# Applicability of Industrial Wastes in Metal Matrix Composites Production – A Review

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**Abstract:** The review study is to investigate the possibility of utilizing industrial waste materials as a strengthening component in the manufacturing of metal-matrix composites (MMCs) and assess the associated environmental benefits. The study focused on examining two distinct sets of waste materials: metal matrix composites that were reinforced with fly ash, and composites produced from different kinds of industrial waste materials. Technical and property-related data were reviewed to evaluate the potential of these waste materials in MMC production. The study results indicated that fly ash-reinforced metal-matrix composites exhibited exceptional physical and mechanical properties, which make them well-suited for various applications, particularly in the automotive sector. The research highlights the necessity for further studies to innovate advanced materials with improved properties while mitigating environmental pollution. Overall, the research demonstrates the potential of utilizing industrial waste materials as reinforcement in MMC production and underscores the importance of this approach for the future development of advanced materials.

**Keywords**: Industrial waste materials; Metal matrix composites; casting; materials engineering

## 1.0 Introduction

Concerns about environmental pollution are raised by an ongoing rise in industrial waste, which puts people and animals at risk of poisoning, and plants at risk of contamination [1-3] Solid wastes are unwanted or worthless solid materials created by various industrial, commercial, and residential activities [4-6] They may be categorized according to how they were made (at home, in an industrial setting, business, structure or an institution), what was inside of them (paper, glass, organic materials, metal, plastic, etc.), or even whether they posed a risk (toxic, non-toxic, flammable, radioactive, infectious, etc.), as shown in Figure 1.

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Therefore, an objective and informed evaluation of waste materials is essential to make sustainable decisions. A thorough and systematic analysis is needed to identify potential benefits and challenges.

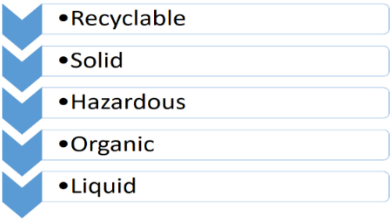

Figure 1: Flow diagram showing waste materials categorization [7]

Recycling is the process of removing objects from the trash stream so that they can be used as raw materials to create new products. Recycling can be achieved through the direct use of recyclable materials or using waste as a raw material for new goods, thus reducing the demand for new raw materials like metals, oil and forests hence, minimizing the environmental impact of resource extraction. The adoption of trash reduction and waste reuse or recycling techniques can have a positive impact on the environment in several ways. They lessen or prevent the release of pollutants, the production of greenhouse gases, the need for waste treatment technologies, and the need for landfill space [5, 8]. Therefore, these techniques should be used and included in the waste management plan. Global habitat destruction is mostly caused by the extraction of virgin materials. For instance, the demand for paper and cardboard is endangering old-growth forests.

To make products, raw materials must be refined and processed. These activities consume a significant quantity of energy and hazardous chemicals. For instance, 8 tons of bauxite (mineral ore) and 4 tons of chemicals are required to produce 1 ton of aluminium and the energy required to produce a recycled aluminium can is 95% lower than that required to produce a can from virgin resources [9]. Another current illustration is the need for extremely high temperatures to produce a full reaction when silicon carbide (SiC) is synthesized by the Acheson process and used as a typical reinforcement in aluminium matrices. Energy is consumed in substantial amounts during the production of the specified granulated final product from SiC and involves the controversial environmental concern of carbon monoxide (CO) emissions generated during the grinding process [10].

Metal matrix composites (MMCs), which have set the standard for remarkable physical and mechanical qualities, are among the innovative materials that could be developed from some industrial wastes, such as fly ash (FA). This is in addition to the potential applications that are being researched in several fields, such as energy production. The original use of MMCs, which focused only on their structural or mechanical characteristics, has changed to include a variety of purposes, new ideas, and even their definition. The term Metal Matrix Composites "MMC" refers to a substance that, after going through the proper manufacturing processes, is made up of two or more distinct engineering constituents at the macro-, micro- or nanoscale levels. These constituents are different from one another in terms of both chemical composition and morphology/geometry (such as platelets, fibers, flakes, particles etc.) [11].

The assembly can be set up in a variety of ways, such as a multilayer panel or monolith, films or coatings with sandwich structures, or functionally graded structures. The layers may be equal, vary in size and depth, or a combination of both. The reinforcing, thermal, or functional phases, which may be "in-situ," "ex-situ" or both, dependent on their origin, are played by one or more components, while the metallic matrix is played by another. A (structural, multifunctional, or functional) material is created when the constituent parts of a composite work together to maximize and exploit their strengths. This results in features that the constituent parts could not achieve on their own [11].

## 2.0 Waste Materials

Waste materials are discarded after their original intended uses have been achieved [12]. Waste materials are classified depending on various reasons. The various utilizations of waste materials are discussed in subsections 2.1 – 2.3.

### 2.1 Composites from Waste Materials

In 1976, a pioneering group of researchers [13] successfully created non-metallic reinforcements for aluminum alloy matrices using solid waste materials. These non-metallic constituents comprised solid waste slag, silica sand, glass SiC, TiC, $Si_3N_4$ and $Al_2O_3$. The researchers discovered that while alloys with a pure matrix had slightly higher average friction coefficients, they wore out faster than composites with 10% or more of these hard non-metals. When compared to the pure matrix alloy, composites with soft particles, such as MgO and boron nitride, performed worse in terms of wear. Despite this, researchers observed that the strength indices of the composites were equivalent to those of the matrix alloy. The addition of fibers, mica flakes and other non-metallic particles also considerably improved the composites' ductility and tensile strength. Another study [14] reviewed various literature works on the use of waste glass fiber in developing polymer composites. Hence, composites could be produced from waste materials including industrial wastes and agricultural wastes [14-18] with some remarkable physicomechanical and tribological properties resulting from the products produced.

