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Sustainable Cement Alternatives: A Comprehensive Review of Sugarcane Bagasse Ash and Waste Glass Powder Utilization

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Abstract: The rapid expansion of the construction industry has led to a significant rise in cement consumption, contributing to increased carbon dioxide emissions and the depletion of natural resources. In response, there is growing interest in sustainable alternatives, particularly the use of industrial and agricultural waste as supplementary cementitious materials (SCMs). This review paper examines the potential of Sugarcane Bagasse Ash (SCBA), a by-product of the sugar industry, and Waste Glass Powder (WGP), derived from discarded glass, as partial replacements for cement in concrete. Owing to their pozzolanic characteristics, both SCBA and WGP can enhance the mechanical strength and durability of concrete while simultaneously reducing its environmental footprint. The paper provides a comprehensive analysis of the physical, chemical, and mineralogical properties of these materials, their influence on the fresh and hardened properties of concrete, and the optimal replacement levels reported in existing literature.

Additionally, it explores the environmental advantages, cost-effectiveness, and practical challenages related to their large-scale adoption. The review concludes that incorporating SCBA and WGP in concrete not only supports sustainable construction but also facilitates effective waste management.

Keywords: Sugar Cane Bagasse Ash (SCBA), Waste Glass Powder (WGP), Sustainable Concrete, Cement Replacement, Eco-friendly Construction.

I. INTRODUCTION

The construction industry is one of the largest contributors to global carbon dioxide emissions, with ordinary Portland cement (OPC) production accounting for approximately 7–8% of total anthropogenic CO_2 emissions [20], [22]. In response to increasing environmental concerns and the urgent need for sustainable development, researchers have been actively exploring alternative cementitious materials that can partially or wholly replace OPC without compromising the performance of concrete. Among the various industrial by-products and agricultural wastes investigated, sugarcane bagasse ash (SCBA) and waste glass powder (WGP) have gained significant attention due to their pozzolanic potential and widespread availability [5], [7], [9].

.Sugarcane bagasse ash is an agro-industrial by-product generated from the controlled combustion of bagasse, the fibrous residue left after extracting juice from sugarcane. SCBA is rich in amorphous silica, which imparts pozzolanic activity, making it a promising supplementary cementitious material (SCM). Similarly, waste glass powder, obtained from finely ground post-consumer or industrial glass waste, also contains high silica content and exhibits pozzolanic behavior when properly processed. Utilizing these materials not only helps in reducing landfill burdens but also minimizes the carbon footprint of concrete production.

Over the past decade, numerous experimental studies have been conducted to evaluate the mechanical, durability, and microstructural properties of concrete incorporating SCBA and WGP. These investigations have reported varying degrees of success depending on parameters such as replacement level, particle fineness, curing conditions, and chemical composition. This review paper aims to consolidate and critically analyze existing literature on the experimental utilization of SCBA and WGP as sustainable cement replacement materials in concrete.

By highlighting key findings, comparative performance metrics, and existing research gaps, the paper provides a comprehensive overview of their potential role in advancing green concrete technology.

II. ENVIRONMENTAL AND SUSTAINABILITY BENEFITS OF USING SUGAR CANE BAGASSE ASH (SCBA) AND WASTE GLASS POWDER (WGP)

The construction industry is a major contributor to environmental degradation due to its high consumption of raw materials and energy, as well as the emission of greenhouse gases, especially from cement production. The integration of Sugar Cane Bagasse Ash (SCBA) and Waste Glass Powder (WGP) as supplementary cementitious materials offers several environmental and sustainability benefits, which are essential in promoting greener construction practices.

