Jurnal Teknik Sipil & Perencanaan 27 (2) (2025) p 27 - 38

UNNES JOURNALS

JURNAL TEKNIK SIPIL & PERENCANAAN

10.15294/jtsp.v27i2/29679

http://journal.unnes.ac.id/nju/index.php/jtsp/index

Performance Index-Based Multi-Criteria Optimization of GGBFS Replacement in Concrete for Enhanced Strength, Durability, and Sustainability

Lodgar Gabriel Mlodi[1, a)] Herry Suryadi Djayaprabha[2]

[1,2] *Faculty of Civil Engineering, Universitas Katolik Parahyangan, JL. Cimbuleut No. 94, Bandung Indonesia 40141*

[a)] Corresponding author: lodgargabriel@gmail.com

Abstract. Using ground granulated blast furnace slag (GGBFS) as a partial replacement for ordinary Portland cement (OPC) has emerged as a sustainable alternative in concrete production, offering notable improvements in durability and long-term strength. However, identifying the optimal replacement level that balances mechanical performance, durability, and sustainability remains challenging. This study addresses this gap by critically reviewing sixteen peer-reviewed studies conducted between 2006 and 2025, the broadest dataset yet applied in a performance index (PI)-based evaluation. A PI was developed to normalize and compare diverse mechanical and durability parameters, integrating them into a multi-criteria framework. The PI was further evaluated under three practical weightings: Balanced (50/50), Durability-prioritized (60/40), and Strength-prioritized (40/60). Results indicate that a 40% GGBFS replacement delivers the highest composite performance under balanced criteria, 20% is optimal for strength-driven applications, and 60–70% provides superior durability in aggressive environments, especially when activation or enhanced curing is applied. This study demonstrates the practical utility of an integrated PI approach for sustainable concrete design.

Keywords: Concrete durability, Compressive strength, Ground Granulated Blast Furnace Slag, Performance Index, Sustainability

INTRODUCTION

The rising demand for sustainable and high-performance construction materials has led to increasing incorporation of supplementary cementitious materials (SCMs), particularly Ground Granulated Blast Furnace Slag (GGBFS), in modern concrete technology. GGBFS, a by-product of the steel industry, is widely recognized for reducing the environmental footprint of Ordinary Portland Cement (OPC), which remains a dominant contributor to CO_2 emissions in the construction sector [21]. In addition to sustainability, slag has shown potential to enhance concrete's mechanical and durability performance under various curing and environmental conditions [6, 22].

However, the performance of slag concrete depends strongly on the replacement level. Lower dosages (10–30%) typically improve early strength and workability. In comparison, higher proportions (50% and above) often enhance durability but may reduce early-age strength due to lower clinker content and slower pozzolanic reactions [18, 29]. Nevertheless, without integrating these outcomes into a unified assessment, most existing research has investigated individual properties in isolation, such as compressive strength, chloride resistance, or sulphate attack. Consequently, no widely accepted framework for determining optimal GGBFS replacement levels balances strength, durability, and sustainability across diverse applications.

Several attempts have been made to address this challenge through performance index (PI)-based approaches. The study of Torkaman et al. (2021) [27] applied multi-criteria decision-making techniques to alkali-activated binders, while Kubissa et al. (2019) [14] introduced ecological and performance indices for evaluating concrete mixtures.

Although these studies illustrate the potential of PI methods, they were constrained either by small datasets or by focusing on narrow aspects of performance, which limits their practical applicability.

To address this gap, the present study synthesizes data from sixteen peer-reviewed investigations conducted between 2006 and 2025, the broadest dataset yet applied in a PI-based evaluation of slag concrete. The analysis integrates both mechanical and durability parameters into a unified framework and employs a flexible weighting scheme balanced (50/50), durability-prioritized (60/40), and strength-prioritized (40/60) that mirrors practical engineering scenarios. The novelty, therefore, lies primarily in the scope of the dataset, supported by an application-oriented weighting strategy, which together provide robust and adaptable guidance for selecting optimal GGBFS dosages across diverse structural and environmental conditions.

