iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 Issue: IV Month of publication: April 2026

DOI: https://doi.org/10.22214/ijraset.2026.79418

Geopolymer-Based Artificial Aggregates for Sustainable Pavement Construction: A Comprehensive Review

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Abstract: The rapid expansion of the construction industry has significantly intensified the demand for natural aggregates, leading to unsustainable quarrying practices and severe environmental degradation, including biodiversity loss, water contamination, and adverse human health impacts. Simultaneously, the accumulation of industrial by-products such as fly ash presents a critical waste management challenge. In this context, geopolymer technology has emerged as a promising sustainable alternative, enabling the conversion of aluminosilicate-rich wastes into value-added construction materials. This study synthesizes existing research on manufacturing techniques and their influence on physical properties and engineering performance. Key process parameters such as production technique, alkaline activator composition, liquid-to-solid ratio, curing conditions are studied in relation to mechanical strength, water absorption, and durability characteristics. This review identifies critical research gaps such as high water absorption, limited precursor diversification and challenges in process scalability, ultimately providing a strategic roadmap for advancing sustainable construction materials in modern infrastructure development
Keywords: Geopolymer, Pavement, Artificial Aggregates, Alkali- Activated, Fly ash

I. INTRODUCTION

The construction industry around the world is facing an important issue of increasing natural resource demand, particularly crushed stone aggregates which are used majorly in concrete and bituminous mixes. This is due to factors like urbanization, industrialization and increase in transportation projects, which have significantly accelerated the rate of natural aggregates usage. Consequently, this has resulted in an unsustainably high rate of quarrying in many places around the world to satisfy construction industry demands. This includes instances where river beds, coastal regions, and mountainous regions have been extensively mined to satisfy construction industry demands.

Land changes resulting from quarrying operations have resulted in land degradation and loss of productivity. For the Jodhpur region, it has been observed that around 71.36 hectares of agricultural land have been destroyed in the region since 2007, of which 24.3% of the land has been converted into active quarry pits, and the remaining land has been degraded into barren land and transportation corridors (Singhal et al.). Similar observations have been recorded in the Dwarka River Basin region, where it has been observed that large areas of land have been converted into stony land surfaces from deciduous forests and scrub lands between 1990 and 2016 (Pal & Mandal, 2017). This phenomenon is consistent with the changes observed in mining regions, where land changes have resulted in the loss of natural vegetation and the development of degraded land surfaces (Ali & Sharma, 2024; Xiang et al., 2025).

Studies have established that the presence of dust particles on the surface of plant leaves leads to a decrease in the concentration of chlorophyll A and chlorophyll B. This affects photosynthesis and plant vitality. Similar results have been obtained in mining areas, suggesting the role of airborne particles in disrupting plant physiology and contributing to the decline in biodiversity (Samaei et al., 2024, Hassan & Ashade, 2025).

Quarrying activites leads to decrease in hydraulic which radius reflects decreased flow efficiency, while an increase in Total Dissolved Solids (TDS) and an increase in alkalinity which reflects high degree of deterioration in water quality (Vandana et al., 2020). Groundwater resources and geomorphological stability are also significantly affected. Deep quarrying activities, which often extend to depths of 30-40 meters, interfere with groundwater levels in neighboring areas (Pal & Mandal, 2019).

Human health consequences represent one of the most important aspects of environmental degradation in quarrying activities. Long exposure to stone dust has been associated with a high prevalence of respiratory disorders, ranging from silicosis, asthma, chronic bronchitis, and tuberculosis among workers and residents around quarrying sites (Singhal et al.; Manzoor et al., 2020).

Noise pollution, resulting from blasting and crushing activities, often exceeding 90 dB, has been associated with hearing loss and psychological disorders, especially in areas such as the Chottanagpur Plateau, which experience high levels of mining activities (Pal & Mandal, 2019).

At the same time, management of industrial waste products, especially fly ash generated by thermal power plants utilizing coal as a fuel, also poses a considerable environmental problem. Every year, millions of tons of fly ash are produced worldwide, a substantial portion of which is either unused or disposed of in landfills or ash ponds. Improper management of industrial waste products may lead to soil pollution, groundwater contamination, and airborne particulate matter hazards, thus posing environmental and health risks.