1) Reduction in CO_2 Emissions: Ordinary Portland Cement (OPC) production involves the calcination of limestone and the use of fossil fuels, both of which release significant amounts of CO_2. By partially replacing OPC with SCBA and WGP, the total clinker content in concrete is reduced, leading directly to a decrease in CO_2 emissions. Studies have shown that each ton of OPC substituted by pozzolanic waste can save up to 0.8 to 0.9 tons of CO_2 emissions [3] [20].
2) Waste Management and Resource Conservation: Sugar industries produce millions of tons of bagasse ash annually, much of which is disposed of in landfills or open spaces, causing environmental pollution. Similarly, waste glass is often dumped in landfills, where it is non-biodegradable and remains intact for centuries. Utilizing these materials in concrete helps divert them from the waste stream, reducing landfill load and promoting circular economy principles. [3], [20], [22].
3) Conservation of Natural Resources: The production of OPC consumes vast quantities of limestone, clay, and other natural minerals. By using SCBA and WGP, there is less dependence on virgin raw materials. Additionally, incorporating recycled materials helps preserve non-renewable resources for future generations [18], [23]
4) Energy Efficiency: Manufacturing cement is highly energy-intensive. SCBA and WGP are by-products or waste materials that do not require extensive processing for use in cementitious applications. Grinding them to a fine powder is relatively low in energy demand compared to clinker production, thereby improving the overall energy efficiency of concrete manufacturing.
5) Improvement in Durability and Lifespan of Structures: Concrete with SCBA and WGP has shown enhanced resistance to chemical attacks (e.g., sulfate and chloride), reduced permeability, and improved long-term strength [9] [23] [30]. These durability improvements can extend the lifespan of concrete structures, reducing the need for repairs and reconstruction, which in turn minimizes the environmental burden over the lifecycle of a building or infrastructure project.
6) Economic Benefits and Local Material Use: SCBA and WGP are often locally available, especially in agricultural and urban regions, respectively. Their utilization reduces transportation costs associated with importing cement and also creates opportunities for local industries in waste processing and green construction material development.

III. PROPERTIES OF SCBA AND GLASS POWDER:

A. Sugarcane Bagasse Ash (SCBA)

Sugarcane bagasse ash is a byproduct of sugar factory found after burning sugarcane bagasse which itself is found after the extraction of all economical sugar from sugarcane. In India, approximately about 2.5 Million tons of sugarcane bagasse ash produced every year. The sugarcane bagasse ash is a voluminous material and is an environmental waste sugarcane bagasse ash is non-biodegradable waste. The disposal of this material is already causing environmental problems around the sugar factories. On the other hand, the boost in the construction activities in the country created shortage in most of concrete making materials especially cement, resulting in an increasing in price

1) Chemical Properties of Bagasse Ash:

a. Silica Content: Bagasse ash contains a significant amount of silica (SiO_2), which is a key component in cementitious reactions. The high silica content of bagasse ash makes it a potential partial replacement for cement, as silica reacts with calcium hydroxide in the presence of water to form calcium silicate hydrate (C-S-H), which contributes to the strength and durability of concrete.

b. Alumina and Iron Oxide: In addition to silica, bagasse ash contains smaller amounts of alumina (Al_2O_3) and iron oxide (Fe_2O_3), which can also contribute to the pozzolanic reaction, improving the overall performance of the concrete.

2) Mechanical Properties of Bagasse Ash:

a. Improved Compressive Strength: Bagasse ash has been shown to enhance the compressive strength of concrete when used as a partial replacement for cement. The pozzolanic reaction between bagasse ash and the calcium hydroxide released during the hydration of cement forms additional binder compounds (C-S-H gel), which improve the concrete's mechanical properties.

b. Reduced Porosity: The fine particles of bagasse ash fill the voids in the concrete matrix, reducing porosity and improving the density of the material. This leads to stronger and more durable concrete.

c. Better Workability: Bagasse ash can also improve the workability of the concrete mix, making it easier to mix, place, and finish, while reducing the risk of segregation and bleeding.

B. Waste Glass Powder (GP)

Glass is extensively used in beverage, food packing, appliances, industry, automotive, medical and chemical industry. The amount of glass in the world was estimated at 130 million tons in 2018, its residues were about 79%, this highlight the need for management of waste glass. Generally, waste glass contains SiO2, Na2O, CaO, Al2O3 and others compounds whereby waste glass can be as pozzolanic material.

