

Research Progress on the Application of Solid Waste-Based Auxiliary Cementitious Materials in Concrete

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Abstract

This paper provides a systematic review of research into the use of solid waste-based supplementary cementitious materials in concrete. It focuses on analysing how typical solid waste materials, such as fly ash, slag and steel slag, influence the workability, mechanical properties and durability of concrete when used as supplementary cementitious materials. The paper summarises the mechanisms of action of these materials and identifies current research challenges, outlining future research directions. The review aims to inform the utilisation of solid waste resources and the green development of high-performance concrete.

Keywords

Solid Waste Utilization; Supplementary Cementitious Materials; Concrete; Mechanical Properties; Durability.

1. Introduction

All Concrete is the most widely used and extensively applied building material in modern construction. It primarily relies on Portland cement as its cementitious component. However, the production of cement is highly energy-intensive and emits a lot of carbon. In fact, statistics indicate that the cement industry accounts for around 8% of global anthropogenic CO₂ emissions[1]. Against this backdrop, identifying alternative materials, or materials that can partially replace cement, to reduce the environmental impact of concrete production has become a significant focus of research in civil engineering materials. The large-scale stockpiling of industrial solid waste not only occupies land resources, but also poses potential threats to the ecological environment. Incorporating industrial solid wastes with cementitious or hydraulic properties as supplementary cementitious materials (SCMs) into concrete can reduce cement consumption and lower carbon emissions, while utilising solid waste resources[2]. This approach aligns with the principles of green, low-carbon and sustainable development. Common SCMs derived from solid waste include fly ash, granulated blast furnace slag, steel slag, silica fume, coal gangue and red mud. This paper aims to systematically review recent research progress on the application of these materials in concrete. It analyses the influence patterns and mechanisms of different types of solid waste on concrete performance, while also discussing existing challenges in current research and future development directions.

2. Research Status of Typical Solid Waste-Based Auxiliary Cementitious Materials

2.1 Fly Ash

The Fly ash, the primary solid waste produced by coal-fired power stations, is currently one of the most widely used and well-researched supplementary cementitious materials. Its main chemical constituents are silicon dioxide (SiO₂), aluminium oxide (Al₂O₃) and iron oxide (Fe₂O₃). Its

pozzolanic activity enables it to undergo secondary hydration reactions when activated by the cement hydration product, calcium hydroxide ($\text{Ca}(\text{OH})_2$), forming calcium silicate hydrate (C-S-H) gel.

Research indicates that incorporating fly ash in the correct proportions can improve the workability of concrete, reduce hydration heat, increase later-stage strength and enhance resistance to chloride ion penetration and sulphate attack [3]. Akyuz et al. [4] found that, at fly ash contents of 20–30%, the 28-day compressive strength of the concrete matched that of the control group, while the 90-day strength showed significant improvement. However, fly ash's low early reactivity leads to slow early strength development in concrete, which remains a primary limiting factor for its application.

To address this issue, researchers have proposed various methods of modification, including mechanical grinding to improve fineness, activation with chemical additives, and the use of composites with other mineral admixtures. For instance, using alkaline activators such as NaOH and Na_2SiO_3 can greatly enhance the reactivity of fly ash in the early stages.

2.2 Granulated Blast Furnace Slag

Granulated blast furnace slag is a by-product of ironmaking. After undergoing water quenching to cool it rapidly, it exhibits potential hydraulic properties. It primarily consists of CaO, SiO_2 , Al_2O_3 and MgO, with a glass phase content of over 85%. It undergoes hydration reactions in alkaline environments.

When incorporated into concrete, blast furnace slag significantly enhances its density and durability. Research indicates that adding slag powder refines concrete's pore structure, reducing permeability and improving resistance to chloride ion attack and freeze-thaw cycles[5]. Furthermore, slag suppresses alkali-aggregate reactions, thereby enhancing the long-term stability of concrete.

Li et al. [6] investigated the effects of varying slag content on the mechanical properties of concrete. Their results suggest that, when the slag content is between 30% and 50%, the 28-day compressive strength of the concrete can match or exceed that of the control group, demonstrating significant later-stage strength development. However, slag concrete exhibits slower early-stage strength development and requires stricter curing conditions and higher water demand.

2.3 Steel Slag

Steel slag is a by-product of steelmaking. China produces enormous quantities of steel slag annually, yet its utilisation rate remains low. Steel slag contains high levels of CaO, SiO_2 and Fe_2O_3 , as well as certain amounts of free calcium oxide (F-CaO) and free magnesium oxide (F-MgO), which gives it some cementitious activity. However, it also suffers from poor volume stability[7].

Researchers have extensively explored using steel slag as an auxiliary cementitious material. Netinger et al. [8]demonstrated that incorporating steel slag powder improves concrete's strength at later stages, although it still takes a long time to develop strength initially. Mechanical or thermal activation treatments can significantly improve the cementitious activity of steel slag.

The primary technical challenge in using steel slag lies in its poor volume stability. The slow hydration of f-CaO and f-MgO in steel slag may continue after the concrete has hardened, resulting in expansion and cracking of the concrete. Therefore, steel slag requires ageing treatment or use in a composite with other materials to mitigate these potential hazards.