METHODOLOGY

Data Collection and Study Selection

An initial pool of 58 peer-reviewed studies on Ground Granulated Blast Furnace Slag (GGBFS) concrete published between 2006 and 2025 was identified through database searches and cross-referencing. Strict inclusion and exclusion criteria were applied to ensure comparability and isolate the role of slag. Studies were included if they reported compressive strength at one or more curing ages, since this property provides a consistent baseline for mechanical performance across all datasets. Durability-related properties such as chloride penetration, water absorption, porosity, sorptivity, or sulphate resistance were also incorporated when available. Additional requirements were that testing procedures follow established international or national standards (ASTM, BS, or IS) and must clearly document mix proportions, slag dosage, and curing conditions. By contrast, studies were excluded if they focused only on fresh-state properties, used non-standardized or experimental procedures without code references, lacked sufficient quantitative data for normalization, or involved ternary and quaternary blends with other supplementary cementitious materials, including fly ash, metakaolin, silica fume, and volcanic ash. After applying these filters, the dataset was refined to 16 representative studies, ensuring consistency and focus on the specific influence of slag.

Managing Variability

The selected studies employed diverse experimental conditions, including water curing [11, 18, 28], steam curing [22], marine exposure [6], acidic curing [5], and lime-saturated curing [28]; water-to-cement ratios ranging between 0.30 and 0.50 used in many studies where some included the use of Superplasticizer to increase workability in High strength concrete (HSC) [22, 28]; Aggregate types such as crushed granite, natural gravel, and river sand, with some cases of partial substitution by steel slag [4]. Some studies also applied chemical activators such as sodium carbonate or sodium hydroxide to enhance slag hydration [6, 13]. This variability reflects practical construction conditions but complicates direct comparison. All results were normalized within each study before aggregation to minimize bias, ensuring that relative performance trends were preserved across diverse methodologies.

Normalization of Data

A min–max normalization approach was applied to standardize performance indicators, converting all results to values between 0 and 1. Parameters positively correlated with performance, compressive strength, ultrasonic pulse velocity, modulus of elasticity, and sulphate resistance were normalized using Equation (1). In contrast, negatively correlated parameters, such as chloride penetration, water absorption, porosity, and sorptivity, were normalized using Equation (2). This method was selected because it preserves relative ranking, accommodates different measurement units, and has been widely used in performance index (PI) studies of concrete [14, 27]. Alternative methods were considered: Z-score standardization assumes normally distributed data, which was inconsistent across the reviewed studies; and TOPSIS, though robust, requires subjective weighting of distances that can reduce transparency in comparative analysis. Given dataset heterogeneity, Min–Max normalization was determined to be the most transparent and unbiased technique.

$$\text{Normalized parameter, } X_{norm} = \frac{X_i - X_{min}}{X_{max} - X_{min}} \tag{1}$$

$$\text{Normalized parameter, } X_{norm} = \frac{X_{max} - X_i}{X_{max} - X_{min}} \quad (2)$$

Performance Index Framework

The normalized results were aggregated into a Performance Index (PI) using a weighted summation method (Equation 3). Two groups of indicators were considered: mechanical performance (α), represented by compressive strength, and modulus of elasticity, while durability performance (β), represented by ultrasonic pulse velocity, chloride penetration, water absorption, porosity, sorptivity, and sulphate resistance. Three weighting schemes were adopted to reflect practical engineering scenarios: balanced, strength-prioritized, and durability-prioritized, with coefficients as shown in Table 1. These scenarios represent general-purpose concrete, strength-critical elements such as precast members, and durability-driven environments such as marine or sulphate-rich exposures. Previous studies have applied similar weighting strategies using performance index-based evaluations to support multi-criteria concrete assessment, ensuring that both short-term and long-term performance are adequately considered [14].

$$\text{Performance Index, } PI = \alpha * N_m + \beta * N_D \quad (3)$$

TABLE 1. Weighting coefficients (α and β) under different performance criteria

Coefficient	Balanced Environment (%)	Severe Environments(%)	High-strength demands (%)
α	50	40	60
β	50	60	40

Source: Weighting schemes (50/50, 60/40, 40/60) selected to reflect practical engineering scenarios. The approach is consistent with the weighting strategies proposed in earlier PI-based evaluations [14, 27].

