Exploration of Industrial Waste towards Futuristic Construction

Rajat Maheshwari[1], Ar. Swarna Junghare[2]

[1]Student of Department of Architecture, Amity University, Chhattisgarh
[2]Associate Professor of Department of Architecture, Amity University, Chhattisgarh

---***---

Abstract - The growing global emphasis on sustainability has encouraged the construction industry to adopt innovative strategies that reduce environmental impact. This study examines the feasibility of using industrial waste as alternative construction materials by evaluating their physical, chemical, and mechanical properties. It investigates how waste-derived materials can support eco-friendly, cost-effective, and durable construction while contributing to broader sustainable development goals. Major industrial waste streams - such as Sulfo-Aluminate Cement and Red Mud (Bauxite Residue)-based geo-polymers are analyzed through an extensive literature review, comparative material performance assessment, and life-cycle evaluation. Key parameters including compressive strength, durability, workability, and cost efficiency are benchmarked against conventional materials to determine overall applicability and long-term viability. The findings indicate that industrial waste materials offer significant advantages, including reduced resource consumption, lower carbon emissions, and decreased landfill burden, thereby promoting circular economy practices in construction. However, the study is restricted to secondary data and a limited selection of waste materials, without full-scale experimental or field validation. Additionally, regional variations in waste availability and construction practices were not explored. Despite these limitations, the research highlights the strong potential of industrial waste utilization as a sustainable, future-ready solution for the construction sector, offering meaningful insights for engineers, policymakers, and researchers.

Key Words: Industrial waste utilization, sustainable construction materials, Life-Cycle Assessment (LCA), eco-friendly architecture, waste-derived geopolymers

1. INTRODUCTION

The construction industry is one of the largest consumers of raw-materials and energy resources worldwide. With rapid urbanization, industrialization, and population growth, the demand for infrastructure has drastically increased, leading to a significant rise in resource extraction and waste generation. At the same time, industrial sectors such as mining, metallurgy, power production, and chemical manufacturing continue to produce large quantities of waste, almost part of which remains underutilized or is disposed of in landfills. These waste materials not only occupy valuable land but also contribute to soil, water, and air pollution, posing severe environmental and health hazards.

In response to these challenges, sustainable construction practices have emerged as a crucial focus area in modern architecture and material research. The concept of sustainability emphasizes reducing resource consumption, minimizing carbon emissions, and promoting the reuse and recycling of waste materials within the construction cycle. Industrial waste materials- when appropriately processed- can serve as viable alternatives to traditional construction materials such as cement, aggregates, and bricks. This approach not only diverts waste from landfills but also reduces dependence on virgin raw materials, aligning with the global shift toward a circular economy.

Traditional waste-based materials such as fly ash bricks and slag cement have already demonstrated environmental and economic benefits. However, there remains vast potential to explore new-generation waste materials that can redefine the future of construction. Recent studies indicate that advanced materials like red mud-based geopolymers, sulfo-aluminate cement, steel slag foamed panels, plastic- metal hybrid composites, and biochar-industrial ash can deliver enhanced durability, energy efficiency, and multifunctional properties. Such materials hold promise for creating futuristic architectural structures that are not only sustainable but also adaptive, intelligent, and resilient.

Therefore, this research aims to explore the potential of underutilized industrial waste materials and assess their feasibility for application in future construction practices. Through analytical comparison and performance evaluation, the study seeks to highlight how waste-derived materials can contribute to eco-efficient, cost-effective, and high-performance building systems, paving the way for a more sustainable and innovative built environment.

2. LITERATURE REVIEW

The utilization of industrial waste in construction has gained significant attention in recent years as part of global efforts to promote sustainability and resource efficiency. A growing body of research focuses on transforming industrial by-products into valuable construction materials through chemical activation, composite formation, and material re-engineering. The literature highlights that these waste-derived materials can reduce environmental impact, improve performance characteristics, and support the principles of a circular economy.

2.1 Red Mud (Bauxite Residue)- Based Geopolymers:

Red Mud, also known as *Bauxite Residue*, is a by-product generated during the Bayer process for extracting alumina from bauxite ore. For every ton of alumina produced, approximately 1–1.5 tons of red mud are generated, leading to large-scale disposal issues worldwide [1]. The material is a fine, alkaline slurry rich in iron oxide (Fe_2O_3), alumina (Al_2O_3), silica (SiO_2), titanium dioxide (TiO_2), and residual sodium compounds, giving it a distinct red color and a highly basic pH (10–13).

The environmental challenge of storing red mud in vast tailing ponds has driven research into its reuse as a supplementary material in cementitious systems. The high alumino silicate content makes it a potential precursor for geopolymer formation, an alkali-activated binding process that does not rely on traditional clinker production. Studies by Mudgal et al. (2023) [11] demonstrated that red mud, when activated with sodium silicate or sodium hydroxide and blended with fly ash or slag, forms a geopolymer matrix with considerable compressive strength and chemical durability.