Fly ash poses serious environmental and health hazards if not managed and disposed of in the right manner. The small size of the particles, between 1 and 100 µm, and their low density make them highly susceptible to wind dispersal, thereby causing air pollution and respiratory problems like asthma, bronchitis, silicosis, and lung cancer (Nomani et al., 2024). Occupational exposure to fly ash has also been studied, and it has been observed that the concentration of particulate matter in thermal power plant environments exceeds the permissible limits, thereby increasing health hazards among the population. Furthermore, the large-scale disposal of fly ash in ash ponds, covering around 65,000 acres in India, also leads to leaching of toxic substances into the soil and groundwater system (Naskar et al., 2024).

This leads to the pollution of drinking water, soil, and the food chain in the ecosystem, posing serious health and environmental hazards. Moreover, improper disposal of fly ash also affects the structure of the soil and the growth of plants, thereby affecting agricultural production in the region (Nomani et al., 2024).

These two problems of scarcity of aggregate materials and waste products generated by industries highlight the need for innovative sustainable materials to solve both problems simultaneously. With the ever-increasing environmental problems related to the over-extraction of natural aggregates and the accumulation of industrial wastes, the innovative technology of geopolymer has been widely recognized as a sustainable and eco-efficient alternative, offering the potential to utilize industrial by-products such as fly ash and slag while significantly reducing carbon emissions, conserving natural resources. A geopolymer is as an inorganic aluminosilicate material that is produced by the alkaline activation of silica and alumina-rich sources such as fly ash, ground granulated blast furnace slag (GGBS), and metakaolin.

The process of geopolymerization is a series of chemical reactions that include dissolution, polycondensation, and hardening, resulting in the development of a dense polymeric structure. This unique structure is responsible for the superior mechanical properties and sustainability of the final product.

The most prominent and innovative achievement in the field of geopolymers is the creation of artificial aggregates, which provide a sustainable source of natural aggregates that are usually obtained from the quarrying process. Artificial aggregates are playing a vital role in the effective and efficient use of industrial wastes, thereby contributing to the reduction of wastes.

In response to the developments and challenges outlined above, this review article seeks to provide a comprehensive and systematic review of evolution of the geopolymer artificial aggregates and highlight the main gaps in the research in order to provide a clear roadmap of the future developments in this field. The main aim of this review is to promote the development of sustainable and reliable materials with high-performance characteristics to meet the demands of modern infrastructure development in a sustainable and environmentally friendly manner.

II. MANUFACTURING OF GEOPOLYMER BASED ARTIFICIAL AGGREGATES

The production of artificial aggregates by utilizing industrial precursors such as fly ash, ground granulated blast furnace slag, and metakaolin is one of the key aspects of sustainable construction materials, addressing waste management and natural aggregates depletion. Following are the various techniques used for production of geopolymer based artificial aggregates.

A. Pelletization

Pelletization is a sophisticated thermo-mechanical process that transforms fine-grained industrial by-products into spherical granules through the synergistic interaction of capillary forces and mechanical agitation.

As a tumble-growth agglomeration technique, the process is primarily driven by the surface tension of liquid binders and the kinetic energy supplied by the granulating equipment. According to Bekkeri et al., (2023), the synthesis of these pellets occurs in three sequential phases:

1) Nucleation: The introduction of a liquid binder (water or alkaline solution) creates liquid bridges between fine particles, forming initial lump.

2) Transition: These nuclei collide and unite, driven by centrifugal forces within the granulator.
3) Ball Development: Fine particles are continuously layered onto the surface of the growing nuclei, increasing both diameter and structural density.

While the traditional disc or pan pelletizer remains the industry standard due to its operational simplicity, recent literature identifies specialized variations designed to optimize the process. Disc/Pan Pelletization utilizes a tilted rotating disc where gravity and centrifugal forces works together to segregate particles by size. This allows larger, completed pellets to spill over the rim while retaining smaller nuclei for further growth.

