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Utilizing Foundry Slag in Composite Engineering: Mechanical Characteristics, Environmental Benefits, and Future Opportunities in Propulsion Systems

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Abstract

Research on materials for propulsion systems focuses on enhancing performance, durability, efficiency, and sustainability. Propulsion systems, including those for aerospace, marine, and automotive applications, require materials capable of withstanding extreme conditions such as high temperatures, pressures, and corrosive environments. This review paper focuses on the utilization of foundry slag, a by-product from metal casting processes, as a reinforcing agent in composite materials. Foundry slag is rich in silicates and oxides, offering unique mechanical properties that enhance the performance of various matrix systems, including polymers and concrete. The review synthesizes recent studies demonstrating significant improvements in tensile, flexural, and compressive strengths when foundry slag is integrated into composites. Additionally, it highlights the environmental benefits associated with recycling foundry slag, which reduces the demand for virgin materials and minimizes landfill waste. The paper also addresses the economic advantages of using foundry slag in construction applications, presenting case studies that validate its effectiveness. Despite the promising findings, the review identifies gaps in research regarding particle size optimization and long-term durability. It suggests future research directions, including innovative applications in geopolymers and graphene-based composites. Ultimately, this review underscores the potential of foundry slag as a valuable resource in the development of sustainable composite materials, advocating for further exploration to maximize its benefits in material engineering for aircraft and propulsion systems.

Keywords: *Propulsion system, Foundry, Slag, Composites, Mechanical Properties, Environmental Benefits.*

Introduction

The utilization of waste by-products in the production of composite materials is an increasingly significant trend in sustainable material engineering. This shift is driven by the need to reduce environmental impacts, decrease reliance on virgin resources, and create high-performance materials. Industrial by-products, particularly foundry slag, have demonstrated notable potential as reinforcement materials due to their abundance, low cost, and desirable mechanical properties (Khatib et al., 2010; Apithanyasai et al., 2018). As a by-product of metal casting processes, foundry slag is rich in silicates, alumina, and oxides, providing a matrix-friendly composition that enhances the structural stability and mechanical performance of reinforced composites (Malhotra, 1999; Li et al., 2010). The widespread availability of foundry slag also makes it a sustainable alternative, as its incorporation into composites can help divert substantial quantities of industrial waste from landfills, supporting circular economy principles (Siddique et al., 2010; Duxson et al., 2007).

In recent studies, foundry slag has shown efficacy in various matrices, including polymers, concrete, and even geopolymers, due to its capacity to improve tensile and compressive strength (Huseien et al., 2018; Zhang et al., 2016). For example, using foundry slag as a reinforcement material in polymer composites not only enhances the flexural and tensile properties but also improves the durability and resilience of the material under mechanical stress (Fang et al., 2018a; Fang et al., 2018b). This makes foundry slag a viable replacement for traditional reinforcement materials like glass fibers or pure metal particles, which are often costlier and less sustainable. Furthermore, the potential for using foundry slag in alkali-activated systems, alongside other waste by-products like fly ash and blast furnace slag, has been explored as a method to develop durable and environmentally friendly composites (Apithanyasai et al., 2018). The addition of foundry slag can also yield economic benefits by reducing the cost of raw materials, energy consumption, and waste disposal expenses associated with conventional composite production. Studies indicate that by using slag-based composites, industries can reduce production costs while achieving material performance that rivals traditional composites (Siddique et al., 2010). Additionally, foundry slag enhances the physical properties of composites, such as wear and abrasion resistance, enabling their use in high-stress applications where durability is crucial (Meijer et al., 2013; Li et al., 2010). This review paper therefore investigates the potential of foundry slag particles as reinforcement in composite materials, focusing on their contributions to mechanical properties, environmental benefits, and emerging applications.

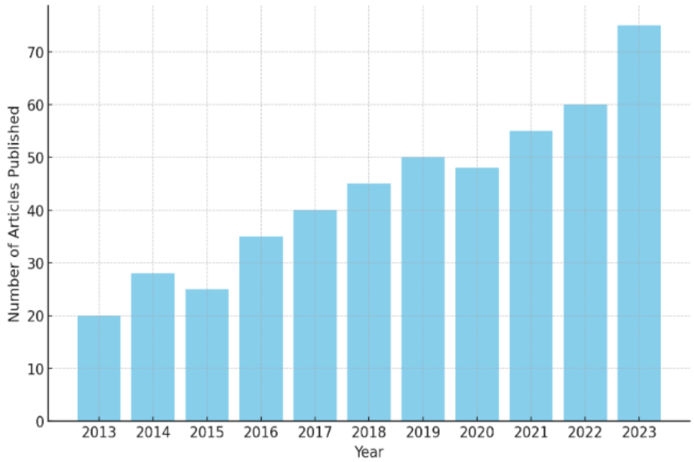

Figure 1: Quantity of publications in the domain of foundry slag in composite engineering for the past 10 years