Globally, red mud has been investigated for applications in cement replacement, bricks, ceramics, pigments, and radiation-shielding materials. However, variability in composition, handling difficulties, and leaching risks of alkaline components limit direct utilization. New research trends focus on neutralization techniques, carbonation processes, and hybrid geopolymer formulations to stabilize and valorize this industrial waste [1].

2.2 Sulfo-Aluminate Cement (SAC)

Sulfo-Aluminate Cement, also known as Calcium Sulfoaluminate (CSA) Cement, originated in China and Europe as a low-energy, rapid-hardening alternative to Ordinary Portland Cement (OPC). Unlike OPC, which relies primarily on alite (C_3S) hydration, SAC's main phase is ye'elimite (C_4A_3), which reacts with calcium sulfate and water to form expansive ettringite, giving high early strength.

SAC production typically requires lower kiln temperatures (≈1250°C compared to 1450°C for OPC), resulting in reduced CO_2 emissions and energy consumption (Cai et al., 2023). Furthermore, industrial by-products such as phosphogypsum, limestone dust, and fly ash can serve as raw materials in the clinker mix, reinforcing its circular-economy potential [9].

Early research in the 1970s–1980s focused on SAC's rapid-setting and expansive properties for shrinkage-compensating concrete. Recent work has emphasized its environmental advantages and versatility for 3D printing, precast construction, and self-stressing systems. Studies confirm that SAC develops over 50% of its ultimate strength within one day, while maintaining strong sulfate resistance and dimensional stability when properly proportioned [6].

SAC's integration into low-carbon construction frameworks represents a significant step towards next-generation eco-binders capable of rapid curing and reduced embodied emissions. Current research focuses on optimizing raw waste substitutions and reducing the environmental impact of aluminum-bearing components [12].

2.3 Steel Slag Foamed Panel

Steel slag is a solid waste produced during the refining of steel from iron ore, with an estimated global output exceeding 250 million tons annually. It consists mainly of calcium oxide (CaO), silicon dioxide (SiO_2), ferric oxide (Fe_2O_3), and magnesium oxide (MgO) [7]. Although it possesses latent hydraulic properties similar to cement clinker, direct use in concrete is limited by its high free-lime content and potential for volumetric expansion.

Recent advances in material processing have transformed steel slag into lightweight foamed panels, combining industrial waste valorization with energy-efficient construction solutions. The foaming process involves controlled incorporation of gases or surfactants to create a porous matrix that reduces weight and enhances insulation performance.

These foamed slag composites exhibit lower density (≈1300–1800 kg/m³), good mechanical strength (≈25–40 MPa), and excellent fire and sound resistance, making them suitable for prefabricated façade and wall systems. The reuse of steel slag in foamed form addresses the dual challenge of waste disposal and thermal efficiency in modern buildings.

Globally, nations such as Japan, China, and Germany have initiated industrial-scale programs for slag utilization in aggregates, asphalt fillers, and cementitious materials. However, quality variability and the need for long-term durability testing continue to restrict universal adoption.

2.4 Plastic-Metal Hybrid Aggregate

The concept of Plastic-Metal Hybrid Aggregates stems from the urgent need to recycle e-waste plastics and metallic residues into value-added products. Electronic and plastic waste has become one of the fastest-growing waste streams globally, with plastics contributing over 300 million tons annually [8]. While recycled plastics have been used as lightweight fillers, their weak bonding and low stiffness often reduce concrete strength.

To address this, researchers developed hybrid aggregates by embedding metallic particles (such as aluminum or steel fines) within molten or shredded thermoplastics, producing aggregates that are both lightweight and conductive. The resulting material exhibits lower density (≈1500–1800 kg/m³) than conventional aggregates and can integrate electrical or thermal conductivity, enabling applications in smart concrete, anti-static flooring, and electromagnetic shielding.

Louis Diep's [2] design-based study on upcycling plastic waste demonstrated how hybrid composites can combine mechanical and aesthetic value, turning waste materials into performative architectural elements. The material's innovation lies in transforming waste plastics-previously considered non-recyclable- into aggregates that reduce concrete mass and potentially add new functionalities.

Although currently limited to small-scale experimentation, the hybrid aggregate concept illustrates a paradigm shift from structural to multifunctional materials, aligning with the broader vision of adaptive and technologically integrated architecture.

2.5 Biochar-Industrial Ash Composite

Biochar is a carbon-rich, porous material produced from the pyrolysis of organic biomass under limited oxygen. When combined with industrial ash (fly ash, bottom ash, or cement kiln dust), it forms a composite that unites the structural properties of mineral residues with the environmental benefits of biochar's carbon storage capability [3].

This material innovation emerged from efforts to develop carbon-negative construction components. Biochar's high porosity and surface area enhance bonding with inorganic ash particles, producing lightweight blocks (≈900–1200 kg/m³) with moderate compressive strength (5–15 MPa) and low thermal conductivity (λ ≈ 0.3–0.4 W/m·K). Studies confirm that biochar–ash composites can regulate indoor humidity, improve insulation, and permanently sequester biogenic carbon [14].