### 2.2 Waste Materials as Matrices

Metal scrap may melt and sinter, which makes it more desirable for use in MMC matrix production. Nickel-iron alloys in particular have drawn a lot of interest because of their mechanical and magnetic characteristics. When compared to typical cast and wrought alloy products, nickel alloys produced using powder metallurgy frequently display improved quality [19-20] starting with powders of elemental Ni and carbonyl Fe to make $Ni_3Fe$-$Y_2O_3$ alloy matrix composites. The production of metal matrix composites (MMCs) utilizing powdered Ni3Fe ferrous nickel alloy as the starting material was evaluated by Elemental Powders [21] for its viability. $Ni_3Fe$'s exceptional ductility, resistance to stress, and magnetic characteristics are some of its advantages. These properties make it a desirable material for various applications.

The inherent properties of $Ni_3Fe$'s composition improve its mechanical performance. The main raw material in the manufacturing process is ferrous scrap, which is readily available and reasonably priced. When recovering $Ni_3Fe$ in powder form from scrap, the hydrometallurgical technique has several benefits. Due to its high hardness, stability, low density, low thermal expansion coefficient, specific stiffness and electrical resistivity, $Al_2O_3$ is used to reinforce the material. These characteristics provide the substance with the ability to tolerate high temperatures and offer resistance to oxidation and corrosion. [21].

The researchers used hydrometallurgy to treat tiny waste fragments, especially ferrous waste material known as alloy steel 316. They emphasized that nickel (Ni) and iron (Fe) chlorides could be reduced with hydrogen by submerging the scrap in hydrochloric acid, which would generate nickel (Ni) and iron (Fe) powders. The chlorides were then crystallized and separated from the acidic solution using Versatic Acid 6. With a weight ratio of Fe/Ni=1:3, $FeCl2•4H_2O$ and $NiCl_2•6H_2O$ were combined as the initial feed for this procedure. The characteristics of the resulting $Ni_3Fe$ alloy powder were found to be comparable to those of widely accessible atomized powders, indicating the possibility of their use in powder metallurgy.

The researchers created $Ni_3Fe$-$Al_2O_3$ composites using $Ni_3Fe$ powder to assess their physical-mechanical characteristics to those of other composites. Then, they combined elemental powders of nickel and iron powders (in a weight ratio of 3Ni+Fe:3/1) with ceramic $Al_2O_3$ particles obtained from the same material to create a composite. As the $Al_2O_3$ percentage increased, the composites' apparent and relative densities fell because the ceramic constituents were less dense than the metallic ones. The electrical resistivity test showed that increasing electrical resistivity was caused by a decrease in the amount of metallic content.

Bose [20] asserts that the high resistivity of alloys causes the (3Ni+Fe)-$Al_2O_3$ composites to have lower conductivity than $Ni_3Fe$-based composites. The researchers discovered that more reinforcing resulted in a harder composite. In comparison to metal powder-based composites with the same $Al_2O_3$ concentration, the $Ni_3Fe$ powder-based composites had greater mean hardness values. The heterogeneity of metal powder-based MMCs consisting of three constituents affected their elastic behaviour by influencing factors like porosity, distribution of reinforcing particles, interface strength, and micro-damage [22]. Although the stiffness of $Ni_3Fe$-$Al_2O_3$ composites was slightly better than (3Ni+Fe)-$Al_2O_3$ composites at a given reinforcement amount.

### 2.3 Waste Materials as Reinforcements

Recently, biomass made from rice husks has been used to generate electricity. But this method produces a lot of trash and greenhouse gases, drawing criticism for its damaging effects on the environment and general health [23]. As a consequence, greener technology is being adopted and sustainable development is receiving more attention [23]. Despite these worries, rice husks may be able to reduce the greenhouse effect since trees collect $CO_2$ during growing and release it when the biomass is burned. As a result, biomass provides an environmentally friendly substitute for fossil fuels throughout its entire lifecycle, including the production of electricity and the manufacture of ash [24] However, there are worries about the environment's possible long-term and negative impacts of rice husk ash emissions, including respiratory failure, grinder's asthma and other health issues [25].

Additionally, the residual biomass that has been burned and is enhanced with carbon and silicon can be used as a filler or reinforcement in composites made of metal or polymer. Due to their low cost, biomaterials or their derivatives are useful as sources of silica and carbon. Biomaterials or their derivatives, although typically regarded as trash or byproducts, are used as templates to make ceramics with distinctive forms that are not possible by normal ceramic processing procedures. The ceramic form of silicon carbide produced from various plant sources has attracted the most interest of all the biomaterials. Plants are a desirable alternative for this task because it is thought that their cellular, fibrous, and anisotropic structures have evolved to an ideal state through millions of years of evolution. Therefore, porous ceramics with a cellular structure made from plants are anticipated to exhibit exceptional quality due to their unique pore structure [25].

Martinez-Fernández [26] claims that very porous ceramics can have great strength and make ideal frameworks for ceramic composites or reinforcements. Table 1 lists a few instances of waste materials that have been used in the manufacturing of metal composites as reinforcements.

