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Use of Industrial Waste and By-products in Concrete: A Comprehensive Review

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Abstract: The construction industry is one of the largest consumers of natural resources and one of the major sources of greenhouse gas emissions. Cement production alone contributes significantly to CO_2 emissions. At the same time, many industrial processes generate large quantities of waste and by-products that pose environmental disposal issues. Utilizing such wastes and by-products in concrete (as supplementary cementitious materials (SCMs), aggregates, or fillers) offers dual benefits: reducing waste and enhancing concrete performance (strength, durability, thermal properties, etc.). This paper reviews the types of industrial wastes/by-products commonly used in concrete, their chemical and physical characteristics, effects on fresh and hardened properties (mechanical & durability), microstructure, environmental and economic implications, challenges (such as variability, processing, standards), and future directions.

Keywords: Industrial waste, CO_2 emission, Concrete, Fly ash, Silica fume

I. INTRODUCTION

- **Motivation**: Cement production is energy-intensive and emits CO_2 due to the calcination of limestone and the burning of fossil fuels. Concurrently, industrial activities—power generation (coal combustion), steel manufacturing, mineral processing, refineries, etc.—produce large volumes of by-products or wastes (fly ash, slag, silica fume, rice husk ash, red mud, bottom ash, etc.). Disposing these wastes has environmental costs (landfill, leachate, pollution).
- **Potential**: Many of these materials have cementitious or pozzolanic behavior, or can serve as aggregates/fillers, thereby allowing partial replacement of cement or natural aggregates and improving certain concrete properties.
- **Scope**: This review surveys current knowledge (recent ~5-10 years) on use of industrial wastes/by-products in concrete, covering types, characteristics, effects on fresh/hardened/durability properties, microstructure, environmental/financial impacts, challenges and research gaps.

Types of Industrial Waste / By-products Used in Concrete

TABLE 1: Major categories, with typical sources and characteristics:

Industrial Waste / By-product	Origin	Chemical / Physical Characteristics Relevant to Concrete
Fly Ash (FA)	Coal-fired power plants	Rich in SiO_2, Al_2O_3; pozzolanic, typically fine; Class F (low Ca) vs Class C (higher Ca) variations; improves workability; slows early strength gain but enhances long-term strength.
Ground Granulated Blast Furnace Slag (GGBFS / Slag)	Steel industry, iron smelting	Glassy, latent hydraulic material; activates in presence of cement or alkali; slows setting sometimes, improves durability, reduces permeability.
Silica Fume (SF)	By-product of silicon or ferrosilicon alloy production	Very fine particles, very high SiO_2; strongly pozzolanic; fills micro-voids; enhances early strength; increases water demand; tends to reduce permeability.
Metakaolin, Rice Husk Ash, Bagasse Ash, Palm Oil Fuel Ash	Agricultural residues or mineral processing	High silica, amorphous forms; pozzolanic; sometimes require processing (calcining, grinding) for high reactivity.

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Industrial Waste / By-product	Origin	Chemical / Physical Characteristics Relevant to Concrete
Steel Slag, Iron Slag, Metallurgical Slags	Steel/iron manufacturing / smelting	Can serve as aggregates or SCM depending on form; issues with free lime or free MgO, expansion risk; physical hardness; good abrasion resistance.
Red Mud, Bauxite Residues	Alumina refining	Highly alkaline, rich in alumina and iron; challenges with handling; potential in geopolymers.
Incinerator Bottom Ash / MSW Ash / Demolition Waste	Municipal solid waste incineration; construction/demolition	Varied composition; sometimes heavy metals; need pre-treatment; frequently used as aggregates; performance depends on leachability, strength, and processing.

Effect on Fresh Properties of Concrete

Incorporating industrial wastes affects the fresh (workability, setting, bleeding, and water demand) behavior of concrete. Key observations:

- **Workability**: Fine materials (e.g. silica fume) increase surface area and tend to increase water demand; fly ash often improves fluidity due to spherical particle shape.
- **Setting Time**: Some wastes retard early hydration (fly ash, slag) particularly at high replacement levels; silica fume may accelerate early strength but can reduce initial setting depending on mix.
- **Heat of Hydration**: Replacement of cement with SCMs (fly ash, slag, silica fume) generally reduces peak temperature and cumulative heat in mass concrete applications. This is beneficial in reducing thermal cracking.

