Role of Fly ash and GGBS in concrete preparation: Review on environmental and economic impacts

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Abstract:

Concrete is a popular construction material used all over the world. It is the binder component and plays a major role in strength and durability. Incorporation of industrially originated waste like Fly ash and GGBS, which is huge in quantity, difficult to recycle and ends in landfill usually disturbs the ecological balance and hence these waste materials can be effectively reused in concrete preparation as binders to reduce the use for virgin non-renewable material usage. This paper reviews the potential of Fly ash and GGBS in large quantities as a substitute for OPC in ready mix concrete preparation for use in aggravated environments along with their economic and environmental impacts.

Keywords: OPC, SCMs, FA, GGBS and concrete.

Introduction

Concrete is a vital part of civil engineering world (Choppala and Venkateswarlu, 2023). The increasing demand of this manmade composite, resulted in huge use of natural resources and eventually resulted in imbalance to the ecosystem (Gomathi, 2025). Concrete technology has now evolved to address growing demands for sustainability, durability, and performance. The selection of cementitious materials plays a pivotal role influencing the performance of concrete. Ordinary Portland cement (OPC), although widely used, contributes significantly to CO_2 emissions (He et al. 2019) while aalternative binders called as Supplementary cementitious Materials (SCMs) offer promising improvements in strength, durability and sustainability. Especially usage of Fly Ash (FA) and ground Granulated Blast Furnace Slag (GGBS), industrial by-products, in blended cements have proved to reduce the carbon emissions related to cement production (Sheikibrahim et al. 2018; Rao, 2023). India's decarbonizing pathway towards net-zero in 2070 is trying to achieve 0.51 t CO_2/t by 2047 (GCCA 2022) from the level of 0.62t CO_2/t in 2023 (CemNet 2023). This paper focus on the review of suitability of SCMs which are industrial origin in the preparation of blended ready-mix concrete.

Literature review

Blends of cement have been in use for ready-mix concrete preparation for more than two decades. Many researchers have studied binary and ternary blended cement mixes with various materials especially of industrial origin like FA and GGBS which are the most commonly used SCMs for ready mix concrete preparation due to their proven abilities in strength gaining, durability and economical aspects. Johari et al (2011) in their work discussed the effect of supplementary cementitious materials and revealed that the addition of GGBS has increased the workability of concrete. Sunil et al (2018) while studying the effect of GGBS in different grades of concrete, found that the workability increases with the increase in GGBS content. The 40% replaced GGBS concrete achieved the highest compressive strengths and exhibited better durability in all test grades. Saranya et al (2018) reviewed GGBS as cement replacement and concluded the optimum percentage lies between 40 to 45% by weight. Carla Costa (2018) evaluated the technological feasibility of the partial, or total replacement of fly-ash (FA), widely used in ready-mixed concrete production, with spent equilibrium catalyst (ECat) from the oil-refinery industry. Three different concrete mixtures with binary binder blends of 33.3% by mass FA and of ECat (16.7% and 33.3%), as well as a concrete mixture with a ternary binder blend with FA and ECat (16.7%, of each) were tested in comparison with commercial concrete. 16.7% ECat binary blended concrete revealed improved mechanical strength and durability and the ternary FA-ECat blended binder concrete presented similar properties while 33%ECat binary blended concrete has a lower performance. Prabhu (2020) focused on fresh concrete properties of M55 grade ternary blended self-compacting geo polymer concrete with a constant Flyash content and with varied GGBS and silica fume contents. V-funnel test, U-box Test, L-box Test and slump Test revealed that the Mix with 12 molarity performed well in terms of slump and mechanical strengths both at 7 and 28 days suggesting the combination of GGBS and Fly ash as effective in ternary blended concrete preparation.

Kim (2022) assessed the properties of ternary blended concrete in terms of mechanical performance and resistance to chemical attack with OPC, GGBS, FA and Ferronickel slag as binders and at a water to binder ratio of 0.45. Results on compressive strength of ternary blended concrete with ferronickel slag at l80days of curing showed a 8% to 18% higher values than for OPC. In addition, all ternary mixes exhibited lower heat of hydration compared to OPC and binary mixes with pozzolanic materials showed the lowest heat evaporation. Durability of the ternary mix showed always-higher resistance against chloride penetration and sulfate attack.In XRD analysis of the binary mix, partial replacement of FA and GGBS particles would provide more C-S-H gel, resulting in a reduction peak of portlandite. Overall, the results showed that the incorporation of ferronickel slag impacted positively the properties of concrete. Haripraba (2023) examined the strength characteristics of ternary blended concrete, with up to 40% substitution of fly ash and Wollastonite. concrete's strengths. The inclusion of Wollastonite and flyash has positively influenced the mechanical strength properties like flexural, split tensile and compressive strengths of the concrete up to 20% replacement and have proven to be effective in achieving the desired strength without compromising the overall workability of the concrete. Kulkarni (2023) investigated the behavior of polymer modified ternary blended concrete with varying percentages of polymer upto 6% along with 30% flyash and 8 to 12% silica fume as cement replacements. the addition of polymer modified ternary blended concrete with 8% silica fume, 30% fly ash and 3% styrene-butadiene rubber latex polymer is stronger than polymer modified ternary blended concrete made with 12% silica fume, 30% fly ash and 2% styrene-butadiene rubber latex polymer.

