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SILICA FUME, RICE HUSK ASH AND IRON SLAG IN SUSTAINABLE CONCRETE: A COMPREHENSIVE REVIEW

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Abstract: The increasing demand for concrete in residential, commercial, industrial, and infrastructure development has resulted in significant consumption of Portland cement, whose production is associated with high energy demand and carbon dioxide emissions. The utilization of industrial and agricultural by-products as supplementary cementitious materials offers a promising approach for reducing cement consumption while improving the sustainability and performance of concrete. This review presents a comprehensive assessment of silica fume (SF), rice husk ash (RHA), and iron slag as partial replacements for cement in concrete. The review discusses their origin, composition, pozzolanic and cementitious characteristics, effects on hydration and microstructure, and influence on the mechanical and durability properties of concrete. Silica fume, owing to its highly reactive amorphous silica and very fine particle size, contributes to matrix densification and the formation of additional calcium silicate hydrate (C-S-H) gel. RHA, derived from controlled combustion of rice husk, provides a silica-rich agricultural waste material with significant pozzolanic potential, while iron slag represents an industrial by-product that can contribute to cementitious reactions and sustainable waste utilization. Recent studies indicate that the performance of these materials strongly depends on their processing conditions, chemical characteristics, particle size, replacement level, and compatibility with other concrete constituents. The review further highlights the potential of combined and optimized use of mineral additives to achieve improved strength, durability, and environmental performance. However, challenges related to material standardization, processing, optimum replacement levels, long-term durability, and large-scale field application remain. Overall, SF, RHA, and iron slag demonstrate considerable potential for developing sustainable concrete while simultaneously addressing industrial and agricultural waste-management challenges.

Keywords: Silica Fume; Rice Husk Ash; Iron Slag; Sustainable Concrete; Supplementary Cementitious Materials; Partial Cement Replacement; Pozzolanic Materials; Mechanical Properties; Durability; Waste Utilization

I. INTRODUCTION

Concrete is one of the most widely used construction materials in the world and is extensively employed in residential, commercial, industrial, and infrastructure projects. However, the production of cement, which is the primary binding material in concrete, consumes considerable energy and releases a significant amount of carbon dioxide (CO_2), contributing to environmental pollution and greenhouse gas emissions. Therefore, the development of sustainable alternatives that can partially replace cement without compromising the required properties of concrete has become increasingly important.

Materials containing high amounts of silica and possessing pozzolanic properties, such as silica fume, rice husk ash (RHA), and iron slag, have significant potential for use as partial cement replacements. These materials can contribute to the development of sustainable and improved-quality concrete while reducing cement consumption. Silica fume is a highly reactive pozzolanic material that can enhance the strength and durability of concrete. Rice husk ash, an agricultural waste product rich in amorphous silica, also exhibits significant pozzolanic activity. Similarly, iron slag generated as a by-product of the iron and steel industry can be utilized in concrete as a supplementary cementitious material.

The disposal of these industrial and agricultural waste materials is also an important environmental concern, particularly in developing countries such as India. Improper disposal and excessive accumulation of such wastes can occupy valuable land and cause adverse environmental impacts. Their utilization in concrete can therefore provide a sustainable method of waste management while reducing the demand for conventional cement.

The compressive strength and flexural strength of hardened concrete are important mechanical properties used to evaluate its load-bearing capacity and

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structural performance. Compressive strength represents the ability of concrete to resist compressive loads, whereas flexural strength indicates its resistance to bending. Since concrete has relatively low tensile resistance and brittle behavior, evaluating its flexural performance is particularly important for structural applications.

II. ADMIXTURE

Admixtures are materials added to concrete, in addition to cement, water, and aggregates, to modify specific properties of fresh or hardened concrete. They are used to improve workability, setting time, strength, durability, water reduction, air entrainment, and resistance to environmental conditions. Admixtures can generally be classified into two major categories: chemical admixtures and mineral admixtures.