Ibrahim et al. (2022) successfully utilized this method to produce cement-based aggregates with diameters ranging from 6 mm to 12 mm. Conversely, Dynamic Counter-Rotating Granulation, introduced by Stempkowska & Gawenda (2024), employs a high-intensity method where the drum and internal mixer rotate in opposite directions. This counter-movement creates high-intensity turbulence, achieving rapid homogenization and higher particle density within a significantly reduced timeframe, which is typically 60 to 180 seconds.

The efficiency of this process is governed by several critical engineering variables. Disc Angle and Speed are paramount; most studies suggest an inclination between 35° and 55° and a rotational speed of 40 to 60 rpm to maintain the necessary cascading motion (Hao et al., 2022).

Furthermore, the Liquid-to-Solid (L/S) Ratio must be precisely calibrated, as insufficient liquid prevents nucleation, while excess moisture leads to slurry formation. If the rotation speed is too high, material clings to the disc wall; if too low, it simply slides along the bottom. The "snowballing" effect created by optimal rotation results in a layered density gradient, contributing to a "core-shell" structure during hardening (Nor et al., 2016).

B. Sintering

Sintering is distinguished in the literature by its ability to produce aggregates with superior mechanical strength and significantly lower water absorption compared to cold-bonded alternatives (Nor et al., 2016).

While energy-intensive, sintered aggregates, such as expanded clay or sintered fly ash, are indispensable for structural lightweight concrete where high crushing resistance is mandatory (Bekkeri et al., 2023).

Sintering involves three primary transformations:

1) Vitrification: Temperatures reach the material's eutectic point, forming a viscous liquid phase at particle contact points (Hao et al., 2022).
2) Pore Structural Evolution: The liquid phase acts as a bridge, drawing particles together through capillary forces and closing open pores.
3) Bloating: If precursors contain organic matter, gases released at high temperatures can be trapped by the viscous melt, reducing bulk density (Kwek & Awang, 2021).

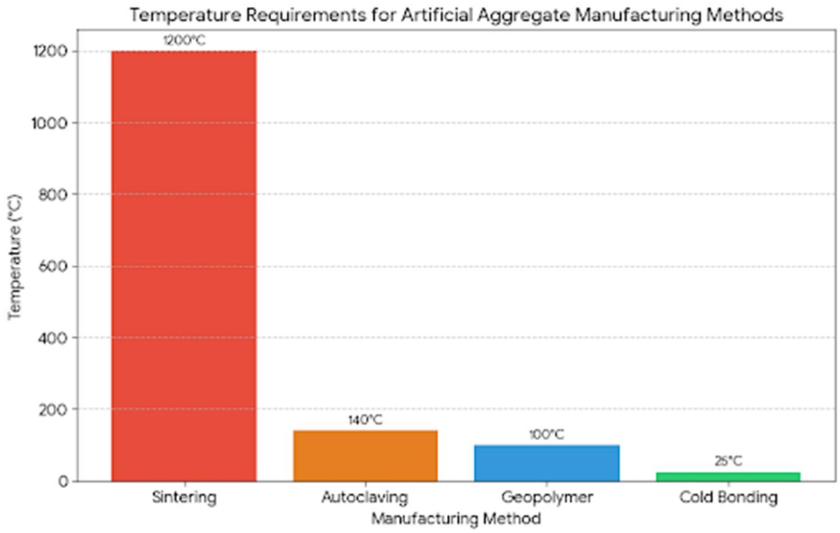
Technical efficacy depends on a precise thermal regime. Research highlights three critical stages: a Pre-heating Phase (300°C–600°C) to remove chemically bound water; a Sintering Zone (900°C–1300°C) for optimal fusion; and Controlled Cooling. Ibrahim et al. (2022) emphasize that exceeding the melting point leads to a fusion where pellets merge into an unusable mass.

C. Autoclaving

Autoclaving utilizes high-pressure saturated steam to catalyze chemical bonds much faster than ambient curing. According to Nor et al. (2016), autoclaving relies on the synergy of moisture, elevated temperature, and high pressure to facilitate rapid transformation. This environment promotes an Accelerated Pozzolanic Reaction, leading to the formation of stable crystalline phases like tobermorite.

