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A Review on New Developments in the Stabilization of Soil

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Abstract*: Expansive soils pose significant challenges for construction due to the shrink-swell behavior of their clay mineral components. These characteristics render them unsuitable for direct engineering applications in their natural state. To improve their suitability for construction, various stabilization materials and techniques have been utilized. This study examines the effectiveness of different additives and methods in enhancing the engineering properties of expansive soils. .We delve into the microstructural interactions, chemical processes, and economic impacts of soil stabilization, as well as the potential applications of nanotechnology. The discussion also includes the reuse of waste materials and sustainability. Emerging trends in expansive soil stabilization present issues in three key areas: geo environmental concerns, standardization, and optimization. To achieve efficient stabilization of expansive soils, we propose the use of predictive modeling and advanced techniques such as reliability-based design optimization, response surface methodology, dimensional analysis, and artificial intelligence.
Keywords: Expansive soil, Engineering properties, Soil stabilization, Optimization

I. INTRODUCTION

In civil engineering, various types of soils are used, but not all are suitable for construction in their natural state. Problematic soils often need to be either excavated and replaced or treated to improve their properties so they can support structural loads. Expansive soils are a typical example of problematic soils, known for their widespread occurrence except in arctic regions (Steinberg, 2000) [1]. These soils have caused significant damage in the United States (Jones and Holtz, 1973) [2] due to their high susceptibility to volume changes with moisture content variations. This volume change is primarily due to the fine-grained clay minerals in the soil.
Given the adverse characteristics of expansive soils, geotechnical engineers continually seek methods to mitigate these issues through soil stabilization technologies. The goal is to normalize the volume change and improve the plasticity and workability of the soil, while significantly enhancing its strength (Petry and little, 2002[3}; Soltani et al., 2017a, 2018a) [4]. Research has generated a vast repository of technical knowledge on improving expansive soils, though the information can be divergent and sometimes complicates issues for construction engineers. Some stabilization results are only suitable for limited applications (Uppal and Chadda, 1967; Ola, 1981; Puppala et al., 2001; Kate, 2005; Dafalla et al., 2015; Zhao et al., 2015) [4][5][6][7][8]. These challenges highlight the need for standardizing soil stabilization results and the use of various additives and composites.
Therefore, both geotechnical engineers and researchers need to align theory with practical applications in expansive soil stabilization. This paper reviews the stabilization of expansive soils using various techniques, discussing the effects of different additives and methods on the engineering properties of the stabilized soil.

II. EXPANSIVE SOIL BEHAVIOR

A. Characterization of Expansive Soil Behaviour

1) Expansion Mechanism

Clay particles have superficial negative charges due to isomorphous substitution (Schmitz, 2006; Sridharan and Choudhury, 2008). This creates electrostatic forces between the negative clay surfaces and the exchangeable cations in the clay-pore fluid. The strength of these forces depends on the chemistry of the exchangeable cations. To maintain neutrality, counter ions are naturally attracted to the clay particles' surfaces, decreasing their concentration with distance from the surface. This change in concentration creates the diffuse double layer, an electrostatic property of the clay surface, and the cation exchange capacity, which is the amount of cations needed to maintain neutrality (Yadav and Tiwari, 2017a).[10]
The diffuse double layer in clay minerals like montmorillonite causes separation between minerals and particles, leading to their swelling behavior (Schmitz, 2006). This layer significantly affects the hydraulic conductivity of clayey soil, with an expanded double layer reducing it and a reduced double layer increasing it (Besq et al., 2003; Sridharan and Nagaraj, 2005; Sridharan and Choudhury, 2008). This explains the swell-shrink behavior of expansive soils with moisture changes. The volume change in these soils is due to expandable clay minerals like montmorillonite, which have an expanding clay lattice and weak intermolecular forces.

These minerals also have negative surface charges, high cation exchange capacity, and a large specific surface area due to significant isomorphic substitution during formation.

2) Clay Mineral Identification

Sridharan and Keshavamurthy (2016) proposed two methods for identifying expandable clay lattices in expansive soils: inferential testing and mineralogical identification.

a) Inferential Testing: Includes direct methods (e.g., liquid limit, shrinkage limit) and indirect methods (e.g., oedometer, free swell tests).

b) Mineralogical Identification: Involves techniques like X-ray diffraction, differential thermal analysis, dye adsorption, chemical analysis, and SEM.