## 3.0 Industrial Waste Materials

There are numerous non-hazardous industrial materials generated by manufacturing and industrial processes that can be recycled or reused in an eco-friendly way. Industrial waste materials can be recycled and used in the production of composite materials, consumer goods, buildings, roads and other constructions. These materials come from sources including electric utility generators, steel mills and aluminum refineries. As demonstrated by the use of coal fly ash in material manufacture, including these waste products in the production process can even develop the quality of the finished produce. This strategy can support sustainability programs, reduce the release of greenhouse gases and help with resources and conservation of energy [39]. Recycling industrial materials can also benefit the environment by reducing the need for new materials and preserving natural resources. The recycling process can save energy by reducing the need for energy-intensive manufacturing of new products, leading to cost savings for consumers. Furthermore, waste materials from various industries are now being utilized in the manufacturing of MMCs, resulting in composites with enhanced physical and mechanical properties [36, 38, 40].

Table 1: Waste material utilization as reinforcements

| **S/N** | **Waste materials as reinforcement** | **Method of MMCs production** | **Reference** |
|---|---|---|---|
| 1. | Rice husk ash | Stir casting | [27] |
| 2. | Dolomite powder and date palm seed ash | Powder metallurgy | [28] |
| 3. | Sugarcane bagasse ash | Powder metallurgy | [29] |
| 4. | Palm kernel shell | Double stir casting | [30] |
| 5. | Bean pod ash | Double stir casting and double-layer feeding | [16] |
| 6. | Groundnut shell ash | Double stir casting | [31] |
| 7. | Rice husk ash | Friction stir casting | [32] |
| 8. | Corn cob ash | Stir casting | [33] |
| 9. | Bamboo leaf ash | Stir casting | [34] |
| 10. | Bamboo leaf ash | Stir casting | [35] |
| 11. | Quarry dust | Stir casting | [36] |
| 12. | Breadfruit seed hull ash | Double stir-casting | [37] |
| 13. | Fly ash | Stir casting | [38] |

## 3.1 Waste Glasses

In producing $Mg/Mg_2Si/MgO$ composites, Kondoh [41] used waste and scrap glasses. Using waste glasses and Mg powder in a solid-state process created $Mg_2Si$ and MgO phases. It was discovered that quick plastic working may create composite billets made of magnesium and waste glass that have a fine structure (RPW) [42]. The billet's refining effect resulted in a lower starting temperature for the solid-state synthesis of Magnesium and Silicon oxide. The billets were preheated at low temperatures before being used to produce ultrafine structured $Mg_2Si/MgO$ distributed Mg composites using waste glass. The resulting composites exhibited similar characteristics to those created using regular $SiO_2$ particles due to the refining and dispersion effects resulting from the combination of hot extrusion and RPW. Waste glasses are crushed into smaller particles and used as reinforcements in composite development. A depiction of the process for converting waste glasses into small particles for use in composite production is shown in Figure 2.

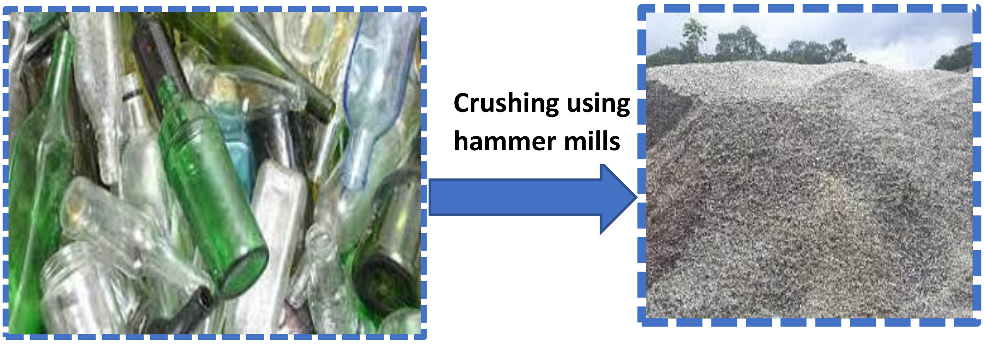

Figure 2: Conversion of waste glass materials

To undertake a rigorous analysis of the use of recycled waste glass that has been crushed as a construction material, Mohajerani [43] reviewed several realistic approaches. The chemical composition of different coloured glasses comprises several oxides such as $SiO_2$, $CaO$, $Na_2O$, $Al_2O_3$, $Fe_2O_3$, $MgO$, $K_2O$, $TiO_2$, $P_2O_5$, $MnO_2$ and $Cr_2O_5$ [44 - 45]. The major chemical constituent of any glass material is silica ($SiO_2$). More so, other oxides present could contribute to the strengthening of materials when used as reinforcements. With a great abundance of waste glasses, limited amounts are permitted to be remanufactured into glasses owing to the stringent disadvantages of glass remanufacturing. It is required that waste glasses are sorted by colour because, in the remanufacturing of glass materials, it is practically and technically not realizable due to contaminations. Waste glass remanufacturing is environmentally friendly and economical as raw material costs are reduced with lowered total energy consumption amount during production.

Recycling waste glass materials can help reduce energy consumption as they have lower melting points than raw materials [43]. Crushed waste glass finds various applications in civil engineering and construction projects, such as fine aggregate in concrete [46 -50], aggregate in asphalt concrete [43, 51-52], usage in ultra-lightweight fiber-reinforced concrete [53] and reinforcement in metal matrix composite [54]. Research on the use of recycled glass as reinforcement in MMC development has been scarce. Researchers can explore this area to establish more reliable information on its utilization, which could contribute to the advancement of engineering materials development.

### 3.2 Electric Arc Furnace Dust (EAFD)

Byproducts like slag and dust are produced when steel is made from scrap metal. However, because of their propensity to evaporate at temperatures higher than the steel bath and condense in the off-gas systems, several oxides, including those of Cr, Zn and Pb are regarded as hazardous solid waste. New methods for waste processing and utilization must be developed because the current pricey mode of disposal is inefficient. As a result, Al/EAFD metal matrix composites were made via powder metallurgy by Flores-Vélez [55].