Materials

All materials used were selected to meet relevant national or international standards, such as ASTM, BS, or IS codes, to ensure comparability of results across different experimental setups [7, 14]

Cementitious Material.

The reviewed studies consistently used Ordinary Portland Cement (OPC**)** as the primary binder, often partially replaced with Ground Granulated Blast Furnace Slag (GGBFS**)** at varying percentages, ranging from 10% to 90% [2, 4, 6]. The slag used was typically sourced from steel manufacturing by-products, with a particle size distribution similar to cement to ensure compatibility and pozzolanic reactivity [16, 18]. The chemical composition of slag varied slightly across studies but typically featured high contents of CaO, SiO_2, and Al_2O_3, contributing to its latent hydraulic activity. X-ray fluorescence (XRF) was employed in several studies to characterize these properties [8, 15]. Some researchers included supplementary cementitious materials (SCMs**)** in ternary blends, such as Metakaolin or Fly Ash (FA), which enhanced the mechanical and durability performance [4, 10].

TABLE 2 Oxide Composition of components of GGBFS by weight

Oxide Component	Chemical Formula	Range (% by weight)
Calcium Oxide	CaO	30 – 45%
Silicon Dioxide	SiO_2	30 – 40%
Aluminum Oxide	Al_2O_3	8 – 18%
Magnesium Oxide	MgO	5 – 10%
Sulfur Trioxide	SO_3	1 – 4%
Iron Oxide	Fe_2O_3	0.50 – 2%
Sodium Oxide	Na_2O	0.30 – 1%
Potassium Oxide	K_2O	0.20 – 1%

Oxide Component	Chemical Formula	Range (% by weight)
Loss on Ignition	LOI	0.10 – 2%

Source: Compiled from studies reporting chemical composition of GGBFS [6, 13, 29, 18, 8, 16, 17, 22].

Fine and coarse Aggregates

Fine aggregates primarily consisted of natural river sand, conforming to ASTM C33 standards. In some studies, alternative fine aggregates such as steel slag were partially substituted to improve sustainability [4]. Coarse aggregates were generally crushed granite or natural gravel with a nominal maximum size of 20 mm [11, 21].

Chemical Admixture, Activator, and water

Superplasticizers based on Polycarboxylate ether (PCE) were commonly added to ensure the desired workability without increasing water content when high-strength concrete was targeted [16, 22]. Certain studies used alkali activators, such as Na_2CO_3, for GGBFS activation in alkali-activated systems [13] while others explored the effect of CaO content to optimize the binder composition [15]. Water used for concrete mixing and curing was potable in most studies; however, some studies incorporated special curing conditions to identify the behavior of concrete under severe environments.

Experimental Parameters and Procedure

Mix proportional and Specimen casting

In all reviewed studies, ordinary Portland cement (OPC) was partially replaced by ground granulated blast furnace slag (GGBFS) at varying proportions, typically ranging from 10% to 90% by mass. Before mixing, all powdered materials were stored in dry, sealed containers to prevent moisture ingress. GGBFS was either commercially sourced or laboratory-processed from local steel industries, ground to pass through a 45 µm sieve [6, 11, 18]. Fine and coarse aggregates were sieved to standard gradations and oven-dried to a constant mass before use. The moisture content and specific gravity of aggregates were determined to accurately adjust the water-to-binder (w/b) ratio. In several studies, including Turuallo (2013) and Samad et al. (2017), superplasticizers were included to enhance workability, especially at high slag dosages, without increasing the w/b ratio [22, 28].