Chemical admixtures include water reducers, superplasticizers, accelerators, retarders, air-entraining agents, waterproofing admixtures, shrinkage-reducing admixtures, and corrosion-inhibiting admixtures. Mineral admixtures include fly ash, rice husk ash, silica fume, and ground granulated blast-furnace slag. These materials are commonly used as supplementary cementitious materials or partial replacements for cement.

Water-reducing admixtures reduce the amount of water required to achieve the desired workability or slump. This reduction in the water-cement ratio can improve the strength and durability of concrete. Accelerating admixtures are used to reduce setting time and promote early-age strength development, whereas retarding admixtures delay setting and are useful in situations where longer working time is required. Air-entraining admixtures introduce small, uniformly distributed air bubbles into concrete and can improve resistance to freezing and thawing.

Superplasticizers are high-range water-reducing admixtures that produce highly workable or flowing concrete without significantly increasing the water content. They are particularly useful in heavily reinforced structures and applications where adequate compaction is difficult. Other specialized admixtures, such as waterproofing, corrosion-inhibiting, shrinkage-reducing, and bonding admixtures, are used for specific construction requirements. The compatibility of chemical admixtures with cement and other concrete constituents should be verified before their use.

Admixtures used in concrete can be classified according to their function as follows:

- **Water-Reducing Admixtures:** Reduce the water requirement of concrete while maintaining the desired workability and slump.
- **Retarding Admixtures:** Delay the setting of concrete by slowing the initial hydration of cement. They are useful in hot weather and for long transportation or placing times.
- **Accelerating Admixtures:** Reduce the setting time and increase the rate of early-age strength development.
- **Air-Entraining Admixtures:** Introduce uniformly distributed microscopic air bubbles into concrete and improve its resistance to freezing and thawing.
- **Pozzolanic or Mineral Admixtures:** Materials such as fly ash, silica fume, rice husk ash, and slag react with calcium hydroxide produced during cement hydration and contribute to the development of additional cementitious compounds. They can improve strength, durability, and resistance to certain aggressive environments.
- **Waterproofing Admixtures:** Reduce water penetration and improve the resistance of concrete to moisture.
- **Gas-Forming Admixtures:** Produce controlled quantities of gas within concrete and are used for specific applications.
- **Air-Detraining Admixtures:** Reduce excessive entrained or trapped air in concrete when the air content is higher than required.
- **Anti-Washout Admixtures:** Improve the cohesion of concrete and reduce the loss of cementitious materials when concrete is placed underwater.
- **Bonding Admixtures:** Improve the bond between new and existing concrete, particularly during repair and rehabilitation works.
- **Biocidal Admixtures:** Certain specialized admixtures can help control the growth of microorganisms such as fungi and bacteria on or within concrete surfaces.
- **Colouring Admixtures:** Pigments are added to concrete to produce the desired colour for architectural and decorative applications. The pigments should not adversely affect the strength and durability of concrete.

III. SILICA FUME

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Silica fume is a very fine pozzolanic material obtained as a by-product during the production of silicon metal and ferrosilicon alloys. It is mainly composed of very fine, amorphous silicon dioxide (SiO_2) particles. Silica fume consists of spherical particles with a very small particle size and a high specific surface area, making it highly reactive with the products of cement hydration.

When incorporated into concrete, silica fume reacts with calcium hydroxide and contributes to the formation of additional calcium silicate hydrate (C-S-H) gel. This reaction can improve the compressive strength, density, durability, and impermeability of concrete. Because of its extremely fine particle size, silica fume also fills the voids between cement particles and produces a denser concrete matrix.

In the present study, silica fume is considered as a partial replacement for cement to investigate its influence on the mechanical properties of sustainable concrete, particularly its compressive and flexural strength.

IV. RICE HUSK ASH

Rice husk ash (RHA) is an agricultural waste material obtained from the controlled burning of rice husk. Rice husk contains a high proportion of silica, and controlled combustion can produce ash containing a large amount of amorphous silica. The properties of RHA depend considerably on the burning temperature, duration, and combustion conditions.

