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Fresh Concrete Properties Required for Vertical Slip-form Concrete

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Abstract: The guidelines available in the present concrete mix design standard IS-10262-2019 [2] are silent about the special mix proportion criteria for slip-form concrete. The slip-form concrete is subjected to dynamic loads in the fresh state due to the movement of the slip-form panel over the fresh concrete. In current practice, particularly in power plant industries where RCC chimneys are required, concrete mix design is often carried out by a third party based solely on hardened concrete design strength criteria. However, such proportioning guidelines as per IS-10262-2009 [2] are suitable only for static concrete pouring operations. For slip-form concrete, special criteria for fresh concrete is needed, like adequate shear strength of the cover concrete to be self-sustaining against the lifting friction of the slip-form panel during its movement, as well as to prevent surface problems in the RCC chimney shell during construction using the slip-form technique. In this research work, addressing real execution problems of RCC chimney shell surface issues, it has been concluded that the greater the shear strength of fresh concrete, the more resistant it will be to the lifting friction of the slip-form panel, resulting in better surface quality of the chimney shell and fewer surface problems. The research also concluded that various properties of concrete ingredients directly influence the shear strength of the concrete and plays an important role in preventing surface problems of the chimney shell during construction.
Keywords: Shear Strength, Effective Stress, Pore Water Pressure, Bleeding, Cohesion, Angle of Friction, Lifting Crack, Delamination, Collapse.

I. INTRODUCTION

The RCC chimney is one of the most important civil structures in any thermal power plant and is usually constructed using the slip-form technique. However, in recent days, frequent severe surface problem in chimney shells have been noticed during the construction of RCC shells using this technique, and in some cases, parts of the chimney shell had to be dismantled. To mitigate the surface problem of the chimney shell concrete, an experimental study has been conducted by the BHEL-PSHQ-CPC-Project team to identify the root cause of the surface problem and its corresponding correction in the mix design of concrete and also correction of the construction method. In the present experimental study, it has been observed that the properties of fresh concrete play an important role in facilitating the smooth movement of the slip-form panel without causing any surface issues in the chimney shell during construction. Moreover, the experimental results indicate that the properties of fresh concrete depend on external ambient conditions and its ingredient properties, such as those of coarse and fine aggregates, as well as the physical and chemical properties of cement and the type of water-reducing admixture used in the mix. The shear strength of fresh concrete also depends on the mix proportions, but the available standard guidelines for concrete mix design as per IS-10262-2019 [2] do not provide instructions on how to improve the shear strength of fresh concrete, which is the primary requirement of slip-form concrete. Considering the surface problem in RCC chimney shells during its construction using the slip-form technique, there is a need to formulate standard guidelines for mix design proportions of chimney shell concrete to prevent such surface issues. In this study, it has been observed that greater the shear strength of fresh concrete, the more capable it will be to mitigate the lifting frictional force, leading to fewer surface problems such as lifting cracks, delamination, and collapse of cover concrete. The cover concrete of the chimney shell is always subjected to tensile stress caused by lifting friction due to the continuous lifting of the slip-form panel. Mitigating such tensile stress on the cover concrete of the chimney shell is possible by increasing the shear strength of the cover concrete and also by increasing the self-weight of the cover concrete against the lifting forces acting on it. The present study identifies various parameters that influence the shear strength of fresh concrete and concludes that the chimney shell concrete mix design shall not be based solely on hardened concrete strength criteria but shall also include additional guidelines for improving the shear strength of fresh concrete.