The researchers investigated the compressive strength and hardness of the sintered compacts while altering the EAFD content in order to assess the mechanical characteristics of the composite material. The EAFD particle formation of zinc oxide ($ZnO$), franklinite ($ZnO\ Fe_2O_3$) and trace amounts of hematite ($Fe_2O_3$) was confirmed by XRD analysis. Pb, Cu and Si oxides were only identified in trace levels in the EAFD particles, which were mostly nanometric spherical particles with sizes under 300 nm. Intermetallic compounds, formed when EAFD components like $SiO_2$, $ZnO$, and the Al matrix interacted chemically, could be seen in the matrix. The following (Eqs. 1 – 4) is the chemical interactions between the components of solid wastes and aluminium powder:

$$\frac{3}{2}\,FeO\,(s) + Al\,(s) \rightarrow \frac{1}{2}\,Al_2O_3\,(s) + \frac{3}{2}\,Fe\,(s) \qquad (1)$$
$$\frac{3}{2}\,ZnO\,(s) + Al\,(s) \rightarrow \frac{1}{2}\,Al_2O_3\,(s) + \frac{3}{2}\,Zn\,(s) \qquad (2)$$
$$\frac{3}{4}\,SiO_2\,(s) + Al\,(s) \rightarrow \frac{1}{2}\,Al_2O_3\,(s) + \frac{3}{4}\,Si\,(s) \qquad (3)$$
$$\frac{1}{2}\,Fe_2O_3\,(s) + Al\,(s) \rightarrow \frac{1}{2}\,Al_2O_3\,(s) + Fe\,(s) \qquad (4)$$

According to the study's results, adding up to 10 weight percent of EAFD during the sintering process at 620°C enhanced the composite's compressive strength and hardness. The composite has a hardness of 74 HV and a compressive strength of 248 MPa thanks to thermodynamic effects on the chemical responses that take place during the process. Beyond this point, however, the material was degraded by the inclusion of additional ceramic particles. Ferric oxide ($Fe_2O_3$) and zinc oxide (ZnO), which made up 32% and 29% of the composition, respectively, were the two main chemical substances discovered in EAFD. Other compounds found in EAFD include $Al_2O_3$, MgO, $SiO_2$, CaO and $CaSO_4$. Dust that comprises different metals, including Pb, Mn, Cr, Zn, Fe and Cr is produced during the production of steel. This dust contains about 7% of the total amount of Zn produced worldwide. The dust produced during the steelmaking process contains Zn and Pb, which makes it difficult to recycle the dust into the steelmaking process. To solve this problem, an in-plant enrichment system that recycles Zn from the dust back into the combustion chamber must be created. In addition to lowering the cost of processing EAFD, this would also lessen the quantity of dust discharged into the environment.

Halli [56] suggested a brand-new, long-lasting approach to treating EAFD. The process comprises leaching citric acid using a 0.8 M citric acid solution at 40°C in an oxygen-free atmosphere for two hours after the EAFD has been alkaline roasted with NaOH at 450°C. This method allows the dangerous EAFD to be separated into valuable secondary fractions of Fe and Zn. A viable strategy for the sustainable use of EAFD is provided by these extracted fractions, which can be used as recyclable materials for initial metallurgical manufacture.

The effects of EAFD on the characteristics of the asphalt-cement mixture used in road construction. This hazardous trash was added to the asphalt cement mixture at various concentrations ranging from 0 to 20% at intervals of 5% by volume of the binder. Environmental waste is reused and environmental issues are addressed through the use of EAFD in road construction. This is corroborated by several tests that were performed on the samples, including those for penetration, fire points, viscosity, flash point, density, softening point and specific gravity. [57]. EAFD can also be employed in the manufacturing of structural ceramics and as an additional cementing component in mortars [58-60].

Granulated slag (GS) and EAFD were used as reinforcements in the powder metallurgy process to create aluminum metal composites (AMCs). Al/GS and Al/EAFD composites were the ultimate compositions. The properties of the produced composites were examined in Al/GS composites revealing the best compressive strength [61]. More so, Alves [62] studied the influence of the inclusion of 5% EAFD into AA7075 alloy for AMCs production via the powder metallurgy route. Uniform distribution of the particles of EAFD was observed, and improved microhardness and strength modulus were reported compared to the base alloy. Unfortunately, there are only a few studies that were found on EAFD utilization in MMCs development. Hence, this present study is suggesting that more studies should be considered on the utilization of EAFD as reinforcement (monolithic or hybrid) in MMCs development.

### 3.3 Slag

Tens of thousands of tons of slag are produced by the steel industry each year, along with furnace dust, making it a main waste product. (Figure 3). This makes it possible to create finished goods with value added. In the aforementioned investigation by Flores-Vélez [55], granulated slag (GS) was added to the Al matrix as a reinforcing phase utilizing a metallurgical powder approach. The slag's mean particle size was 35 m, and the distribution of the particles was irregular. Minor concentrations of MnO, $Al_2O_3$ and MgO were also identified in the GS, while FeO, CaO and $SiO_2$ were revealed to be its main constituents. Trace amounts of iron are always present in slag from the steel industry. Therefore, further chemical processes can be anticipated in addition to the creation of the intermetallic complex $FeAl_3$ as shown in Eq. (5):

$$1/3\ Fe\ (s) + Al\ (s) \rightarrow 1/3\ FeAl_3\ (s) \quad (5)$$

Flores-Vélez [55] proposed that the compressive strength and greater hardness values found in composites containing 10% GS were caused by the development of intermetallic compounds comprised of Al-Fe during the heat treatment procedure. The research revealed that GS-reinforced composites have superior mechanical characteristics over Al/EAFD composites.