The mixing procedure generally began with dry blending of OPC, slag, and fine aggregates in a mechanical mixer for 2–3 minutes to ensure homogeneity. Subsequently, water (and in some cases, chemical admixtures) was added gradually during continuous mixing for another 2–3 minutes [11, 18]. For alkali-activated systems, the alkaline solution (sodium silicate and/or sodium carbonate) was prepared and allowed to cool to ambient temperature before blending with the binders [13]. In ternary systems, such as that involving metakaolin and Slag, all powders were dry-mixed before liquid components were introduced [4].

Fresh concrete was poured into standard molds: 100 mm cubes for compressive strength, 100 × 200 mm cylinders for modulus of elasticity and durability tests, and disc specimens (50 mm × 100 mm) for sorptivity and chloride penetration tests. Compaction was done using either table vibration or manual tamping. The molds were covered with plastic sheets to avoid moisture loss and demolded after 24 hours.

Curing Conditions

Curing regimes significantly impacted the hydration and pozzolanic activity of GGBFS-blended concrete. Most reviewed studies employed standard water curing, in which specimens were submerged in potable water at 23 ± 2°C until testing ages, typically at 7, 28, and 90 days. This approach was consistently followed in studies by Karri et al. (2015), Turuallo (2013), and Miah et al. (2023) [11, 18, 28]. As detailed below, several other studies adopted specialized curing protocols to simulate aggressive environments or enhance slag activation.

- Acidic Curing: Dewi et al. (2019) subjected specimens to sequential immersion in 5% sulfuric acid for 7 days, followed by 5% hydrochloric acid for another 7 days, aiming to assess resistance against industrial chemical exposure [5].

- Marine Curing: Elchalakani et al. (2015) cured samples in actual Persian Gulf seawater at 45°C to simulate harsh coastal environments and evaluate chloride-induced deterioration [6].
- Steam Curing: Samad et al. (2017) applied steam curing at 60°C for 6–8 hours, promoting early strength gain in high-GGBFS mixtures [22].
- Alkali-Activated Curing: Kim and Jun (2018) eliminated external curing, allowing samples to harden under ambient conditions (25°C), relying solely on internal activation via alkaline solutions [13].
- Lime-Saturated Water: Turuallo (2013) utilized saturated lime water to maintain elevated pH levels, enhancing pozzolanic reactions in GGBFS systems [28].

These varied curing strategies underscore the adaptability of GGBFS-based concretes and highlight the experimental diversity necessary for comprehensive durability evaluation under different exposure conditions.

Mechanical Testing

In mechanical tests, the compressive strength was the most frequently tested property, typically performed in accordance with ASTM C39 or equivalent standards, using either cube or cylindrical specimens (100–150 mm) tested at various curing ages, commonly 7, 28, 56, and 90 days. While most studies followed conventional methods, Kim and Jun (2018) used cylindrical specimens specifically to assess the effect of Na_2CO_3 activation on GGBFS cement paste [13]. Modulus of elasticity was also investigated in a few studies, including Elchalakani et al. (2015) and Yang et al. (2020), which typically determined according to ASTM C469, by measuring stress-strain responses under axial loading [6, 10].

Durability Testing

A comprehensive suite of standardized tests was employed across the reviewed studies to assess the durability performance of GGBFS-modified concrete. Chloride ion permeability was commonly evaluated using the Rapid Chloride Penetration Test (RCPT), following ASTM C1202 procedures, to quantify ionic transport and infer potential corrosion risk in reinforced systems [8, 16]. Water absorption and porosity were typically determined based on ASTM C642, providing measures of permeable voids and total pore volume relevant to moisture ingress and durability [11, 28]. Capillary water transport was assessed through sorptivity tests aligned with ASTM C1585 or equivalent procedures, offering insight into early-stage moisture dynamics [22]. Chemical resistance tests were conducted to simulate aggressive environmental exposures by immersing specimens in acidic media such as sulphuric and hydrochloric acids [5, 8], supporting durability assessments under industrial or sulphate-rich conditions.