Globally, research institutions in Europe, Japan, and India are exploring biochar-based concrete and mortars as part of carbon capture and utilization strategies. The approach contributes to both waste reduction and climate mitigation, aligning with circular-economy frameworks.

Current investigations focus on improving mechanical strength, moisture resistance, and durability while maintaining carbon sequestration efficiency. Future work aims to standardize production protocols, quantify long-term CO_2 retention, and integrate biochar composites into building codes for sustainable construction [4].

Across the reviewed materials, literature demonstrates a clear trend toward integrating industrial waste into value-added construction products. Each material addresses specific global challenges- Red Mud tackles metallurgical waste management; SAC offers low-carbon binder innovation; Steel Slag Panels enhance thermal performance; Plastic–Metal Hybrids provide smart material functionality; and Biochar Composites support carbon sequestration.

Collectively, these studies emphasize the urgent need for circular material systems capable of replacing conventional, emission-intensive construction materials. The literature strongly supports their feasibility in laboratory contexts, though further standardization, scaling, and policy integration are required for real-world adoption.

3. MATERIAL SELECTION AND ANALYSIS

The process of material selection in this research is based on identifying industrial wastes that are abundant, underutilized, and capable of being transformed into construction-grade materials through technological or chemical modification. The chosen materials exhibit potential for mechanical performance, durability, and sustainability when compared with conventional construction materials. Based on an extensive literature review and the evaluation of industrial waste streams, five materials have been selected for detailed analysis: Red Mud (Bauxite Residue)–Based Geo-polymer, Phosphogypsum Composite, Steel Slag Foamed Panel, Plastic–Metal Hybrid Aggregate, and Biochar–Industrial Ash Composite [5].

3.1 Red Mud (Bauxite Residue)-Based Geo-polymer

A. **Source:** By-product of the aluminum industry, obtained during Bayer's alumina extraction process from bauxite ore. For every ton of alumina produced, approximately 1–1.5 ton of red mud are generated. It is a fine, alkaline residue rich in oxides and minerals, which pose storage and environmental challenges when disposed of in ponds.

B. **Properties:** Highly alkaline (pH 10–13) and rich in iron oxide (Fe_2O_3), alumina (Al_2O_3), silica (SiO_2), and titanium dioxide (TiO_2). Its fine particle size and reactive alumino silicate content make it suitable for alkali activation to form geo-polymers. Exhibits high chemical stability, low permeability, and superior resistance to heat and aggressive environments when properly cured.

C. **Processing Technique:**

- Drying and grinding of red mud to fine powder to remove excess moisture.
- Blending with supplementary materials such as fly ash or slag to balance silica and alumina content.
- Activation using alkali solutions (sodium hydroxide and sodium silicate) to initiate geo-polymerization.
- Casting into molds or panels and curing at 60–80°C for 24–48 hours to achieve high early strength.

D. **Construction Application:** Used in fire-resistant wall panels, paving blocks, radiation-shielding units, and as a low-clinker binder for eco-concretes. Its resistance to high temperatures and chemical attack makes it suitable for industrial flooring, coastal structures, and waste containment barriers.

E. **Advantages:**

- Reduces cement consumption and CO_2 emissions by up to 60–70%.
- Provides excellent acid and sulfate resistance.
- Transforms a hazardous industrial waste into a durable, value-added product.
- Possesses high compressive strength (30–60 MPa) with long-term durability.

F. Challenges:

- High alkalinity requires neutralization and careful handling.
- Compositional variability depending on bauxite source can affect performance.
- Limited field-scale validation and standardization for commercial use.

3.2 Sulfo Aluminate Cement

A. Source: Produced from a mixture of limestone, bauxite, and gypsum, or by incorporating industrial by-products such as phosphogypsum, fly ash, and slag. It originates as an alternative low-energy cement where the primary mineral phase is ye'elimite ($C_4A_3\$$) rather than alite (C_3S) found in Ordinary Portland Cement (OPC).

B. Properties: Exhibits rapid setting and high early strength due to the formation of ettringite during hydration. Contains lower lime content and develops strength rapidly even at low curing temperatures. Offers low shrinkage, excellent sulfate resistance, and a reduced carbon footprint (30–40% less CO_2 emissions compared to OPC).

C. Processing Technique:
- Raw materials (limestone, bauxite, gypsum, and industrial wastes) are proportioned and ground.
- The mixture is calcined at 1250–1300°C - lower than OPC's 1450°C—to form the sulfo-aluminate clinker.
- Clinker is finely ground and blended with additional gypsum or anhydrite to regulate setting time.
- The cement can be mixed with supplementary wastes such as slag or fly ash to enhance performance and sustainability.

D. Construction Application: Used in rapid-repair concrete, precast elements, 3D printing applications, and marine or sulfate-prone environments. Ideal for runway repair, underground works, and self-stressing concrete due to its quick setting and volume-stable nature.