Figure 3: A typical example of a furnace slag

In a 2013 study, Mantry [63] investigated the solid particulate degrading response of fusion-sprayed composite coatings made of copper and aluminum slag from industrial waste. Using Taguchi's L16 orthogonal array design, the study examined the effects of five operating parameters on the erodent temperature and feedstock aluminum concentration, including impact velocity, erodent size, impingement angle and erosion rate output. The findings proved that impact velocity had a very great influence on the coated samples' erosion wear rate. The highest erosion was seen at a 60° impingement angle, demonstrating the coating's semi-ductile sensitivity to solid particle erosion.

In the meantime, Yi [64] reported that steel slag had numerous uses, including the recovery of scrap steel, the production of sintered materials, hot metal dephosphorization, the building of roads and hydraulic systems, cement and concrete, as well as the preparation of glass ceramics and colored paving bricks and tiles. In addition, it can be used as a fertilizer for farming and for the treatment of wastewater, $CO_2$ capture, and exhaust gas. Table 2 lists some of the conclusions and uses of steel slag from several studies.

Table 2: Various utilization of steel slag

| S/N | Application | Findings | Reference |
|---|---|---|---|
| 1. | AMCs production using AA2024 alloy | A composite was created using the stir casting technique by adding 5 weight percent of slag to the matrix alloy. In comparison to their non-reinforced counterparts, the resultant composites had increased compressive strength and hardness, and the particles were | [65] |

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| | | distributed evenly inside the matrix. However, these properties lagged behind those found in the composite reinforced with 5 wt% fly ash. | |
| 2. | AMCs production | The quality of the AA2024 composites' machining was examined while using the double stir casting method. The twist drill's process parameters were adjusted with the expectation that the twist drill's feed rate of 0.10 min/rev and spindle speed of 1000 rpm would limit burr formation and surface roughness. | [66] |
| 3. | AMCs production using Al 6063 | The stir casting method was used to include welding slag particles for reinforcement into a composite at weight percentages varying from 0 to 15%. The composites' tensile and wear resistance properties were evaluated, and the results showed that the composite having 15% welding slag demonstrated the best efficiency in both categories. | [67] |
| 4. | $CO_2$ mineralization and utilization as supplementary cementitious materials | Electric arc furnaces' carbonated slag quickly turned into calcite precipitation, and flue gas $CO_2$ could be used to make mixed cement mortar, an environmentally acceptable building material. | [68] |
| 5. | Sustainable construction applications, e.g. cementitious binders, building products, soil improvement, aggregates in pavement and concretes, wastewater treatment | The potential of slag for various utilizations was highlighted in the study. | [69-70] |
| 6. | Alternatives to aggregate and filler in road pavements | The physicomechanical characteristics of cement-bound and asphalt mixtures are made with varying amounts of building and demolition debris and steel slag. The bituminous mixes' stiffness qualities increased as a result of the use of slag. The research showed that it would be possible to use these materials for road infrastructure. | [71] |
| 7. | Utilization in agricultural soil | Soil nutrient contents such as phosphorus, magnesium, calcium, silicon, and some micronutrients are | [72] |

| | | | |
|---|---|---|---|
| | | increased. Acid toxicity in the soil is neutralized and pH is elevated. | |
| 8. | Utilization in building construction | Steel slag can partially replace cement and coarse aggregate in building construction. | [73] |
| 9. | Utilization of pulverized, powdered blast furnace slag to cement-based materials | Technical advancements that altered the setting period of cement paste allowed for the sustainable use of industrial waste, and the combined addition quickly increased the compressive strength of mortars as they cured over time. | [74-75] |

### 3.4 Red Mud

Red mud is a byproduct of the Bayer process, which is used all over the world to separate alumina from bauxite. A ton of aluminum and 66 million tons of red mud are produced annually by this process from 3.45 tons of bauxite. According to the procedure, for every ton of alumina used, nearly one ton of red mud is created as waste. The output of this trash has been steadily rising on a global scale. Red mud has limited industrial applications such as in the manufacture of ceramics, cement, bricks, pigments, and glazed sewers. It can also be used to recover valuable metals like titanium, vanadium, and zinc [76]. Red mud's potential use as a low-cost reinforcing phase in metallic matrices was explored due to the desire to produce MMCs using cost-effective materials

Acharya [77] discovered that red mud-reinforced aluminum composites outperformed metals in terms of resistance to erosion when the red mud component was 30% by weight as opposed to 10% or 15% by weight. When tested at various impingement angles, the composite displayed brittle behaviour, with the greatest wear rate being noted at a 45° contact angle. When the eroded surface was examined optically under a microscope, it became clear that plowing and cutting operations were evident at low-impact angles, which made it simpler to remove the material.

In aluminum-based MMCs reinforced with red mud, Rajesh [78] employed the Taguchi method to reduce the coefficient of friction and specific wear. To create composite samples, a powder metallurgy method and an L27 Taguchi standard array experimental design were used. ANOVA was used to determine how factors like applied stress, sliding velocity, reinforcing %, and counterpart material hardness affected the outcome. According to the study, high loads, slow sliding speeds, low reinforcing percentages, and medium levels of counterpart material hardness resulted in the lowest specific wear. The ANOVA findings showed that the friction coefficient and specific wear rate coefficient of friction were most significantly impacted by the reinforcing percentage.