These structures provide higher strength and lower drying shrinkage compared to the amorphous gels formed during standard cold bonding (Bekkeri et al., 2023). The process typically requires pressures between 0.8 and 1.5 MPa and temperatures between 140°C and 200°C (Hao et al., 2022). While hardening can be completed in 4 to 10 hours, Stempkowska & Gawenda (2024) highlight the necessity of a 24-hour pre-conditioning period to prevent the pellets from deforming or "exploding" due to sudden internal steam pressure.

FIGURE I
TEMPERATURE REQUIREMENT OF ARTIFICIAL AGGREGATE MANUFACTURING METHODS



D. Mechanical Reduction and Specialized Casting

The Crushing Method involves the mechanical reduction of a monolithic hardened mass into discrete granular fractions. High-density pastes are cast into slabs and, once cured, subjected to jaw or industrial crushers. Unlike the smooth surface of pelletized aggregates, crushed aggregates possess irregular, angular surfaces that enhance the mechanical interlock within a concrete matrix (Kwek & Awang, 2021). However, this method is often less efficient for high-volume manufacturing due to labor costs and dust production (Bekkeri et al., 2023). Alternative synthesis techniques include Mould Casting, where reactive pastes are placed into pre-defined templates (such as grid-based trays).

III.LITERATURE SURVEY

The following is the chronological synthesis of the pivotal research that has shaped the current understanding of geopolymer artificial aggregate technology.

1) *Gomathi and Sivakumar (2014):* This study constitute one of the earliest comprehensive investigations into the production of geopolymer artificial aggregates through disc pelletization of Class F fly ash. In their methodology, a custom-fabricated pelletizer was utilized, wherein the alkali activator (10M NaOH) was continuously sprayed during rotational motion to trigger geopolymerization. A key contribution of this work lies in the systematic evaluation of binary blends (Fly Ash combined with GGBS, Metakaolin, and Bentonite), where the 70:30 FA–GGBS proportion exhibited superior performance. Furthermore, this investigation reported that the 70:30 FA–GGBS blend achieved the highest crushing strength of 22.81 MPa.
2) *Efendy et. al., (2019):* This study examined the creep behavior of geopolymer aggregates within asphalt mixtures, with a particular focus on their response under repeated loading conditions. Under cyclic loading tests, the mixtures were able to endure approximately 1559 load cycles, after which failure occurred primarily due to bitumen stripping at the aggregate interface.
3) *Gusti Made Bagus Baskara et al., (2019):* This study investigated the performance of geopolymer aggregates in asphalt concrete mixtures, with a specific focus on evaluating the stiffness modulus. The resulting asphalt mixtures achieved a stiffness modulus of 3542 MPa at 20 degrees Celsius and 147 MPa at 60 degrees Celsius, indicating satisfactory structural performance. However, the study also identified a key limitation in the form of increased asphalt demand, which was attributed to the inherently porous surface texture of the aggregates.
4) *Karyawan et al., (2019):* This study focused on the volumetric properties and mix design optimization of geopolymer aggregates for pavement applications. The aggregates were produced using cold-bonded pelletization, followed by 28 days of ambient curing to stabilize their physical characteristics. The slope of 50 degrees and Alkaline ratio of 2.5 was found as optimum.

5) *Ab Manaf et al., (2020):* This study advanced the field by implementing the cast-and-crush production method, resulting in angular aggregates that closely resemble natural granite in morphology and performance. In this process, geopolymer paste derived from fly ash was cast into blocks, cured under ambient conditions, and subsequently crushed mechanically. The produced aggregates achieved an Aggregate Impaact Value of 22.7 % and Aggregate Crushing Value of 37.7 %, Los Angeles Abrasion value of 27.40% was observed for artificial aggregates. .
6) *Karyawan et al., (2020):* This study conducted a detailed investigation into the influence of the $Na_2SiO_3/NaOH$ ratio (ranging from 1.0 to 3.0) on the microstructural development of geopolymer artificial aggregates. The aggregates were synthesized using laboratory-scale pelletization with a granulator slope of 50°, ensuring uniform formation conditions. Advanced characterization techniques, specifically Scanning Electron Microscopy (SEM) was employed after a 28-day curing period to evaluate the internal bonding. The study identified that an optimal $Na_2SiO_3/NaOH$ ratio of 2.5 resulted in the smallest absorption value.
7) *Candel Ago et al., (2023):* This study focused on the optimization of angular geopolymer aggregates produced via the cast-and-crush technique, employing molarity NaOH solutions (8 M). The geopolymer paste was cast into slabs and subjected to room temperature for 10 days then controlled heat curing at 90°C for 10 days and next 8 days at room temperature. The resulting aggregates exhibited a Los Angeles Abrasion (LAA) loss of 40%, which falls well within the acceptable limits.

