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A Sustainable Alternative: Geopolymer Concrete Synthesized from Fly Ash, GGBS, and CDW

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Abstract: The present study explores the potential of developing an eco-friendly geopolymer concrete (GPC) by utilizing industrial by-products—Ground Granulated Blast Furnace Slag (GGBS) and Fly Ash—as binders and replacing natural coarse aggregates partially with Construction and Demolition Waste (CDW). Manufactured sand (M-sand) was used in place of conventional river sand to enhance sustainability. The experimental investigation includes the preparation of geopolymer concrete with varying proportions of CDW and detailed evaluation of its mechanical properties such as compressive strength, split tensile strength, and flexural strength. Durability aspects like water absorption, acid resistance, and sulphate attack resistance were also studied. The results indicate that a mix with 30% CDW substitution and a 70:30 blend of Fly Ash to GGBS delivered optimum performance in both strength and durability parameters, making it a viable sustainable alternative to traditional concrete.
Keywords: Geopolymer Concrete, Fly Ash, GGBS, CDW, Sustainable Concrete

I. INTRODUCTION

The rapid urbanization and increasing demand for infrastructure have led to the extensive consumption of natural resources, particularly for the production of conventional concrete. The cement industry is one of the largest contributors to carbon dioxide emissions globally, contributing approximately 5-6% of the total emissions [2]. As a result, there is an urgent need to explore alternative materials and processes to make concrete more sustainable and reduce its environmental impact. One promising solution lies in the development of Geopolymer Concrete (GPC), which is made using industrial by-products such as Fly Ash (FA) and Ground Granulated Blast Furnace Slag (GGBS) as binders, eliminating the need for Portland cement [11]. This shift not only reduces the carbon footprint but also makes use of abundant industrial waste materials, promoting a circular economy.

Geopolymer concrete is formed by activating these industrial by-products using alkaline solutions such as sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), which triggers the polymerization process that binds the aggregates together [5]. Research has shown that geopolymer concrete exhibits comparable, if not superior, mechanical and durability properties to conventional concrete, including enhanced resistance to aggressive environments like acid and sulfate attacks [6]. The incorporation of construction and demolition waste (CDW) as an aggregate replacement is an emerging trend in sustainable concrete development. CDW is typically underutilized, contributing to landfills and environmental degradation. However, replacing natural aggregates with CDW not only reduces waste but also conserves valuable natural resources [10].

Another important consideration in sustainable concrete production is the use of Manufactured Sand (M-sand) as a replacement for conventional river sand. M-sand is produced by crushing rocks, and its use helps in conserving river ecosystems, which are otherwise depleted by the indiscriminate extraction of sand [8]. The combination of these alternatives—GGBS, Fly Ash, CDW, and M-sand—can lead to the development of eco-friendly, high-performance geopolymer concrete, which is the primary focus of this study. By replacing conventional materials with sustainable alternatives, geopolymer concrete provides a potential solution to mitigate the environmental impact of construction while offering comparable or superior properties for construction applications [3].

This paper investigates the performance of geopolymer concrete developed with GGBS and Fly Ash as binders and CDW as a partial replacement for coarse aggregates, using M-sand as the fine aggregate. The global construction industry has been increasingly moving towards sustainability due to the escalating environmental concerns and depletion of natural resources. Concrete, being one of the most widely used construction materials, accounts for a significant portion of global CO_2 emissions. Portland cement, the primary binding material in concrete, contributes about 8% of global carbon emissions [7]. To address this issue, alternative materials are being explored to reduce the dependence on conventional cement. Geopolymer concrete, made using industrial by-products like fly ash and GGBS, emerges as a potential solution. Unlike ordinary Portland cement concrete, geopolymer concrete does not require heat curing, which further reduces energy consumption and CO_2 emissions [6].

In addition to its environmental benefits, geopolymer concrete has demonstrated superior properties in terms of fire resistance, acid resistance, and high-temperature stability compared to traditional concrete. These enhanced properties make it a promising material for applications in aggressive environments such as chemical plants and offshore structures [15]. Moreover, the use of Construction and Demolition Waste (CDW) as a replacement for natural aggregates offers a twofold benefit—reducing the accumulation of construction waste in landfills and conserving the consumption of natural aggregates like gravel and crushed stone [1]. This practice not only promotes sustainability in the construction industry but also helps reduce the strain on natural resources that are vital for other industries. Studies have shown that CDW, when processed correctly, can provide adequate structural integrity to the concrete without compromising its strength or durability [14].

