

A Comprehensive Review on the Role of Silica Fume and Recycled Aggregates in Enhancing Concrete Performance

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Abstract:

Concrete remains the most widely used construction material due to its strength, versatility, and durability; however, its large-scale production poses environmental challenges, particularly the depletion of natural resources and high carbon emissions from cement manufacturing. The integration of recycled aggregates (RA) from construction and demolition (C&D) waste, alongside supplementary cementitious materials (SCMs) such as silica fume (SF), has emerged as a sustainable approach to improve concrete performance while reducing environmental impact. This review comprehensively examines the role of RA and SF in enhancing both the mechanical and durability properties of concrete. The use of RA alone is often limited by its high porosity, adhered mortar, and weaker interfacial transition zone (ITZ), which compromise performance. However, studies indicate that pretreatment of RA and its partial replacement with natural aggregates can mitigate these limitations. Furthermore, silica fume, due to its ultrafine particle size and high pozzolanic reactivity, significantly refines the ITZ, improves density, and enhances compressive, tensile, and flexural strength. Literature findings reveal that the combined use of RA and SF leads to improved mechanical properties, reduced water absorption, enhanced resistance to chemical attack, and greater long-term durability. Additionally, incorporating RA and SF contributes to sustainability by reducing landfill waste, conserving natural aggregates, and lowering CO₂ emissions. This review highlights that optimized mix designs, incorporating treated RA and appropriate dosages of silica fume, offer a viable solution for developing high-performance, eco-friendly concrete for modern infrastructure.

Keywords: Cement, Concrete, Recycled Aggregates (RA), Silica Fume (SF), Supplementary Cementitious Materials (SCMs).

1. Introduction

Concrete has long been recognized as one of the most widely used construction materials, playing a vital role in addressing numerous infrastructure challenges. Its versatility, strength, and durability have made it a cornerstone of modern construction and one of the greatest achievements of the industry. However, in recent years, with the growing emphasis on sustainability and environmental responsibility, attention has increasingly shifted toward the incorporation of recycled

and alternative materials in concrete production.

The rapid pace of urbanization, combined with the demolition of old and deteriorated structures, has led to the generation of massive quantities of construction and demolition (C&D) waste. If this waste is not effectively managed, it is typically disposed of in landfills, leading to several critical environmental issues. These include the depletion of natural resources due to continuous quarrying for fresh aggregates, uncontrolled disposal practices, and the

adverse environmental impacts caused by waste accumulation at dumping sites.

One of the most promising solutions for managing C&D waste is the recycling of this material into Recycled Aggregates (RA), which can be reused in the production of concrete. Despite its potential, RA is generally considered to be of lower quality compared to conventional natural aggregates. This is because RA usually exhibits higher water absorption, lower density, and greater porosity. These inferior characteristics are primarily attributed to the adhered mortar, lime, and microcracks present on the surface of recycled aggregate particles. As a result, the use of Recycled Coarse Aggregate (RCA) significantly influences the fresh and hardened properties of concrete.

The performance of RCA-based concrete depends not only on the replacement level but also on the quality of the aggregates and the extent of the adhered mortar. One of the most critical factors affected by the use of RA is the Interfacial Transition Zone (ITZ), which is the thin layer of cement paste surrounding the aggregate particles. The ITZ plays a decisive role in governing the mechanical and durability properties of concrete. In RA concrete, the ITZ tends to be weaker and more porous compared to conventional concrete, primarily due to the presence of residual mortar. This weakness often leads to reduced stiffness, higher shrinkage, and a greater loss of elasticity, even when compressive strength is only moderately affected.

Extensive research indicates that the challenges associated with RA concrete can be mitigated through several approaches. These include partial replacement of RA with natural aggregates, mechanical or chemical treatment of RA to improve its quality, and the incorporation of supplementary cementitious materials (SCMs), such as silica fume, fly ash, or slag. These methods enhance the bond between RA and cement paste, refine the microstructure of the ITZ, and ultimately improve the performance of RA concrete.

Another important sustainability concern arises from surplus fresh concrete, which is often returned unused to batching plants. Due

to uncertainties in estimating exact material requirements for construction projects, significant amounts of fresh concrete frequently go to waste. This practice not only increases overall material wastage but also adds to the environmental burden, as cement production is a major contributor to global carbon emissions.

Therefore, the effective and sustainable use of recycled aggregates in concrete holds significant potential for reducing environmental impact. By incorporating RA in concrete, it is possible to minimize landfill waste, conserve natural aggregate resources, and lower the carbon footprint of construction activities. Such practices are in alignment with global sustainability goals and contribute to the development of greener and more resource-efficient construction systems.