IV. DISCUSSION: SYNTHESIS OF PREVIOUS STUDIES

A. Materials

The production of artificial aggregates by utilizing industrial precursors such as fly ash, ground granulated blast furnace slag, and metakaolin is one of the key Early studies, particularly those by Gomathi and Sivakumar (2014), established Class F fly ash (FA) as the dominant precursor due to its spherical morphology and favorable packing characteristics, which enhance pellet formation during cold-bonded granulation. Subsequent research introduced supplementary precursors such as Ground Granulated Blast Furnace Slag (GGBS) and metakaolin, creating binary and ternary binder systems.

Parallel to the evolution of precursor systems, the chemical composition of alkaline activators has undergone substantial refinement. Early research primarily focused on the molarity of sodium hydroxide (NaOH), typically ranging from 10M to 14M, to ensure sufficient dissolution of aluminosilicate phases. However, more recent studies, including those by Karyawan et al. (2020) have demonstrated that the sodium silicate to sodium hydroxide ratio ($Na_2SiO_3/NaOH$**)** plays a more decisive role in controlling geopolymerization. An optimal ratio of approximately 2.5 has been consistently identified as providing the best balance between workability, viscosity, and gel formation. This ratio ensures adequate silica availability for polymer chain formation while maintaining a workable slurry for pellet growth.

TABLE II
CLASSIFICATION OF STUDIES BASED ON BINDER SYSTEMS

Sr. No.	Binder System	Studies	Properties
1)	Fly Ash-Based (Class F) Geopolymer	Karyawan et al., (2019); Ab Manaf et al., (2020); Candel Ago et al., (2023)	Fly ash-based binders dominate due to their consistent aluminosilicate composition, enabling stable geopolymerization and controlled mechanical performance under both ambient and heat curing conditions.
2)	Fly Ash + GGBS (Binary Blend)	Gomathi & Sivakumar (2014)	The incorporation of GGBS enhances early-age reactivity and strength development by promoting simultaneous formation of C–S–H and geopolymer gels.
3)	Fly Ash + Metakaolin	Wilkinson et al., (2025); Bekkeri et al., (2022)	The addition of metakaolin improves binder homogeneity and reactivity, resulting in denser microstructures and enhanced long-term durability.
4)	Fly Ash + Rice Husk Ash (RHA)	Winardi et al.,(2022)	The use of RHA contributes additional reactive silica, improving microstructural refinement and resistance to cracking under thermal curing regimes.
5)	Fly Ash + Asbuton (Natural Asphalt Modifier)	Karyawan et al., (2023)	The integration of Asbuton introduces bituminous characteristics within the geopolymer matrix, enhancing compatibility with asphalt mixtures.

Studies by Baskara et al., (2019) and Efendy and Ahyudanari (2019) highlight that highly porous or chemically inert geopolymer surfaces can lead to bitumen absorption or stripping, compromising pavement performance. Despite the considerable progress in precursor optimization and chemical engineering, a critical research gap remains in understanding the long-term chemical stability of geopolymer matrices, particularly when derived from heterogeneous waste streams. Many studies continue to prioritize short-term performance indicators such as compressive strength, aggregate crushing value, and specific gravity, with limited attention to long-term durability under aggressive environmental conditions. There is substantial opportunity for future investigations in utilization of various Industrial and agricultural waste in combinations as percusor with conventional materials like fly ash.

B. Process Parameters

The synthesis of geopolymer artificial aggregates is governed by a complex interaction of process parameters that directly influence their physical, mechanical, and durability properties. Across the reviewed studies, it is evident that aggregate performance is not solely dependent on material composition but is significantly controlled by the method of formation, chemical activation conditions, and curing regimes. These parameters collectively determine the internal pore structure, surface characteristics, and ultimately the water absorption and strength of the aggregates.