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II. LITERATURE REVIEW

During slip-forming, the fresh concrete in the interfacial zone i.e. the cover concrete will be exposed to shear stresses as a result of the friction that takes place during lifting of the slipform panel. If the friction force is equal to the shear strength of the fresh concrete, then the concrete in the interfacial transition zone will displace or flow along with the panel when slip-form panel is lifted. Conversely, if the friction force is lower than the shear strength of the concrete, the friction force will be transferred as shear stress into the cover zone concrete without lifting it. However, it is primarily the various ingredients of fresh concrete that can resist such lifting friction and transfer it in the form of shear stress. Water cannot transfer shear stress, but it can transfer pressure (both positive and negative). Since shear stress is governed by the actual ingredient pressure, factors affecting the pressure between the ingredients must be considered when evaluating shear stress in the concrete [4]. Concrete properties change considerably during the period leading to initial set, which can be divided into two phases: the liquid phase and the semi-liquid phase (Hammer, 1999) [4]. The liquid phase begins when the concrete is mixed and placed; during this phase, the concrete is workable and cannot withstand significant shear stress or deformation. The duration of this phase depends primarily on the concrete mix design, chemical composition of the cement, setting of the cement, ambient temperature, wind speed, and relative humidity. Lifting of the slip-form panel will only commence once the concrete attains a semi-solid state. The semi-solid phase starts when the concrete skeleton is adequately rigid and has sufficient shear strength to support its own weight [4]. This phase ends when hydration and heat development increase rapidly. According to ASTM C403 [10], the initial and final setting of concrete can be determined by measuring penetration resistance, with initial setting defined at a penetration resistance of 3.5 MPa and final setting at 27.6 MPa. It is important to note that these values do not indicate the strength of the concrete, which is approximately 0 MPa at initial set and 0.5 MPa at final set. Another commonly used method which is frequently used in construction sites involves using a steel peg/rod to measure the portion of concrete that resists the penetration of steel rod / peg in the concrete. Fresh concrete imposes shear strain immediately upon the application of stress. When the shear stress is below the yield value, concrete behaves like an elastic solid. At higher shear stress levels, the bond strength between particles becomes insufficient to prevent flow, and the concrete gradually adopts a more liquid-like consistency (Bache, 1977; Lane et al., 1993) [4]. The yield value in fresh concrete is low during the liquid phase but increases as the workability decreases and hydration progresses. When exposed to shear, concrete can be assumed to exhibit both ideal elastic and ideal plastic behavior. The shear strength in concrete results from internal friction and cohesion, primarily from bonding due to cement hydration. According to Alexandridis et al. (1981), the Mohr-Coulomb model is fundamentally incorrect because fresh concrete exhibits dilatant behavior during shearing. However, he determined that the model adequately represents the shear stress to which fresh concrete is subjected. Internal friction (Bache, 1977) in a particulate system requires strain to be mobilized. Internal friction of aggregates depends on the size and shape of particles, particle size distribution, packing of particles, and the friction coefficient during sliding between particles. The angle of friction (φ) increases with the sharpness and roughness of the particles i.e., angularity of the aggregate, increased packing, and friction coefficient. Internal friction also increases with increase in effective pressure. Immediately after mixing, the shear strength of fresh concrete mainly results from internal friction due to particle interaction [4]. Internal friction remains constant with time and temperature changes (Alexandridis et al., 1981). The main source of cohesion in concrete is chemical bonding due to cement hydration. The chemical bonding will be small when concrete is fresh but increases with time as hydration progresses (Alexandridis et al., 1981) [4]. Capillary stresses are not true cohesion but rather friction strength generated by positive effective pressure created by negative pore water pressure (Michelle, 1993). Generally, cohesion increases with decreasing particle size due to the increasing ratio of surface area to volume [4]. This is also independent of the mechanisms effecting the cohesion in the concrete. The concrete can be divided into two phases, the particle phase and the water phase. The water phase can transfer pressure (positive as well as negative), but it cannot resist shear forces. The effective pressure is transmitted through the points of contact between the particles. The particle phase can resist shear forces; thus, shear force in fresh concrete relies on effective pressure. Effective pressure represents the average grain-to-grain pressure and can be calculated using the equation (3). After the concrete is mixed and placed, pore water pressure depends on how the particles are distributed in the concrete. The water carries the particles when the water pressure corresponds to the weight of the concrete at the measuring point.

After placing, the concrete begins to settle, and bleeding may appear on the top surface after some time. Radocea (1992) conducted experiments with cement paste and concluded that the settlement and bleeding rates are affected by particle size distribution, particle concentration, and the use of plasticizers. Pore pressure decreases during settlement due to direct contact between solid particles.