Mineralogical methods, while accurate, are costly and complex, making them less effective for characterizing swelling behavior. Inferential testing, especially the free swell ratio method, is cost-effective and practical for identifying swelling behaviors and dominant clay minerals. This method, validated in several studies, helps classify expansive soils by combining the free swell ratio with liquid limit tests using water and carbon tetrachloride, the latter inhibiting diffuse double layer formation in kaolinitic soils.

B. Expansive Soil Behavior

1) Characterization of Expansive Soil Behavior

a) Expansion Mechanism

Clay particles have negative surface charges due to a process called isomorphous substitution (Schmitz, 2006; Sridharan and Choudhury, 2008). This creates electrostatic forces between the negatively charged clay surfaces and the exchangeable cations in the surrounding fluid, with the strength of these forces depending on the chemistry of the cations (Schmitz, 2006). To maintain electrical neutrality, counter ions are naturally attracted to the clay surfaces, leading to a concentration gradient away from the surface. This creates an electrostatic property known as the diffuse double layer and defines the cation exchange capacity—the amount of cations needed to balance the negative charges on the clay surface (Yadav and Tiwari, 2017a).

The diffuse double layer causes the clay particles to separate, leading to swelling behavior in expandable clay minerals like montmorillonite (Schmitz, 2006). This double layer significantly affects the engineering properties of clay soils, particularly their hydraulic conductivity (Besq et al., 2003; Sridharan and Nagaraj, 2005; Schmitz, 2006). An expanded double layer reduces hydraulic conductivity, while a contracted double layer increases it (Sridharan and Choudhury, 2008). This mechanism underlies the swell-shrink behavior of expansive soils in response to moisture changes.

The volume change behavior of expansive soils is due to their expandable clay minerals, such as montmorillonite, which have an expanding clay lattice. These minerals feature weak intermolecular forces between adjacent layers but significant isomorphous substitution during their formation, resulting in negative surface charges, high cation exchange capacity, and a large specific surface area.

b) Clay Mineral Identification

Sridharan and Keshavamurthy (2016) proposed two methods for identifying expandable clay lattices in expansive soils: inferential testing and mineralogical identification.

- *Inferential Testing:* Measures index properties (liquid limit, shrinkage limit, particle size distribution) and includes oedometer and free swell tests (free swell value, differential free swell, free swell ratio).
- *Mineralogical Identification:* Uses techniques like X-ray diffraction, differential thermal analysis, dye adsorption, chemical analysis, and SEM.

Mineralogical methods, while accurate, are costly and complex, requiring expert interpretation, and thus less practical for characterizing swelling behavior. Inferential testing, particularly the free swell ratio method, is cost-effective and practical for identifying swelling behaviors and dominant clay minerals. This method has been validated in recent studies.

The free swell ratio is determined by comparing the sediment volume of soil in water to that in carbon tetrachloride/kerosene. For soils with both kaolinite and montmorillonite clays, this ratio, combined with liquid limit tests using water and carbon tetrachloride, helps identify the dominant mineral. Carbon tetrachloride, being non-polar, prevents diffuse double layer formation, yielding higher liquid limit values for kaolinite soils.

2) Unsaturated Soil Mechanics and Expansive Soil Behavior

Expansive soils undergo significant volume changes, complicating the modelling of their unsaturated behavior. Their partially saturated behavior is evident due to their bimodal nature. This complexity stems from the presence of varying pore sizes and structures, which interact differently with moisture. Accurately understanding and predicting the behavior of partially saturated expansive soils necessitates considering these distinctive characteristics and their impact on the soil's response to moisture fluctuations

Table 1
Free Swell ratio of Exoansive soil

Oedometer expansion (%)2	Free swell ratio	Clay type	Soil expansivity
<1	<1	Non-swelling	Negligible
1-5	1-1.5	Mixture of swelling and non-swelling	Low
5-15	1.5-2	Swelling	Moderate
15-25	2-4	Swelling	High
>25	>4	Swelling	Very high

The soil-water characteristic curve helps understand expansive soils on a large scale, but it's crucial to consider the internal structure of expansive soils. These soils consist of saturated clumps with high suction values before reaching the air entry threshold (Cui et al., 2006; Buzzi et al., 2007). Fityus and Buzzi (2009) [15] [16] [17] observed that the standard unsaturated soil mechanics framework does not accurately capture the volume change behavior of expansive soils during modeling. This is due to their coarse granular nature and the porosity created by large desiccation cracks.