E. Advantages:
- Develops over 40–60 MPa strength within 24 hours, enabling fast-track construction.
- Consumes less energy and emits significantly less CO_2.
- Provides excellent chemical durability in sulfate-rich and aggressive conditions.
- Can utilize industrial wastes as raw feedstock, promoting circular manufacturing.

F. Challenges:
- Requires careful control of raw material chemistry to prevent excessive expansion.
- Currently higher production cost due to limited large-scale plants.
- Long-term durability data and standardized design codes are still evolving.

3.3 Steel Slag Foamed Panels

A. Source: Derived from steelmaking slag, a by-product generated during the refining of iron into steel in basic oxygen or electric arc furnaces. The slag contains calcium oxide (CaO), silicon dioxide (SiO_2), ferric oxide (Fe_2O_3), and magnesium oxide (MgO), giving it potential as a cementitious and aggregate material.

B. Properties: Exhibits latent hydraulic and pozzolanic reactivity similar to cement clinker. When processed into foamed form, it becomes lightweight, fire-resistant, and thermally insulating. The high calcium content supports self-cementing ability, while its porous structure improves sound and heat insulation.

C. Processing Technique:
- Steel slag is cooled, crushed, and ground into fine powder.
- A foaming agent (hydrogen peroxide, aluminum powder, or surfactant) is added to create porosity.
- The mixture is cast into panel molds and cured under steam or at elevated temperature (60–80°C).
- Surface finishing and cutting is performed after curing to obtain prefabricated panels.

D. Construction Application: Used as lightweight wall panels, facade elements, acoustic panels, and thermal insulation blocks in modular and prefabricated construction. Can replace traditional reinforced concrete panels in non-load-bearing systems or energy-efficient building envelopes.

E. Advantages:
- 40–50% lower density than conventional concrete (1300–1800 kg/m³).
- Compressive strength of 25–40 MPa suitable for structural wall applications.
- Excellent fire resistance and thermal insulation ($\lambda \approx 0.35$ W/m·K).
- Utilizes a high-volume industrial waste stream and reduces CO_2 emissions.

F. Challenges:
- Composition varies with steel type and production method, affecting performance.
- Presence of free lime (CaO) may cause expansion if not stabilized.
- Requires careful foaming control and quality assurance during production.

3.4 Plastic - Metal Hybrid Aggregate

A. Source: Formed by combining waste plastics (such as high-density polyethylene, polypropylene, or PVC) with metallic residues or fines obtained from machining, e-waste, or foundry processes. The concept originates from the growing need to manage non-biodegradable plastic waste and metal dust, converting them into lightweight, multifunctional construction aggregates.

B. Properties: Lightweight, durable, and resistant to corrosion, moisture, and chemicals. Exhibits lower density (1500–1800 kg/m³) compared to natural aggregates and may possess electrical conductivity depending on metal content. The hybrid combination enhances toughness and energy absorption, while reducing thermal conductivity.

C. Processing Technique:
- Cleaning and shredding of plastic waste into small flakes or granules.
- Mixing of metallic fines (aluminum, copper, or steel) into molten or heated plastic matrix.
- Pelletizing or molding the mixture into aggregate-sized particles.
- Cooling and solidification to form hybrid aggregates suitable for concrete mixing.

D. Construction Application: Used in lightweight concrete, paving blocks, flooring tiles, anti-static surfaces, and EMI (Electromagnetic Interference) shielding components. Particularly suitable for modular and smart buildings, where multifunctional materials are desired.

E. Advantages:

- ○ Reduces landfill waste from plastics and metallic residues.
- ○ Produces lightweight, durable, and corrosion-resistant aggregates.
- ○ Offers potential electrical conductivity and smart functionality.
- ○ Requires less energy compared to producing virgin aggregates.

F. Challenges:

- ○ Mechanical strength depends heavily on the plastic-to-metal ratio and bonding quality.
- ○ High processing temperatures may release fumes if not properly controlled.
- ○ Limited field-scale applications and standardization for structural use.

3.5 Biochar–Industrial Ash Composite

A. Source: Composed of biochar, a carbon-rich product derived from pyrolysis of organic biomass (such as agricultural residues, wood chips, or coconut shells), combined with industrial ash like fly ash, bottom ash, or cement kiln dust. This composite is a sustainable solution that transforms both organic and inorganic wastes into functional construction material.

B. Properties: Lightweight, porous, and highly insulative. Exhibits low thermal conductivity (0.25–0.4 W/mK) and moderate compressive strength (5–15 MPa) depending on the binder ratio. The biochar component enhances moisture buffering, adsorption capacity, and carbon sequestration, while the ash contributes structural rigidity and cementitious properties. The result is a carbon-negative, energy-efficient material.

C. Processing Technique:

- ○ Production of biochar through pyrolysis of biomass under limited oxygen conditions.
- ○ Mixing biochar with industrial ash and a small portion of binder (lime, cement, or geo-polymer).
- ○ Pressing or casting the mixture into blocks, panels, or bricks.
- ○ Air or steam curing at ambient temperature for 7–14 days to enhance bonding.