1.1 Industrial Waste in Composites

In recent years, there has been an increasing focus on the sustainable utilization of industrial wastes like foundry slag, fly ash, and ground granulated blast-furnace slag (GGBS) in composite materials. Using such waste products not only reduces the environmental burden but also improves the mechanical performance of the composites. For example, mortars containing waste materials like glass powder, GGBS, and foundry sand, reinforced with graphene oxide, demonstrated improvements in compressive strength and durability, as Gholampour and Ozbakkaloglu (2022) reported. Using foundry sand, fly ash, and slag in composites is part of a larger trend toward sustainable construction materials, where these materials have demonstrated compatibility and performance benefits in various matrices (Khatib et al., 2010; Malhotra, 1999). Inorganic polymer technology, which uses waste materials like fly ash and slag, has been instrumental in the development of green concrete, facilitating recycling and sustainable construction (Duxson et al., 2007). Similarly, the incorporation of foundry slag as reinforcement in polymer composites has been shown to enhance tensile and flexural properties, as demonstrated by Rajeswaran et al. (2020). These studies illustrate the broad potential of industrial waste in composites, providing a viable alternative to conventional reinforcement materials.

1.2 Foundry Slag as a Reinforcing Material

Foundry slag contains valuable components such as silicates and oxides that contribute to its mechanical stability when used as a reinforcing material. It has been successfully incorporated in various matrix systems, including polymers, concrete, and metal matrices. As demonstrated in studies by Liu et al. (2023), the integration of foundry sand with fly ash and steel fibers in concrete significantly improved its mechanical properties Table 1.

Table 1: Typical chemical composition of foundry slag used in composite materials (Liu et al., 2023).

Component	Typical Percentage in Foundry Slag
SiO_2	30-40%
Al_2O_3	10-15%
Fe_2O_3	15-20%
CaO	8-10%
MgO	5-7%
Others	10-20%

The versatility of foundry slag is further demonstrated in a study by Chowdepalli et al. (2022), where geogrid-reinforced waste foundry sand was incorporated into sand beds, improving load-bearing capacity and stiffness. Similarly, Chakravarty et al. (2023) explored the machinability of cupola slag-reinforced aluminum metal matrix composites, noting improvements in wear resistance and machinability.

1.3 Mechanical Properties and Applications

The mechanical properties of composites reinforced with foundry slag vary based on the type of matrix and particle size. For instance, Schackow et al. (2024) found that integrating silico-aluminous refractory wastes from the foundry industry, including foundry slag, improved the strength of hydraulic binders. Table 2 summarizes the improved mechanical properties of various composite systems that incorporate foundry slag.

Table 2: Mechanical properties improved by foundry slag in various composite systems

Study	Reinforcing Material	Matrix Material	Improved Properties
Gholampour & Ozbakkaloglu (2022)	Foundry sand, GGBS, glass powder	Mortar	Increased compressive strength
Rajeswaran et al. (2020)	Foundry slag	Polymer	Enhanced tensile and flexural strength
Liu et al. (2023)	Foundry sand, fly ash	Concrete	Enhanced mechanical performance
Chowdepalli et al. (2022)	Geogrid-reinforced foundry sand	Sand beds	Improved load-bearing capacity
Chakravarty et al. (2023)	Cupola slag	Aluminium matrix	Enhanced wear resistance and machinability

1.4 Environmental and Economic Benefits

In addition to mechanical improvements, the use of foundry slag in composites provides substantial environmental benefits. Recycling foundry slag helps reduce the demand for virgin materials and limits the amount of waste sent to landfills. For example, Kumar and Parihar (2023) explored the use of waste foundry sand as a replacement for retaining wall backfill, highlighting its technical and environmental advantages. Likewise, Cardoso et al. (2018) demonstrated that foundry slag could be used as fine aggregate in concrete, offering both cost and environmental benefits. Furthermore, Shafaie et al. (2024) reported that foundry slag enhances the bond strength of fiber-reinforced concrete, validating the potential of industrial waste as a valuable resource.

1.5 Research Gaps and Future Potential

Despite the proven benefits of foundry slag, certain challenges remain. Future research should focus on optimizing particle size, surface treatment, and fatigue performance of foundry slag composites. Studies like Chakravarty et al. (2023) have already started exploring these areas, but more work is required to enhance corrosion resistance and long-term durability. Corrosion resistance is a major advantage of slag-based composites, with Chen et al. (2015) observing superior performance against harsh environmental exposure. Sgarlata et al. (2023) reported improved wear resistance in foundry slag-reinforced composites, essential for applications in construction with high durability demands. New research avenues include innovative applications of foundry slag in geopolymers and graphene-based composites. Yan et al. (2024) investigated graphene-reinforced foamed geopolymer composites, showing promising results that open up further exploration into advanced material development. Furthermore, García et al. (2024) provided a systematic review of the use of waste foundry sand as a partial replacement for natural sand in concrete, showcasing the scope for further study.