Due to its high silica content and pozzolanic activity, RHA can be used as a supplementary cementitious material and as a partial replacement for cement in concrete. The fine particles of RHA can contribute to pore refinement and improve the microstructure of concrete. Its utilization also provides an effective method of managing agricultural waste while reducing cement consumption.

The use of RHA in concrete can therefore provide both environmental and engineering benefits. In the present study, RHA is incorporated at different replacement levels to evaluate its effect on the compressive and flexural strength of concrete.

V. IRON SLAG

Iron slag is a by-product generated during iron and steel production. When molten slag is rapidly cooled, particularly through water quenching, it forms a granular material. After suitable processing and grinding, slag can be used as a

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supplementary cementitious material in concrete.

Finely ground slag can exhibit cementitious and pozzolanic properties and can contribute to the formation of additional binding compounds during hydration. Its incorporation into concrete can improve selected mechanical, physical, and durability properties, depending on the replacement level and characteristics of the slag.

The use of iron slag as a partial replacement for cement also provides an environmentally beneficial method of utilizing industrial waste and reducing the consumption of conventional cement. In the present study, iron slag is incorporated at different replacement levels and its influence on the compressive and flexural strength of concrete is experimentally evaluated. The results are compared with those of conventional concrete to determine its suitability for sustainable concrete production.

VI. LITERATURE REVIEW

Miah et al. (2026) [1] investigated the use of rice husk ash (RHA) as a partial replacement for ordinary Portland cement. The study found that 10% RHA replacement provided comparable long-term strength to conventional concrete while reducing CO_2 emissions by approximately 7%, demonstrating its potential as a sustainable supplementary cementitious material. Istanbullu et al. (2026) [2] conducted a bibliometric and systematic review of RHA-based concrete. The study reported that RHA, particularly at suitable replacement levels, can improve concrete strength and durability through enhanced pozzolanic activity and microstructural densification. The authors also highlighted challenges related to standardisation, large-scale validation, and the need for advanced data-driven approaches. Ali et al. (2026) [3] examined the combined use of tyre waste steel fibers, silica fume, and RHA in natural and recycled aggregate concrete. The optimum mix containing 10% silica fume, 20% RHA, and 1% tyre waste steel fibers improved compressive strength and reduced water absorption, indicating enhanced mechanical and durability performance. Pahsha et al. (2025) [4] investigated sustainable self-compacting concrete using recycled concrete aggregate (RCA) and granite cutting waste (GCW). The results showed that up to 30% GCW improved strength, durability, and microstructural properties, with the R50G30 mix achieving about 4% higher 90-day compressive strength and 41% lower carbonation depth than the RCAonly mix. Higher GCW contents reduced performance due to microcracking and inadequate paste coverage. Prajapati et al. (2025) [5] studied concrete incorporating fly ash, silica fume, rice husk ash (RHA), and calcium nitrate. The modified concrete showed improved compressive and tensile strengths compared with conventional concrete, attributed to pozzolanic reactions and microstructural refinement. The study demonstrated the potential of industrial and agricultural by-products for producing sustainable concrete, while recommending further research on durability and field applications.