III. CUTTING-EDGE IN EXPANSIVE SOIL STABILIZATION

A. Historical Lens

Significant advancements have been made in stabilizing expansive soils, thanks to a deeper understanding of their behavior. Geotechnical engineers have studied how expansive soils respond to loads through scientific principles and extensive lab experiments. In the late 20th century, efforts were made to identify and understand the characteristics of expansive soils. Palit (1953) developed a method to determine the swelling pressure of black cotton soil, noting a correlation between sample height increase and swell pressure. Jennings and Knight (1957) used oedometer tests to study soil heave, while later researchers like Lambe (1960), Jennings (1961), and Seed et al. (1962) focused on swell potential through lab experiments, predictive techniques, and field observations. Lytton (1994) employed various tests to define the essential characteristics of expansive clays. These studies provide a concise overview of laboratory techniques for understanding expansive soil behavior.

B. Techniques for Expansive Soil Stabilization

In the realm of soil stabilization, engineers commonly utilize two methods: mechanical and chemical stabilization (Estabragh et al., 2013a, 2014[23]; Radhakrishnan et al., [24] 2017; Soltani et al., 2018b). These approaches can be applied either independently or concurrently to maximize their respective advantages. When dealing with expansive soils like clay, engineers typically opt for physicochemical alteration of the soil to enhance its durability (Petry and Little, 2002) [25]. This process involves adjusting consolidation volume changes by either preserving or improving strength-related properties over an extended duration, often accomplished through chemical stabilization. Consequently, this review primarily focuses on discussing various additives, although it briefly touches on alternative techniques for stabilizing expansive soils. It's crucial to acknowledge the interplay between the diverse techniques utilized for soil stabilization in this context.

Table 2
Summary of various fibres used in the reinforcement of soil

Fibre source	Fibre type	Dosage/optimal content (%)	Fibre configuration (length)/optimal length (mm)	Information source
Natural	Coir fibre	0.2-1	>4.75	Jayasree et al. (2015)
	Coir pith	0.5-3	<4.75	Jayasree et al. (2015)
	Sisal fibre	0.25-1	10-25	Prabakar and Sridhar (2002)
	Palm fibre	0-1	20-40	Marandi et al. (2008)
	Jute fibre	0.3-0.9	6-18	Wang et al. (2017)
	Flax fibre	0.6"	85	Segetin et al. (2007)
	Barley-straw fibre	0-3.5	10-500	Bouhicha et al. (2005)
Synthetic	Carpet waste fibre	1-5	2-20	Mirzababaei et al (2013a)
	Polypropylene fibre	0.5-1.5	10-30	Estabragh et al. (2014)
	Waste rubber fibre	0-10	<15	Yadav and Tiwari (2017b)
	Polyester fibre	0-2	3-12	Kumar et al. (2006)
	Glass fibre	0.25-1	10-30	Patel and Singh (2015)

1) *Mechanical techniques*

a) *Compaction:* Compaction is a commonly employed method for addressing expansive soils. It involves using mechanical force to remove air voids from the soil mass, enabling it to support loads without immediate compression, which distinguishes it from the long-term consolidation seen in soft clays. Therefore, it's essential to determine the moisture-density relationship of soils, where the optimal moisture content (OMC) corresponds to the maximum dry density (MDD).

b) *Reinforcement:* Soil reinforcement, a mechanical technique for stabilizing weak soils, involves utilizing fibrous materials like geosynthetics (geogrids, geotextiles, geocomposites, geonets, and geocells) or randomly distributed fibers of natural or synthetic origin (Hejazi et al., 2012)[32]. Essentially, this method entails embedding these engineered components within the soil to create a three-dimensional (3D) reinforcement network, effectively intertwining the soil grains and enhancing mechanical performance. Various types and arrangements of natural and synthetic fibers used for soil reinforcement are outlined in Table 2. Hejazi et al. (2012) conducted an extensive review of natural and synthetic fibers for soil reinforcement, discussing the effects of randomly distributed fibers on soil engineering properties. The findings indicated that for compacted clay with 10% activated sodium bentonite content at maximum dry unit weight (MDU) and optimum moisture content (OMC), the swelling pressure decreased by around 20% with 1% type 1 fiber content but increased with higher fiber contents. Conversely, for type 2 fibers, the soil's swelling pressure significantly rose, reaching a peak increase of approximately 83% at 3% fiber content. The study also investigated the effects of varying moisture content at a constant dry unit weight and varying dry unit weight at a constant moisture level. The results revealed that the swelling pressure decreased with increasing moisture content at a constant dry unit weight but increased with an increase in dry unit weight at a fixed moisture content.