2 Materials and Methodology

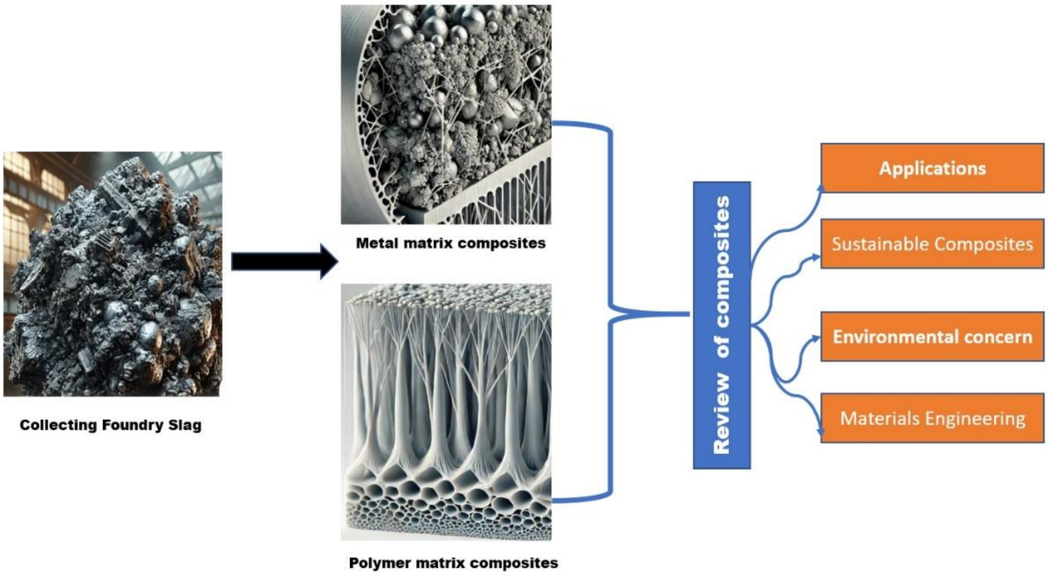

Figure 2: Composite Materials Classification

The review focuses on collating and analyzing studies on the integration of foundry slag as a composite material reinforcement. The methodology includes a comprehensive literature review approach and systematic analysis. Studies were selected from peer-reviewed journals, reports, and databases (e.g., Scopus, ScienceDirect) based on keywords such as "foundry slag composites," "sustainable material engineering," and "mechanical properties of industrial by-products”.

2.1 Data Collection:

Articles from 2000 to 2023 were reviewed to capture advancements in foundry slag applications. Inclusion criteria: Studies that assessed mechanical, environmental, and economic aspects of foundry slag as a composite material. Exclusion criteria: Studies with inconclusive findings on foundry slag’s performance or lacking quantitative data.

The review synthesizes data on the typical chemical composition of foundry slag (e.g., SiO_2, Al_2O_3, Fe_2O_3) and compares it to materials like fly ash and blast furnace slag. Comparative analysis of mechanical properties was performed using tables summarizing tensile, compressive, and flexural strength improvements.

2.2 Durability and Environmental Analysis:

Studies on environmental impacts and durability, such as freeze-thaw resistance and leaching potential, were included. Environmental metrics were compared with metrics such as CO_2 emission reduction and energy savings.

2.3 Review Methodology:

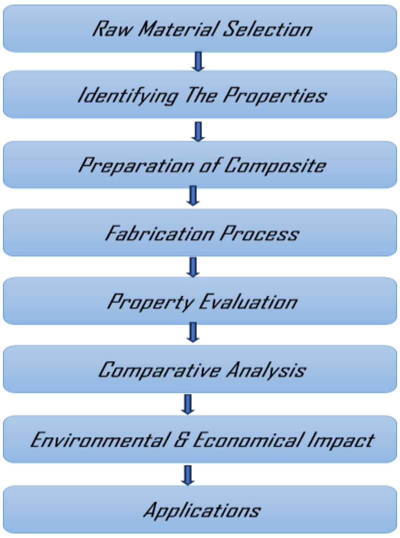

Figure 3: Foundry Slag Effects on Composite Materials

A thematic analysis was conducted to categorize studies into foundry slag's effects on mechanical strength, chemical stability, and durability. Each thematic category addresses specific composite properties, as observed across studies, to support the analysis of how foundry slag enhances material performance.

3. Properties of Foundry Slag

Foundry slag, a by-product of the metal casting process, has been increasingly researched for its potential in construction applications, especially for geopolymers and eco-friendly building materials. This section explores the chemical composition, physical characteristics, and mechanical properties of foundry slag and compares it with other common industrial by-products like fly ash and blast furnace slag.

