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Mechanical and Microstructural Behaviour of Expansive Soil Stabilised with Granite Waste Powder

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Abstract: Expansive soils exhibit significant volume change behaviour due to moisture variation, leading to serious stability and durability issues in geotechnical and pavement structures. This study evaluates the mechanical and microstructural behaviour of expansive soil stabilized with granite waste powder (GWP), an industrial by-product generated during granite processing. Soil samples were treated with varying GWP contents (0%, 5%, 10%, 15%, and 20%) and tested for index properties, compaction characteristics, strength parameters, and swelling behaviour. Results indicated a substantial reduction in liquid limit (62% to 47%) and plasticity index (34% to 15%), signifying decreased soil plasticity. The maximum dry density increased from 16.2 to 18.0 kN/m³, while optimum moisture content decreased with increasing GWP content. Strength behaviour showed significant improvement, with unconfined compressive strength increasing from 185 kPa to 410 kPa and soaked CBR from 3.8% to 10.8% at 15% GWP. Swell potential and swell pressure were markedly reduced, confirming the effectiveness of stabilization. Microstructural analyses using SEM, XRD, and EDS revealed a denser soil matrix, improved particle bonding, and mineralogical alterations due to physico-chemical interaction and filler effects. The study concludes that granite waste powder is an effective, sustainable, and economical stabilizing agent for expansive soils, particularly suitable for subgrade and pavement applications.

Keywords: Expansive soil; Granite waste powder; Soil stabilization; Mechanical behaviour; Microstructural analysis; Swell reduction; Sustainable construction

I. INTRODUCTION

Expansive soils pose significant challenges to civil engineering infrastructure due to their pronounced swelling and shrinkage behaviour under moisture fluctuations. These volume changes lead to differential settlement, cracking, and loss of bearing capacity in pavements, foundations, and embankments, thereby increasing maintenance costs and compromising structural durability. Conventional stabilization methods such as lime and cement treatment are effective but often associated with higher costs, carbon emissions, and limited availability in certain regions. Consequently, there is a growing emphasis on sustainable and cost-effective alternatives that can enhance the engineering performance of expansive soils while also addressing environmental concerns. In this context, granite waste powder (GWP), a by-product generated during the cutting and polishing of granite stones, has emerged as a promising stabilizing material. The fine particles of GWP possess filler characteristics and reactive mineral components that can modify soil fabric, reduce plasticity, and improve strength and stiffness. Incorporating GWP into expansive soil not only contributes to waste utilization and environmental sustainability but also enhances the mechanical properties through physico-chemical interactions and microstructural densification. Therefore, the present study focuses on evaluating the mechanical and microstructural behaviour of expansive soil stabilized with varying proportions of granite waste powder to establish its suitability for geotechnical and pavement subgrade applications.

Thermal stabilization is an emerging sustainable technique to reduce the swelling and shrinkage behaviour of expansive soils by altering their mineralogical and mechanical properties. It improves strength and lowers plasticity through methods such as conventional heating and microwave treatment, though challenges related to cost and field implementation remain. Integrating thermal treatment with additives like lime can further enhance performance while supporting environmentally friendly soil stabilization [1]. Expansive soils pose significant challenges for construction due to their shrink–swell behaviour, necessitating effective stabilization methods. Various admixtures such as marble waste powder, fly ash, eggshell powder, stone waste, and lime have been explored to enhance geotechnical properties while addressing environmental and economic concerns.

Evaluating these stabilizers highlights their potential for sustainable soil improvement, though practical performance and long-term viability remain key considerations [2]. This paper reviews advanced characterization and stabilization approaches for expansive soils, highlighting the limitations of conventional methods and introducing models that integrate hydro, chemical, and mechanical soil behaviours. Case studies demonstrate improved stabilization through detailed analysis of clay mineralogy, sulfate content, and unsaturated soil behavior, along with forensic evaluation of slope failures. The study emphasizes the importance of comprehensive soil chemistry data and emerging monitoring tools, such as UAV-based health assessment, for enhancing infrastructure performance on expansive soils [3]. Expansive soils undergo harmful swelling and shrinkage with moisture variation, threatening engineering stability, but industrial solid wastes offer a sustainable improvement approach. These materials enhance strength, compaction, durability, and reduce volume change through mechanisms such as cation exchange, flocculation, pozzolanic reactions, and carbonation. Microstructural studies indicate that the formation of C–S–H and C–A–H gels is a key factor in improving the geotechnical performance of treated expansive soils [4].