2. Supplementary Cementitious Materials (SCMs)

Supplementary Cementitious Materials (SCMs) are inorganic materials that are either naturally occurring, industrial by-products, or processed materials. When used in combination with cement, they contribute to the properties of the hardened concrete through hydraulic or pozzolanic activity. The choice and proportion of SCMs in a mix design depend on the desired performance characteristics such as strength, durability, workability, and sustainability. The inclusion of SCMs not only enhances the mechanical and durability properties of concrete but also reduces cement consumption, thereby lowering the overall carbon footprint of construction.

Some of the commonly used SCMs are as follows:

- **Ground Granulated Blast Furnace Slag (GGBS):** GGBS is a by-product obtained during the production of iron in a blast furnace. It is widely used as a partial replacement of cement. The addition of GGBS in self-compacting concrete (SCC) improves its rheological properties, enhances workability, and reduces the risk of segregation. Furthermore, GGBS contributes to long-

term strength and improves resistance to chemical attacks, particularly sulfate and chloride penetration.

- **Fly Ash:** Fly ash is a fine powder, a by-product of coal combustion in thermal power plants. It is classified into Class F and Class C based on its chemical composition. Fly ash improves the particle packing in the concrete matrix, filling voids and reducing pore size. This results in improved density, reduced permeability, and enhanced durability. Additionally, the pozzolanic reaction of fly ash contributes to the long-term strength of concrete while also reducing the heat of hydration.
- **Silica Fume:** Silica fume, also known as microsilica, is an ultrafine material produced as a by-product of silicon or ferrosilicon alloy industries. Its particles are about 100 times smaller than cement grains. The incorporation of silica fume significantly improves the mechanical properties of SCC by enhancing compressive strength, tensile strength, and bond strength. It also reduces the permeability of concrete, thereby increasing durability and resistance to aggressive environments.
- **Stone Powder (or Quarry Dust):** Stone powder, obtained as a by-product from the crushing of stones, is sometimes added to concrete mixtures to increase the powder content. Its presence helps improve the cohesiveness of the mix and reduces bleeding and segregation. It also aids in achieving the desired flowability in self-compacting concrete.

The use of SCMs in self-compacting concrete not only improves its performance characteristics but also contributes to sustainable construction by reducing reliance on conventional cement and utilizing industrial by-products effectively.

3. Literature Review

Haider et al. (2025) investigated the combined effect of recycled aggregates (RA), silica fume (SF), and metakaolin (MK) on the mechanical and durability properties of

concrete. The study revealed that 50% RA with 10% MK and 5% SF significantly enhanced performance, achieving 31.5 MPa compressive strength, 5.7 MPa tensile strength, and 10.6 MPa flexural strength after 28 days improvements of 5.19%, 16.47%, and 8.52% over control concrete. Ultrasonic pulse velocity increased by 16.13%, while water absorption decreased by 20.87%, indicating a denser matrix and stronger bonding. Although higher RA content ($\geq 75\%$) reduced acid resistance, the optimized mix (R50-MK10-SF5) exhibited superior durability and fire resistance compared to conventional concrete. The improvements were attributed to the filler effect and pozzolanic reaction of MK and SF, which refined the microstructure and strengthened the interfacial bonding.

Peiris et al. (2025) reviewed treatment methods for recycled aggregates (RA) to overcome challenges of high porosity, water absorption, and reduced strength caused by attached mortar in construction and demolition waste (CDW). The study synthesized over 150 works, highlighting effective mortar removal techniques such as ball milling and autogenous cleaning, and strengthening methods like accelerated carbonation, polymer (PVA) impregnation, and nano-silica treatments. These approaches improved density, strength, and chloride resistance of RA concrete, with the triple mixing method showing potential for better mechanical properties. The review emphasized that combined techniques often yield enhanced performance, though they may be costly and energy-intensive. However, gaps remain in assessing long-term durability, large-scale structural applications, and life-cycle cost and environmental impacts. The authors stressed that further research on durability properties, real-scale structural elements, and comprehensive environmental assessments is essential to ensure the feasibility of RA treatments for sustainable construction.

Dharmadhikari et al. (2024) investigated the use of recycled concrete aggregates (RCA) as a partial replacement for natural aggregates in concrete to achieve environmental and economic benefits. RCA typically exhibits

high water absorption, reducing its mechanical and durability performance. The study explored combined pretreatment methods thermal, mechanical (abrasion), and chemical (fly ash slurry) to enhance RCA properties. Results indicated that pretreated RCA, along with the use of superplasticizers and optimized water cement ratios (0.4–0.6), improved both workability and compressive strength of RAC compared to untreated RCA. The research highlights that RCA, when properly treated, can serve as a sustainable and viable alternative to natural aggregates in concrete production.