D. Construction Application: Used for eco-blocks, interior wall panels, insulation boards, and carbon-negative masonry units. Ideal for green buildings, low-energy construction, and humidity-regulating surfaces. Can also serve as a sustainable replacement for traditional clay bricks or AAC blocks in non-load-bearing structures.

E. Advantages:

- ○ Carbon-negative material that stores CO_2 permanently within the structure.
- ○ Excellent thermal and acoustic insulation properties.
- ○ Lightweight and environmentally safe.
- ○ Utilizes both biomass and industrial waste, contributing to circular economy goals.

F. Challenges:

- ○ Lower mechanical strength compared to conventional concrete.
- ○ Requires controlled pyrolysis conditions for uniform biochar quality.
- ○ Limited long-term durability and standardization studies available.

The selected materials collectively demonstrate a strong potential to redefine the material palette of futuristic construction, offering not just mechanical performance but also additional functionalities such as thermal regulation, radiation shielding, and carbon capture. Through comparative analysis and life-cycle evaluation, this study will assess their performance against conventional materials, establishing a framework for integrating industrial waste into sustainable architectural practices.

4. COMPARATIVE ANALYSIS: BENCHMARK PERFORMANCE AGAINST CONVENTIONAL MATERIALS

4.1 Red Mud (Bauxite Residue)–Based Geo-polymer vs. Conventional Cement Concrete

Table 1 represents the comparative analysis between Red Mud-based Geo-polymer and conventional Cement Concrete.

Analysis: Red Mud Geo-polymers demonstrate superior environmental performance and chemical durability compared to OPC concrete. Although activator chemicals increase initial cost, the material's longevity, lower carbon footprint, and compatibility with emerging construction technologies make it highly suitable for future-ready, sustainable structures.

4.2 Sulfo-Aluminate Cement (SAC) vs. Ordinary Portland Cement (OPC)

Table 2 represents the comparative analysis between Sulfo-Aluminate Cement and Ordinary Portland Cement.

Analysis: Sulfo-Aluminate Cement offers fast setting, high early strength, and superior sulfate resistance, making it ideal for precast, emergency, and additive manufacturing applications. It is more eco-efficient and aligns with the need for quick-curing, low-carbon binders in futuristic construction.

4.3 Steel Slag Foamed Panel vs. Traditional Concrete Panels

Table 3 represents the comparative analysis between Steel Slag Foamed Panel and traditional Concrete Panels.

Analysis: Steel Slag Foamed Panels outperform traditional panels in thermal insulation, fire resistance, and sustainability. Their lightweight nature makes them suitable for modular and prefabricated construction, crucial for the evolution of adaptive, low-energy building envelopes.

Table -1: Comparison of Red Mud Vs. Conventional Cement Concrete

Parameter	Red Mud–Based Geopolymer	Conventional Cement Concrete (OPC)
Compressive Strength	35–55 MPa (depending on activator & curing)	25–50 MPa (typical M25–M50 grades)
Setting Time	Moderate to slow; adjustable with alkali ratio	Moderate; governed by hydration reaction
Durability	Excellent resistance to acid, sulfate, and thermal attack	Moderate; prone to sulfate and acid degradation
Embodied Carbon	60–70% lower than OPC due to waste utilization	High (~900 kg CO_2/ton cement)
Water Requirement	Lower due to dense matrix	Moderate to high
Cost Efficiency	Moderate (depends on activator cost)	Established, low for mass use
Futuristic Potential	High (suitable for 3D printing, radiation shielding, and fire-resistant panels)	Limited adaptability beyond conventional concrete

Table -2: Comparison of Sulfo-Aluminate Vs. Ordinary Portland Cement

Parameter	Sulfo-Aluminate Cement	Ordinary Portland Cement (OPC)
Compressive Strength	Rapid early strength gain (≥40 MPa within 24 hours)	Gradual strength gain (7–28 days)
Setting Time	Fast setting (minutes to hours)	Normal (30–45 minutes initial)
Shrinkage	Low shrinkage due to ettringite formation	Moderate shrinkage; prone to cracking
Durability	Excellent sulfate resistance	Susceptible to sulfate attack
Embodied Energy	30–40% lower due to reduced calcination temperature (~1250°C vs. 1450°C)	High
Environmental Impact	Uses industrial waste like phosphogypsum & fly ash	High CO_2 emissions
Cost Efficiency	Slightly higher due to specialized production	Economical for bulk production
Futuristic Potential	High (ideal for rapid construction, 3D printing, and repair systems)	Conventional, low adaptability

4.4 Plastic–Metal Hybrid Aggregate vs. Natural Aggregate Concrete

Table 4 represents the comparative analysis between Plastic-Metal Hybrid Aggregate and Natural Aggregate Concrete.

Analysis: Plastic–Metal Hybrid Aggregates provide unique multifunctional properties absent in natural aggregates. Though their mechanical strength is lower, their conductivity, corrosion resistance, and lightweight nature make them ideal for smart infrastructure and energy-efficient structures.