Chaitanya et al. (2025) [6] examined the performance of concrete containing fly ash, silica fume, and 100% M-sand under elevated temperatures. The mix containing 10% fly ash and 12% silica fume showed the best residual strength and microstructural performance up to 750°C. SEM and EDS analyses confirmed improved matrix densification due to pozzolanic reactions, although strength decreased at higher temperatures because of C-S-H decomposition. Cai et al. (2025) [7] investigated rice husk ash, steel slag, and iron tailing powder as waste-based stabilizers for cement-treated soil. Steel slag and iron tailing powder significantly improved mechanical strength and densified the pore structure, with strength increases of up to 40% and 60%, respectively. RHA showed comparatively lower reactivity but its performance improved with increasing cement content, demonstrating the potential of waste materials for sustainable soil stabilization. Barbhuiya et al. (2025) [8] reviewed the application of rice husk ash (RHA) in concrete, focusing on its effects on strength, workability, durability, hydration, and microstructure. The study reported that RHA can improve the mechanical and durability properties of concrete when used at suitable replacement levels and produced under controlled burning conditions. The authors also highlighted the need for further research on long-term durability, standardization, compatibility with different cement types, and the environmental and economic feasibility of RHA-based concrete. Bayrak et al. (2024) [9] experimentally investigated the influence of silica fume (SF) and RHA on slag-based prepacked geopolymers exposed to elevated temperatures. RHA and SF were used as partial replacements for ground granulated blast furnace slag (GGBFS). The results showed that curing temperature and precursor type significantly affected the physical and mechanical properties. RHA-containing mixtures generally demonstrated better resistance to mass loss at elevated temperatures, while SF mixtures exhibited comparatively higher strength under certain curing conditions. The study demonstrated the potential of RHA as a sustainable material for improving the high-temperature performance of geopolymer concrete. Pradhan et al. (2023) [10] studied the incorporation of RHA into GGBS-based alkali-activated concrete at ambient temperature. The study evaluated compressive, split tensile, and flexural strengths along with microstructural characteristics using SEM and FTIR. The results indicated that a low RHA content improved the strength and produced a denser microstructure, whereas higher RHA contents resulted in cracks and voids and reduced strength. The study concluded that incorporating an optimum proportion of RHA can enhance the performance of alkali-activated concrete while reducing dependence on conventional cement. Montoya et al. (2023) [11] investigated highly reactive rice husk ash (TRHA) as a partial replacement for Portland cement in high-performance concrete and compared its performance with conventional silica fume. The results showed significant improvements in compressive and flexural strengths, together with reduced chloride ion penetration. TRHA promoted pozzolanic reactions and produced denser hydration products, resulting in improved strength and durability. The study concluded that properly processed RHA can serve as an effective and sustainable alternative to silica fume in high-performance concrete.

VII. CONCLUSION

This review examined the potential of silica fume, rice husk ash, and iron slag as sustainable supplementary cementitious materials for partial replacement of conventional cement in concrete. The reviewed literature demonstrates that these materials can provide both environmental and engineering benefits by reducing cement consumption, utilizing industrial and agricultural waste, and contributing to improved concrete performance. Silica fume is characterized by its extremely fine particle size and high amorphous silica content, which promote pozzolanic reactions, additional C-S-H formation, pore refinement, and matrix densification. These characteristics can enhance compressive strength, durability, and impermeability when an appropriate replacement level is selected. Rice husk ash also exhibits significant pozzolanic potential because of its high silica content, particularly when produced under controlled combustion conditions. Its use can contribute to pore refinement and improved microstructure while providing an effective method of agricultural-waste utilization. Iron slag, after suitable processing and grinding, can act as a supplementary cementitious material and contribute to the formation of additional binding compounds, while simultaneously reducing the environmental burden associated with industrial waste disposal.

The reviewed studies indicate that the performance of these materials is strongly dependent on replacement percentage, particle characteristics, processing conditions, curing conditions, and the interaction among different concrete constituents. Low or optimized replacement levels generally provide better mechanical and microstructural performance, whereas excessive replacement can result in reduced strength because of inadequate binder reactivity, increased voids, or microcracking. Recent research also demonstrates the potential benefits of combining silica fume and rice husk ash with other supplementary materials and waste products. Despite the promising results, further research is required to establish standardized processing and quality-control procedures, determine optimum replacement ranges, evaluate long-term durability, and validate performance under field conditions. The environmental and economic feasibility of large-scale implementation should also be investigated. Overall, silica fume, rice husk ash, and iron slag represent promising materials for the development of sustainable concrete. Their optimized utilization can simultaneously reduce dependence on conventional cement, lower waste-disposal requirements, conserve natural resources, and support the development of durable and environmentally responsible construction materials.

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