Zhu et al. (2022) treated RCA with silica fume cement (SFC) paste and compared the resulting concrete with natural coarse aggregate concrete. The study showed that treated RCA concrete (TRCAC) exhibited significantly improved mechanical performance due to the incorporation of silica fume, which enhanced RCA quality and reduced the thickness of the interfacial transition zone (ITZ). Workability was also improved, as soaking TRCA prior to mixing helped balance its higher water absorption. Compressive strength tests revealed that TRCAC achieved results comparable to conventional concrete, while microstructural analysis using SEM and EDS confirmed a denser ITZ and enhanced bonding.

Baid et al. (2021) highlighted the importance of finding alternative materials to reduce the excessive consumption of natural resources in concrete. With rapid population growth and rising housing demands, the construction industry generates significant waste, including floor tiles that are typically disposed of in landfills. Their study focused on recycling locally available marble, granite, and porcelain tile waste as substitutes for fine aggregates. Four mortar mixes were designed, including one control mix with natural sand and three mixes with complete replacement of sand by tile waste. In all mixtures, 10% of cement was replaced by silica fume (SF). The performance tests on workability, mechanical properties, and durability showed that the combination of tile scrap with silica fume significantly enhanced performance, yielding a 99%

increase in compressive strength and a 53% increase in flexural strength compared to conventional mixes.

Shmll et al. (2021) examined the performance of recycled aggregate concrete (RAC) and explored methods to mitigate the performance loss commonly associated with recycling concrete. Their work discussed the role of additives such as steel fibers, silica fume, and fly ash in improving the properties of RAC. The review of existing studies revealed that, in many cases, RAC demonstrated excellent mechanical properties comparable to or even better than conventional concrete. The authors also suggested the possibility of repeatedly recycling concrete through optimized mix designs, presenting a future outlook for sustainable construction.

Lesovik et al. (2021) conducted an experimental study to evaluate the mechanical properties of recycled aggregate concrete made from demolition waste in Iraq and crushed laboratory-tested cubes. The replacement of natural coarse aggregates with recycled coarse aggregates was investigated at various levels (33.3%, 66.7%, and 100%), with silica fume added as a supplementary cementitious material. The results showed that concrete made from demolished building waste exhibited reduced compressive and tensile strengths compared to reference concrete, while concrete made from laboratory-tested recycled cubes demonstrated improved strength. Furthermore, the inclusion of silica fume enhanced the compressive and tensile strength of all RAC mixes.

Manivel et al. (2021) emphasized the significance of recycled coarse aggregates in addressing sustainability challenges in concrete production. Their experimental research studied the effect of replacing conventional coarse aggregates with recycled aggregates, alongside the incorporation of silica fume as a partial cement replacement. The study demonstrated that the combined use of recycled aggregates and silica fume improved the strength properties of RAC when compared to conventional concrete, making it a viable alternative for both structural and non-structural applications.

4. Conclusion

This review establishes that the integration of recycled aggregates (RA) and silica fume (SF) represents a sustainable and effective strategy for enhancing concrete performance. While the use of RA addresses the pressing issue of construction and demolition waste management, its inherent drawbacks such as higher porosity, weaker ITZ, and lower strength limit its standalone application. Silica fume, with its superior pozzolanic reactivity and ultrafine particle size, counterbalances these deficiencies by densifying the microstructure, strengthening the ITZ, and improving overall mechanical and durability properties. Studies consistently demonstrate that concrete mixes containing treated RA and optimized proportions of silica fume achieve superior compressive strength, tensile strength, flexural strength, reduced permeability, and greater resistance to chemical and environmental attacks compared to conventional concrete. Furthermore, the combined use of RA and SF not only reduces reliance on natural aggregates and cement but also contributes significantly to lowering the environmental footprint of concrete production. However, challenges remain, including the variability in RA quality, the cost and practicality of pretreatment methods, and the need for long-term performance assessments in real-scale structures. Future research should focus on optimizing treatment methods for RA, determining the ideal replacement levels, and conducting comprehensive life-cycle analyses to ensure large-scale implementation. In conclusion, RA and silica fume, when used together, provide a synergistic effect that transforms concrete into a high-performance, eco-friendly material. Their combined application has strong potential to drive the construction industry toward more sustainable, durable, and resource-efficient practices.

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