Non-destructive testing was also utilized, with Ultrasonic Pulse Velocity (UPV) performed in accordance with ASTM C597 to evaluate internal microstructural integrity and uniformity [17]. These tests provided a consistent and comparative framework to characterize the long-term performance potential of concrete incorporating slag across diverse curing and environmental regimes.

RESULT AND DISCUSSION

Compressive Strength Performance

When assessed independently through the PI framework, the compressive strength data showed a consistent optimum at 40% GGBFS replacement as shown in Figure 3. This dosage balances the competing effects of clinker dilution and slag hydration. At lower replacement levels (<30%), the cementitious system retains sufficient clinker to develop strength, but the contribution of slag to microstructural refinement is limited [22, 12]. At higher levels (>50%), the reduced clinker content generally slows early hydration and strength development [26]. However, several studies reported that when chemical activators such as sodium carbonate, sodium hydroxide, or lime-saturated curing are employed, high-slag mixtures can achieve strength comparable to or exceeding that of OPC control mixes [19]. In such cases, the activator accelerates slag hydration and enhances C–S–H formation, overcoming the dilution effect of reduced clinker. The 40% level, therefore, represents the optimum under conventional curing, but higher slag contents can perform equally well if chemical activation strategies are applied [9].

TABLE 3. Performance Index (PI) for Compressive Strength Data

GGBFS (%)	0	10	20	30	40	50	60	70	80	90
Performance Index (PI)	0.57	0.52	0.53	0.52	0.64	0.44	0.57	0.65	0.68	0.50

Note: PI values calculated using normalized compressive strength data extracted from 16 peer-reviewed studies published between 2006 and 2025.

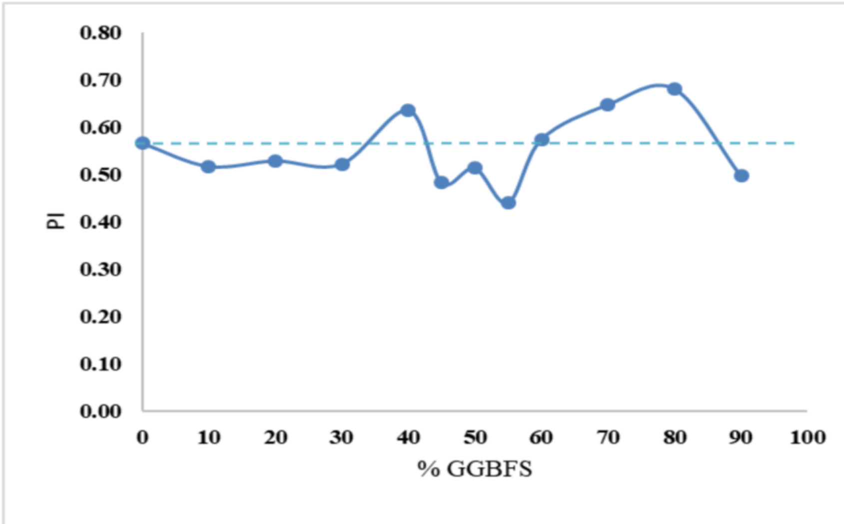

FIGURE 1. Performance Index (PI) on compressive strength (CS) at different proportions of GGBFS.

Durability Performance

Durability performance was critically analyzed using data primarily derived from the Rapid Chloride Penetration Test (RCPT), as this method was consistently reported across multiple peer-reviewed studies. RCPT PI trends revealed a different pattern, with optimum performance occurring at higher replacement levels (50–80%) as in Figure 2. High slag dosages promote continued pozzolanic activity, consuming calcium hydroxide and generating additional C–S–H, significantly reducing porosity and permeability [19]. As a result, chloride penetration resistance, sulphate resistance, and sorptivity improved with increasing slag content, consistent with recent findings on GGBFS–silica fume geopolymer systems under harsh conditions [7, 20].