Expansive soils cause significant infrastructure damage, highlighting the need for resilient and sustainable stabilization methods. Recent advances emphasize chemical additive-based treatments, including lime, cement, biopolymers, and deep soil mixing technologies to improve strength and durability under climatic variations. These approaches support long-term performance of civil and transportation infrastructure while guiding future research toward sustainable ground improvement practices [5]. Problematic soils, especially expansive soils, adversely affect pavements and foundations due to low strength, high compressibility, and significant volume change. Sustainable stabilization methods, particularly those using pozzolanic materials from agricultural and industrial wastes, offer environmentally friendly alternatives to conventional treatments. These materials effectively reduce swelling and plasticity while improving compaction and strength, though optimal dosage varies widely depending on soil and material type [6]. Clayey and expansive soils lose strength upon saturation, causing excessive settlement and significant damage to foundations and infrastructure worldwide. Early identification of soil expansiveness is crucial, as traditional replacement methods are costly, leading to increased use of stabilization with additives like lime, cement, fly ash, and slag. While these treatments enhance geotechnical properties, challenges such as heave in sulfate-rich soils highlight the need for careful selection and advanced stabilization approaches. [7]. Soil stabilization with additives is a sustainable approach to address material shortages and improve soil performance, with effectiveness influenced by soil type, compaction, and curing conditions. Cement-based stabilizers generally perform consistently across soil types, while lime-based stabilizers are more suitable for high-plastic soils under appropriate pH and temperature conditions. Overall, additive treatment reduces plasticity and enhances strength, with cost, energy use, and CO_2 efficiency varying depending on the stabilizer and soil characteristics [8].

Soil stabilization enhances shear strength, bearing capacity, and overall performance of soils that are otherwise unsuitable for construction. It reduces permeability, compressibility, and shrink–swell behaviour while improving load-bearing capacity for pavements and foundations. Stabilization is broadly achieved through mechanical methods that alter soil gradation and chemical methods that use additives to react with soil particles and form a stable, moisture-resistant framework [9]. The study investigates the combined use of nanoclay and glass fiber to enhance the performance of lime-stabilized marl soil. Results show that optimal additions of 1% nanoclay and 0.75% glass fiber significantly improve strength and durability, even under freeze–thaw cycles. Microstructural analyses confirm that improved interlocking and bonding mechanisms contribute to enhanced stabilization through chemical, physical, and mechanical effects [10]. Soil stabilization traditionally relies on compaction and chemical agents like lime and cement to improve engineering properties. Recent trends highlight the growing use of waste materials such as fly ash and rice husk ash, either alone or combined with conventional stabilizers, to achieve comparable performance. This approach supports sustainable soil engineering by enhancing soil properties while providing an eco-friendly solution for waste utilization and environmental concerns [11]. Expansive clays cause structural damage due to moisture-induced volume changes, and fly ash stabilization is a common and sustainable treatment method. The addition of natural and synthetic fibers further enhances soil strength, bearing capacity, and reduces volume change significantly. Overall, fiber-reinforced fly ash stabilization offers an effective, low-cost approach with notable geotechnical and environmental benefits for improving expansive soils [12]. The study introduces a sustainable approach for recycling granite waste powder by stabilizing it with an inorganic binder mix to produce durable pavement subgrade filler. Results show that the optimized combination of cement, lime, slag, and surfactant significantly enhances compressive strength and freeze–thaw durability. This method offers an effective way to utilize industrial waste while improving mechanical performance and reducing environmental pollution [13]. Granite dust, a mining by-product, can be effectively utilized as a stabilizer to enhance the geotechnical behavior of expansive soils while addressing waste disposal concerns. Its inclusion improves plasticity, strength, bearing capacity, and reduces swelling, with an optimum performance observed around 20% replacement.