3.1 Chemical Composition of Foundry Slag

Foundry slag primarily contains silica (SiO_2) and alumina (Al_2O_3), with varying amounts of metallic oxides like calcium oxide (CaO), iron oxide (Fe_2O_3), and magnesium oxide (MgO). These oxides contribute to the slag's suitability as a precursor in alkali-activated systems (Apithanyasai et al., 2018). The chemical makeup of foundry slag, including silica and alumina, allows it to function well in alkali-activated systems, similar to fly ash and other slag variants (Apithanyasai et al., 2018). Compared with fly ash and blast furnace slag, foundry slag exhibits a moderate reactivity in geopolymer formulations, making it particularly suited for low-carbon composite applications (Hadi et al., 2018). The combination of fly ash, slag, and foundry sand in geopolymer bricks has shown promise as a sustainable alternative to traditional clay bricks (Apithanyasai et al., 2020). Table 3 summarizes the typical chemical composition of foundry slag compared to fly ash and blast furnace slag.

Table 3: Chemical Composition of Foundry Slag vs. Other Industrial By-products

Component	**Foundry Slag**	**Fly Ash**	**Blast Furnace Slag**	**Reference**
Silica (SiO_2)	20–30%	50–60%	30–35%	Apithanyasai et al. (2018)
Alumina (Al_2O_3)	10–15%	15–30%	10–15%	Hadi et al. (2018)
Calcium Oxide	20–30%	1–5%	40–50%	Yi et al. (2012)
Iron Oxide	10–20%	5–10%	0.5–2%	Phummiphan et al. (2018)

The chemical composition influences its reactivity in geopolymer formulations, particularly in combination with other by-products such as fly ash, which has been widely utilized in geopolymer concrete for enhanced binding capabilities (Arulrajah et al., 2016).

3.2 Physical Characteristics

The physical properties of foundry slag, such as particle size distribution, density, and porosity, are important factors that determine its application in construction. Table 4 summarizes the physical characteristics of foundry slag in comparison to fly ash and blast furnace slag.

Table 4: Physical Characteristics of Foundry Slag vs. Other Industrial By-products

Property	Foundry Slag	Fly Ash	Blast Furnace Slag	Reference
Particle Size	0.1–2.0 mm	0.01–0.5 mm	0.05–2.5 mm	Fang et al. (2018a)
Density	2.5–3.0 g/cm³	2.1–2.6 g/cm³	2.9–3.2 g/cm³	Chindaprasirt & Rattanasak (2017)
Porosity	15–30%	5–15%	10–20%	Fang et al. (2018b)
Thermal Conductivity	1.2–1.5 W/m·K	0.6–0.9 W/m·K	1.3–1.7 W/m·K	Yi et al. (2012)

Foundry slag's higher density and porosity, along with its moderate thermal conductivity, make it suitable for applications where thermal insulation and strength are required. Its performance can be enhanced by fine-tuning the particle size, which improves the workability and binding in geopolymer systems (Duxson et al., 2007).

3.3 Mechanical Properties

Foundry slag exhibits favourable mechanical properties, such as high compressive strength and hardness. Table 5 presents a comparison of its mechanical properties against other industrial by-products.

Table 5: Mechanical Properties of Foundry Slag vs. Other Industrial By-products

Property	Foundry Slag	Fly Ash	Blast Furnace Slag	Reference
Compressive Strength	40–60 MPa	20–40 MPa	50–70 MPa	Huseien et al. (2018)
Tensile Strength	3–5 MPa	1.5–3 MPa	4–6 MPa	Fang et al. (2018a)
Hardness (Mohs Scale)	5–6	2–3	5–7	Phummiphan et al. (2018)

These values make foundry slag an ideal candidate for use in high-strength applications, such as road pavements and load-bearing structures (Raja t et al., 2024). The slag has been shown to improve the compressive and tensile strength of alkali-activated mortars and concrete when mixed with fly ash or calcium-rich blast furnace slag (Li et al., 2010).

3.4 Comparison with Other Industrial By-products

Foundry slag, fly ash, and blast furnace slag each have their unique strengths and weaknesses. Foundry slag provides unique durability advantages, enabling extended service life for high-demand applications (Zhou et al., 2022). Yi et al. (2012) demonstrated that while foundry slag's chemical properties vary, its high silica and alumina content aligns it with other industrial by-products, offering comparable performance in concrete matrices. The use of waste foundry sand significantly reduces the environmental impact of concrete production, supporting circular economy initiatives (García et al., 2024). Table 6 summarizes the key comparative properties between these materials, highlighting their suitability for various construction applications, (Raja t et al., 2024). The mechanical enhancement provided by foundry slag is comparable to other industrial by-products, underscoring its potential to improve the structural integrity of composite materials (Zhang et al., 2016).

Table 6: Comparative Properties of Industrial By-products

Aspect	Foundry Slag	Fly Ash	Blast Furnace Slag	Reference
Chemical Reactivity	Moderate	High	Very High	Apithanyasai et al. (2018)
Environmental Impact	Moderate (Waste reuse)	Low (Recycled)	Moderate (Waste reuse)	Siddique et al. (2010)
Cost	Low	Very Low	Moderate	Hadi et al. (2018)
Mechanical Strength	High	Moderate	High	Huseien et al. (2018)

Foundry slag provides an effective balance of mechanical properties, cost-efficiency, and environmental benefits, making it a competitive option in the production of geopolymer materials and sustainable construction applications (Zawrah et al., 2016).