The use of Manufactured Sand (M-sand) in concrete production further enhances sustainability by reducing the demand for river sand, which is often extracted in an environmentally damaging manner. M-sand is produced by crushing rocks, making it a more consistent and controlled material than natural sand, and its use in concrete mix designs helps mitigate the ecological impact associated with natural sand mining [8].

In recent years, extensive research has been focused on optimizing the mix design of geopolymer concrete to improve its mechanical and durability characteristics. Studies have highlighted the importance of the fly ash-to-GGBS ratio, as the two materials exhibit complementary properties. While fly ash offers good workability and chemical resistance, GGBS contributes to enhancing the strength and durability of the concrete, especially under aggressive environmental conditions [9]. The interaction between these materials during the polymerization process results in a dense and stable matrix that enhances the longevity of the concrete, particularly in applications exposed to chemical attacks like acids and sulfates [12]. Research by [16 & 14] showed that a mix design incorporating 60% fly ash and 40% GGBS provided optimum performance in terms of both strength and resistance to environmental degradation.

The incorporation of CDW as a coarse aggregate replacement in geopolymer concrete not only contributes to sustainability but also promotes the reuse of construction waste, which is an otherwise underutilized resource. Studies by [3] have shown that the mechanical properties of concrete made with recycled CDW aggregates were comparable to those of conventional concrete. However, CDW concrete mixes need to be optimized in terms of the replacement percentage, as high amounts of CDW can weaken the bond between the aggregate and the binder.

As the construction industry continues to evolve, the adoption of eco-friendly and sustainable alternatives like geopolymer concrete is gaining momentum. This paper investigates the potential of geopolymer concrete made with GGBS and fly ash, with CDW as a partial replacement for coarse aggregates and M-sand as the fine aggregate. The study aims to assess the mechanical properties, such as compressive strength, split tensile strength, and flexural strength, along with durability aspects, including water absorption, acid resistance, and sulfate attack resistance. By exploring the performance of geopolymer concrete with these materials, this research seeks to contribute valuable insights into sustainable construction practices and help reduce the environmental footprint of the construction industry.

II. OBJECTIVES

1) To develop an eco-efficient geopolymer concrete by incorporating Ground Granulated Blast Furnace Slag (GGBS) and Fly Ash as alternative binders to conventional Portland cement.
2) To investigate the feasibility of utilizing Construction and Demolition Waste (CDW) as a partial replacement for natural coarse aggregates, thereby promoting circular economy principles in construction.
3) To assess the effectiveness of Manufactured Sand (M-sand) as a sustainable alternative to natural river sand in geopolymer concrete applications.
4) To evaluate the mechanical properties (compressive, split tensile, and flexural strength) and durability performance (resistance to water absorption, acid, and sulfate attacks) of the developed geopolymer concrete mixes.

III. MATERIALS

1) Ground Granulated Blast Furnace Slag (GGBS): GGBS is a by-product of the iron industry and is used as a binder in geopolymer concrete due to its high calcium content and pozzolanic properties.
2) Fly Ash: Class F fly ash obtained from thermal power plants from Karnataka was used, rich in silica and alumina, essential for geopolymerization.
3) Alkaline Activator Solution: The alkaline activator was prepared using sodium hydroxide (NaOH) solution of 12M concentration and sodium silicate (Na_2SiO_3) solution in a 1:2.5 ratio.