A. Summary Of Fresh Concrete Properties

Concrete properties change significantly from the time of placement to initial set. During the liquid phase, concrete has a fluid or plastic consistency, and shear strength is low due to low cohesion and less internal friction between the particles. In the semi-liquid phase, shear strength increases primarily due to higher effective pressure, but also due to cement reactions. Higher effective pressure results in increased internal friction, while cement reactions enhance cohesion among concrete particles [4]. Effective pressure is calculated based on measured total pressure and pore water pressure. While total pressure in concrete remains constant, pore water pressure decreases due to capillary force development. Capillary forces arise from self-desiccation in concrete or drying at the surface. In self-desiccation, the decrease in pore water pressure depends mainly on cement type and content, water-to-cement ratio, and total fines in the mix. A finer pore system will lead to a higher rate of decrease in pore water pressure compared to a coarser system. For surface drying, pressure development depends primarily on evaporation rate, pore system, and particle geometry at the surface. The free water in concrete will eventually decrease to such a low content that the water meniscus cannot find a new stable position. Consequently, capillary pressure cannot be maintained and in such a case the water system becomes discontinuous. This stage is represented by a collapse of the capillary pressure, and is called the breakthrough pressure.

B. Lifting Force And Concrete Pressure During Slip-Forming

When the slip-form panel slides on fresh or green concrete surface, friction arises due to contact between the moving panel and the concrete. The nature of the materials (concrete and slip-form panel) will determine the magnitude of the friction force. In the early phase, the friction depends on fresh concrete properties and its ability to create a lubricant layer on the panel surface, as well as the surface roughness of the panel. In the later phase, it is assumed that the effective pressure and cohesion in the lubricant layer from cement hydration and its adhesion to the panel surface affect friction. Skew lifting, asymmetric loading of the working deck, and other unplanned factors may also impact both concrete pressure and friction.

C. Concrete In A Slipform

The shear strength in fresh concrete results from frictional resistance, particle interlocking, and bonding due to cement hydration. Frictional resistance and particle interlocking are referred to as internal friction. Chemical bonding due to cement hydration is the primary source of cohesion in concrete. Cohesion is low when concrete is fresh but increases over time as hydration progresses. Generally, cohesion increases with decreasing particle size due to the increasing ratio of surface area to volume. A lubricant layer forms between the panel and concrete during placing and vibration. Especially during vibration, the process consolidates the concrete and envelops larger aggregates in a slurry of binder and finer aggregate particles. This slurry behaves like a lubricant during sliding when the concrete is still fresh. According to Spech (1973), the actual physical phenomenon that reduces friction is attributed to the lubricant creating a pressure pillow that separates the sliding surfaces, thereby decreasing friction. Near setting, the lubricant changes character and behaves like a glue (Reichverger, 1979). This occurs due to increasing cohesion in the concrete and its adhesion to the slip-form panel. The concrete properties and its ability to create a lubricant layer depends on its composition and compaction method.

D. Static and Sliding Friction

Before lifting the slip-form panel, the lifting force must overcome the friction between the concrete and the slip-form panel. This friction force is defined as the smallest driving force that initiates sliding, and is termed as static friction. When the panel begins to slide on the concrete, friction decreases. The lower friction level is known as sliding friction. The relationship between friction force and normal force (lateral force) can be expressed by the general friction equation:

$$F = \mu \cdot N, \tag{1}$$

Where,
F = friction force,
N = normal force
μ= friction coefficient. The friction coefficient is the coefficient of static friction or sliding friction.
$\mu H > \mu G$,
where μH is static friction coefficient and μG is sliding friction coefficient

The static friction increases when the lifting frequency is reduced, because the adhesion force at the interface between the concrete and the panel increases with time in rest. The static friction is low when the concrete is fresh and becomes high near setting. It is assumed that the highest static friction will be in the concrete layer just above the detach zone on the slip-form panel.

Reichverger et al. (1982) found that the lifting force decreases with increasing slip-forming rate, even when the concrete pressure against the slip-form panel increases. Increased concrete pressure will normally give a higher lifting force, while increased lifting frequency will decrease the lifting force. This means that the lifting frequency has a much higher contribution to the friction force than the concrete pressure on the slip-form panel. The lifting frequency has varied from 4 lifts of 25 mm per hour (10 cm/h) to 12 lifts of 25 mm per hour (30 cm/h). By doubling the slip-form rate or frequency, the lifting force is reduced by 30 – 40 % when the concrete is hand compacted and 25 – 30 % when vibrated. This relationship is applicable for smooth panels with 0.47 mm thick GI sheet or glossy Polyethylene cover sheet between the steel panels & concrete surface.