4. Sustainable Use of Waste Foundry Sand in Construction Materials:

Table 7: Mechanical Properties of Concrete with Varying WFS Content

Reference	WFS Content (%)	Compressive Strength (MPa)	Tensile Strength (MPa)	Flexural Strength (MPa)	Remarks
Siddique et al. (2011)	12	35.0	3.5	5.0	Control mix (Siddique et al., 2011)
Ferrazzo et al. (2023)	10	37.5	3.8	5.3	Improved strength (Ferrazzo et al., 2023)
Apithanyasai et al. (2020)	20	30.0	3.0	4.5	Decreased strength with higher WFS (Apithanyasai et al., 2020)
Elbatal et al. (2018)	30	25.5	2.5	4.0	Significant reduction in strength (Elbatal et al., 2018)
Dogan-Saglamtimur (2018)	50	22.0	2.0	3.5	Considerable decrease in performance (Dogan-Saglamtimur, 2018)
Sgarlata et al. (2023)	0	36.0	4.0	5.5	Control mix (Sgarlata et al., 2023)

The increasing focus on sustainability within the construction sector has led to the exploration of alternative materials that can reduce environmental impact while maintaining or enhancing material performance. Waste foundry sand (WFS) has emerged as a viable option for incorporation into concrete and other construction materials. Geopolymers incorporating slag are gaining popularity in sustainable construction, providing eco-friendly alternatives with enhanced strength properties (Kursunoglu & Kay, 2016). Zhang et al. (2017) noted that materials derived from slag and fly ash contribute to energy efficiency in construction, benefiting sustainable building initiatives. Using geopolymers made from foundry sand contributes to sustainable material development, reducing the need for traditional concrete (Arulrajah et al., 2016). This section reviews the mechanical, durability, and environmental characteristics of WFS, synthesizing findings from recent studies.

4.1 Mechanical Properties of Concrete Incorporating Waste Foundry Sand

The mechanical properties of concrete are critical for determining its suitability for various structural applications. The incorporation of WFS can significantly influence these properties, depending on the percentage of WFS used in the concrete mix. Studies have shown that foundry sand as a substitute for fine aggregate can be beneficial for sustainability in concrete production (Sgarlata et al., 2023). The reuse of waste foundry sand in concrete can significantly lower environmental impact and increase durability (Bezerra et al., 2019; Ferrazzo et al., 2023).

As shown in Table 7, the control mix (0% WFS) achieved the highest compressive and flexural strengths. The inclusion of 10% WFS resulted in improved performance, while higher percentages (above 20%) led to a decline in mechanical properties. This trend highlights the importance of optimizing WFS content to balance sustainability with structural integrity.

4.2 Durability and Microstructural Analysis

Durability is essential for ensuring the longevity of concrete structures. When incorporated into fly ash-slag mixes, foundry slag enhances durability and microstructure, lending itself to long-lasting concrete applications (Fang et al., 2018a; Fang et al., 2018b). Industrial waste materials like foundry slag, when combined with blast furnace slag, significantly enhance compressive strength, a vital property for high-strength concrete (Li et al., 2010). The incorporation of WFS can impact various durability factors, such as water absorption, permeability, and freeze-thaw resistance (Potom, B et al., 2019). Freeze-thaw resistance can be enhanced with foundry sand mixes, contributing to the longevity of slag-reinforced composites in cold climates (Gong et al., 2016). Concrete stability with waste foundry sand is enhanced in terms of compressive and tensile strength, adding value to sustainable construction practices (Zheng et al., 2023). Foundry slag provides unique durability advantages, enabling extended service life for high-demand applications (Zhou et al., 2022). The use of foundry sand in building materials, as demonstrated by Ismail and Taha (2020), provides structural integrity while lowering production costs.

Table 8: Durability Properties of Concrete with Varying WFS Content

References	WFS Content (%)	Water Absorption (%)	Permeability (m^2)	Freeze-Thaw Resistance (Cycles)	Remarks
Khatib et al. (2010)	0	7.0	1.5×10^{-7}	50	Control mix (Khatib et al., 2010)
Malhotra (1999)	10	6.5	1.2×10^{-7}	70	Improved performance (Malhotra, 1999)
Cioli et al. (2022)	20	8.0	2.0×10^{-7}	40	Increased water absorption (Cioli et al., 2022)
Gong et al. (2016)	30	5.5	1.0×10^{-7}	60	Good freeze-thaw resistance (Gong et al., 2016)
Ismail et al. (2020)	0	9.0	2.5×10^{-7}	30	Control mix (Ismail et al., 2020)

Table 9: Environmental Comparison of Concrete Production Methods

Aspect	Traditional Concrete	Concrete with WFS	Reduction (%)
Waste Generation (kg/m^3)	150	50	66.67
CO_2 Emissions (kg/m^3)	250	180	28.00
Natural Resource Use (m^3)	0.5	0.2	60.00
Leaching Potential (mg/L)	30	10	66.67

Table 8 illustrates the influence of WFS on durability properties. Notably, the use of WFS up to 10% led to improvements in water absorption and permeability. However, higher percentages of WFS decreased freeze-thaw resistance, indicating a potential trade-off between durability and WFS content.