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4) Coarse Aggregates: Natural crushed stone aggregates of size 20 mm and down was used.
5) Construction and Demolition Waste (CDW): Crushed and graded concrete debris collected from demolition sites was used as a partial replacement for coarse aggregates. Construction and demolition waste (CDW) can be effectively processed in the laboratory to produce coarse aggregates for concrete applications. The process begins with the careful selection of CDW materials such as broken concrete, bricks, mortar debris, ceramic tiles, and stones, while excluding non-recyclable components like wood, plastics, and insulation. The selected waste is thoroughly washed to remove dust, soil, and other contaminants, followed by drying under sunlight or in an oven to eliminate moisture. Once cleaned and dried, the material is subjected to primary crushing using a jaw crusher, reducing it to manageable sizes. Further size reduction is achieved through secondary crushing, typically using a cone or impact crusher. The crushed material is then passed through sieves to classify the particles, with those passing a 20 mm sieve but retained on a 4.75 mm sieve designated as coarse aggregates. After sieving, the recycled aggregates undergo additional processing to remove remaining impurities through magnetic separation and manual picking. Processed aggregates are then stored properly to prevent contamination, and often pre-wetted to account for their typically higher water absorption.
6) Fine Aggregates: Manufactured sand (M-sand) was used in place of river sand to enhance sustainability and improve consistency in the concrete mix.

IV. METHODOLOGY

The methodology adopted in this study was structured systematically to ensure the accurate assessment of mechanical and durability properties of geopolymer concrete using GGBS and Fly Ash as binders, CDW as partial coarse aggregate replacement, and M-sand as fine aggregate. The entire methodology includes the following steps:

A. Mix Design

Five mixes were prepared as given in table 4.1 with varying CDW content: 0%, 10%, 20%, 30%, and 40% as partial replacement of natural coarse aggregates. The binders—Fly Ash and GGBS—were maintained at a 60:40 ratio. M-sand was used as 100% replacement for river sand across all mixes. The alkaline activator used was a combination of sodium hydroxide (NaOH) solution of 12M concentration and sodium silicate (Na_2SiO_3), in a ratio of 1:2.5. The total binder content was kept constant at 400 kg/m³ with a fixed liquid-to-binder ratio of 0.45.

Table 4.1 Mix proportions used in the study (%)

Mix ID	FLYASH	GGBS	CDW
M0	0	0	0
M1	90	10	10
M2	80	20	20
M3	70	30	30
M4	60	40	40

B. Material Preparation

All raw materials, including CDW aggregates, were pre-treated. CDW was crushed and sieved to match standard aggregate sizes. It was washed and dried to eliminate dust and old mortar content. M-sand was oven-dried and sieved to ensure uniformity. The alkali activator solution was prepared 24 hours prior to mixing to ensure adequate reactivity.

C. Mixing Procedure

Concrete was mixed in clean flat dry surface area. Dry components (aggregates and binders) were first mixed uniformly. Then, the alkaline solution was gradually added, followed by superplasticizer (0.5% of binder weight) to improve workability. The mixing process lasted about 5 minutes to ensure homogeneity.

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Figure 4.1: Dry mixing of aggregates and binders

D. Casting and Curing

Concrete was poured into standard molds (150 mm cubes, 150 mm diameter × 300 mm cylinders, 100 mm × 100 mm × 500 mm beams) and compacted using a vibrating table. After demolding (after 24 hours), specimens were cured at ambient temperature (25 ± 2°C) to simulate realistic site conditions. Tests were conducted at 7 and 28 days.

Figure 4.1: Casted moulds

E. Testing Procedures

Mechanical properties including compressive strength (IS 516), split tensile strength (IS 5816), and flexural strength (IS 516) were evaluated. Durability tests included water absorption (ASTM C642), acid resistance (5% H_2SO_4 for 28 days), and sulfate attack resistance (5% Na_2SO_4 for 28 days). Mass loss and residual strength were recorded post exposure.

V. RESULTS AND DISCUSSION

The experimental results for compressive strength, split tensile strength, flexural strength, and durability characteristics are presented below. Five different mixes were prepared with 0%, 10%, 20%, 30%, and 40% replacement of natural coarse aggregates by CDW. All mixes used M-sand as the fine aggregate.