A primary distinction in production lies between cold-bonded pelletization and cast-and-crush techniques**,** both of which produce aggregates with fundamentally different structural characteristics. Pelletization, as investigated by Gomathi and Sivakumar (2014) and Karyawan et al. (2020), relies on rotational motion within a pan granulator, where parameters such as disc inclination and rotational speed dictate particle size distribution and sphericity.

While this method enables uniform and scalable production, it inherently promotes the formation of layered structures that often contain a porous core due to rapid agglomeration. In contrast, the cast-and-crush method adopted by Ab Manaf et al. (2020) and Candel Ago et al. (2023) produces angular aggregates by mechanically fragmenting bulk geopolymerized material. This approach enhances interlocking properties and reduces internal voids through vibration during casting; however, it introduces sensitivity to the timing of crushing, as premature crushing leads to deformation while delayed crushing increases energy demand and micro-cracking.

The chemical activation process forms the core of geopolymer synthesis, with the ratio of sodium silicate to sodium hydroxide ($Na_2SiO_3/NaOH$) consistently identified as a critical parameter. Studies such as Karyawan et al. (2019, 2020) converge on an optimal ratio of approximately 2.5, which balances the dissolution of aluminosilicate precursors and the viscosity required for effective binding and pellet growth. Deviations from this ratio result in either insufficient gel formation or excessive viscosity, leading to poor workability and increased porosity. Additionally, the molarity of NaOH plays a significant role, with values ranging from 10M to 14M depending on the desired reaction kinetics.

The liquid-to-solid (L/S) ratio further complicates this balance, as lower ratios (0.35) enhance density and strength but may hinder complete reaction within the aggregate core. These findings collectively indicate that chemical parameters must be precisely tuned to achieve a homogeneous and dense geopolymer matrix**.**

Curing conditions represent another critical dimension in the synthesis process, governing the transition from a fresh geopolymer paste to a hardened, stone-like material. Early studies, particularly Gomathi and Sivakumar (2014), relied heavily on thermal curing at elevated temperatures to accelerate geopolymerization and reduce porosity. While effective in enhancing early strength, such methods are energy-intensive and may induce thermal stresses that contribute to micro-cracking. More recent studies, including Wilkinson et al. (2025), have shifted toward ambient and moisture-controlled curing, which offers a more sustainable approach while maintaining adequate performance.

Optimization of geopolymer aggregates production increasingly focuses on the integration of multiple process parameters to achieve a balance between strength and porosity.

Despite these advancements, a significant research gap remains in the real-time control and automation of the production process**.** Most existing studies rely on batch-based experimentation, with fixed parameters such as disc speed, activator dosage, and curing conditions. There is limited understanding of the dynamic interactions between environmental factors, particularly ambient humidity. Furthermore, the influence of various moulding shapes to cast the geopolymer mortar for making artificial aggregates has not been investigated.

TABLE IIII
CLASSIFICATION OF STUDIES BASED ON PRODUCTION TECHNIQUES

Sr. No.	Production Method	Studies	Process Details
1.	Pelletization (Cold-Bonded / Disc / Pan)	Karyawan et al. (2020); Karyawan et al. (2019); Baskara et al. (2019); Efendy & Ahyudanari (2019); Gomathi & Sivakumar (2014)	Artificial aggregates are produced by agglomerating alkali-activated precursor materials in a rotating pan or disc, followed by ambient curing to achieve spherical particles with controlled size and strength.
2.	Cast-and-Crush	Candel Ago et al. (2023); Ab Manaf et al. (2020);	Geopolymer mixtures are cast into bulk forms, cured under controlled conditions, and subsequently crushed and sieved to obtain angular aggregates with desired gradation.

C. Physical Properties

Unlike conventional natural aggregates, geopolymer aggregates exhibit inherently higher porosity due to the geopolymerization process, making volumetric control a critical challenge. Consequently, researchers have consistently emphasized that even when sufficient mechanical strength is achieved, excessive porosity and water absorption can render the material unsuitable for practical implementation.