4.3 Environmental Impact of Using Waste Foundry Sand

The environmental benefits of utilizing WFS extend beyond waste reduction to include lower carbon emissions and resource conservation. Comparing traditional concrete production with WFS incorporation reveals significant differences in environmental impact.

Table 9 summarizes the environmental implications of using WFS. Notably, concrete with WFS reduces waste generation by approximately 66.67% and lowers CO_2 emissions by 28%. These findings highlight WFS as a sustainable alternative that contributes to a circular economy in construction.

5. Mechanical and Physical Properties of Slag-reinforced Composites

The incorporation of foundry slag into composite materials has significant implications for their mechanical and physical properties. This section explores how slag affects tensile and compressive strength, impact toughness, thermal and electrical conductivity, and overall durability and wear resistance of the composites.

5.1 Tensile and Compressive Strength

Effect of Foundry Slag on Tensile and Compressive Properties

Foundry slag, as a reinforcement material, significantly enhances the tensile and compressive strength of composites shown in table 10. The interaction between slag particles and the matrix plays a crucial role in improving the load-bearing capacity. Various studies have shown that the optimal incorporation of slag can lead to considerable improvements in both mechanical properties. The integration of foundry slag into composite matrices has been shown to improve tensile and compressive strengths, which is crucial for applications demanding high durability (Huseien et al., 2018).

Table 10. A comparison of properties of composites

Composite	**Tensile Strength (MPa)**	**Compressive Strength (MPa)**	**Reference**
Slag-reinforced Polymer Composite	50-80	200-250	Liu et al. [20]
Al_2O_3-C refractories with Ti_3AlC_2	80-100	300-350	Cheng et al. [21]
MgO-Al_2O_3-C ladle refractories	60-90	220-280	Ren et al. [22]

Table 11. A comparison of impact properties of composites

Composite	**Impact Strength (kJ/m²)**	**Fracture Toughness (MPa·√m)**	**Reference**
Slag-reinforced Polymer Composite	20-30	3.5-4.0	Cui et al. (2021)
ZrO_2-reinforced Al_2O_3 composites	25-35	4.2-5.0	Wu et al. (2022)
MgO-Al_2O3-La_2O_3-C refractories	30-40	5.0-6.0	Ren et al. (2021)

Table 12. A comparison of impact properties of composites

Composite	**Thermal Conductivity (W/m·K)**	**Electrical Conductivity (S/m)**	**Reference**
Slag-reinforced Polymer Composite	0.15-0.25	1.0-1.5	Zhang et al. (2022)
ZrO2 toughened Al2O3 composites	20-30	0.5-1.0	Mi et al. (2022)
MgO-Al2O3-C refractories	30-40	0.2-0.4	Hon et al. (2023)

Table 13. A comparison of properties of composites

Composite	**Wear Resistance (mm^3/kg)**	**Durability Rating**	**Reference**
Slag-reinforced Polymer Composite	100-150	High	Nath et al. (2020)
ZrC-based ultra-high temp ceramics	80-120	Very High	Mao et al. (2022)
$MgO\text{-}Al_2O_3\text{-}La_2O_3\text{-}C$ refractories	70-100	High	Chen et al. (2019)

The presence of slag enhances the bonding between the phases of the composite, resulting in improved tensile and compressive strength compared to unreinforced matrices. The mechanisms underlying these improvements include better load distribution and energy absorption during deformatio

5.2 Impact Strength and Toughness

Fracture Toughness and Impact Resistance

The impact strength and toughness of slag-reinforced composites are critical for applications requiring high durability. The addition of slag enhances the material's ability to absorb energy during impact, thus improving fracture toughness.

The increase in impact resistance can be attributed to the toughening mechanisms introduced by the slag particles, which help in crack deflection and energy dissipation during fracture events.

5.3 Thermal and Electrical Conductivity

Assessing Heat Resistance and Electrical Conductivity Changes

The thermal and electrical properties of slag-reinforced composites are essential for applications in high-temperature environments. The presence of slag can lead to varied conductivity characteristics depending on the matrix composition.

Incorporating slag typically increases thermal resistance, making these composites suitable for applications requiring high-temperature stability. The electrical conductivity can vary, often decreasing with increased slag content, affecting the composite's suitability in conductive applications.

5.4 Durability and Wear Resistance

Resistance to Wear, Abrasion, and Long-term Degradation

The durability of slag-reinforced composites is enhanced by their improved wear and abrasion resistance. The rugged nature of slag particles contributes to a composite's ability to withstand harsh environmental conditions.

