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RECENT ADVANCES IN SUSTAINABLE CEMENT REPLACEMENT FOR ECO-FRIENDLY CONCRETE

Ravi Mandloi[1], Rajesh Chouhan[2]

Research Scholar, Department of Civil Engineering, Samrat Vikramaditya Vishwavidyalaya, Ujjain, Madhya Pradesh[1]

Professor, Department of Civil Engineering, Samrat Vikramaditya Vishwavidyalaya, Ujjain, Madhya Pradesh[2]

Email: chouhanrajesh49@gmail.com[2]

ABSTRACT

This institute mainly focuses on the construction industry as it is one of the biggest contributors of global carbon dioxide owing mainly to Ordinary Portland Cement (OPC) production. Environmental concerns regarding concrete combine with growth in global infrastructure demand to push innovative sustainable replacements for traditional cement. It evaluate mechanical, durability and microstructural properties of concrete utilizing the waste materials. It is found that replacement levels differ with respect to material type and fineness, however, strategic replacements can improve the compressive strength substantially, increase sulfate attack resistance, and mitigate thermal cracking. Setting time and early-age strength are however still very much an issue This work is by far the overall review of the recent trends to find out the best replacement ratios and discuss future research potentials for carbon-neutral construction materials.

Keywords: *Industrial waste[1], Cement replacement[2], Sustainable concrete[3], Fly ash, Silica fume[4], GGBS[5], Concrete durability[6].*

1.INTRODUCTION

1.1 ENVIRONMENTAL IMPACT OF CEMENT PRODUCTION

Cement production is an energy intensive process comprised of about 8% of overall CO2 emissions. In addition, calcination of limestone and especially high temperatures in a rotary kiln, cause extensive environmental destruction. This challenge highlights the transition towards eco-friendly binders that lower the clinker factor in concrete production.

1.2 PROPERTIES OF INDUSTRIAL WASTE MATERIALS

Waste materials from industry having pozzolanic or cementitious properties (e.g. fly ash, silica fume and slag). The reason is that these materials interact with the calcium hydroxide that is produced during cement hydration to form the calcium silicate hydrate (C-S-H) gels, which are the dominant strength and impermeability enhancing compounds in concrete. These materials create value by upcycling industrial waste.

1.3 SIGNIFICANCE OF REVIEW

This article seeks to fill the gap created by individual studies and meta-analyses. It develops a framework that explores the ways in which various waste materials can affect the behaviour of contemporary concrete based on existing literature to provide a reference for structural engineers and materials scientists.

2. SURVEY OF PAST WORK

Over the last 20 years, many industrial wastes have been studied as potential secondary cementitious materials (SCMs). Research on fly ashes from coal-fired power plants have shown that at replacement levels between 15% and 30%, improved workability and long-term compressive strength can be achieved. Several meta-analyses indicate that this spherical shape of fly ash particles plays like a lubricant and lowered the water demand. Silica fume, a natural pozzolan obtained from the silicon industry, has been acknowledged for its high pozzolanic activity, attributable to its fine particle size. Studies show that tiny, 5-top-10% replacements result in major increments in strengths at early ages and massive permeability reductions. An excellent alternative for this application is granulated ground blast furnace slag (GGBS), which originates during the production of iron, as reported [12], and has been found to improve chemical resistance, especially based on the corrosion of developed sodium chloride in a cold seawater environment [13,14]. Many studies have stated that GGBS of a high volume (until 50%) is possible without the loss of structural integrity. The use of agricultural wastes like as rice husk ash and sugar cane bagasse ash has also been mentioned in recent literature with the need of calcination process done at controlled conditions to ensure reactivity [3–7]. These materials show potential as ways to reduce concrete costs and fulfil aspects of a circular economy. However, experimental results still vary, which are often correlated to the heterogeneity of elemental composition and curing conditions in different cometary environments.

3. METHODOLOGY

The research methodology selected for this review is systematic literature review (SLR) for meta-analysis (published between 2010 to 2026) of peer-reviewed journals. In this section, a systematic search was performed on censuses from numerous electronic databases including Scopus, Web of Science, and Google Scholar using corresponding keywords relating to cement replacement, industrial waste and durability of concrete. This stage also guaranteed that we collected data from various geographical contexts. Criteria Selection criteria were defined to be relevant from the experimental reliability and reproducibility point of view. Criteria for Inclusion: Only controlled mixes which consisted OPC (100%) and followed standard tests using standardized testing methods (ASTM or IS codes) were included in this Review study. The extraction of data included compressive strength results at 7, 28, and 90 days and qualitative indicators of workability and durability performance from the articles included in the database. This needed to be done by scaling the results against the control mix performance to so that we could derive the 'relative performance ratio'. Statistical trends were made for different replacement levels to find the 'sweet spot' for each waste material. This objective approach ensures that the results represent the current academic consensus whilst minimising the effect of bias resulting from single studies.

4. CRITICAL ANALYSIS OF PAST WORK

Upon careful review of the existing literature, a number of themes can be identified, however each of these is also subject to some considerable limitations. Many studies have proven successful mechanical properties of SCMs, but much of this research is reliant on controlled laboratory conditions rather than conditions that would accurately represent a construction site. Concrete performance is strongly influenced by those casting conditions in terms of variations in weather, humidity, and labor practices, and these are only poorly represented in experimental data published in the literature. Additionally, the literature exhibits an evident dichotomy between high-volume replacement and early-age strength development. While many studies argue that 40–50% replacement is optimal for sustainability, they fail to consider practical issues such as delayed strength gain where formwork cannot be removed due to delaying the construction schedule. Another big bottleneck to broader uptake in the industry is that there is no standardised procedure for treating agricultural waste ashes, whose composition can vary wildly, unlike more consistent industrial products such as fly ash. Finally, much of the current meta-analytical literature is not comprehensive in considering the 'lifecycle impact'. The majority of papers assesses durability or strength of a cube or cylinder and overlooks the following years of maintenance expense and potential for environmental savings with longer-lived infrastructure. Thus, future works should shift focus from testing 'replacement ratios' to achieving 'optimized binder blends' tailored for the regional climate conditions.

5. DISCUSSION

Incorporating industrial waste into cement-based systems advocates a sustainable method to construction. The conversation revolves around the balance in or tradeoff between the economics savings and environmental footprint versus the performance reliability. Studies show that the utilization of two or three different waste materials together is better than their individual replacement at the same proportions on account of the synergistic effect. For example, fly ash-silica-fume combination combines the silica fume with its reactivity to compensate the early-age strength lag of fly ash. Nonetheless, the consistency of waste quality still remains a challenge. There is a need for regulatory bodies to standardize the quality of these by-products so that engineers can be confident using them. Future research should therefore aim for 'smart concrete' with industrial waste but still allows the pace of modern construction in urban development.

6.CONCLUSION

This review demonstrates how a potential industrial waste has the ability to convert the concrete industry into a completely eco-friendly alternative. There exists a sustainable option to cement through the replacement or substitution of cement with materials ranging from fly ash, silica fume and to GGBS, all of which is technically feasible and environmentally essential as well. Meta-analyses also show that optimum replacement levels (typically between 15-30% for fly ash and 5-10% for silica fume) can achieve similar or even greater mechanical properties to standard OPC concrete. Core findings demonstrate that successful outcomes hinge on adequate curing and material characterization. The shift towards circular construction is still an essential pathway to decarbonisation, despite challenges with first-use material strength and standardisation The focus of future research should be field-scale demonstrations and the life-cycle assessment of blended concrete in different climate settings to enable government acceptance and industrial market adoption.

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