When the applied stress is above the yield value, concrete begins to flow. The Mohr-Coulomb flow model can be used to describe the shear strength related to the effective pressure at failure (Bache, 1987)

$$\tau = c + \sigma' \mu = c + \sigma' \tan \varphi \quad (2)$$

$$\sigma' = \sigma - u \quad (3)$$

Where,

τ = shear strength [KPa]

c = cohesion [KPa]

σ'= effective pressure at failure [KPa]

$\tan \varphi = \mu$ = coefficient of friction

σ = Total pressure

u = pore water pressure.

The shear strength of semisolid concrete can be increased by enhancing cohesion among concrete ingredients, increasing surface area to volume ratio, increasing angle of friction of the aggregate particles & effective stresses.

III. MATERIAL

In this present experimental studies M-30 grade of concrete with OPC-43 grade cement and high range water reducing admixture of PCE-Type-G superplasticiser as per ASTMC-494 were used. The following are the different test parameters of the various ingredients of concrete are shown in Table below.

Table-I

Physical parameters of Single Size Coarse aggregate of 20 mm size

SL No	Test Parameters	UOM	Test Results
1	Specific Gravity	-	2.832
2	Angularity Number	-	5
3	Voids % in the aggregate	%	38
4	Flakiness Index	%	18
6	Elongation Index	%	20
7	Fineness Modulus	-	6.5

Table-II

Physical parameters of Single Size Coarse aggregate of 10 mm size

SL No	Test Parameters	UOM	Test Results
1	Specific Gravity	-	2.832
2	Angularity Number	-	8
3	Voids % in the aggregate	%	41
4	Flakiness Index	%	21
6	Elongation Index	%	16
	Fineness Modulus	-	5.57

Table-III
Physical parameters of combined graded Coarse aggregate of 20 mm +10 mm (70%:30%)

SL No	Test Parameters	UOM	Test Results
1	Specific Gravity	-	2.832
2	Angularity Number	-	**6**
3	Voids % in the aggregate	%	39
4	Flakiness Index	%	19
6	Elongation Index	%	18
	Fineness Modulus	-	**6.22**

Table-IV
Physical parameters of combined graded Coarse aggregate of 20 mm +10 mm (30%:70%)

SL No	Test Parameters	UOM	Test Results
1	Specific Gravity	-	2.832
2	Angularity Number	-	**7**
3	Voids % in the aggregate	%	40
4	Flakiness Index	%	20
6	Elongation Index	%	17
	Fineness Modulus	-	**5.85**

Table-V
Physical parameters of Fine aggregate

SL No	Test Parameters	UOM	Test Results
1	Specific Gravity	-	2.67
2	Gradation Zone conforming as per IS-383:2016	-	Conforming to Zone-II as per IS-383:2016
3	75 microns passing by weight	%	1.83%

Table-VI
Physical & chemical parameters of Cement OPC-43 grade

SL No	Test Parameters	UOM	Test Results
1	Specific Gravity	-	3.153
2	Blaine Fineness	M^2/kg	297
3	Lime Saturation Factor (LSF)	-	0.86
4	Silica Modulus (SM)	-	2.1
6	Alumina Ratio (AR)	-	1.51
7	C_3A	%	8.58
8	C_3S	%	57
9	C_2S	%	13.19
10	Standard consistency	%	29
11	Initial Setting Time (IST)	Minute	165
12	Final Setting Time (FST)	Minute	255
13	Compressive Strength at 7-days	N/mm2	39.9
14	Compressive Strength at 28-days	N/mm2	52.5

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Table-VII
Physical parameters of Superplasticiser.

SL No	Test Parameters	UOM	Test Results
1	Relative Density	-	1.090
2	Solid content	%	30.66
3	Chloride content	%	0.030
4	pH	-	6.05
5	Optimum dosage by weight of cement	%	0.5

IV. EXPERIMENT & METHOD

In this experimental study, four different types of concrete mixes were used by varying the percentage of coarse aggregate combinations and the cement content, while keeping all other ingredients in the mix constant. The mixes, labeled as M1, M2, M3, and M4, represent the four different combinations used in this study. The experiment was conducted with and without using a buffer sheet made of 0.47 mm thick GI sheet with an MS slip-form panel plate for all four mixes and the surface finish of the shell concrete was observed.