A. Mechanical Properties (Compression, Split tensile and flexural strength tests)

Refer below table 5.1 for the compression, split tensile and flexural strength test results

Table 5.1 Compression, Split tensile and Flexural strength test results

Mix ID	Compressive Strength		Split Tensile Strength	Flexural Strength
	7-Day (MPa)	28-Day (MPa)	28-Day (MPa)	28-Day (MPa)
M0	27.0	41.2	3.2	4.2
M1	29.8	40.5	3.5	4.4
M2	30.3	43.1	3.7	4.6
M3	32.5	46.8	4.2	4.9
M4	28.8	40.0	3.8	4.3

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1) Compressive Strength

The compressive strength results show that all modified mixes performed better than the control mix at 7 days and 28 days. M3 exhibited the highest strength at both 7 days (32.5 MPa) and 28 days (46.8 MPa), indicating its effectiveness in enhancing strength over time. M2 also showed good performance, reaching 43.1 MPa at 28 days. M1 and M4 exhibited lower 28-day strengths, with M1 slightly outperforming M0. Overall, M3 proved to be the most effective mix for both early and long-term strength development.(Refer figure 5.1)

2) Split tensile strength

The 28-day split tensile strength results show that all modified mixes performed better than the control mix. The control mix (M0) achieved 3.2 MPa, while M1, M2, and M3 recorded 3.5 MPa, 3.7 MPa, and 4.2 MPa respectively. M3 exhibited the highest tensile strength, indicating a significant improvement due to the modification. M4 also showed a good performance with 3.8 MPa, slightly less than M3. Overall, the modifications enhanced the tensile strength, with M3 being the most effective.(Refer figure 5.2)

3) Flexural strength

The 28-day flexural strength results show an improvement in all modified mixes compared to the control mix. The control mix (M0) recorded 4.2 MPa, while M1, M2, and M3 achieved 4.4 MPa, 4.6 MPa, and 4.9 MPa respectively. Among all mixes, M3 showed the highest flexural strength, indicating better bending resistance. M4 reached 4.3 MPa, slightly higher than M0 but lower than other modified mixes. Overall, the modifications were effective, with M3 demonstrating the most significant enhancement.(Refer figure 5.3)