1) Chemical Properties of Glass Powder

a. High Silica Content: Similar to bagasse ash, glass powder has a high silica (SiO_2) content, which is a primary contributor to its pozzolanic activity. The chemical composition of glass powder is similar to that of sand, making it an effective substitute for fine aggregates in concrete.

b. Alkaline Nature: Waste glass powder is alkaline in nature, and when mixed with cement, it reacts with calcium hydroxide (CH_3OH) to form additional calcium silicate hydrate (C-S-H), improving the strength and durability of concrete.

2) Mechanical Properties of Glass Powder

a. Improved Compressive and Flexural Strength: Glass powder as a partial replacement for sand has been shown to increase the compressive strength of concrete. This is due to its fine particle size, which fills the pores in the concrete matrix, enhancing its strength and making it more durable.

b. Increased Durability: Glass powder can help improve the durability of concrete by reducing the permeability of the material. This results in better resistance to water ingress, chemical attack, and freeze-thaw cycles.

c. Higher Strength at Early Stages: Glass powder has been found to accelerate the early hydration of cement, which can lead to an increase in early-age strength development, an important factor for construction schedules.

IV. CONTRIBUTION TO CIRCULAR ECONOMY AND GREEN BUILDING PRACTICES

The integration of sugarcane bagasse ash (SCBA) and waste glass powder (WGP) into concrete production aligns strongly with the principles of the circular economy and promotes environmentally responsible practices in the construction sector. The circular economy model emphasizes the reutilization of waste materials, minimizing resource extraction, and extending the lifecycle of materials—objectives that are increasingly critical in modern sustainable development frameworks.

By valorizing SCBA and WGP—both of which are abundant yet underutilized waste products—concrete production can transition from a linear "take-make-dispose" model to a more circular, resource-efficient process. SCBA, a by-product of the sugar industry, is often landfilled or incinerated, leading to potential environmental hazards.

When used in concrete, it not only reduces waste disposal problems but also enhances the performance of concrete through its pozzolanic activity. WGP, derived from non-biodegradable post-consumer or industrial glass waste, poses long-term environmental risks due to its persistence in landfills. Its incorporation into concrete provides a viable recycling route and reduces demand for virgin raw materials like silica.

In the context of green building practices, replacing cement with SCBA and WGP contributes significantly to lowering the embodied carbon of concrete—a key metric in sustainable construction. This substitution helps in achieving certification targets in green building rating systems such as LEED (Leadership in Energy and Environmental Design), BREEAM (Building Research Establishment Environmental Assessment Method), and IGBC (Indian Green Building Council), which reward the use of recycled content and low-impact materials.

Moreover, utilizing these materials supports local resource utilization, reduces the energy intensity of cement production, and promotes regional sustainability by encouraging industries to source SCMs from nearby agricultural and municipal waste streams. This localized circularity enhances supply chain resilience while reducing transportation-related emissions.

V. LITERATURE REVIEW

The literature review for the study of use of sugarcane bagasse ash (SCBA) and waste glass powder (WGP) in the cementious material is given in the below figure.1