Microstructural analyses confirm that mineralogical and morphological changes in the soil–granite dust mix govern the stabilization mechanism [14]. The study examines the influence of granite waste powder on compacted clay soil through laboratory and field tests, showing significant improvement in strength, density, and bearing capacity while reducing moisture sensitivity and porosity. Enhanced performance is attributed to the denser and less hydrophilic nature of granite particles compared to the natural soil. Optimal improvement is observed at about 40% granite waste content, with laboratory results generally showing greater gains than field conditions due to differences in compaction and testing environments [15]. The study develops a cement–granite composite using waste granite powder and ordinary Portland cement, producing a lightweight material with low water absorption, adequate compressive strength, and good thermal and radiation stability. The composite's properties depend on the granite–cement and water–cement ratios, offering an economical use of granite waste. This material shows potential for construction applications and safe containment matrices while providing environmental benefits through effective waste recycling [16].

A. *Research Hypotheses*

Based on the study objectives and identified research gaps, the following hypotheses are formulated.

H1: Addition of granite waste powder (GWP) reduces the plasticity index and swelling characteristics of expansive soil.

H2: Stabilization with GWP increases the unconfined compressive strength (UCS) and California Bearing Ratio (CBR) of expansive soil.

H3: The compaction characteristics of expansive soil are improved with GWP, leading to higher maximum dry density and lower optimum moisture content.

H4: Microstructural analysis will show a denser soil matrix and improved particle bonding in GWP-stabilized soil compared to untreated soil.

B. *Objectives of the Study*

1) To evaluate the effect of granite waste powder (GWP) on the index and compaction properties of expansive soil.
2) To investigate the improvement in mechanical behaviour, particularly unconfined compressive strength (UCS) and California Bearing Ratio (CBR), of expansive soil stabilized with varying percentages of GWP.
3) To assess the influence of GWP on the swelling characteristics, including free swell index and swell pressure, of expansive soil.
4) To examine the microstructural changes in stabilized soil using techniques such as SEM, XRD, and EDS to understand the stabilization mechanism.
5) To determine the optimum percentage of granite waste powder that provides maximum improvement in strength and durability of expansive soil.
6) To establish the suitability of GWP-stabilized expansive soil for geotechnical and pavement subgrade applications from both mechanical and microstructural perspectives.

II. MATERIALS AND METHODS

TABLE I
SUMMARY OF MATERIALS AND MIX PROPORTIONS

Material	Description	Key Properties / Characteristics	Mix Proportions (% by dry weight of soil)
Expansive Soil	Locally collected clayey soil, air-dried and sieved through 4.75 mm sieve	Classification: CH; LL = 62%, PL = 28%, PI = 34%; Specific Gravity = 2.68	100%, 95%, 90%, 85%, 80%
Granite Waste Powder (GWP)	By-product from granite cutting and polishing industry, oven-dried and passed through 75 µm sieve	Fine, silica-rich particles; Specific Gravity = 2.63; Particle size < 75 µm	0%, 5%, 10%, 15%, 20%

For evaluating the stabilization effect, the soil was mixed with varying percentages of granite waste powder by dry weight of soil, namely 0%, 5%, 10%, 15%, and 20%, and mentioned above in Table-I. These mix proportions were selected based on earlier pilot trials and literature recommendations to capture the optimum stabilizing range.

The required quantities of dry soil and GWP were thoroughly blended in dry condition to ensure homogeneity, after which water corresponding to the optimum moisture content (approximately 16–18%) was gradually added. The moist mixtures were sealed in airtight polyethylene bags and allowed for moisture equilibration for 24 hours. Compaction of samples was carried out using the Standard Proctor energy (2.6 kg rammer, 310 mm drop, 25 blows per layer in three layers) to achieve uniform density. For strength and swelling tests, compacted specimens were cured in a humidity-controlled environment at 27±2°C for curing periods of 7, 14, and 28 days to assess both short-term and long-term stabilization effects.