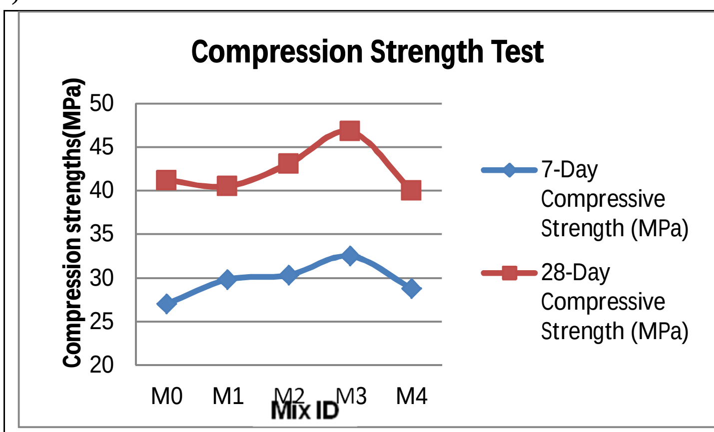

Figure 5.1 Graph indicating Compression strength test results at 7and 28 days

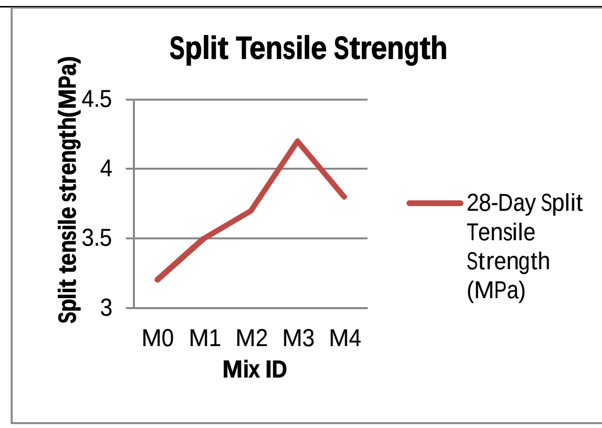

Figure 5.2 Graph indicating Split tensile strength at 28 days

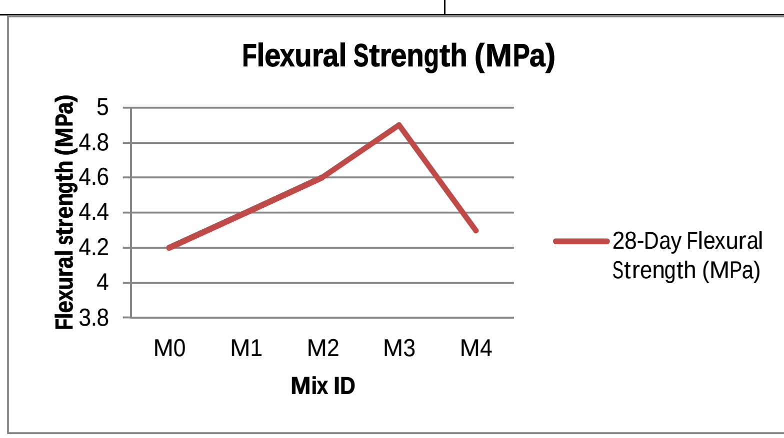

Figure 5.3 Graph indicating Flexural strength at 28 days

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B. Durability Tests

Refer below table 5.2 for the water absorption, acid resistance and sulphate attack test results

Table 5.2 Durability test results

Mix ID	Water Absorption (%)	Acid Resistance (5% H_2SO_4 for 56 Days)		Sulfate Attack (5% Na_2SO_4 for 56 Days)	
		Mass Loss (%)	Strength Loss (%)	Mass Loss (%)	Strength Loss (%)
M0	4.2	6.2	5.5	4.8	4.2
M1	4.0	5.8	5.1	4.5	4.0
M2	3.8	5.2	4.8	4.0	3.6
M3	3.5	4.9	4.5	3.7	3.2
M4	3.9	5.4	5.0	4.2	3.9

1) Water Absorption

The water absorption results shown in table 5.2, a decreasing trend in all modified mixes compared to the control mix. The control mix (M0) had the highest absorption at 4.2%, while M1, M2, and M3 showed reduced values of 4.0%, 3.8%, and 3.5% respectively. M3 exhibited the lowest water absorption, indicating better density and lower porosity. M4 recorded 3.9%, which is an improvement over M0 but slightly higher than M1 and M2. Overall, the modifications effectively reduced water absorption, with M3 performing the best.(Refer figure 5.4)

2) Acid Resistance (5% H_2SO_4 for 56 Days)

The durability test results shown in table 5.2 that all modified mixes had lower mass loss and strength loss compared to the control mix. M3 exhibited the least mass loss (4.9%) and strength loss (4.5%), highlighting its superior resistance to deterioration. M2 also showed good performance with lower losses than M0. Overall, the modifications enhanced durability, with M3 performing the best among all mixes. (Refer figure 5.5)

3) Sulfate Attack (5% Na_2SO_4 for 56 Days)

The results for mass loss and strength loss indicated in table 5.2, that all modified mixes showed better durability than the control mix. M3 demonstrated the lowest mass loss (3.7%) and strength loss (3.2%), suggesting superior resistance to degradation. M2 also performed well, with lower losses compared to M0. Overall, the modifications improved both mass retention and strength, with M3 being the most durable mix. (Refer figure 5.6)