A. Comprehensive Structured Approach for Literature Analysis

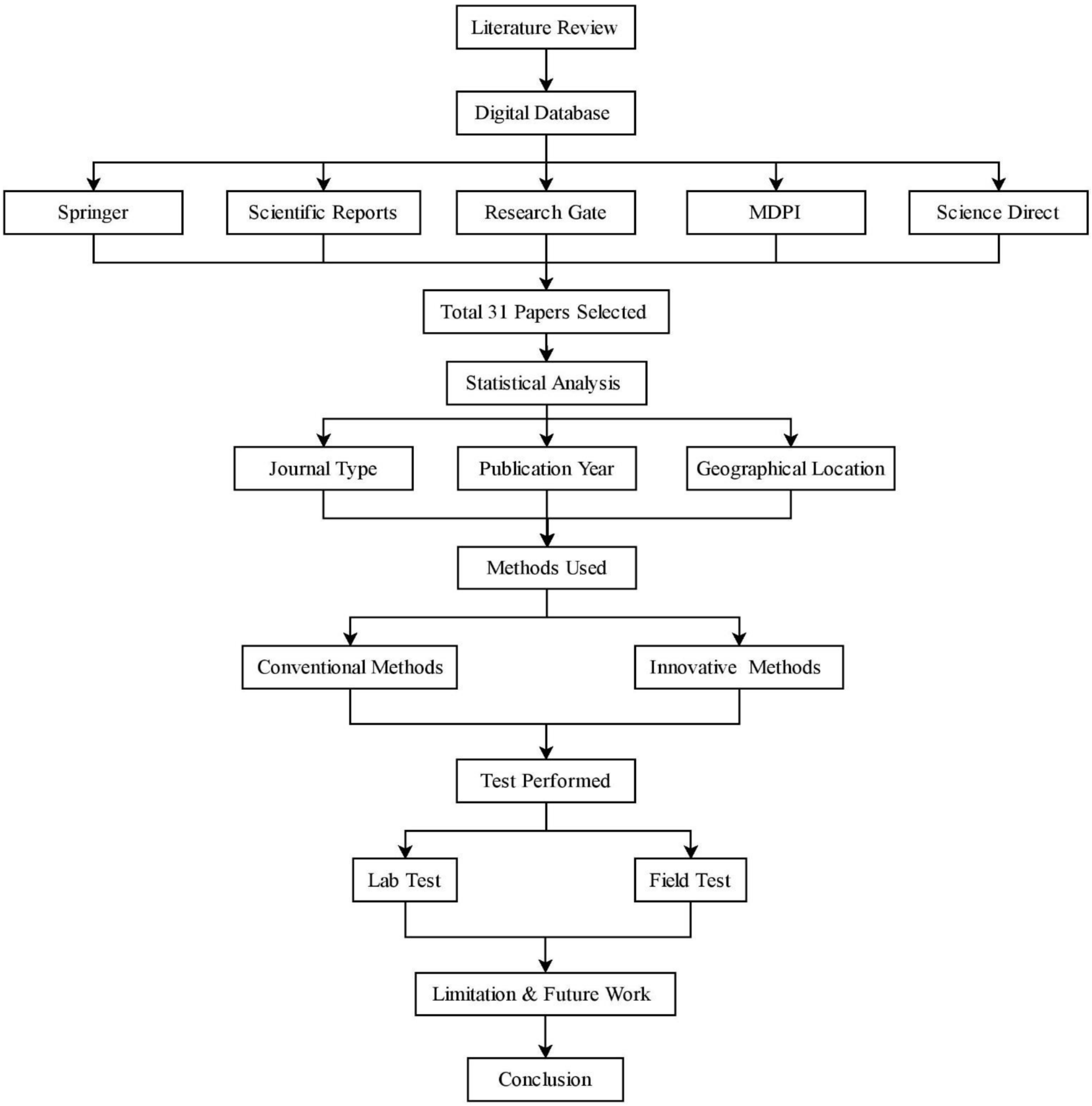

Figure 1. Flow chart summarizing the literature review approach.

VI. COMBINED EFFECT OF SCBA AND WGP IN CONCRETE

A. Fresh Concrete Properties

a) Workability:

- Incorporating SCBA and WGP can affect the workability of concrete. SCBA's porous nature may increase water demand, potentially reducing workability. Conversely, finely ground WGP can improve particle packing, enhancing followability [5][7] [22].
- Studies indicate that up to 10% replacement of cement with SCBA and WGP maintains acceptable workability levels without the need for additional water or superplasticizers. [5], [9], [21].

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b) Setting Time:
- The presence of SCBA and WGP can influence the setting time of concrete. SCBA may accelerate setting due to its pozzolanic activity, while WGP's effect varies based on its fineness and chemical composition.
- Optimal replacement levels (around 10–15%) have been observed to have minimal adverse effects on setting times. [6], [7], [12]