Table-VIII
Mix Proportion of M_1, M_2, M_3 & M_4 & its physical test results

SL No	Ingredient details	UOM	Mix-M_1	Mix-M_2	Mix-M_3	Mix-M_4
1	Cement	Kg/Cum	410	410	425	425
2	Water	Kg/Cum	172	172	178	178
3	Superplasticiser	Kg/Cum	2.46	2.46	2.55	2.55
4	20 mm Aggregate	Kg/Cum	826 (70%)	354 (30%)	826 (70%)	354 (30%)
5	10 mm Aggregate	Kg/Cum	354 (30%)	826 (70%)	354 (30%)	826 ((70%)
6	Fine Aggregate	Kg/Cum	731	731	731	731
7	Angularity Number	-	6	7	6	7
8	Voids % in Coarse Aggregates	Cum	39%	40%	39%	40%
9	Paste volume	Cum	0.578	0.578	0.589	0.589
10	Slump (Immediate)	mm	190	200	200	210
11	Nature of mix	-	Poorly Cohesive	Cohesive	Moderately cohesive	Highly Cohesive
12	7-Days Compressive Strength	N/mm2	27.5	30.4	32.4	35.5
13	28-Days compressive Strength	N/mm2	40.2	43.6	45.3	48.6

V. RESULTS & DISCUSSIONS

From the experimental results, it has been observed that the concrete mix with increasing the angularity number of the coarse aggregate combination resulted in an increase in voids % & paste volume requirement. The results also show that with increasing the paste volume, the cohesiveness of the mix increases, which in turn increase the shear strength of the concrete mix Additionally, the test results indicate that as paste volume and cement content in the mix increase, the workability (slump), compressive strength, and cohesiveness of the mix improve, along with the shear strength. Pictorial view of the slip form concrete surface with all four different types of concrete mix is as below.

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Mix Designation	Without buffer sheet	With Buffer sheet
M-1		
M-2		
M-3		
M-4		
Total View of Chimney with before & after adopting remedial measure in concrete mix & also using of buffer sheet	RCC-Chimney shell with normal mix & without buffer sheet	RCC-Chimney shell with corrected mix with buffer sheet
		

VI. CONCLUSIONS

Based on the present studies on fresh concrete properties required for vertical slip-form concrete, the following outcomes have been observed regarding the influence of a thin (0.47 mm thick) colour-coated GI sheet on the surface finish of the chimney shell:

1) The concrete mix proportions suitable for normal concrete works are not necessarily suitable for slip-form concrete. Slip-form concrete requires sufficient shear strength of fresh concrete to handle the lifting force during the sliding of the form over the concrete surface, thus preventing surface problems.
2) Increasing the smaller fraction of coarse aggregate in the total aggregate combination e.g., 70% 10 mm size and 30% 20 mm size shows better fresh concrete properties (greater cohesiveness) and improved surface finish compared to a mix with 70% 20 mm size and 30% 10 mm size coarse aggregate.
3) Concrete with 425 kg of cement shows greater cohesiveness and a better surface finish compared to a mix with 410 kg of cement. Therefore, while sufficient strength can be achieved with lower cement content, the minimum cement content for slip-form concrete should preferably be between 420 kg and 430 kg, depending on the fineness of the fine aggregate used.
4) For vertical slip-form concrete, paste volume is a basic requirement for creating a pressure pillow for the slip-form panel, facilitating smooth sliding. The study shows that concrete with a higher paste volume yields a better surface finish.
5) The study also shows that the percentage of fine aggregate in the total aggregate plays an important role in creating a pressure pillow during the sliding of the slip-form panel. The minimum percentage of fine aggregate should not be less than 38% and not more than 42% of the total aggregate content in the mix.
6) The higher the surface area-to-volume ratio of coarse aggregate and the higher the angularity number of the coarse aggregate, the greater the paste volume requirement. This results in improved cohesiveness of the mix and higher shear strength.
7) The application of a 0.47 mm thick color-coated GI buffer sheet along with the slip-form panel can help permanently avoid common surface problems such as lifting cracks, delamination, collapse of cover concrete, and lump formation of concrete.
8) The study concludes that when the C3A content of the mix exceeds 8%, the normal consistency of the cement will be slightly higher, and the optimum dosage of superplasticizer will also be higher compared to cement with less than 8% C3A content. Additionally, cement with higher C3A content will result in faster initial setting of concrete.
9) The flakiness and elongation indices of coarse aggregate significantly impact the shear strength of fresh concrete. Higher FI and EI correlate with lower shear strength and an increased likelihood of surface problems. Therefore, the combined FI and EI should preferably be kept below 40% to mitigate surface issues.