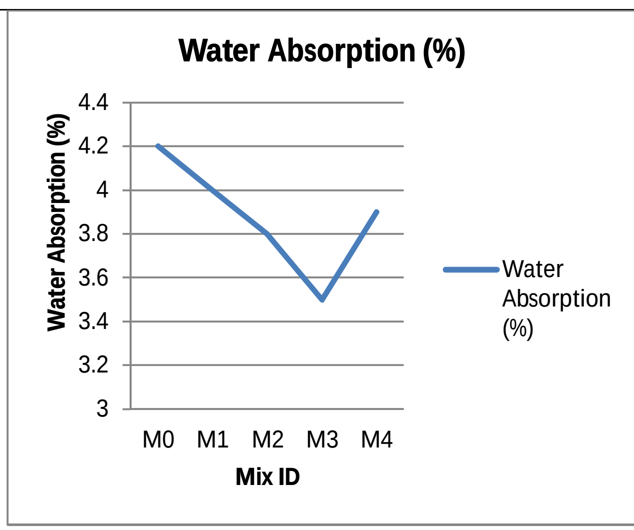

Figure 5.4 Graph indicating water absorption test results

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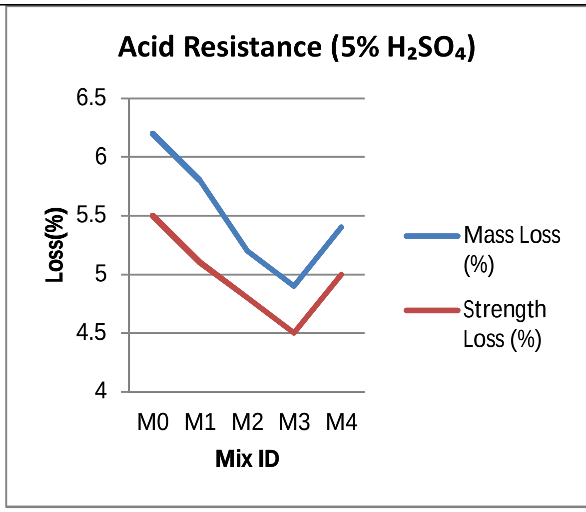

Figure 5.5 Graph indicating Acid Resistance (5% H_2SO_4) at 56 days)

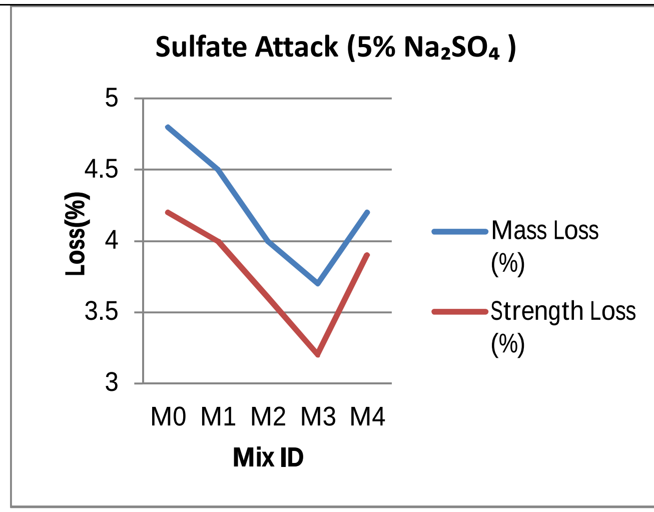

Figure 5.6 Graph indicating Sulfate Attack (5% Na_2SO_4) at 56 days

VI. CONCLUSIONS

The study on the development of eco-friendly geopolymer concrete with GGBS, Fly Ash as binders, and CDW as a partial replacement for coarse aggregates has yielded the following conclusions:

1) The geopolymer concrete mix with 30% replacement of CDW (Mix M3) exhibited the highest compressive strength of 44.0 MPa at 28 days, demonstrating that up to 30% CDW can be effectively utilized without compromising the structural strength of the concrete.
2) Similarly, the split tensile strength showed a consistent increase, reaching its peak at 30% CDW replacement (3.9 MPa), highlighting the improved bonding and cohesion between the geopolymer matrix and aggregates.
3) The flexural strength also exhibited an upward trend, with Mix M3 achieving a value of 4.8 MPa, which is indicative of the enhanced ductility and toughness of the concrete at this level of CDW incorporation.
4) Durability tests showed that the geopolymer concrete with up to 30% CDW replacement demonstrated superior resistance to water absorption, acid, and sulfate an attack, which suggests improved chemical stability and durability due to the alkali-activated binders (GGBS and Fly Ash). The mix also showed the lowest mass and strength losses in acid and sulfate resistance tests at 30% CDW.
5) Beyond 30% CDW replacement (i.e., Mix M4 with 40% CDW), a slight decline in all mechanical and durability parameters was observed. This suggests that higher CDW content adversely affects the interfacial bond and matrix cohesion, leading to a decrease in performance.
6) The use of Manufactured Sand (M-sand) in place of river sand did not negatively impact the performance of the geopolymer concrete and further enhanced its sustainability without compromising the mechanical or durability characteristics.
7) The use of industrial by-products (GGBS and Fly Ash) and construction waste (CDW) as a partial replacement for conventional materials demonstrates the potential for reducing the environmental footprint of concrete production and promoting sustainable construction practices.
8) Based on the results, geopolymer concrete with up to 30% CDW replacement is a promising alternative to conventional concrete for construction applications, offering both technical and environmental benefits.