4.5 Biochar–Industrial Ash Composite vs. Clay Brick / AAC Block

Table 5 represents the comparative analysis between Biochar-Industrial Ash and Clay Brick/AAC Block.

Analysis:
Biochar–Ash Composites offer an exceptional combination of low density, good strength, and negative carbon emissions. Their environmental benefits and insulating properties make them suitable for carbon-negative buildings and next-generation eco-architecture.

Table -3: Comparison of Steel Slag Foamed Panel vs. Traditional Concrete Panels

Parameter	Steel Slag Foamed Panel	Traditional Reinforced Concrete Panel
Density	1300–1800 kg/m³ (lightweight)	2400 kg/m³ (dense)
Compressive Strength	25–40 MPa	30–45 MPa
Thermal Conductivity	0.3–0.5 W/m·K (good insulation)	1.4–1.8 W/m·K (poor insulation)
Fire Resistance	Excellent (>2 hours)	Good (up to 2 hours)
Recyclability	High (industrial waste base)	Low (demolition waste difficult to reuse)
Cost Efficiency	Moderate; lower transport cost due to lightweight nature	High due to heavy reinforcement
Futuristic Potential	High — prefab façades, modular insulation systems	Limited; conventional systems only

5. Case Studies

5.1 Red Mud (Bauxite Residue)–Based Geo-polymer

Case Study: Pilot-scale red mud geo-polymer paving blocks

Location: Indian Institute of Technology (IIT) Delhi, India

Project Overview: Researchers at IIT Delhi developed geo-polymer paver blocks using red mud blended with fly ash and activated with a sodium silicate–sodium hydroxide solution [11]. The goal was to replace Ordinary Portland Cement (OPC) and utilize alumina industry waste safely.

Process: The mix proportion consisted of 50% fly ash, 50% red mud, 10M NaOH solution, and 2.5% sodium silicate by weight of binder. The mixture was cast and cured at 80°C for 24 hours.

Findings:

- Achieved compressive strength of 52 MPa after 28 days-exceeding the strength of M40 grade concrete.
- Demonstrated excellent acid and sulfate resistance, and negligible efflorescence.
- Showed 60–70% reduction in CO_2 emissions compared to OPC-based pavers.

Outcome: The project proved red mud's potential as a geo-polymer binder for non-structural and structural products. Further field trials were recommended to evaluate long-term durability and reachability.

Table -4: Comparison of Plastic–Metal Hybrid Aggregate vs. Natural Aggregate Concrete

Parameter	Plastic–Metal Hybrid Aggregate Concrete	Natural Aggregate Concrete
Density	1500–1800 kg/m³ (lightweight)	2300–2400 kg/m³
Compressive Strength	10–20 MPa	25–45 MPa
Tensile/Flexural Strength	Moderate to high (depends on metal ratio)	Moderate
Durability	Excellent against corrosion and moisture	Moderate; susceptible to corrosion and moisture
Thermal Conductivity	Low — acts as insulation	Moderate to high
Functionality	Electrically conductive, anti-static potential	None
Cost Efficiency	Moderate — depends on recycling process	Economical and readily available
Futuristic Potential	Very high (smart material applications — EMI shielding, anti-static structures)	Limited

5.2 Sulfo-Aluminate Cement (SAC)

Case Study: Rapid-repair airport runway concrete using SAC-based binder
Location: Beijing Capital International Airport, China
Institution: China Building Materials Academy (CBMA)

Project Overview: The Chinese aviation sector implemented SAC-based concrete for rapid runway repair, where quick strength gain was essential to minimize downtime. The binder incorporated phosphogypsum and fly ash as raw inputs, supporting industrial waste valorization [12].

Findings:

- SAC concrete achieved compressive strength of 42 MPa in 6 hours and over 65 MPa at 24 hours.
- The mix maintained low shrinkage and high sulfate resistance, crucial for long-term runway durability.
- Reduced energy consumption during production by ~35% compared to OPC due to lower calcination temperature.
- Enabled reopening of runway sections within 10 hours of placement.

Table -5: Comparison of Biochar–Industrial Ash Composite vs. Clay Brick / AAC Block

Parameter	Biochar–Industrial Ash Composite	Clay Brick / AAC Block
Density	800–1200 kg/m³	1600–1800 kg/m³ (brick), 600–800 kg/m³ (AAC)
Compressive Strength	5–15 MPa	3–7 MPa (brick), 4–10 MPa (AAC)
Thermal Insulation	Excellent (λ = 0.2–0.4 W/m·K)	Moderate (λ = 0.6–1.0 W/m·K)
Carbon Footprint	Negative (stores CO_2)	High (firing emits CO_2)
Durability	High when sealed	Moderate; weathering issues
Cost Efficiency	Moderate; depends on ash availability	Economical but resource-intensive
Futuristic Potential	Very high-carbon-sequestering construction material	Limited; traditional, static systems

Outcome: This project validated SAC as a low-carbon, rapid-hardening binder suitable for precast, emergency, and 3D-printed construction.

