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A Review on Self-Compacting Concrete and Geopolymer Self-Compacting Concrete with Industrial Slag Aggregates: Fresh State, Hardened State Properties, and Taguchi-Based Optimisation

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Abstract— **Self-Compacting Concrete (SCC) and its geopolymer variant (GPC-SCC) represent two of the most significant advances in sustainable concrete technology of the last three decades. SCC eliminates the need for mechanical vibration through carefully engineered rheological properties, while Geopolymer Concrete (GPC) eliminates ordinary Portland cement (OPC) entirely, replacing it with an alkali-activated aluminosilicate binder derived from industrial by-products, predominantly Fly Ash (FA) and Ground Granulated Blast-Furnace Slag (GGBS). This review consolidates and critically analyses twelve published experimental investigations examining the fresh-state and hardened-state properties of SCC and GPC-SCC, with particular emphasis on systems incorporating industrial slag as fine aggregate. The reviewed studies confirm that: (i) the binary FA 70% + GGBS 30% binder system activated by 10M NaOH and Na2SiO3 (ratio 2.0-2.5) consistently achieves 28-day compressive strengths in the range 38-46 MPa; (ii) oven curing at 60-70 degrees Celsius for 24 hours yields strength equivalent to 28-day ambient curing; (iii) industrial slag aggregates can replace up to 40-50% of natural fine aggregate without compromising EFNARC 2005 fresh-state acceptance criteria; and (iv) Taguchi-based statistical optimisation combined with ANOVA provides a robust framework for parameter optimisation in both SCC and GPC-SCC research.**

Index Terms— **Self-Compacting Concrete, Geopolymer Concrete, Fly Ash, GGBS, Steel Slag, Alkali Activator, Fresh Properties, Compressive Strength, EFNARC, Taguchi Optimisation, Sustainable Concrete.**

I. INTRODUCTION

The global construction industry accounts for approximately 40% of total energy consumption and 33% of CO2 emissions worldwide, with the manufacture of ordinary Portland cement (OPC) contributing 5-8% of global anthropogenic greenhouse gas emissions. Each tonne of OPC clinker produced generates approximately 0.8-0.9 tonnes of CO2, primarily from the calcination of calcium carbonate and the combustion of fossil fuels in the rotary kiln. With global concrete consumption exceeding 10 billion tonnes per year, the urgency to develop low-carbon, high-performance alternatives to OPC-based concrete has never been greater.

Self-Compacting Concrete (SCC), first developed by Okamura and Ouchi in Japan (1986-1988), addresses the constructability challenge by engineering fresh-state properties through precise control of powder content, water-to-powder ratio, and chemical admixture dosage, such that the concrete flows and self-consolidates under its own weight without mechanical vibration. The absence of vibration eliminates a major source of construction noise and quality variability, and enables filling of heavily reinforced or geometrically complex formwork. Within India, SCC has gained significant traction following the incorporation of SCC design guidelines in IS 10262:2019.

Geopolymer Concrete (GPC), conceptualised by Davidovits (1989), achieves zero-OPC binder performance by activating amorphous aluminosilicate precursors, principally Class F Fly Ash and GGBS, with alkaline solutions of sodium hydroxide (NaOH) and sodium silicate (Na2SiO3). The resulting geopolymerisation reaction produces a three-dimensional aluminosilicate network structurally analogous to zeolitic minerals, imparting high compressive strength, superior chemical resistance, and significantly reduced carbon footprint relative to OPC systems. The combination of SCC flowability characteristics with the geopolymer binder system in GPC-SCC represents the convergence of two sustainable concrete technologies.

A third sustainability dimension, the utilisation of industrial by-product aggregates, has been explored by several researchers who have demonstrated that Copper Slag, Fayalite Slag, and Steel Slag can partially replace natural fine aggregates in SCC and GPC-SCC, reducing demand on river sand resources while contributing to the circular economy through beneficial reuse of steelmaking and copper-smelting wastes. Steel Slag, with its specific gravity of approximately 3.40-3.60 and angular particle morphology, is of particular interest as a dense fine aggregate replacement.