The experimental programme consisted of mechanical and microstructural investigations to comprehensively evaluate the behaviour of stabilized soil. Mechanical tests included Atterberg limits to observe changes in plasticity, Standard Proctor compaction tests to determine maximum dry density and optimum moisture content, Unconfined Compressive Strength (UCS) tests on cylindrical specimens (38 mm diameter × 76 mm height), California Bearing Ratio (CBR) tests under soaked conditions, and swell characteristics such as free swell index and swell pressure using oedometer apparatus. To understand the stabilization mechanism at the microscopic level, selected samples (untreated soil and soil with optimum GWP content) were subjected to microstructural analyses. Scanning Electron Microscopy (SEM) was used to examine particle arrangement and bonding, X-ray Diffraction (XRD) was performed to identify mineralogical alterations and formation of new compounds, and Energy Dispersive X-ray Spectroscopy (EDS) was employed to determine elemental composition and confirm the interaction between clay minerals and granite waste powder. These combined analyses enabled correlation between macroscopic strength improvement and underlying microstructural modifications.

III. RESULTS AND DISCUSSIONS

A. Index Properties Modification

TABLE II
VARIATION OF INDEX PROPERTIES WITH GWP CONTENT

GWP Content (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Soil Classification
0	62	28	34	CH
5	58	29	29	CH
10	54	30	24	CI
15	50	31	19	CI
20	47	32	15	CL

The incorporation of granite waste powder (GWP) as mentioned above in Table-II mentioned led to a gradual reduction in liquid limit from 62% to 47% and plasticity index from 34% to 15%, indicating a significant decrease in soil plasticity. The plastic limit showed a slight increase due to improved workability of the mix. This reduction in plasticity is attributed to the dilution of active clay minerals and replacement with non-plastic granite fines. Consequently, the soil classification shifted from highly plastic clay (CH) to low plastic clay (CL) at higher GWP content, demonstrating the effectiveness of GWP in modifying index properties.

B. Compaction Characteristics

TABLE III
COMPACTION PARAMETERS OF SOIL–GWP MIXES

GWP Content (%)	Maximum Dry Density (kN/m³)	Optimum Moisture Content (%)
0	16.2	18.5
5	16.8	17.8
10	17.4	17.0
15	18.0	16.2
20	17.7	16.0

From the above table-III it is found that the maximum dry density (MDD) increased from 16.2 to 18.0 kN/m³ with up to 15% GWP addition, while the optimum moisture content (OMC) decreased from 18.5% to 16.0%. The increase in MDD is mainly due to the filler effect of finer GWP particles occupying voids and improving packing density. Beyond 15% replacement, a slight reduction in MDD was observed due to excess non-cohesive fines. The decrease in OMC indicates reduced water affinity of the stabilized soil due to the reduction in clay activity.

C. *Strength Behaviour*

TABLE IV
STRENGTH CHARACTERISTICS OF STABILIZED SOIL

GWP Content (%)	UCS (kPa)	Soaked CBR (%)
0	185	3.8
5	245	5.6
10	325	7.9
15	410	10.8
20	395	10.2

D. *Swelling Behaviour*

TABLE V
SWELL CHARACTERISTICS WITH GWP ADDITION

GWP Content (%)	Free Swell Index (%)	Swell Pressure (kPa)
0	72	82
5	58	65
10	45	48

The addition of GWP as shown above in Table-V, significantly reduced the free swell index from 72% to 28% and swell pressure from 82 kPa to 26 kPa. This reduction is due to the replacement of expansive clay particles with inert granite fines and the formation of a denser soil matrix that restricts moisture-induced expansion. The stabilization mechanism involves reduction in diffuse double layer thickness and improved soil aggregation.