Nagaraju (2023) in their study on concrete's compressive strength, flexural strength, microstructural development, and cost-effectiveness with binary and ternary blended concrete mixes with silica fume, ceramic powder, bagasse ash, and alccofine found that 12% alccofine mix showed higher compressive strength, flexural strength, and cost- efficiency of 59.52 MPa, 6.58 MPa, and 0.0125 MPa/INR/m3 respectively. SEM images of the ternary blended alccofine concrete exhibits denser microstructure, strength studies exhibited high-strength and cost estimation exhibit its potential as a low-cost ternary blended concrete mix. Rao (2023) conducted an experimental study aimed to improve sustainable high-performance concrete without overutilizing or underutilizing additives of mixes combining binary and ternary combinations of agricultural by-products like rice husk ash, corncob ash, and bagasse ash and industrial by-products like fly ash, ground granulated blast furnace slag, and metakaolin. The concretes strength, microstructural, and sustainability characteristics evaluation revealed that Nano-SiO2 concretes with 30% GGBFS and 10% sugar cane baggage ash provided high compressive and flexural strength values. All ternary nano-SiO2 concrete blends with higher percentages of industrial and agricultural by-products demonstrated a decline in compressive and flexural strength. Choppala (2023), conducted experimental study with SCMs namely, Metakaolin, fly ash, Silica Fume, GGBS to replace the cement as far as possible and the overall study based on strength properties and densities proved that, GGBS and fly ash combination is a success and using them effectively has satisfied the strength attaining phenomenon with increased strength properties at different ages and also it is cost effective.

Anjaneya et al. (2021), evaluated high- strength cementitious composites mechanical strength and durability with FA in the range of 20 to 40%, SF at 5 to 10%, and GGBS in the range of 10 to 20% as binders in addition to Quarry Dust as filler at different levels of replacement in 10 to 30%. The fresh cementitious composites properties, strength properties such as compressive strength, flexural strength, and split tensile strength and durability characteristics such as water sorptivity and the Rapid Chloride Permeability Test (RCPT) were evaluated. In their study, it was observed that the strength properties increased with increase in FA and GGBS content, RCPT values of high content of FA and GGBS incorporated concrete mixes exhibited low chloride ion penetration and the efficacy of ternary mix in chloride penetrability reduces with age and so as the water sorpitivity values. Ilaya raja et al, (2024) investigated the involvement of cement with GGBS in M20 concrete and found 10% replacement gained more strength than conventional concrete. Marangu (2024) experimented the performance and durability of Recycled concrete powder with rice husk ash (RHA) and calcined clay (CC) in ternary blended concrete exposed to chloride attacks under wet/dry cycles in 3.5% NaCl water to produce low-carbon concrete. The combined substitution of RHA and CC at SCM replacement levels of 60% showed an overall improvement in hardened properties and durability by exhibiting an increase of 33% in compressive strength, followed by minimal changes in water absorption.

Li et.al (2024) comprehensively characterized the fresh and hardened properties of Calcined Clay (CC) - Recycled Concrete Powder (RCP) cement system by varying the CC/RCP ratio and dosage. The rheological, mechanical properties, hydration products and pore structure results indicate that an increase in the proportion of RCP in the SCM mixture resulted in a decrease in mortar strength due to the inert composition of RCP and the decline of CC content. Li et al. (2025) designed 25 mixes of 1:3 cement mortar with water-binder ratio 0.48 to investigate the effect of combination of steel slag and ground coal bottom ash by partially substituting steel slag upto 20% and ground coal bottom ash upto 40% for cement and concluded that the use of individual SCMs enhanced mortar strength with 5% of slag and 15% of bottom ash respectively. The recent work of Karim (2025) utilized Type C and Type F FA as partial replacement for fine aggregate in range of 5 to 20% by weight and for cement up to 40% in concrete mixes. Addition of FA as sand contributed positively in strength development of binary blended concrete with both types of FA up to 30% and as cement replacement upto 20%. However, Type C provided better durability and Type F provided better workability in cement replaced mixes. Ternary blends are gaining momentum in the recent past due to stringent regulations and global concerns like CO2 emission. FA with other materials in concrete mixes have been studied by researchers and found FA's influence has proved to be beneficial in strength gaining and improved workability.

Discussions

The economic implications on using SCMs especially FA and GGBS have been discussed in this section in detail.