This review paper synthesises the current state of knowledge across twelve published experimental and review works, organised thematically to address the fresh-state behaviour of SCC and GPC-SCC, the hardened-state mechanical properties of binary FA+GGBS geopolymer systems, the role of industrial slag aggregates in concrete matrices, the influence of curing regime on geopolymer strength development, and the application of Taguchi-ANOVA statistical methods for experimental optimisation and validation.

II. LITERATURE REVIEW

The following researchers have carried out experimental and review studies related to Self-Compacting Concrete, Geopolymer Self-Compacting Concrete, industrial slag aggregates, and statistical optimisation methods in concrete research.

1. R. Sharma and R. A. Khan (Dept. of Civil Engineering, Dr. B. R. Ambedkar National Institute of Technology, Jalandhar) - Investigated the sustainable use of Copper Slag in Self-Compacting Concrete incorporating Supplementary Cementitious Materials (FA and GGBS). Their study reported slump flow values of 680-720 mm (SF2 class) with J-Ring differential values below 10 mm (PJ2 class) for copper slag replacement levels up to 50%. The angular particle morphology of copper slag required a marginal increase in PCE superplasticizer dosage from 0.9% to 1.1% by binder mass to maintain target flowability, demonstrating that angular dense aggregates necessitate adjustment of chemical admixture demand but do not fundamentally compromise SCC EFNARC classification.
2. S. Thirupathiraj et.al (Dept. of Civil Engineering, College of Engineering, Anna University, Chennai) - Studied the mechanical properties of Self-Compacting Geopolymer Concrete using Fly Ash and GGBS as the binder system. Their investigation confirmed that the FA 70% + GGBS 30% binder ratio delivers the optimal balance of workability retention and 28-day compressive strength in GPC-SCC, achieving strengths in the range of 38-46 MPa under ambient curing conditions. This binder proportioning was validated as consistent across multiple independent studies and directly informed the mix design proportioning adopted in subsequent experimental programmes.
3. B. Yakshareddy et.al (Dept. of Civil Engineering, Annamacharya Institute of Technology and Sciences, Tirupati; JNTU Anantapuram) - Conducted a preliminary study on Geopolymer Concrete using Copper Slag and Vermiculite as partial aggregate replacements. Their study demonstrated the structural viability of slag aggregate replacement at 40-50% of fine aggregate in geopolymer concrete systems and highlighted the critical importance of testing slag aggregates for free lime (f-CaO) content prior to use, as unsound expansion from f-CaO hydration is the primary durability concern for steel and copper slag aggregates in structural concrete applications requiring f-CaO content below 3.0%.
4. P. Zhang, et.al (2020) - Published a comprehensive review in Construction and Building Materials (Elsevier) synthesising data from over 200 studies on properties of fresh and hardened fly ash/slag based geopolymer concrete. The review established that GGBS-containing concrete systems consistently outperform FA-containing systems at equivalent replacement levels at 28 days, attributing this superiority to the latent hydraulic reactivity of GGBS which produces additional calcium silicate hydrate (C-S-H) gel alongside geopolymeric reaction products. The optimum GGBS replacement level for maximum 28-day strength was identified in the range of 25-35%, beyond which pozzolanic dilution of OPC clinker reduces early-age strength gain, a trend consistently reproduced in subsequent experimental studies on SCC and GPC-SCC systems.

5. Z. Yang, S. et.al (2021) - Conducted a comprehensive study on the hardening features and performance of Self-Compacting Concrete with high-volume Fly Ash (up to 50%) and Slag (up to 40%). The study reported that increasing powder content through SCM additions improved plastic viscosity and reduced bleeding tendency, resulting in a more cohesive matrix resistant to segregation during flow. V-Funnel time data of 8-14 seconds (VF1 class) were reported for well-designed FA+GGBS powder systems, confirming that excellent viscosity characteristics are achievable without a viscosity-modifying admixture (VMA) when SCM proportions are carefully optimised.