E. *Microstructural Behaviour*

TABLE VI
SUMMARY OF MICROSTRUCTURAL OBSERVATIONS

Test Method	Untreated Soil	Soil + 15% GWP	Observed Effect
SEM	Flaky, dispersed clay particles with large voids	Dense matrix with bonded particles and reduced voids	Matrix densification and improved bonding
XRD	Dominant montmorillonite and illite peaks	Reduced clay mineral peaks; increased quartz intensity	Formation of stable mineral phases
EDS	High Al and Si from clay minerals	Increased Si and Ca content due to GWP	Evidence of physico-chemical interaction

SEM images as mentioned above in Table-VI, revealed a dispersed and porous fabric in untreated soil, whereas stabilized soil showed aggregated particles and a compact matrix. XRD patterns indicated a decrease in expansive clay mineral intensity and increased quartz peaks due to GWP addition. EDS analysis confirmed an increase in silica and calcium content, suggesting interaction between soil minerals and granite waste powder.

F. *Mechanism of Stabilization*

The stabilization of expansive soil with granite waste powder occurs through combined physico-chemical and mechanical mechanisms. The fine GWP particles act as fillers, occupying void spaces and enhancing packing density, which directly improves strength and reduces compressibility. Additionally, the silica-rich composition of GWP contributes to mild pozzolanic reactions in the presence of moisture, leading to the formation of cementitious bonds that enhance particle cohesion and stiffness. Microstructural evidence strongly correlates with the observed macroscopic improvements.

SEM analysis confirmed matrix densification, while XRD and EDS results indicated mineralogical alterations and elemental interactions. These changes collectively reduce clay activity, limit swell potential, and enhance strength behaviour. Thus, the improved mechanical performance of stabilized soil is directly linked to the microstructural transformation induced by granite waste powder, confirming its effectiveness as a sustainable stabilizing agent for expansive soils.

IV. SUSTAINABILITY AND PRACTICAL IMPLICATIONS

The reuse of granite waste powder (GWP) in expansive soil stabilization offers significant environmental benefits by promoting sustainable waste management and reducing the burden on landfills. Granite processing industries generate large quantities of fine powder as a by-product, which often poses disposal and dust pollution problems. Utilizing this waste material as a soil stabilizer helps in conserving natural resources, minimizing environmental degradation, and reducing the carbon footprint associated with the production and transportation of conventional stabilizers such as cement and lime. Moreover, the incorporation of GWP supports the principles of circular economy by transforming industrial waste into a value-added construction material.

From a practical perspective, the use of granite waste powder can lead to considerable reduction in construction costs due to its local availability and low processing requirements compared to traditional chemical stabilizers. The improved strength, reduced swelling potential, and enhanced bearing capacity of GWP-stabilized expansive soil make it highly suitable for subgrade improvement in flexible pavements, embankments, and low-cost road construction projects. Its application is particularly beneficial in regions with abundant granite processing units, where sustainable and economical ground improvement solutions are required for long-term pavement performance and infrastructure durability.

V. CONCLUSION

The present study investigated the mechanical and microstructural behaviour of expansive soil stabilized with varying percentages of granite waste powder (GWP). The results demonstrated that the inclusion of GWP effectively modified the index properties by reducing liquid limit and plasticity index, thereby decreasing the soil's expansive nature. Compaction characteristics improved with an increase in maximum dry density and a corresponding reduction in optimum moisture content up to an optimum GWP content of about 15%. Significant enhancement in strength behaviour was observed, with notable increases in unconfined compressive strength and soaked CBR values, indicating improved load-bearing capacity suitable for pavement subgrade applications. Additionally, swell potential and swell pressure were considerably reduced, confirming the effectiveness of GWP in mitigating the adverse volume change behaviour of expansive soils. Microstructural analyses through SEM, XRD, and EDS revealed densification of the soil matrix, improved particle bonding, and mineralogical modifications due to the presence of silica-rich granite fines. These findings established a strong correlation between microstructural transformation and macroscopic strength improvement. Overall, granite waste powder proved to be an efficient, sustainable, and cost-effective stabilizing agent for expansive soils, with optimum performance observed around 10–15% replacement. The study confirms that the reuse of industrial granite waste not only enhances soil engineering properties but also contributes to environmentally sustainable ground improvement practices in geotechnical and pavement engineering applications.