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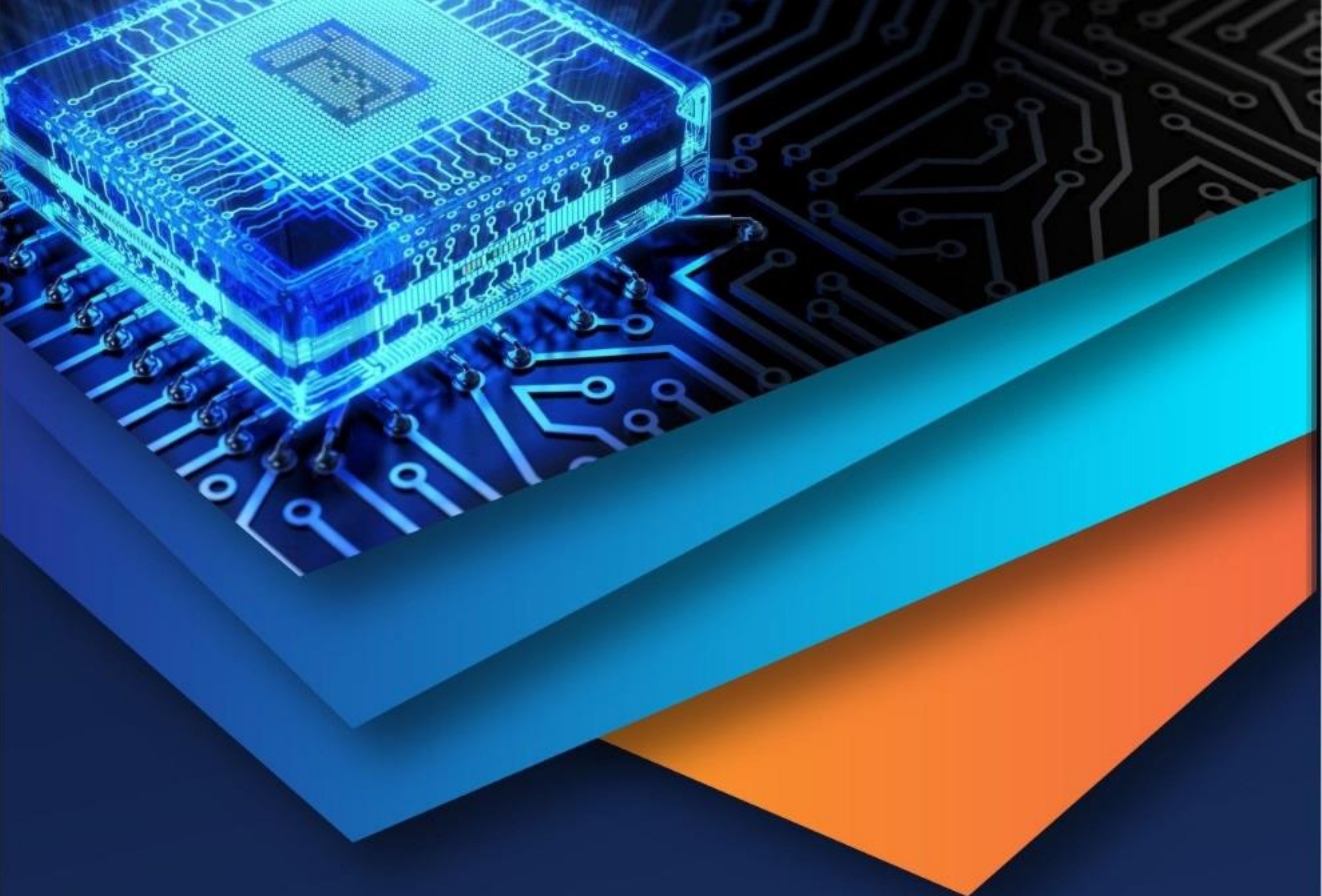

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