To combine red mud with pure aluminum in their investigation, Prasad [79] used stir casting. According to the findings, the wear coefficient of the composite materials increased with the percentage volume of red mud but reduced with pin weight and rotation speed. It is advised to conduct additional research on hybrid reinforcement combinations, such as red mud with other industrial wastes, agricultural wastes or ceramics (SiC, $TiB_2$, $Al_2O_3$, etc.), to produce MMCs for a variety of applications.

### 3.5 Industrial Sludge

Waste products generated during the painting of autos include paint sludge, used spray booth scrubber water and exhaust spray booth air containing volatile organic compounds (VOCs). The amount of paint sludge generated in an auto manufacturing plant annually ranges from 2555 to 4380 tons [80]. The amount of sludge being transported is one of the key costs associated with the process. Some automobile assembly factories have begun drying the sludge to reduce its volume. Figure 4 shows both the wet and dried industrial sludge. The dried industrial sludge is stocked for future utilization. Sludge pyrolysis is another procedure that might be utilized to reduce the volume of paint sludge, which could result in a char as well as a lesser volume than would be obtained by drying. Char, a form of carbonaceous substance produced by the pyrolysis process, has a variety of uses. In polymer matrix composites or metal matrix composites, it can act as a filler or reinforcing phase. By adding it back to the scrubber water, it can also be employed as an adsorbent to remove volatile organic chemicals, particularly nonpolar VOCs, from the contaminated exhaust booth air.

Figure 4: Industrial sludge (a) wet (b) dried and stocked

Nakouzi [81] investigated the potential use of pyrolyzed paint sludge in an Al matrix as a reinforcing phase. The sludge, which consists of amorphous alumina, crystalline $BaTiO_3$, $CaTiO_3$, $TiO_2$, titanium nitride and carbon typically contains 35.1 weight percent ceramic composites, 36.5 weight percent off-gas and the rest volatile liquids. Three pyrolysis methods were used to produce ceramic powders, which were analyzed using X-ray diffraction (XRD) and revealed the presence of $BaTiO_3$, $TiO_2$ and TiN. Powder metallurgy was utilized to create the composites, and 10 to 70 weight percent of pyrolyzed paint sludge was utilised. Due to inadequate compaction, the density of the MMCs deteriorated from 10 to 30 weight percent for compositions containing 50 weight percent more ceramic. When the ceramic component was raised to 70% by weight, the manufacturing process failed. Interestingly, the Al-based matrix composites produced during characterization did not contain $Al_4C_3$, which is known to cause corrosion in such composites.

In a 2016 study by Fukumoto [82], it was examined how adding heat-treated sludge-derived alumina using the spark-induced plasma sintering process affected the mechanical characteristics of Al matrix composites. The reinforcing content, pressure applied, and heating temperature were found to have an impact on the composites' bending strength. The aggregated sludge particles that prevented fracture propagation and improved the composite's general mechanical properties were responsible for the composite with the maximum bending strength, which had a 2-wt% alumina load.

### 3.6 Recycled Hard Particles

Businesses are embracing the usage of recycled materials as the need to save resources and safeguard the environment grows. Due to the increased cost of production, hard metal waste, a type of metal scrap, has become a pressing issue. Making discarded objects into powder materials is one of the most common ways to recycle waste. Because of this, secondary producers must research emerging technology and other developments [83]. To increase wear resistance, In order to strengthen NiCrBSi composite hard-facing, Zikin [84] investigated the use of recycled hard particles of $Cr_3C_2$-Ni, TiC-NiMo and WC-Co. The recovered cermet particles were combined in a 60:40 volume ratio with the NiCrBSi matrix powder. The reference material was hard-facing NiCrBSi with 40% hard $WC/W_2C$ particles. The results showed that the hard-facing material's wear resistance was enhanced by the addition of recycled cermet particles.

For the purpose of determining the wear and erosion properties of the composite coatings, testing on all samples was conducted. The trials' findings demonstrated that NiCrBSi hard-facings reinforced with recycled hard particles displayed wear resistance equivalent to that of $WC/W_2C$ reinforced systems under 3-body abrasive wear conditions. This might be caused by the low hardness values of the cermet zone and the vast spaces between matrix particles.

Due to the cermet's reinforcing effects on the hard-facing microstructural characteristics, the material's reinforced cermet particles demonstrated outstanding wear resistance when put under impact and abrasive circumstances. When compared to $WC/W_2C$ particles, cermet particles had a lower concentration of severe stress. The findings were obtainable with TiCNiMo reinforced coating's erosion wear likewise showed nearly little influence on the oblique and normal impact angles. High wear resistance was achieved in both situations. This can be attributed to the hard-facing's dual structure, in which fine precipitation of TiC with spherical shapes supports and boost the matrix material resistance [84]. The viability of incorporating this industrial waste into the production of MMCs needs to be further studied. A study of the corrosion behaviour of the resultant composites in simulated settings like acidic or saline conditions should be conducted along with an assessment of the impact of varied weight percentages of reinforcements on the physical, tribological and mechanical features.

### 3.7 Mines Waste Colliery Shale

Shale or other argillaceous material, which is typically produced in large quantities during the mining of coal but is typically worthless and dumped, forms dumps that are visible at almost all collieries. This shale has occasionally been found to be appropriate for building bricks using the standard procedure, and some minor uses for tiny amounts of it have been discovered, but often it is worthless and costs money to dispose of. Furthermore, because of the combustibles they contain, shale heaps frequently catch fire and burn slowly, resulting in negative side effects including smoke annoyance [85].