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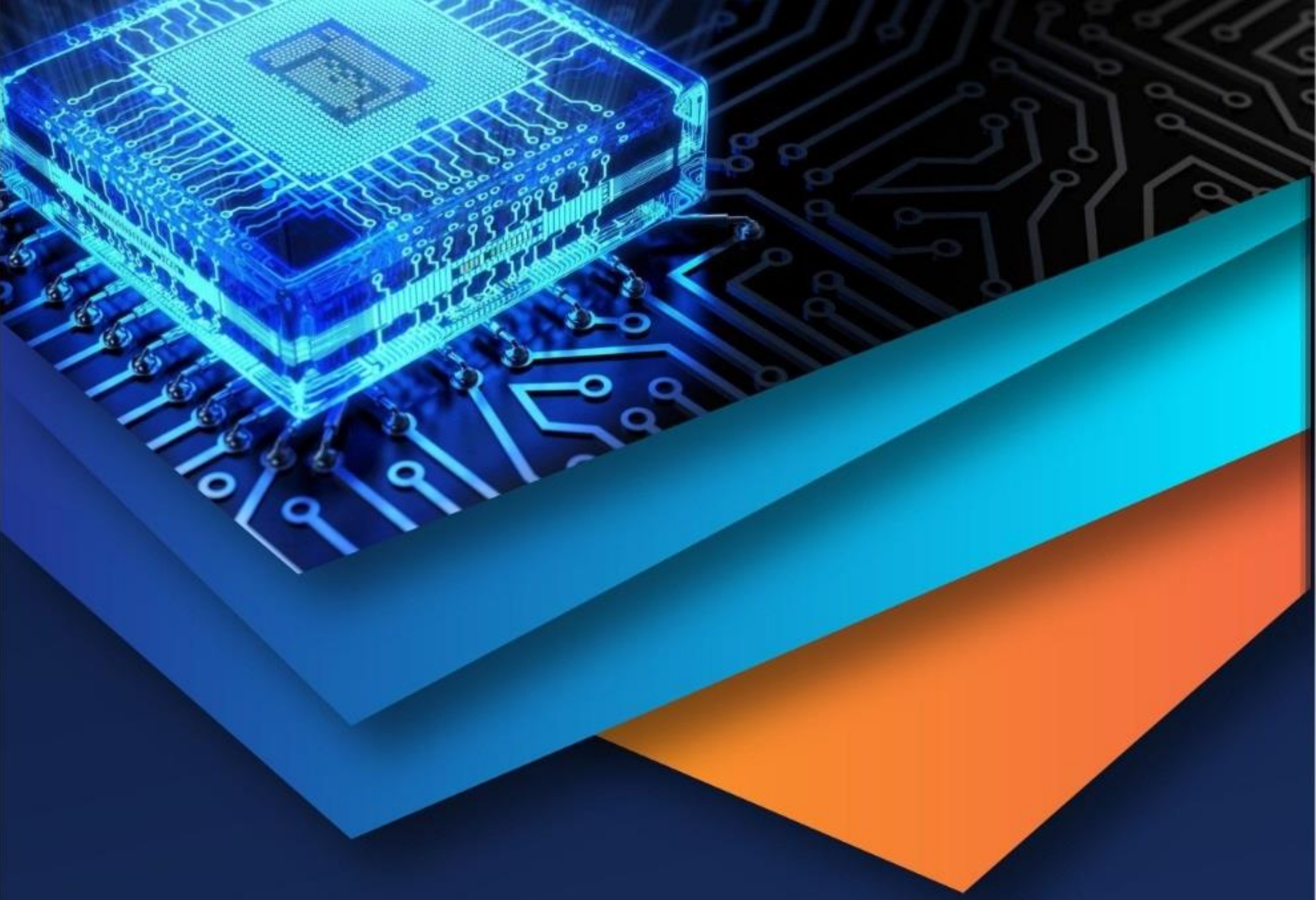

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