II. HARDENED PROPERTIES: MECHANICAL PERFORMANCE

1. Compressive Strength

- Replacement of cement by fly ash (in moderate levels, e.g., 20-40%) often shows lower early age strength (7 days), but similar or sometimes superior 28- and 90-day strength.
- Silica fume tends to enhance early age strength due to its high fineness and reactivity. Combinations (ternary blends) of FA + SF + slag often give good balance of strength and cost. For example, a study found replacing 15% SF + 10% FA + coarse aggregate replacement with steel slag yielded compressive strength higher than control.
- Self-compacting lightweight concrete with SCMs (FA, SF, GGBS) shows that compressive strength can be maintained or improved if mix design properly adjusted.

2. Tensile, Flexural, Modulus of Elasticity

- Flexural strength tends to follow compressive strength trends; sometimes less improvement with SCMs because microcracks and weaker ITZ (interfacial transition zone) might limit flexural performance. SF helps to refine microstructure so flexural strength tends to benefit when used in blends.
- Tensile splitting strength also benefits from improved microstructure from fine wastes. Data show combining SF & FA leads to increased splitting tensile strength compared to control in certain mixes.

3. Durability Performance

Durability aspects are critical if industrial wastes are to be used in structural concrete.

Durability Factor	Effect of Industrial Wastes / Findings
Permeability / Water Absorption	SCMs reduce porosity and permeability (especially silica fume, GGBS). Replacement of cement by FA and addition of SF improve resistance to water penetration.
Chloride Penetration / Corrosion Resistance	Lower permeability and refined microstructure delay ingress of chlorides; Fly ash + SF admixtures improve corrosion resistance of embedded steel, particularly in marine or deicing environments.
Sulfate / Chemical Attack	Slag and fly ash (especially Class F) help sulfur resistance. Silica fume also helps. However, care must be taken if waste contains sulfates or reactive components.
Alkali-Silica Reaction (ASR)	Some SCMs mitigate ASR by consuming alkalis or reducing permeability. FA and slag are commonly used to control ASR.

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Durability Factor	Effect of Industrial Wastes / Findings
Freeze-Thaw, Abrasion, Thermal Stability	Improved performance in freeze-thaw cycles with low permeability. Highly reactive SCMs (SF) improve abrasion resistance. Thermal stability (e.g. elevated temperature exposure) may see mixed behaviour; some studies (e.g. replacing cement with FA and SF) show retention of strength at elevated temperatures up to certain thresholds.

4. Microstructural and Morphological Aspects

- Use of SCMs refines the microstructure. Silica fume's fine particles fill micro-voids and enhance the interfacial transition zone (ITZ).
- Hydration products: Increased C-S-H gel density, possible formation of additional calcium silicate hydrate (CSH), possibly other gel phases in blended or geopolymer systems. Slag contributes latent hydraulic phases. FA contributes pozzolanic reactions producing secondary C-S-H.
- Pore structure modifications: Reduced capillary porosity, smaller pore sizes, more discontinuous pore network. SF especially effective in reducing micro-cracks.

5. Geopolymer / Alternative Cementitious Systems

Industrial by-products are not only used as partial replacements in OPC (Ordinary Portland Cement) concrete, but also as primary reactive materials in alternative systems:

- Use of **geopolymers**: Alumino-silicate wastes such as fly ash, GGBFS, red mud, rice husk ash etc., in alkali activation systems. These have shown high compressive strengths (50-70 MPa in many studies).
- Advantages: lower embodied carbon, potential to reduce or eliminate Portland cement; also often better chemical resistance.

6. Environmental, Economic, and Sustainability Considerations

- **Carbon Footprint**: Replacing a portion of cement with wastes (SCMs) can significantly reduce CO_2 emissions, owing to lowered clinker content. For example, SF + FA replaced cement in roller-compacted concrete and resulted in reduced embodied carbon.
- **Resource Conservation**: Using waste reduces demand for raw materials (limestone, clay, virgin aggregates), preserves natural aggregates. Also mitigates waste disposal problems.
- **Cost**: Many by-products are cheaper (sometimes "free" or low cost, considering disposal requirements). However, processing (grinding, classifying, curing) can add to cost.
- **Regulatory / Standardization Issues**: Variability of waste sources (chemical composition, fineness, moisture content) impose challenges. Standards differ among regions; quality control is important.

7. Challenges and Limitations

- **Variability**: Chemical composition (e.g. CaO, SiO_2, Al_2O_3 content), fineness, reactivity differ between sources/times. This affects consistency.
- **Early-age Strength / Setting Time**: Many SCMs retard early strength; in construction where early strength is needed, this poses constraints.
- **Durability risks**: If wastes contain harmful substances (e.g. heavy metals in incinerator ash, free lime in slag, residual alkali or sulfates), potential for deleterious reactions or leaching.
- **Processing requirements**: Some wastes need grinding, sieving, heat treatment (e.g. rice husk ash must be burned under controlled conditions to produce reactive amorphous silica). Transportation cost, moisture control.
- **Standards and codes**: Acceptance in structural concrete depends on national/international standards; sometimes lack of guidelines for newer by-products or high replacement percentages.