2.4 Recycled Micro-Powder from Waste Concrete

As construction waste generation increases annually, the utilisation of waste concrete as a resource has received increasing attention. Recycled micro-powder, obtained by crushing and screening waste concrete, contains unhydrated cement particles and partial hydration products, and exhibits certain cementitious activity [9].

Research indicates that the activity of recycled micro-powder depends primarily on the strength and age of the original concrete, as well as the fineness of the grinding. Ren et al. [10] found that, at low addition rates of 10–20%, recycled powder has a minimal impact on concrete strength; however, excessively high dosages lead to a significant reduction in strength. Incorporating recycled powder

improves concrete density and water resistance, though it increases water demand and has a slight effect on workability.

2.5 A Variety of Solid Waste Composite Systems

Individual solid waste materials often have performance limitations. However, combining multiple solid waste materials can create synergistic effects by complementing each other's strengths and weaknesses. For example, blending fly ash with slag improves the balance between the early- and late-stage strengths of concrete[11]; mixing steel slag with fly ash mitigates steel slag's volume stability issues[12]; and combining silica fume with other solid wastes enhances concrete density[13].

Lu et al. [14] investigated the effects of a ternary composite system of fly ash, slag and steel slag on concrete properties. The results demonstrated that the optimised composite system exhibits not only excellent mechanical properties, but also significantly superior durability compared to single-admixture systems. These findings provide valuable insights into the efficient utilisation of solid waste-based supplementary cementitious materials.

3. The Mechanism of Action of Solid Waste-Based Supplementary Cementitious Materials

The use of solid waste-based supplementary cementitious materials in concrete involves multiple effects, primarily physical filling, pozzolanic reactions, latent hydraulic properties and micro-aggregate effects.

Firstly, solid waste materials usually have a finer particle size distribution than cement particles. These materials can fill the voids between cement particles and aggregates, resulting in a denser concrete microstructure. This physical filling effect reduces the overall porosity and refines the pore size distribution. Consequently, pathways for the penetration of harmful media are blocked, laying the foundation for enhanced concrete strength and durability.

Secondly, the abundant active SiO_2 and Al_2O_3 components in solid waste materials undergo secondary hydration reactions with the $\text{Ca}(\text{OH})_2$ produced during cement hydration, a process known as the pozzolanic reaction. This reaction consumes the mechanically weak and erosion-prone $\text{Ca}(\text{OH})_2$ crystals while generating additional C-S-H gel. This gel further fills pores and enhances the matrix's binding capacity. Materials with potential hydraulic properties, such as slag, can undergo direct hydration in alkaline environments, producing cement-like hydration products. Although this process is slower than cement hydration, it significantly contributes to the development of strength over time.

Additionally, solid waste particles act as a micro-aggregate skeleton that supports the concrete matrix. When these particles bond well with the cement matrix, their uniform dispersion improves stress distribution and inhibits microcrack initiation and propagation. This enhances the overall mechanical properties and deformation capacity of concrete. These four effects do not operate in isolation, but rather reinforce each other synergistically, collectively forming the comprehensive enhancement mechanism of solid waste-based auxiliary cementitious materials.

4. Conclusion

Using solid waste-based supplementary cementitious materials in concrete is a key way to utilise solid waste and make the building materials industry more environmentally friendly and low-carbon. Significant progress has been made in researching typical solid waste materials such as fly ash, slag and steel slag, with promising results in terms of enhancing concrete workability, mechanical properties and durability. However, further investigation is required in areas including reactivity activation, long-term performance and standardised application. As multi-solid-waste composite systems develop and our understanding of micro-mechanisms deepens, solid waste-based supplementary cementitious materials will increasingly play a vital role in green, high-performance concrete.

5. Problems and Prospects

Although substantial results have been yielded by research into the application of solid waste-based supplementary cementitious materials in concrete, a number of key issues remain to be addressed. Firstly, the low initial reactivity of most solid waste materials makes it difficult to stimulate their reactivity efficiently and economically. While methods such as chemical, thermal and mechanical activation have each demonstrated effectiveness, the most suitable method must be selected and combined based on the specific properties of the materials. Secondly, current research largely focuses on the short-term mechanical properties of solid waste concrete, while the long-term performance evolution and durability mechanisms of such concrete, particularly with regard to the volume stability of materials containing unstable components such as steel slag, remain insufficiently explored. Additionally, concrete used in engineering projects is often subjected to complex conditions involving multiple interacting factors, such as loads, environmental conditions and temperature. The long-term performance of solid waste concrete under such conditions requires further research. Furthermore, given the diverse sources and significant compositional variability of solid waste materials, it is a pressing practical challenge to establish scientific quality control standards and mix design methods to facilitate their large-scale application in major engineering projects. Finally, the utilisation of solid waste resources must balance performance with environmental benefits. A comprehensive life-cycle environmental and economic evaluation system should be established to provide a scientific basis for selecting and applying green building materials.

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