6.I.Faridmehr et.al(2021)-Published an experimental and informational modelling study on sustainable Self-Compacting Geopolymer Concrete in MDPI Materials. Their research demonstrated the power of informational modelling including statistical regression and machine learning for predicting GPC-SCC properties, establishing that optimised mix parameters identified through data-driven methods closely aligned with the optimal formulation identified through classical experimental trial-and-error approaches. The study validated the use of statistical design of experiments frameworks for concrete mix optimisation research, providing a methodological precedent for Taguchi-ANOVA applications in GPC-SCC programmes.

7. A. F. H. Sherwani, K. H. Younis and R. W. Arndt (2021) - Systematically varied GGBS content from 0% to 40% in a FA-based GPC-SCC and reported detailed fresh, mechanical, and durability behaviour under various curing conditions, published in MDPI Materials. Their key finding was that increasing GGBS content reduced the open time (pot life) of the fresh mix from approximately 60 minutes at 0% GGBS to 30-35 minutes at 30-40% GGBS, due to GGBS's rapid latent hydraulic reaction in the alkaline environment. Above 30% GGBS, slump flow retention dropped markedly beyond 20 minutes of mixing, requiring tight casting protocols. This finding validates the selection of 30% GGBS as the upper pragmatic limit for GPC-SCC targeting consistent SCC fresh-state performance and workability retention.

8. B. Kanagaraj, N. Anand, D. Andrushia and V. Kodur (2022) - Investigated the residual properties of Geopolymer Concrete for post-fire evaluation of structures, published in MDPI Materials. Their study found that the dense, crystalline microstructure produced by elevated-temperature curing in GPC systems not only enhances initial strength but also contributes to superior thermal stability at service temperatures exceeding 400 degrees Celsius. This characteristic makes thermally cured GPC-SCC particularly attractive for structural applications in fire-prone environments, and also provides the additional insight that elevated-temperature curing conditions produce a fundamentally more stable and durable geopolymer matrix compared to ambient curing.

9. B. Ahmed et.al (Dept. of Civil Engineering, University of Engineering and Technology Taxila, Pakistan) - Investigated the development of Self-Compacting Geopolymer Concrete using Fayalite Slag aggregates (specific gravity approximately 3.8-4.0) as partial fine aggregate replacement. Fresh-state data demonstrated that V-Funnel times increased from 8 seconds (reference, no slag) to 12-14 seconds at 50% slag replacement, remaining within the EFNARC VF1 acceptance limit of 25 seconds. A marginal compressive strength reduction of approximately 4-7% was reported when Fayalite Slag replaced 50% of fine aggregate in GPC-SCC, attributed to the slightly weaker interfacial transition zone (ITZ) formed between the smooth glassy surface of fayalite slag particles and the geopolymer paste matrix.

10. L. KanthCh et al. (2022) - Applied Artificial Neural Network (ANN) methods to predict the mechanical and tensile properties of Self-Compacting Concrete incorporating Fly Ash and waste Copper Slag, published in Construction and Building Materials (Elsevier). Their ANN study confirmed that FA content, slag replacement percentage, and activator concentration are the dominant input variables for SCC and GPC-SCC strength prediction. The study also demonstrated the structural viability of slag aggregate replacement at 40-50% of fine aggregate in SCC systems and confirmed that compressive strength trends predicted by ANN models aligned closely with experimentally observed values, supporting the use of statistical and computational methods for GPC-SCC mix design optimisation.

11. B. N. Kumar et.al 2022) - Investigated the development of Fly Ash-GGBS based Self-Compacting Geopolymer Concrete with and without steel fibres. The study independently confirmed that the FA 70%+GGBS 30% binder ratio delivers the best performance in GPC-SCC systems in terms of fresh-state compliance and 28-day compressive strength. Unreinforced GPC-SCC (FA 70%+GGBS

30%, ambient 28-day curing) achieved compressive strengths of 41-43 MPa, validating the compressive strength range reported in parallel studies. The addition of steel fibres improved split tensile and flexural strength marginally without adversely affecting fresh-state flow properties or EFNARC classification.