B. Hardened Concrete Properties
a) Compressive Strength:
- Partial replacement of cement with SCBA and WGP has shown improvements in compressive strength up to certain levels.
- An experimental study revealed that a combination of 10% SCBA and 10% WGP replacement resulted in higher compressive strength compared to conventional concrete at 7, 14, and 28 days of curing.
- However, increasing the replacement percentage beyond 15% may lead to a reduction in strength due to dilution of the cementitious matrix. [6], [18], [29]

b) Split Tensile and Flexural Strength:
- The inclusion of SCBA and WGP can enhance the tensile and flexural strength of concrete.
- A study reported that concrete with 10% SCBA and 10% WGP exhibited higher split tensile strength than conventional concrete.
- Flexural strength improvements have also been noted, attributed to the refined microstructure and improved interfacial bonding. [7], [12], [30]

c) Durability:
- The pozzolanic reaction of SCBA and the filler effect of WGP contribute to a denser concrete matrix, enhancing durability.
- Studies have shown that concrete with 10% SCBA and 10% WGP replacement exhibits reduced water absorption and improved resistance to chloride penetration.
- However, higher replacement levels may increase porosity, potentially compromising durability. [9], [19], [23]

VII. CHALLENGES AND LIMITATIONS

A. Variability in Material Properties
SCBA:
- The properties of SCBA can vary significantly depending on factors such as the combustion process, temperature, and the type of sugarcane used.
- High carbon content and unburnt particles in SCBA can adversely affect the strength and durability of concrete. [8], [14], [16], [17]

WGP:
- The chemical composition and particle size of WGP can differ based on the source of the glass, affecting its pozzolanic activity and reactivity.
- Contaminants in waste glass can introduce alkalis, leading to potential durability issues in concrete. [8], [14], [16], [17]

B. Need for Proper Processing and Quality Control
Both SCBA and WGP need to be properly processed—mainly ground to a fine size—to behave effectively as pozzolanic materials. Poor grinding or sieving can lead to particles that are too coarse to react adequately with calcium hydroxide during hydration. Inconsistent fineness affects the workability, strength, and durability of the final concrete. Therefore, consistent quality control and standardized processing techniques are essential before these materials can be used on a large scale.

C. Risk of Alkali-Silica Reaction (ASR)
Waste glass powder, especially when used in higher amounts, poses a risk of alkali-silica reaction (ASR). This reaction occurs when reactive silica in the glass reacts with alkalis from the cement in the presence of moisture, leading to the formation of an expansive gel. This gel can cause internal stresses, resulting in cracking and deterioration of the concrete over time. This risk limits the amount of WGP that can be safely used unless mitigation techniques (such as using SCMs like fly ash or slag) are adopted. [19], [21], [30]

D. Issues with Workability and Water Demand

SCBA typically has a high surface area and porous structure, which can increase the water demand of the concrete mix. This means that more water or chemical admixtures (like superplasticizers) might be needed to achieve the desired workability. If not properly adjusted, this can compromise the strength and durability of the concrete. WGP, on the other hand, may affect the rheology of the mix depending on its fineness and particle shape.

E. Potential Durability Concerns

Although both SCBA and WGP have been shown to improve certain durability characteristics under controlled conditions, their long-term effects in different environmental exposures are still not fully understood. For instance, poor-quality SCBA with high carbon or impurity content may increase the porosity of concrete, leading to issues like carbonation or chloride ingress. Similarly, the long-term durability of WGP-containing concrete in marine or freeze-thaw environments needs more research. [6], [24], [25]

F. Lack of Standard Codes and Guidelines

Despite growing interest in sustainable materials, there is currently a lack of widely accepted standards or guidelines for incorporating SCBA and WGP into structural concrete. This makes it difficult for engineers and construction professionals to specify these materials in conventional projects. Standardization is crucial to ensure uniformity in performance and safety. [11], [16], [17], [24]

VIII. RECOMMENDATIONS FOR PRACTICAL APPLICATION

To ensure the successful and sustainable use of SCBA and WGP in concrete, a number of practical recommendations should be followed. These recommendations are based on findings from various experimental studies and practical insights from the field:

A. Optimal Replacement Levels

Research suggests that SCBA and WGP can effectively replace 10% to 30% of cement by weight, depending on the specific properties of the materials and the concrete application. For structural concrete, a total replacement of up to 20% (e.g., 10% SCBA and 10% WGP) is often recommended to balance strength, workability, and durability. Exceeding these limits may require additional adjustments in the mix design. [6], [12], [28]

B. Material Pre-treatment and Processing

Both materials require proper pre-treatment:

- SCBA should be collected from controlled combustion processes and ground to a fine powder (preferably with a particle size less than 45 microns).
- WGP should be cleaned to remove contaminants, sorted by color (if necessary), and ground to achieve high fineness for better pozzolanic activity.

