

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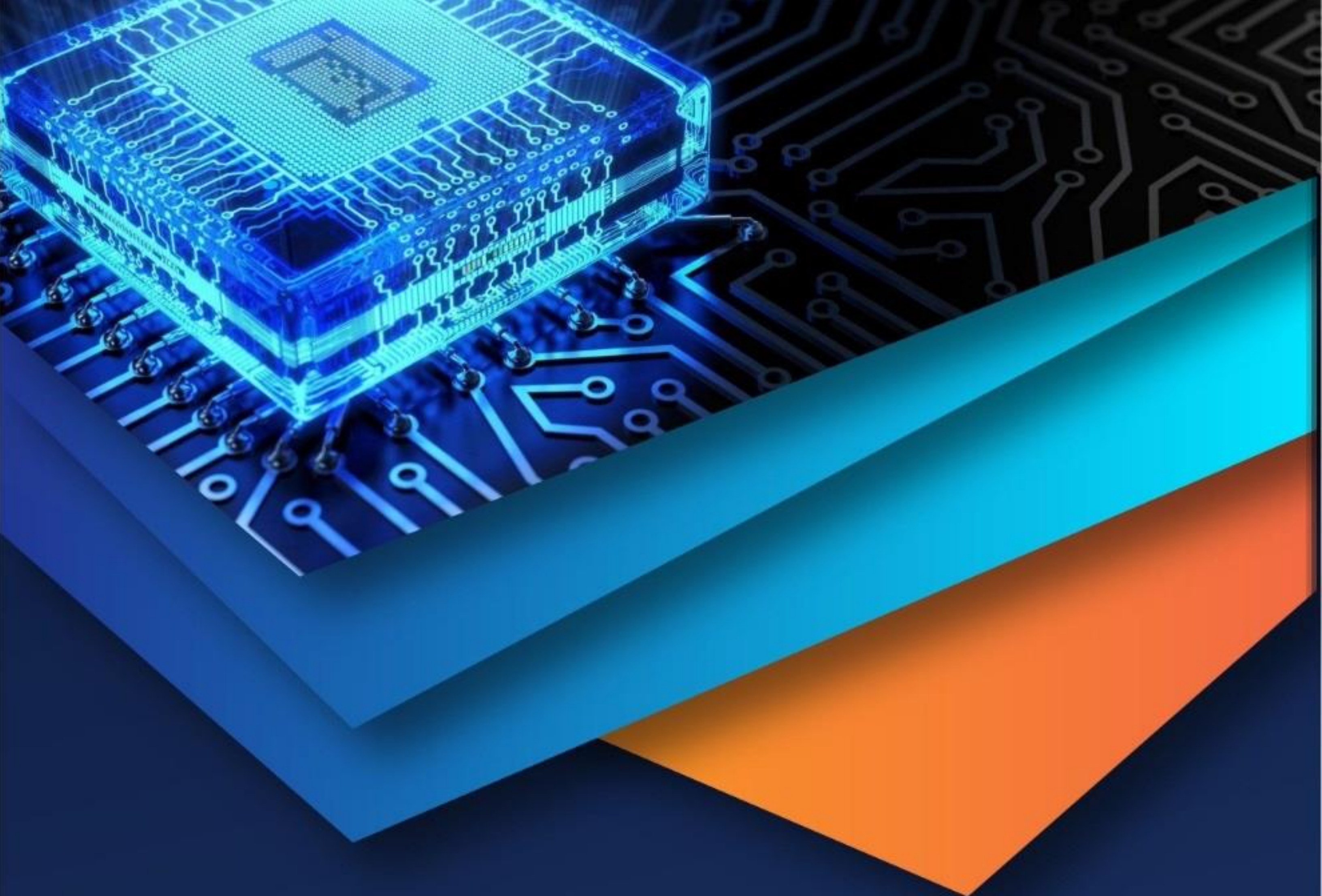

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