c) *Solid Wastes:* Solid wastes, commonly generated in large quantities within urban areas, typically comprise paper, glass, wood, plastics, reusable items, rubber scraps, plant debris, metals, and other materials, with organic matter as the predominant component (Puppala et al., 2007). Managing and disposing of such waste on a large scale present significant environmental challenges, such as landfills. However, in recent years, some of these materials have been found suitable for soil stabilization applications .Signs et al. (2016) investigated the utilization of rubber particle crumbs as an additive to argillaceous marlstone to evaluate their impact on the soil's swelling potential. They observed a decrease from 3.71% to 1.37% in swelling potential with the incorporation of 25% rubber crumb particles. Kamei et al. (2013) [34] examined recycled basanite, a solid waste derived from gypsum waste plasterboard, to assess its effect on the durability of cement-modified soft clay. They found that the stabilized soil exhibited durability, with a slight decline in its unconfined compressive strength (UCS) from the 1st to the 3rd cycle, which was nearly restored by the 5th cycle when a basanite-soil ratio of 10% and cement-soil ratios of 5% and 10% were used.

2) Chemical technique

a) *Traditional Agents:* Traditional chemical additives such as lime, cement, and fly ash are commonly used to stabilize expansive soils. These calcium-based materials react with water, causing both immediate and long-term chemical changes that improve soil structure by reducing swelling, enhancing shear strength, and increasing resistance to wetting and drying (Soltani et al., 2017a). The proven effectiveness of these additives in stabilizing expansive soils is well-documented (Zhao et al., 2013, 2015; Tran et al., 2014; Dafalla et al., 2015; Nweke and Okogbue, 2017)[35]..

b) *Non-traditional Agents:* Non-traditional agents are additives that chemically interact with soil and/or other additives, often requiring sufficient moisture to initiate physicochemical reactions within the soil matrix. These materials encompass a range of industrial by-products, such as cement kiln dust, lime kiln dust, ground granulated blast furnace slag, pulverized coal bottom ash, steel slag, and mine tailings. They also include other calcium oxide-rich waste products like waste paper sludge ash, as well as sulfonated oil sand polymers (Petry and Little, 2002; Alazigha et al., 2016[38]; Fasihnikoutalab et al., 2017[39]; Soltani et al., 2017b, 2018a; Estabragh et al., 2018). Understanding the stabilization mechanism for each material category allows engineers to select the appropriate material based on the desired level of physicochemical modification. Petry and Little (2002) explained that industrial by-products function similarly to traditional stabilizers, while other materials stabilize soil through different processes. Onyejekwe and Ghataora (2015) [40] described that sulfonated oils and polymers stabilize soil by aligning clay particles and changing the surface charge polarity of the clay. This increases inter-particle cohesion, alters the clay lattice, and affects the diffuse double layer zone. This ultimately enhances the binding of soil particles, reducing their sensitivity to moisture.

C. Comparative Analysis of Various Stabilization Techniques

The stabilization methods discussed engineers with options for reinforcing weak soils on-site. After conducting geotechnical site investigations and testing, engineers consider several factors when selecting a stabilization method. These factors include the site's expansion potential, the design active zone, the extent of soil fracturing, the uniformity or variability of the soils, the soil's chemical reactivity, and the presence of harmful chemical compounds, water distribution, soil hydraulic conductivity, and the required soil strength (Nelson et al., 2015). Engineers rely on their expertise to make informed decisions about the best technique to use. Table 3 offers a comparative analysis of the benefits and drawbacks of different stabilization techniques.

D. Engineering Properties of Stabilized Soils using Various Techniques

Soil stabilization for expansive soils started in the 1950s (Petry and little, 2002). Since then, significant progress has been made. However, with the advancements in technology in the 21st century, it is essential for engineers to keep up-to-date with the latest trends in stabilizing expansive soils, as there is no universally accepted standard for applying soil stabilization in situ.