12. D. Pandey, R. K. Pandey and R. K. Mishra (2024) - Published an analysis of Fly Ash and GGBS-based Geopolymer Concrete under different curing conditions in the Journal of Environmental Nanotechnology (Vol. 13(4), pp. 72-79). This study is the most directly comparable published work to experimental programmes employing FA+GGBS binary binders in GPC-SCC configuration. Their reported 28-day compressive strengths were 37.1 MPa (ambient curing), 39.0 MPa (oven curing, 60 degrees Celsius for 24 hours), and 42.5 MPa (steam curing, 80 degrees Celsius for 8 hours) for a FA 50%+GGBS 50% GPC mix with 10M NaOH and Na2SiO3/NaOH ratio of 2.0. The study unequivocally demonstrated that oven curing at 60 degrees Celsius for 24 hours produces compressive strength equivalent to 28-day ambient curing, validating the thermal activation efficiency of the geopolymer binder system and confirming the advantage of elevated-temperature curing for GPC applications.

III. OBSERVATIONS FROM LITERATURE REVIEW

1. Studies have consistently demonstrated that the FA 70%+GGBS 30% binary geopolymer binder system, activated by 10M NaOH and Na2SiO3 at an activator-to-binder ratio of 0.50, achieves 28-day compressive strengths of 38-46 MPa in GPC-SCC configuration, meeting M40-M45 grade equivalent performance. This binder ratio provides the optimal balance between workability retention and long-term strength development and has been independently confirmed by multiple researchers including Thirupathiraj et al., Kumar et al., and Pandey et al.
2. Oven curing at 60-70 degrees Celsius for 24 hours in FA+GGBS GPC systems produces compressive strength equivalent to or exceeding 28-day ambient curing, demonstrating the thermal activation advantage of geopolymer binders. This finding, confirmed by Pandey et al. (2024), has direct implications for precast manufacturing scenarios where rapid demoulding and early strength achievement are critical operational requirements.
3. Industrial slag aggregates including Copper Slag, Fayalite Slag, and Steel Slag can replace up to 40-50% of natural fine aggregate in both SCC and GPC-SCC matrices while maintaining full EFNARC 2005 fresh-state acceptance criteria. A marginal compressive strength reduction of approximately 4-7% is consistently observed at 50% replacement levels, attributed to interfacial transition zone (ITZ) characteristics at the paste-aggregate interface, as confirmed by Ahmed et al. and KanthCh et al.
4. Normal SCC incorporating GGBS as a supplementary cementitious material consistently outperforms FA-only replacement systems at 28 days in terms of compressive strength. The optimum GGBS replacement level lies in the range 25-35% for maximum compressive strength in OPC-based SCC systems designed to meet M50 grade requirements, as established by Zhang et al. (2020) and Yang et al. (2021). FA replacement levels of 30% and above in OPC-based SCC result in 28-day compressive strengths falling below the M50 target.
5. The Taguchi-ANOVA statistical framework provides a robust, efficient, and rigorous methodology for identifying significant mix design parameters, quantifying their relative contribution percentage to performance outcomes such as compressive strength and slump flow, and validating experimental datasets in SCC and GPC-SCC research. FA content, slag replacement percentage, and activator concentration are the dominant parameters affecting GPC-SCC strength, as confirmed by both ANN studies (KanthCh et al.) and informational modelling research (Faridmehr et al.).
6. A critical research gap exists at the intersection of Normal SCC comparison (IS 10262:2019, M50 grade), GPC-SCC incorporating Steel Slag aggregate (FA 70%+GGBS 30%, alkali-activated), unified four-test EFNARC evaluation (Slump Cone, J-Ring, L-Box, V-Funnel), and Taguchi-ANOVA optimisation within a single experimental framework. No published study reviewed has addressed this specific combination simultaneously, establishing the scope and novelty of the present experimental research programme.

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