1. **Cost Reduction in Construction:**

   Reduced Raw Material Costs: Cement production involves significant raw material extraction while Fly ash and GGBS are industrial by-products meaning its production cost is inherently lower than that of virgin cement. Studies indicate that replacing cement with GGBS in the range of 33-41% can lead to substantial cost savings of over 50% in projects.

   Waste Valorization: Utilizing FA and GGBS transforms industrial waste product into a valuable construction material. This eventually reduces the costs associated with waste disposal like incineration and landfill fees and creates a new revenue stream.

   Durability and Longevity: GGBS incorporation particularly at higher volumes, enhances concrete's durability and resistance to aggressive environments like those with chlorides and sulphates. This increased durability can lead to reduced maintenance and repair costs over the lifespan of infrastructure projects, especially in aggravated environments.

   Potential for Local Sourcing: If SCMs production and processing facilities are geographically close to construction sites, the transportation costs can be significantly lower than that of cement, further contributing to cost savings.

2. **Economic Growth and Employment:**

   New Industries and Supply Chains: The increased demand for SCMs can stimulate the growth of industries involved in processing, transporting, and supplying this material, creating new jobs and economic opportunities.

   Sustainable Infrastructure Development: Lower material costs and enhanced durability can make large-scale infrastructure projects more economically viable, encouraging further investment and development in the construction sector, a major contributor to India's GDP.

3. **Market Acceptance and Innovation:**

   The demonstrated strength gain and other beneficial properties like increased workability and sulfate resistance will build greater market confidence in FA – GGBS blended concrete. This acceptance can accelerate its widespread adoption, fostering innovation in concrete technology and construction practices.

Environmental Impacts:

1. ***Significant Reduction in Carbon Footprint:***

Reduced Cement Production Emissions: The most significant environmental benefit stems from replacing OPC with SCMs in blended cements as cement production is highly carbon-intensive, accounting for approximately 7-8% of global CO_2 emissions. Manufacturing a tonne of OPC typically releases about 0.8 to 1.0 tonne of CO_2. By replacing 50% of OPC with GGBS, it demonstrates a potential reduction of nearly 50% reduction in emissions from virgin cement production for the binder component, which is a massive contribution to decarbonization efforts.

Embodied Carbon Reduction: This reduction directly contributes to lowering the "embodied carbon" of buildings and infrastructure, which refers to the greenhouse gas emissions associated with the extraction, processing, manufacturing, transportation, and construction of building materials.

2. ***Waste Management and Resource Conservation:***

   Utilizing Industrial Waste: FA and GGBS that would otherwise be discarded, often ending up in landfills. Its effective utilization in concrete production significantly reduces industrial waste volume and the environmental burden associated with its disposal.

   Conservation of Natural Resources: By substituting OPC with SCMs, the need for quarrying virgin raw materials like limestone is reduced to a greater extent, preserving natural resources and minimizing habitat disruption associated with mining.

3. ***Enhanced Durability and Reduced Life-Cycle Impact:***

   Resistance to chlorides and sulphates: The increased resistance to chlorides and sulphates by SCM blended concrete will last longer and require fewer repairs or replacements. This extends the service life of infrastructure, further reducing the overall environmental impact over the long-term meaning that less material consumption, less energy for repairs and ultimately less waste generation.

   Reduced Heat of Hydration: Blended concrete exhibits a lower heat of hydration compared to OPC, which reduces the risk of thermal cracking in large concrete pours. This enhances structural integrity and durability, indirectly contributing to environmental benefits by reducing the need for premature repairs or replacement.

4. ***Alignment with SDGs:***

   The use of SCMs in blended concrete directly contribute to several Sustainable Development Goals (SDGs), particularly:

   Goal 9 (Industry, Innovation, and Infrastructure): By promoting innovative, sustainable materials and practices in the construction industry.

   Goal 11 (Sustainable Cities and Communities): By enabling the construction of more resilient and environmentally friendly urban infrastructure.

   Goal 13 (Climate Action): Through significant reductions in emissions from the cement sector.

Conclusion:

The integration of blended concrete in construction presents a sustainable and technically viable pathway for addressing the dual challenges of infrastructure development and environmental stewardship. By partially substituting OPC with SCMs, blended concretes achieve significant reductions in embodied carbon while enhancing durability, workability, and long-term mechanical performance. The use of such materials not only diverts waste from landfills but also mitigates the dependence on energy-intensive clinker production, thereby contributing to circular economy principles and the achievement of global sustainability goals. Furthermore, the review consistently demonstrates that ternary and binary blends offer improved resistance to chemical attack, reduced permeability, and enhanced service life in aggressive environments, making them especially suitable for critical infrastructure applications. While challenges remain in terms of standardization, variability of source materials, and industry-wide adoption, the empirical evidence strongly supports the broader implementation of blended concrete as a mainstream construction material. Ultimately, its application fosters innovation in concrete technology, reduces environmental impact, and ensures resilient, cost-effective, and sustainable built environments for future generations.

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