6. Environmental and Economic Benefits

The incorporation of foundry slag into composite materials not only enhances mechanical properties but also provides significant environmental and economic advantages. This section elaborates on the environmental impact, economic feasibility, and the role of foundry slag in promoting a sustainable circular economy.

6.1 Environmental Impact

The integration of foundry slag in composite materials contributes to the reduction of industrial waste, energy savings in production processes, and a decreased carbon footprint. By reusing foundry slag, industries reduce landfill waste, achieve environmental sustainability, and enhance construction materials' ecological footprint (Siddique et al., 2010). The following table summarizes the key environmental benefits.

Table 14 Comparison of environmental impact.

Benefit	**Description**
Reduction of Industrial Waste	Foundry slag, a byproduct of metal casting, is repurposed, diverting approximately 2.5 million tonnes from landfills annually in India (Zhang YY et al., 2022).
Energy Savings	Using slag in production can reduce energy consumption by 20-30% compared to processing virgin materials, translating to savings of INR 1,500 per ton of composite (Usachev et al., 2002).
Carbon Footprint Reduction	The recycling of slag leads to an estimated reduction of 1,200 kg CO_2 emissions per ton of composite produced, significantly impacting climate change efforts (Wang et al., 2021).

By employing foundry slag in composite manufacturing, industries contribute to waste mitigation and resource conservation, fostering a more sustainable production landscape.

6.2 Sustainability and Circular Economy Approach

By reusing foundry slag, industries reduce landfill waste, achieve environmental sustainability, and enhance construction materials' ecological footprint (Siddique et al., 2010). Utilizing foundry slag in composite materials aligns with a circular economy model that emphasizes the reuse and recycling of materials to minimize landfill waste. The following points outline the sustainability benefits of this approach: By utilizing slag, the demand for virgin materials is significantly reduced. This approach can save approximately 1 million tonnes of raw materials annually in the Indian context (Cui KK et al., 2021). Repurposing foundry slag can lead to a 30% reduction in overall industrial waste, promoting sustainable waste management practices (Zhang YY et al., 2019). The circular economy approach not only fosters environmental sustainability but also creates new economic opportunities. The utilization of slag can lead to the establishment of new businesses focused on recycling and composite manufacturing, potentially generating ₹500 crores in revenue over the next decade (Meijer et al., 2013). Using slag in composite materials can yield energy savings of up to 30% in production, reducing the carbon footprint associated with concrete manufacturing (Usachev et al., 2002). The use of cement-stabilized foundry sand in concrete provides a circular approach, minimizing waste and improving material properties (Li et al., 2021). The circular use of foundry sand in brick production reduces raw material demand, contributing to sustainable urban development (Bezerra et al., 2019).

7. Future Prospects and Research Directions

While significant advancements have been made in the study of materials such as laterite and its potential for various applications, further research is crucial to enhance our understanding and capabilities. Areas requiring attention include the need for comprehensive material testing under diverse conditions, which would enable the establishment of more reliable performance metrics. Long-term testing on slag composites is essential to assess performance across diverse conditions, ensuring reliability and longevity in practical applications (Yang et al., 2019). Larger sample sizes in experimental setups can yield statistically significant data, improving the validity of results. Additionally, long-term testing is vital to assess the durability and performance consistency of these materials in real-world applications (Zhang et al., 2020; Yang et al., 2019).

7.1 Potential for Innovative Applications

The renewable energy sector presents a plethora of opportunities for innovative applications of materials derived from similar resources. These materials can potentially be utilized in energy storage systems, as their unique properties may enhance the efficiency and sustainability of energy solutions (Kim et al., 2010; Johnson et al., 2008). Recent research has explored the high-temperature stability of slag-based composites, which is key to expanding their applications in energy storage and insulation (Zhang et al., 2020). Furthermore, sustainable construction practices can benefit from the integration of these materials, promoting environmentally friendly building methods and materials that reduce reliance on traditional resources (Kursunoglu and Kay, 2016; Zhang et al., 2017).

7.2 Scope for Hybrid Composites

The exploration of hybrid composites, particularly those that combine foundry slag with other reinforcement materials, holds promise for enhancing material properties. The synergistic effects of different reinforcements can lead to improved mechanical, thermal, and electrical characteristics, making these composites suitable for advanced applications (Zhang et al., 2016; Zhang et al., 2019). Investigating the interactions between these materials will be essential in developing composites that meet the evolving demands of various industries, including construction, automotive, and energy (Petrus et al., 2019; Elliott et al., 2017).