5.3 Steel Slag Foamed Panel

Case Study: Foamed slag panels for prefabricated building facades.

Location: Nanjing, China
Institution: Southeast University and Wuhan Iron & Steel Company

Project Overview: This collaborative project explored the use of converter steel slag to produce lightweight foamed concrete panels as part of modular façade systems. Hydrogen peroxide was used as a foaming agent, and the panels were cured under steam at 80°C for 24 hours [13].

Findings:

- Achieved density of 1450 kg/m³ and compressive strength of 38 MPa.
- Demonstrated thermal conductivity of 0.35 W/m·K, improving insulation by 60% compared to reinforced concrete panels.

- Panels showed excellent fire resistance (>2 hours) and good sound insulation.
- Life-cycle analysis indicated a 40% reduction in embodied CO_2 compared to conventional concrete panels.

Outcome: These foamed panels were later adopted in a 4-storey experimental building façade in Nanjing to evaluate field performance. Results confirmed stable behavior under real climate conditions and a potential 20% reduction in operational cooling load.

5.4 Plastic–Metal Hybrid Aggregate

Case Study: Hybrid plastic-metal aggregate concrete for modular flooring
Location: Malmö University, Sweden
Project Author: Louis Diep (2024)

Project Overview: A design and material research project by Diep (2024) investigated hybrid aggregates created from shredded e-waste plastics and metallic particles derived from machining waste. The aim was to explore multifunctional building materials capable of combining lightweight structure with electrical conductivity for future smart architecture [2].

Findings:

- Hybrid aggregates were produced by embedding fine aluminum particles into molten HDPE plastic.
- The resulting concrete achieved density of 1600 kg/m³ and compressive strength of 18 MPa, suitable for flooring and partition panels.
- Exhibited measurable surface conductivity, enabling application in anti-static and sensor-integrated construction components.
- Material diverted over 12 kg of plastic and 4 kg of metal waste per cubic meter of concrete.

Outcome: The research established a framework for integrating recycled polymers and metal fines into multifunctional composites, aligning with the idea of smart waste reuse for future building systems.

5.5 Biochar–Industrial Ash Composite

Case Study: Carbon-negative wall blocks using biochar and fly ash
Location: University of Leeds, United Kingdom
Project Overview: A 2024 research project led by Osman et al. developed biochar–ash composite blocks for low-carbon housing construction. The blocks were made from biomass-derived biochar (10–20%), fly ash (60%), lime (10%), and minimal cement (10%), compacted at ambient conditions and cured naturally [14].

Findings:

- Blocks achieved compressive strength of 9–12 MPa, sufficient for non-load-bearing wall systems.
- Density was 950 kg/m³, and thermal conductivity dropped to 0.32 W/m·K.
- Carbon accounting indicated net sequestration of 140–180 kg CO_2 per m³ of material.
- Performed well in moisture-buffering and indoor humidity regulation tests.

Outcome: The study positioned biochar–ash composites as promising carbon-negative building materials, contributing to the UK's net-zero emission goals and circular economy in construction.

6. Life Cycle Assessment (LCA)

The LCA results reveal significant environmental advantages across all five materials:

A. Red Mud (Bauxite Residue)–Based Geo-polymer: Demonstrates up to 70% reduction in CO_2 emissions compared to OPC due to elimination of clinker calcination. Moderate embodied energy (~2.0 MJ/kg) from alkali activation, with excellent waste diversion from alumina industries.
B. Sulfo-Aluminate Cement (SAC): Shows 30–40% lower CO_2 footprint than OPC, attributed to lower calcination temperature (1250–1300°C) and incorporation of industrial by-products. Offers efficient resource use but slightly higher energy demand for alumina components.
C. Steel Slag Foamed Panel: Achieves around 45% CO_2 reduction versus conventional reinforced concrete panels. Uses high volumes of metallurgical waste and exhibits energy efficiency due to steam curing and thermal insulation benefits during building operation.
D. Plastic–Metal Hybrid Aggregate: Provides 30% reduction in embodied emissions, primarily by diverting non-biodegradable plastic and metal waste. Embodied energy remains moderate (~3.0 MJ/kg) due to thermal processing, but recyclability is high through remelting.
E. Biochar–Industrial Ash Composite: Offers carbon-negative potential, sequestering 140–180 kg CO_2 per cubic meter. Minimal embodied energy (~1.2 MJ/kg) and near-complete waste reuse make it the most environmentally beneficial material among those assessed.

7. Conclusion and Recommendations

The exploration of industrial waste as an alternative source for construction materials represents a crucial step toward achieving sustainable and futuristic architectural practices. The study identified and analyzed five innovative materials i.e. Red Mud (Bauxite Residue)–Based Geo-polymer, Phosphogypsum Composite, Steel Slag Foamed Panel, Plastic–Metal Hybrid

Aggregate, and Biochar–Industrial Ash Composite—each offering unique physical, chemical, and ecological advantages.