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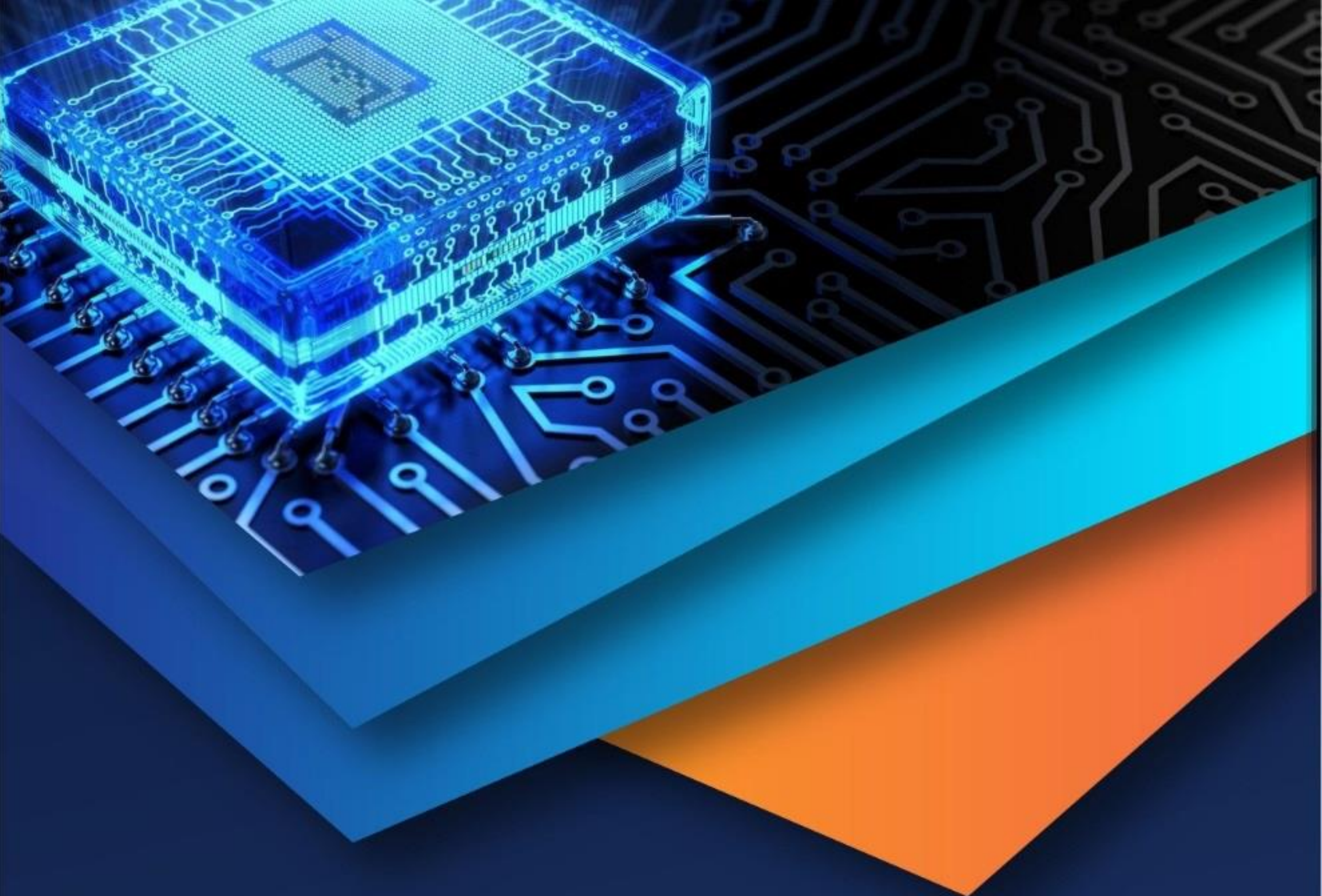

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