8. Case Studies & Representative Findings

Here are some illustrative studies:

- **Silica fume + Fly Ash + Steel Slag:** One study found that replacing 15% silica fume + 10% fly ash + 30% steel slag (aggregate replacement) gave compressive strengths exceeding the normal concrete mix. Flexural strength best with 15% SF + FA + 10% slag coarse-aggregate replacement.
- **Self-compacting lightweight concrete:** Use of combined SCMs (FA, SF, GGBS) yielded good fresh and hardened properties, with strength comparable or better than control, provided mix design optimized for flowability etc.

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- **High-temperature exposure:** When concrete with FA and various levels of SF was exposed to elevated temperature (250-750 °C), the mechanical and microstructural approach shows that certain combinations retain performance under fire, with SF aiding retention.
- **Incinerator Bottom Ash + Recycled Demolition Waste:** In a study using M20 concrete, replacing fine aggregate partly with bottom ash and coarse aggregate with recycled demolition aggregate gave improved or comparable durability/strength when replacement levels kept moderate; leaching tests indicated environmental safety.

9. Optimization / Mixture Design Considerations

To get good performance when using industrial by-products, several design and optimization aspects must be addressed:

1. **Replacement levels**: There is usually an optimal range: e.g. fly ash replacement 20-40% of cement; silica fume replacement usually lower (5-15%) due to fineness and cost; slag may go higher.
2. **Blends / Ternary mixes**: Combining two or more by-products (FA + SF; FA + slag; SF + slag + FA) often gives better balance between early strength, durability, and cost. Ternary blends allow mitigation of drawbacks of individual SCMs.
3. **Particle size, surface area, fineness**: Finer particles help in filling voids, enhancing pozzolanic reactivity. Silica fume is ultra-fine; other ashes/granulated slags benefit from grinding.
4. **Activation / curing regimes**: Higher temperatures / moisture curing improve fly ash/slag reaction. For geopolymers, activator type (alkali, silica, etc.) is critical.
5. **Water/binder ratio and admixtures**: To compensate increased water demand (especially with SF, RHA), superplasticizers or water reducing admixtures are often necessary. Lower w/b improves durability.
6. **Quality control of waste materials**: Test for chemical composition (SiO_2, Al_2O_3, CaO, MgO, SO_3), loss on ignition, fineness, presence of deleterious components (chlorides, heavy metals, carbon, sulfates).

10. Environmental and Life-Cycle Impact

- **Embodied Carbon / Emissions Saving**: Substituting cement with SCMs reduces CO_2 emissions; as cement is – in many assessments – the main contributor. Studies show embodied carbon can be significantly reduced, depending on replacement level and source distances.
- **Waste Reduction**: Using industrial by-products helps divert them from landfills or stockpiles, reduces environmental hazards (e.g. leaching of heavy metals, dust pollution).
- **Cost Benefit**: Savings on cement and aggregate, although sometimes offset by processing or transportation costs. Lifecycle cost likely favourable especially in large-volume structures or mass concrete.

11. Research Gaps and Future Directions

- **Standardization**: Need better international and regional standards for characterization of by-products (e.g. classification, safety), and for accepted replacement percentages, especially for newer materials.
- **High replacement percentages**: More work needed to maintain early age strength when very high SCM replacement is used.
- **Durability under extreme conditions**: Long-term performance (50+ years), performance under cyclic loading, freeze-thaw cycles, high sulfate, industrial pollution exposure, elevated temperature (fire) needs more data.
- **Geopolymer concrete and hybrid systems**: Understanding far-field behavior, field implementation, scaling up production, cost and regulatory acceptance.
- **Environmental toxicity / leaching**: Particularly for ash, incinerator ash, bottom ash, MSW ash, etc., ensuring no harmful leaching.
- **Sustainability beyond carbon**: Considering water usage, energy for processing, transportation, ecological impact of extracting wastes, and full life cycle assessment.

III. CONCLUSION

Industrial wastes and by-products have enormous potential to enhance sustainability of concrete. Many such materials (fly ash, silica fume, slag, ashes, bottom ash, etc.) provide benefits in durability, reduced permeability, long-term strength, and environmental impact. Properly designed blends and replacement levels allow balancing trade-offs (e.g. early strength, workability). Challenges remain in ensuring consistency, durability in harsh environments, standardization, and large-scale deployment. For a greener construction industry, widespread adoption of industrial byproduct use in concrete (both in OPC-based and alternative binders such as geopolymers) is essential.

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