Proper sieving and grinding not only enhance reactivity but also improve uniformity in the final mix. [13], [18], [26]

C. Mix Design Adjustments

Concrete mixes incorporating SCBA and WGP often need modifications to water content and admixtures:

- SCBA increases water demand due to its porous structure, so the use of water-reducing agents or superplasticizers is recommended.
- WGP may also alter workability, especially if it's very fine or angular. It's important to conduct trial mixes to determine the optimal combination of ingredients that satisfies both performance and workability requirements.

D. Use in Non-Structural and Low-Risk Applications

Before wide-scale structural use, it's advisable to begin by applying SCBA and WGP concrete in non-structural elements like:

- Paving blocks
- Sidewalks
- Driveways
- Non-load bearing walls

These applications provide opportunities to test performance under real-world conditions without posing structural risks.

E. Long-Term Durability Testing

Concrete made with SCBA and WGP should undergo durability testing over time. This includes:

- Resistance to sulfate and chloride attack
- Shrinkage and cracking behavior
- Freeze-thaw resistance (if used in cold climates) Understanding long-term performance is crucial for using these materials in critical infrastructure. [9], [23], [30]

F. Quality Control and Standardization

Establishing quality control protocols is essential. Each batch of SCBA and WGP should be tested for:

- Chemical composition
- Fineness
- Loss on ignition (especially for SCBA) As more research is conducted, there's also a strong need for developing local or national guidelines that can help engineers use these materials with confidence. [8], [17], [24]

G. Collaboration with Industry and Government

The practical use of these materials can be promoted through partnerships between:

- Concrete manufacturers
- Sugar and glass industries
- Research institutions
- Government agencies

Government incentives, awareness programs, and pilot projects can encourage adoption, while industries can benefit from lower disposal costs and sustainability credentials.

H. Promote Education and Training

Finally, promoting awareness and training programs for engineers, contractors, and students is important. Many professionals are unfamiliar with how to handle or design mixes using SCBA and WGP. Seminars, workshops, and inclusion in academic curricula can bridge this gap and increase usage in the construction industry. [2], [16]

IX. CONCLUSION

The growing demand for sustainable and eco-friendly construction materials has driven extensive research into alternative binders that can partially or fully replace conventional Portland cement. Among the various industrial and agricultural by-products, Sugarcane Bagasse Ash (SCBA) and Waste Glass Powder (WGP) have emerged as promising supplementary cementitious materials due to their high silica content and pozzolanic reactivity.

This review highlights that both SCBA and WGP, when properly processed and used within optimal replacement levels, can significantly enhance the mechanical and durability properties of concrete. SCBA contributes to improved strength development and pore refinement due to its pozzolanic action, while WGP improves the microstructure of concrete through filler effects and chemical reactivity. Together, their combination has shown potential to create blended cement systems that are not only cost-effective but also environmentally beneficial by reducing CO_2 emissions associated with cement production.

However, the practical application of these materials is not without challenges. Variability in raw material quality, concerns related to alkali-silica reaction (especially with WGP), and the absence of standardized guidelines limit their widespread acceptance in mainstream construction. Additionally, more long-term studies and field-scale implementations are needed to understand the performance of SCBA and WGP concrete in real-world conditions.

To bridge these gaps, future research must focus on establishing consistent quality control measures, developing standards and mix design procedures, and expanding the scope of application to include high-performance and specialty concretes. Governmental support, industry collaboration, and academic engagement are crucial to promoting the use of these sustainable materials in the construction sector.