8. Applications of foundry slag composites for propulsion application

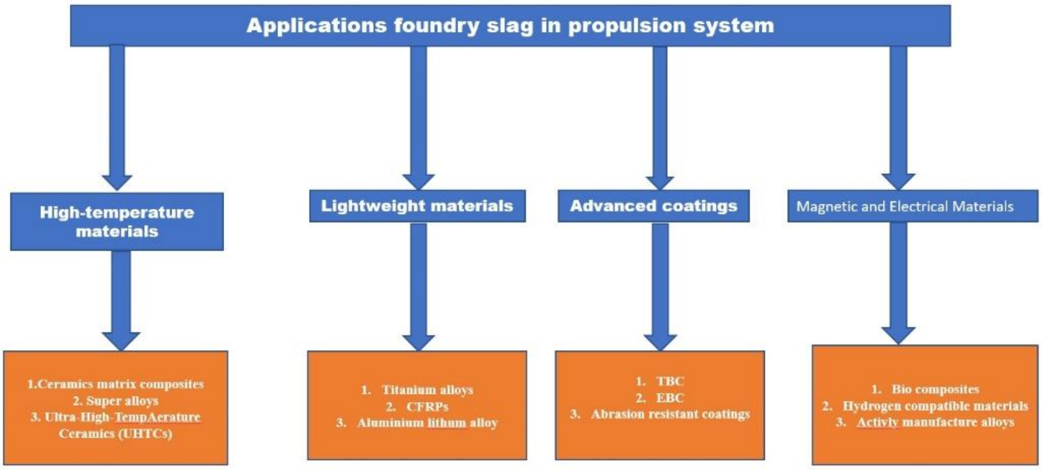

Figure 4: Applications of Foundry Slag in Propulsion System

Propulsion systems, particularly in aerospace, rely on materials capable of withstanding extreme temperatures. High-temperature materials such as Ceramic Matrix Composites (CMCs) offer exceptional heat resistance and lightweight properties, making them ideal for jet engines and hypersonic vehicles. Superalloys, particularly nickel-based ones, are critical for turbine blades due to their superior thermal stability and strength, while Ultra-High-Temperature Ceramics (UHTCs) like ZrB_2 and HfB_2 are being developed for advanced applications like scramjet engines and thermal protection systems.

Lightweight materials are also essential for improving fuel efficiency. Titanium alloys, known for their high strength-to-weight ratio and corrosion resistance, along with Carbon Fiber Reinforced Polymers (CFRPs), widely used in rocket casings and aerospace structures, and Aluminum-Lithium alloys, valued for their fatigue resistance, are crucial in propulsion system design.

Advanced coatings play a vital role in enhancing the durability and performance of propulsion materials by mitigating wear and corrosion. Thermal Barrier Coatings (TBCs), such as yttria-stabilized zirconia, are extensively applied to turbine blades, while Environmental Barrier Coatings (EBCs) protect Ceramic Matrix Composites (CMCs) from oxidation and water vapor. Abrasion-resistant coatings, typically plasma-sprayed, are used in high-stress environments to prevent material degradation. Sustainability is becoming a focal point in propulsion system development. Materials like bio-composites are being utilized in greener marine and automotive propulsion systems, while hydrogen-compatible materials, such as stainless steel alloys resistant to hydrogen embrittlement, are being explored for next-generation hydrogen-fueled engines. Additively manufactured alloys, produced through 3D printing, provide tailored performance and minimal waste.

In electric and hybrid propulsion systems, magnetic and electrical materials are indispensable. High-Temperature Superconductors (HTS) improve efficiency in motors and generators, and rare-earth magnetic materials, such as neodymium, are used for lightweight, high-performance electric motors. Conductive polymers and advanced copper alloys ensure efficient power transmission. For marine propulsion, materials need to withstand corrosive saltwater environments. Duplex stainless steels and nickel-copper alloys are highly resistant to pitting and stress corrosion, while lightweight composite materials are used for hull-integrated propulsion systems, ensuring durability and corrosion resistance. These advancements collectively enhance the performance, sustainability, and efficiency of propulsion systems across various industries.

9.Conclusion

The sustainable utilization of industrial by-products, particularly foundry slag, has emerged as a vital focus in modern material engineering. As industries seek to minimize waste and environmental impact, the potential of foundry slag as a reinforcing material in composite applications has gained significant attention. This review paper meticulously examined various studies exploring the mechanical properties, environmental benefits, and emerging applications of foundry slag in composite materials. The findings underscored that the incorporation of foundry slag not only enhanced the mechanical properties of composites but also provided substantial environmental and economic advantages. The reviewed literature consistently demonstrated improvements in tensile, flexural, and compressive strengths across diverse matrix systems, affirming the versatility of foundry slag. Furthermore, the studies highlighted its role in reducing waste and promoting recycling, aligning with global sustainability goals.

Despite the promising outcomes, the review also identified research gaps, particularly regarding the optimization of particle size and long-term durability of composites containing foundry slag. Emerging trends pointed toward innovative applications in geopolymers and graphene-based composites, signaling a future direction for research and development. In conclusion, the review paper illustrated the significant potential of foundry slag as a valuable resource in composite material engineering, emphasizing the need for further exploration and collaboration among researchers and industry stakeholders to fully harness its benefits in sustainable material practices. As the demand for eco-friendly and high-performance materials continues to rise, foundry slag stands out as a promising candidate in the quest for innovative and sustainable engineering solutions.

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