1) Emphasis on Microstructural Interaction

Understanding the physicochemical changes in stabilized soil is vital for engineers. Microstructural analysis offers a clear explanation of these changes. This analysis can be shown through qualitative digital images, like Scanning Electron Microscopy (SEM), or quantitative methods, such as X-ray diffraction (XRD). These techniques help clarify the effects of stabilization on the soil's components, structure, and pore system. Mirzababaei et al. (2009) examined how polymers affect soil microfabric. They found that adding furan polymer at concentrations of 3%, 5%, and 10% by weight significantly decreased the free swell percentage of three expansive soils compacted at Optimum Moisture Content (OMC) and Maximum Dry Density (MDD), with an average maximum reduction of about 83.5%. Figures 1 to 3 show the microfabric changes at 5% and 10% furan. At magnifications of 500x and 1000x, the natural soil primarily consists of discrete granules with sparse aggregations, a few silt grains, and some connectors. The pores between these structures are evident. However, with 5% and 10% furan, the soil fabric becomes densely aggregated, forming intra-assemblage pores and reducing the visibility of inter-assemblage pores, indicating smaller pore sizes. A recent study by Osinubi et al. (2015) [42] observed similar changes in pore pressure

2) Emphasis on Chemical Process

A deep understanding of the chemistry involved in soil stabilization allows engineers to modify soil properties to achieve specific outcomes. For instance, Soule and Burns (2001) used four Quaternary ammonium cations (benzyl tri-ethyl ammonium chloride, tetra methyl ammonium bromide, decyltri methyl ammonium bromide, and hexadecyl tri methyl ammonium bromide) to replace the cations in Wyoming bentonite through cation exchange capacity.

This method relies on the clay's cation exchange capacity, which determines how well organic cations can bond to the mineral surface (Jaynes and Vance, 1996). This substitution led to reduced specific gravity, improved swell-shrink characteristics, and increased shear friction angle of the soil.

Fasihnikoutalab et al. (2017) [39] took advantage of the lack of a strong Si-O-Si bond in olivine (Mg_2SiO_4) by using a strong alkaline compound (NaOH) to break the bond between MgO and SiO_2, resulting in the production of silica gel. Adding alkali-activated olivine (at 5%, 10%, 15%, and 20%) significantly improved the unconfined compressive strength (UCS) of the untreated soil.

3) Emphasis on Economic Implication

While it's important to enhance soil properties to meet predetermined standards during stabilization, engineers must also ensure cost-effectiveness. To strike this balance, researchers often conduct comparative analyses to evaluate both the efficiency and affordability of different additives.

Geocell, a rigid geosynthetic material comprising intricately blended cells forming 3D honeycomb structures, offers beneficial confinement effects (Asha et al., 2012). Dutta and Mandal (2016) proposed that the geocell system's boundary effect significantly enhances the shear strength of confined materials. They also observed that using geocell confinement reduces settlement when distributing footing load compared to other two-dimensional (2D) composite materials in mesh form.

This claim is backed by studies conducted by Latha and Somwanshi (2009) [45] and Moghaddas Tafreshi and Dawson (2010) [46], who found that geocell reinforcement systems outperformed planar reinforcement systems with equivalent material quantities.

IV. TRANSITIONING FROM STATE-OF-THE-ART TO STATE-OF-THE-PRACTICE

The geotechnical community has witnessed a substantial volume of research on stabilizing expansive soils in the 21st century. However, to enhance effectiveness and practicality, it's imperative to tackle challenges arising in certain aspects of the practice. These are not merely limitations but opportunities to refine the use of available techniques, aiming for sustainable and efficient expansive soil stabilization. Addressing these challenges will undoubtedly shift expansive soil stabilization from an art to a highly practical tool.

This would facilitate better field application without the necessity for arduous, time-consuming, and expensive trial tests that may not be feasible on-site

Since the advent of soil stabilization technology, addressing this issue has remained pivotal within the geotechnical community. Determining whether the rate of advancement in this technology contributes to the problem is not straightforward. A comprehensive standard manual for applying expansive soil stabilization using various techniques and materials has not yet been developed. While some efforts have been made, such as the publication of a manual by the American Coal Ash Association (ACAA) in 2008, which provided guidelines for using coal fly ash as a sole stabilizing agent (ACAA, 2008), and the release of a guide by the American Society for Testing and Materials (ASTM) in 2011 (ASTM D7762-11, 2011), focused solely on fly ash usage, other published guidelines are limited to traditional agents or specific applications (Terrel et al., 1979[47]; White et al., 2005[48], 2013). This underscores the need for experts in the field to collaborate and devise an appropriate response to this challenge, which has hindered the practical application of expansive soil stabilization. Drawing from experience, existing research findings, and the potential of artificial intelligence techniques, there is a possibility of developing a comprehensive and universally accepted standard for executing expansive soil stabilization across various engineering applications.