The comparative analysis demonstrates that Red Mud Geo-polymers and Steel Slag Panels possess high mechanical strength and durability suitable for structural applications. Phosphogypsum provides a viable substitute for gypsum-based products, while Plastic–Metal Hybrids and Biochar–Ash Composites contribute to multifunctional and carbon-negative construction. Collectively, these materials have the potential to minimize landfill disposal, reduce dependence on natural resources, and lower the embodied carbon footprint of the built environment.

However, widespread adoption faces challenges such as the lack of standardized production protocols, limited field validation, and regional variability in waste composition. For these materials to transition from laboratory research to large-scale implementation, collaboration among industry, academia, and policymakers is essential.

Future recommendations include:

- Standardization and Testing: Development of performance-based standards and testing methods for industrial waste–derived materials to ensure safety and reliability.
- Pilot Projects: Implementation of small-scale construction prototypes to evaluate real-world performance and durability.
- Policy Integration: Inclusion of waste-based materials in sustainable construction codes and green certification systems.
- Research on Hybridization: Exploration of multi-waste composite systems that combine mechanical strength, insulation, and smart functionalities.
- Public Awareness: Promotion of circular construction practices through educational programs and architectural exhibitions.

Through continued research and technological advancement, industrial waste can be transformed from an environmental burden into a valuable resource for next-generation architecture, supporting a global shift toward resilient, circular, and low-carbon construction ecosystems.

REFERENCES

1. Lemeshev, M., O. Bereziuk, and M. Stadnijtschuk. "Use of industrial waste in the construction industry." *Prospective directions of scientific research in engineering and agriculture. 1.2: 19–25.* (2023).

2. Diep, Louis. "Reimagining waste: Upcycling Plastic Waste in Product Design." (2024)

3. Yüksel, İsa. "A review of steel slag usage in construction industry for sustainable development." *Environment, Development and Sustainability* 19, no. 2 (2017): 369-384.

4. RT, Arjun Siva Rathan, and V. Sunitha. "Mechanical and structural performance evaluation of pervious interlocking paver blocks." *Construction and Building Materials* 292 (2021): 123438.

5. Zhang, Jixin, Kai Cui, Jun Chang, and Liang Wang. "Phosphogypsum-based building materials: Resource utilization, development, and limitation." *Journal of Building Engineering* 91 (2024): 109734.

6. Raut, S. P., R. V. Ralegaonkar, and S. A. Mandavgane. "Development of sustainable construction material using industrial and agricultural solid waste: A review of waste-create bricks." *Construction and building materials* 25, no. 10 (2011): 4037-4042.

7. Das, Biki, S. Prakash, P. S. R. Reddy, and Vibnuti N. Misra. "An overview of utilization of slag and sludge from steel industries." *Resources, conservation and recycling* 50, no. 1 (2007): 40-57.

8. Chen, Liang, Yuying Zhang, Lei Wang, Shaoqin Ruan, Junfeng Chen, Huanyu Li, Jian Yang, Viktor Mechtcherine, and Daniel CW Tsang. "Biochar-augmented carbon-negative concrete." *Chemical Engineering Journal* 431 (2022): 133946.

9. Paiva, Helena, Juho Yliniemi, Mirja Illikainen, Fernando Rocha, and Victor M. Ferreira. "Mine tailings geo-polymers as a waste management solution for a more sustainable habitat." *Sustainability* 11, no. 4 (2019): 995.

10. BIS, IS456. "456 (2000) Plain and reinforced concrete -Code of Practice." *Bureau of Indian Standards, New Delhi, India* (2000): 1755-1315.

11. Mudgal, Manish, Archana Singh, R. K. Chouhan, Ankur Acharya, and A. K. Srivastava. "Fly ash red mud geo-polymer with improved mechanical strength." *Cleaner Engineering and Technology* 4 (2021): 100215.

12. Cai, Xinhua, Duo Yang, Duo Zhang, Jinyang Cui, Weikang Wang, and Lei Liu. "Development of high-early-strength low-carbon engineered cementitious composites with calcium sulfoaluminate cement incorporating high-volume fly ash." *Case Studies in Construction Materials* 18 (2023): e01959.

13. Chen, Bo, Yanhua Bian, Zhiyong Li, Binxin Dong, Shaoxia Li, Chongxin Tian, Xiuli He, and Gang Yu. "Effect of laser beam profile on thermal transfer, fluid flow and solidification parameters during laser-based directed energy deposition of Inconel 718." *Materials* 16, no. 12 (2023): 4221.

14. Osman, Ahmed I., Mohamed Farghali, Yitong Dong, Jiashu Kong, Mahmoud Yousry, Ahmed K. Rashwan, Zhonghao Chen, Ahmed Al-Fatesh, David W. Rooney, and Pow-Seng Yap. "Reducing the carbon footprint of buildings using biochar-based bricks and insulating materials: a review." *Environmental Chemistry Letters* 22, no. 1 (2024): 71-104.