Aluminum and colliery shale were combined to create composite materials using the vortex melt process, and the materials' mechanical characteristics and machinability were assessed. The goal was to compare these properties to those of composites constructed of aluminum/silicon carbide and aluminum/aluminum oxide [86]. By heating colliery shale with argon gas in a high-temperature plasma reactor, a useful in-situ ceramic composite was made. Alumino-silicate makes up the majority of coal mine shale's composition. It is possible to split it into alumina, silicon carbide, and carbon at extremely high temperatures in a plasma or a tube furnace. The carbothermal process that might have occurred in the plasma reactor or tube furnace is described by equations (6) to (8).

$$C\ (s) + SiO_2\ (s) \rightarrow SiO\ (g) + CO\ (g) \tag{6}$$

$$2C\ (s) + SiO\ (g) \rightarrow SiC\ (s) + CO\ (g) \tag{7}$$

$$SiO_2 + 3C \rightarrow SiC + 2CO \tag{8}$$

In line with the results of mechanical tests, Al-colliery shale composites are stronger than $Al\text{-}Al_2O_3$ composites in terms of tensile strength, elongation, and stiffness. The stress-strain curves indicate that Al-colliery shale composites are stronger than their $Al\text{-}Al_2O_3$ counterparts. In terms of resistance to wear, these composites perform better than $Al\text{-}Al_2O_3$ and pure aluminum. In order to evaluate the machinability of the samples produced, variables including surface roughness, radial force, power consumption cutting force and feed force were compared with Al/SiC and $Al/Al_2O_3/SiC$ composites. For the same volume %, in-situ ceramic composites manufactured using colliery shale as the reinforcing phase showed superior machinability than AMCs built with $Al_2O_3$ and $Al_2O_3\text{-}SiC$, according to Siva's study

[86]. Surface roughness was minimized and tool wear was diminished. The effect of using colliery shale on the corrosion behaviour of the composites has to be further investigated.

### 3.8 Fly ash

Over a billion tons of mining output are used to produce coal, a mixture of organic and inorganic materials that are burned to produce 90% of the fuel for power plants. Slag, bottom ash, and fly ash are produced by the burning of coal in the United States of America more than 100 million tons annually. The two most common types of coal ash are fly ash and bottom ash. The microscopic particles that make up fly ash are smaller than the bottom ash that collects at the bottom of the furnaces. Separators and cenospheres are the two divisions of fly ash. Fly ash cenospheres are hollow, lightweight granules that can be utilized to create reinforced composites that are incredibly lightweight.

Studies have shown that bottom ash and fly ash from coal can be used as reinforcing agents in composite materials. Fly ash, especially in the form of solid particles, has been found to increase wear resistance and durability while reducing material density [88]. The specific gravities of fly ash particles range from 0.6 to 2.8 g/cc, and their rounded shape makes them useful as reinforcing agents. Bharathi [89] developed MMCs reinforced with fly ash at 2.5 and 5% wt using the friction stir processing method. The preheated fly ash particles were combined with LM 25-7% Si liquid metal, which improved wear resistance because it made the reinforcement particles stronger, stiffer, and harder. The link between the matrix and the particles, however, might deteriorate at greater speeds and loads, increasing wear and friction. Additionally, the material's hardness was increased using the friction stir processing method, with fly ash particles serving as consistent reinforcement throughout the matrix.

Additionally, fly ash dispersion lowers dislocation, which enhances the mechanical qualities of the composites. Increased hardness is inversely proportional to the rate of wear. The wear rates are 411 x $10^{-5}$ $mm^3/m$ at 0% volume and 203 x $10^{-5}$ $mm^3/m$ at 18% volume. According to Archard's Law, a relationship between a metallic material's hardness and wear rate can be established as the sliding wear resistance of AMCs increases and the wear rate reduces with increasing hardness [90]. Fly ash's impact on aluminium composites has been examined by Fan [91] such that fly ash had a consistent dimension between 53 mm and 106 mm before being employed as aluminium composite reinforcement. The fly ash is then heated to 800°C after that. After cooling for 0, 5, 10, 15, 20, 25, 30, 35, and 40 hours, the mixture is warmed and fly ash is added at a rate of 5 wt.%.

In this study, the effects of adding fly ash and S-glass fibers to Al-4046 alloy were examined. It was discovered that adding fly ash increased the composite hardness after 40 hours of heating, from 48.21 BHN to 54.96 BHN. The porosity of the composite material was reduced by the breakdown reaction of the non-solid fly ash particles. Additionally, the in-situ method increased the bond between the reinforcement and matrix, resulting in better mechanical properties. S-glass fibers were also added, which prevented dislocation and increased the composite's impact strength by up to 6%. [92]. The interfacial offset was influenced by variations in the thermal coefficients between the matrix and the reinforcement. Additionally, the use of fly ash made the composite less dense, lighter, and more resistant to wear. These findings imply that adding fly ash and S-glass reinforcement to Al-4046 crossover composites may improve their mechanical characteristics, making them suitable for a range of industrial applications. A successful hybrid composite with evenly distributed particles was created using the stir-casting technique. [93].

Additionally, reinforced hybrid Al-Fly ash composites, such as those made from rice husk ash (RHA) have also been researched by Narasaraju [94]. The mechanical characteristics of hybrid composites are enhanced by the inclusion of reinforcement up to 20 wt.%. Up to 10% by weight of fly ash and RHA results in the highest tensile strength. When the RHA is increased to 15% by weight, the composite hardness also drops when the reinforcement composition variation is 10% by weight. When a load is given to the sample, its enhanced tensile strength, increased hardness, expanded surface area, and softened particle size make it difficult for the sample to dislocate. Al-SiC fly ash hybrid composites were made and characterized and it was discovered that adding reinforcement will increase hardness, UTS and reduce wear [95].