In conclusion, the utilization of SCBA and WGP in concrete offers a viable pathway toward greener construction practices. With the right advancements in research, processing, and policy support, these waste materials have the potential to play a significant role in building a more sustainable future for the concrete industry. [3], [6], [12], [18], [22], [26], [27], [30]

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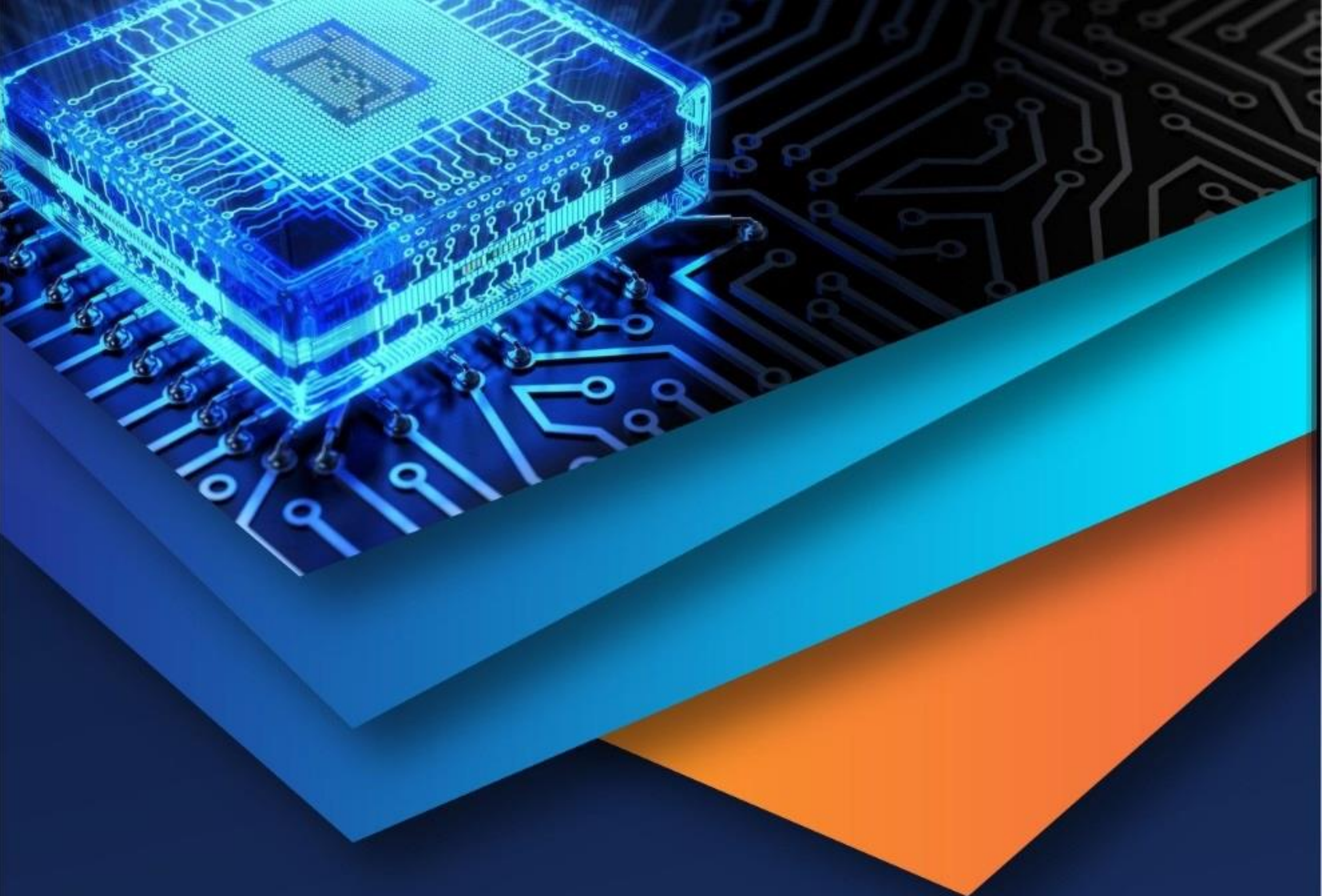

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