Early studies such as Gomathi and Sivakumar (2014) reported absorption values of 13.01% for Fly ash GGBS Aggregate. Similarly, Karyawan et al. (2019) reported absorption values of 6.1% with 50 degree granulator slope. Moderate improvements were observed in studies such as Ab Manaf et al. (2020), who achieved 5.53 % absorption using a cast-and-crush method. Karyawan et al. (2020) and highlighted the importance of maintaining an optimal Na_2SiO_3/NaOH ratio (around 2.5), which ensures a continuous geopolymer gel and minimizes inter-particle voids. High molarity activators and finer precursor materials further enhance dissolution and reduce unreacted particles that contribute to porosity. At the microstructural level, surface texture and porosity, as revealed through scanning electron microscopy (SEM), play a decisive role in governing volumetric performance. Karyawan et al. (2020) demonstrated that a Na_2SiO_3/NaOH ratio of **2.5** produces a homogeneous and continuous geopolymer gel, minimizing voids and reducing effective porosity. In contrast, lower ratios result in discontinuous “honeycomb” structures with high permeability.

There is significant research gap in reducing the water absorption of geopolymer aggregates, through integral treatment and surface coating techniques. There is limited understanding about enhancement of specific gravity of aggregates, thereby enhancing its physical properties.

V. FUTURE SCOPE

The production of artificial aggregates by utilizing industrial precursors such as fly ash, ground granulated blast furnace slag, and metakaolin is one of the key Early studies, particularly those by Gomathi and Sivakumar (2014), established Class F fly ash (FA) as the dominant precursor due to its spherical morphology. Despite significant progress in the development of geopolymer-based artificial aggregates, a critical analysis of existing literature reveals several unresolved challenges that limit their large-scale adoption and long-term performance in infrastructure applications. Current research, while extensive, remains largely confined to laboratory-scale experimentation, with limited translation to industrial production and field implementation. This gap highlights the urgent need for innovative materials and advanced processing techniques that can bridge the divide between experimental feasibility and practical applicability. One of the most prominent research gaps lies in the limited diversity and optimization of precursor materials. Although fly ash, GGBS, and metakaolin have been widely studied, there is a need to explore novel alternative precursors, including agricultural waste and other industrial wastes as hybrid material systems, to enhance material reliability and sustainability. Another critical limitation is related to high water absorption and porosity, which adversely affect durability and mechanical performance. Although surface treatments and coatings have shown potential in mitigating these issues, further research is required to develop advanced densification techniques, such as nano-modification, fiber reinforcement, and multi-layer coating strategies. In addition, scalability and production efficiency remain major challenges. Existing manufacturing methods, including cold bonding and sintering, often involve high energy consumption, complex processing conditions, or limited production capacity. The absence of standardized production protocols further complicates large-scale implementation. Therefore, the development of cost-effective, energy-efficient, and scalable production technologies, such as one-part geopolymer systems and automated pelletization processes, is essential.

Furthermore, there is a noticeable lack of long-term performance data under real environmental and loading conditions. Most studies focus on short-term mechanical properties, with insufficient attention to durability aspects such as creep, fatigue, thermal cycling, and chemical resistance. This limits confidence in the material's reliability for critical infrastructure applications. Future research must prioritize field trials, life-cycle assessment (LCA), and performance monitoring to validate laboratory findings.

Another emerging gap is the limited integration of advanced technologies, such as artificial intelligence (AI) and machine learning (ML), in material design and performance prediction. These tools have the potential to optimize mix design, predict long-term behavior, and reduce experimental costs, yet their application in geopolymer aggregate research remains in its early stages.

VI. CONCLUSIONS

Geopolymer-based artificial aggregates present a sustainable alternative to natural aggregates by utilizing industrial by-products such as fly ash and GGBS, thereby addressing both resource depletion and waste management challenges. Their performance is strongly influenced by manufacturing techniques such as pelletization and cast-and-crush, along with precise control of chemical parameters. The properties of artificial aggregates are significantly enhanced by optimizing key factors, including the $Na_2SiO_3/NaOH$ ratio of 2.5, optimum molarity of alkaline activators, controlled liquid-to-solid ratio, and appropriate curing regimes. Additionally, improvements in microstructure and durability can be achieved through precursor blending (e.g., FA–GGBS), finer particle size distribution, surface treatments, and advanced approaches such as nano-modification and fiber reinforcement, which reduce porosity and water absorption while increasing strength.