V. CONCLUSIONS

This paper reviews recent advancements in soil stabilization technology, particularly for expansive soils. It discusses key areas such as microstructural changes, chemical stabilization processes, economic considerations, sustainability, waste reuse, and nanotechnology. New methods have emerged to study soil microstructure changes, while various chemical additives and techniques like deep soil mixing optimize cost-effectiveness. Sustainability is a focus, with soil stabilization aiding in waste management. Nanotechnology shows promise for soil stabilization.

However, challenges remain, including environmental concerns post-stabilization, such as soil pH changes, harmful emissions, and heavy metal leaching. Additionally, the lack of standardized techniques for field implementation hinders widespread application, necessitating the development of universal standards and possibly leveraging AI for this purpose.

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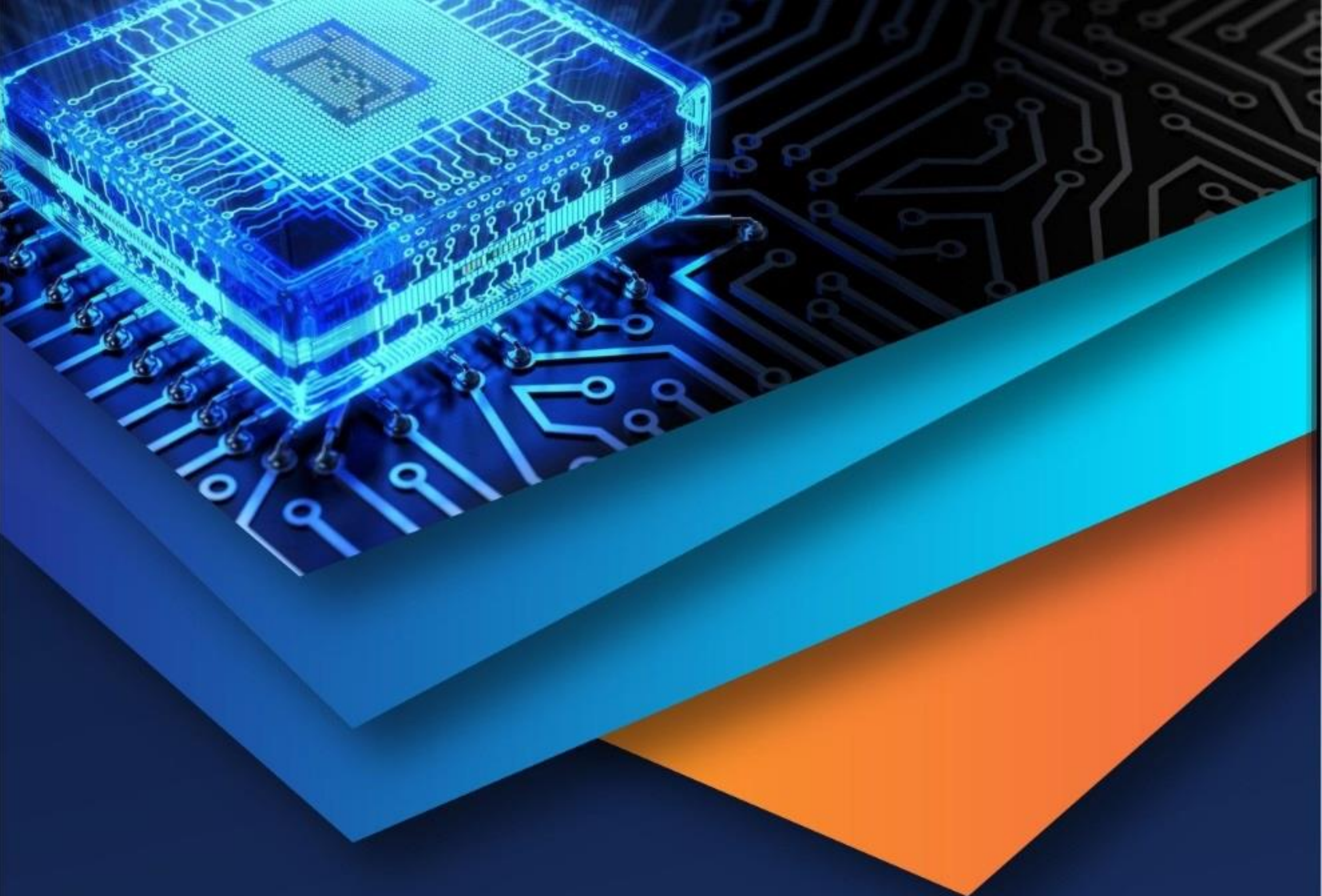

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