It has been proven that by preventing dislocation movement, the addition of fly ash and SiC reinforcement particles increases the strength and hardness of metal matrix composites. However, performance may suffer as a result of the distributed reinforcing particles' higher hardness as compared to the matrix. Previous studies have looked into the effects of processing bottom ash particles on composites for propeller applications. Bottom ash is also used as a sort of reinforcement in metal matrix composites. With increasing magnesium content and oxidation temperature, electroless plating as a reinforcing process has been observed to decrease composite density and increase porosity. At an oxidation temperature of 300°C and a weight fraction of 0.005% Mg, the maximum density was obtained.

Al fly ash/bottom ash composites have been found to benefit from heat treatment in terms of their mechanical and physical characteristics. According to a study, the as-cast composite reinforced with bottom ash had the maximum thermal conductivity, reaching a value of 7.03 W/mK after undergoing a 12-hour T6 heat treatment at 225°C [97]. After heat treatment, the composite's thermal expansion coefficient was decreased. With increasing time and temperature, the thermal expansion coefficient of the as-cast composite with bottom ash reinforcement dropped from 2.46/K at 200°C to 1.77/K at 250°C. However, after being heated for 12 hours at 250°C, the composite lost some of its hardness. The creation of a unique phase known as $Al_2MgSiO4$ following T6 heat treatment was another remarkable discovery. This phase was brought about by the reinforcement and matrix interface reaction products in Al bare bottom composites [98].

By developing green metal matrix composites (MMCs), Yadav [99] intended to aid the UN's green revolution and decrease environmental pollution. Fly ash and graphite were used as reinforcement in these MMCs. The MMCs gained 26.60% more hardness and 16.10% more strength after the addition of 3.75% fly ash and 3.75% graphite. The use of fly ash in MMCs has also been investigated in other research, and they have shown benefits in mechanical characteristics and wear resistance over the basic alloy [100-107]. The mechanical qualities reported in this research, which used fly ash as the only reinforcement or as a supplementary reinforcement, are summarized in Table 3.

Table 3: Mechanical properties of MMCs reinforced with fly ash

| **Composition** | **Hardness (BHN)** | **YS (MPa)** | **UTS (MPa)** | **%Elongation** | **Reference** |
|---|---|---|---|---|---|
| A354 | 143 HV | 104 | 173 | 8.50 | [108] |
| A354/5% FA | 170 HV | 130 | 216 | 6.50 | |
| A354/10% FA | 164 HV | 113 | 188 | 5.70 | |
| A354/15% FA | 128 HV | 109 | 181 | 4.90 | |
| AA 2024/1.5%Mg | 80.00 | 220 | 236 | 19.40 | [109] |
| AA 2024/5%FA/1.5%Mg | 80.00 | 233 | 245 | 16.30 | |
| AA 2024/10%SiC/1.5%Mg | 87.00 | 257 | 265 | 18.20 | |
| AA 2024/5%SiC/10%FA/1.5% Mg | 90.00 | 269 | 278 | 13.80 | |
| AA 2024/5%SiC/1.5%Mg | 85.00 | 236 | 248 | 19.00 | |
| AA 2024/10%SiC/10%FA/1.5% Mg | 95.00 | 287 | 293 | 11.90 | |
| AA 2024/10%SiC/5%FA/1.5% Mg | 93.00 | 275 | 285 | 12.80 | |
| AA 6061 | 38.00 | - | 149.00 | 13.5 | [110] |
| AA 6061/7.5%SiC/7.5%FA | 50.00 | - | 175.00 | 10.0 | |
| AA 6061/10%SiC/7.5%FA | 59.00 | - | 220.00 | 5.5 | |

*FA-Fly Ash, SiC-Silicon carbide, Mg- Magnesium

## 4.0 Conclusions and Future Research Opportunities

The goal of this captious evaluation is to offer knowledge and insights that could be beneficial for future studies on metal-matrix composites manufactured from industrial waste materials. Such materials are attractive substitutes for matrix or reinforcing phases in metal-matrix composites due to their distinctive architectures, diverse chemical compositions, and extensive availability. However, their morphology, origin, chemical composition and processing method all have a significant impact on how effectively they perform.

Cenosphere fly ash, referred to as Celceram, is a form of metal-cenosphere fly ash that was generated from coal fly ash from power plants. It is one possible method for making use of industrial waste materials. This material was presented to the industry by the University of Wisconsin-Milwaukee's Center for Composite Materials and Center for Advanced Materials Manufacture for use in crumple zones, frame members, batteries, intake manifolds and other components.

To achieve the broad application of these materials, cost-related issues must be solved. Changing the chemical composition of fly ash and other industrial wastes is one way to enhance the final physical and mechanical properties of composites. Industrial waste products frequently have useful oxides like $MgO$, $Fe_2O_3$, $SiO_2$ and $Al_2O_3$ that can be treated to serve as reinforcing phases in their original compositions. Due to its advantageous chemical makeup, recycling metallic industrial waste can also save production costs.

The physical and mechanical properties of composite materials can be improved by altering the chemical composition of ceramic phases generated from industrial waste materials. However, the potential for using industrial and agricultural wastes in the development and production of metal-matrix composites has been largely disregarded or underrated. Although the number of industrial waste materials may not always be competitive, it is nevertheless a great accomplishment to produce high-value goods from them. Adopting a method that eliminates the requirement for creating synthetic phases can assist in the advancement of environmentally friendly procedures in the field of materials engineering.

In conclusion, thorough research and exploration of industrial waste materials can unlock their potential as valuable resources for the development of novel and economically viable sectors. The use of such materials in metal-matrix composites can not only enhance sustainability but also lead to reduced production costs.

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