Despite these improvements, challenges such as higher water absorption, durability and scalability remain. Future research focusing on standardized production, long-term performance, and advanced material optimization techniques will be critical to enabling the widespread adoption of geopolymer artificial aggregates in sustainable construction

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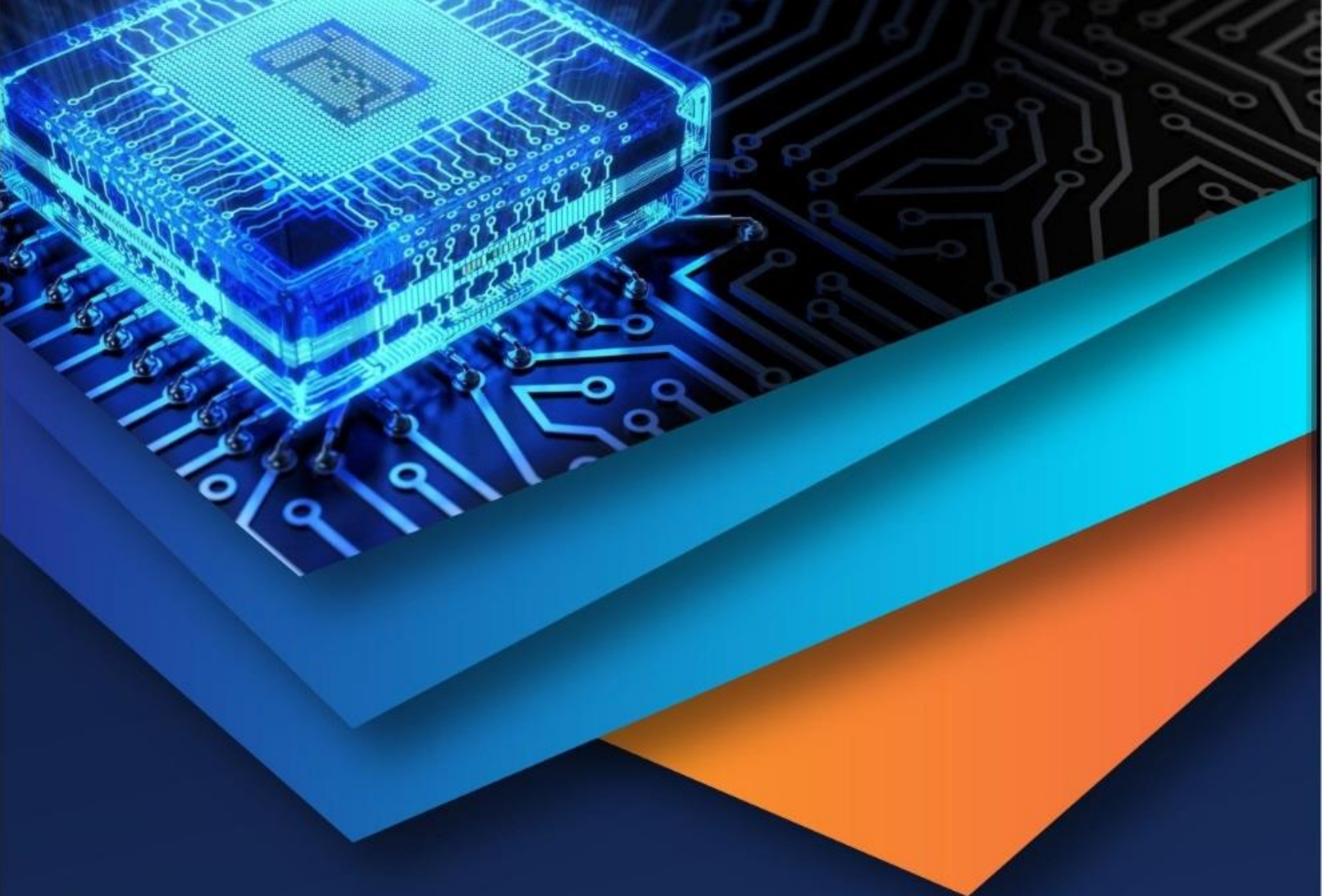

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