An anomaly was observed at 40% GGBFS replacement (Table 4), where chloride penetration resistance was lower than adjacent levels. This can be explained by a transitional microstructure: clinker dilution reduces aluminate phases that aid chloride binding. At the same time, the pozzolanic reaction of GGBFS has not yet fully refined the pore structure. As a result, capillary pores remain relatively larger, and C–S–H gel distribution is heterogeneous, temporarily limiting chloride resistance. Microstructural studies in similar systems [24, 25]. Support this by showing that intermediate slag contents can produce incomplete pore refinement. This emphasizes evaluating durability alongside curing regimes and highlights the potential benefit of chemical or thermal activation to accelerate slag hydration at intermediate replacement levels.

TABLE 4. Performance Index (PI) for RCPT data

GGBFS (%)	0	10	20	30	40	50	60	70	80
Performance Index (PI)	0.00	0.26	0.78	0.88	0.49	1.00	0.75	0.98	1.00

Note: PI values calculated using normalized compressive strength data extracted from 16 peer-reviewed (2006-2025).

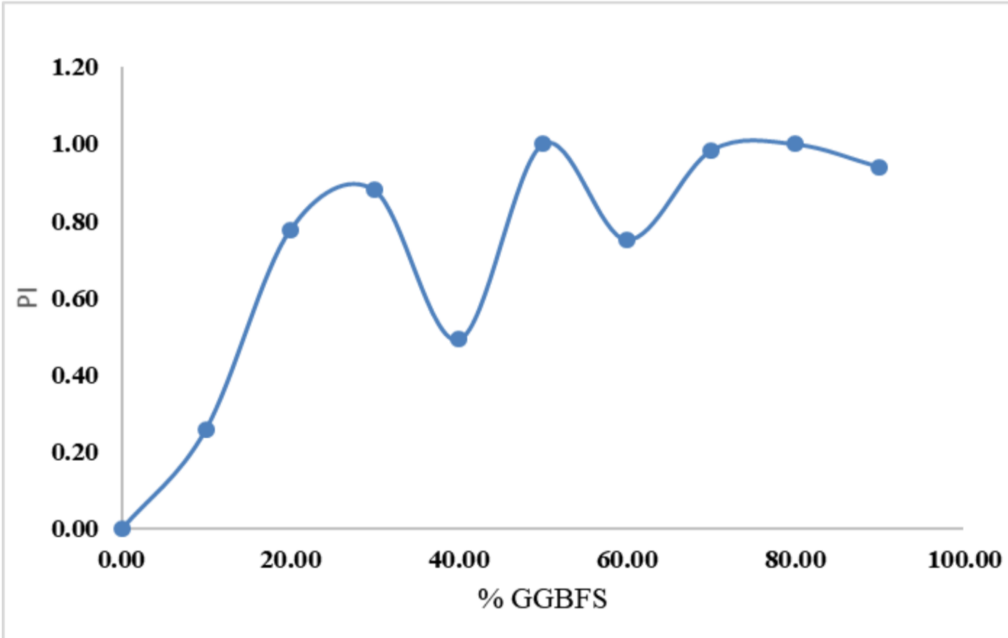

FIGURE 2. Performance Index (PI) on RCPT at different proportions of GGBFS.

Composite Performance

Composite indices were developed by combining normalized strength and durability data with varying weightings (α, β) to reflect design priorities (Table 1).

Balanced criteria (α = 0.50, β = 0.50).

The highest PI was at 40% GGBFS (0.75), followed by 60% (0.63). At this level, clinker hydration and slag reactivity are optimally balanced: sufficient clinker ensures early strength, while slag contributes to secondary C–S–H formation and pore refinement. This balance, also reported by Miah et al. (2023) and Dandaboina et al. (2025) [4, 18], makes 40–60% replacement most suitable for general structural applications.

Durability-prioritized criteria (α = 0.40, β = 0.60).

Optima were observed at 20%, 60%, and 70% (0.62 each). Higher slag dosages enhance pozzolanic $Ca(OH)_2$ consumption, refining pore structure, and reducing chloride/sulphate ingress. Even 80% showed resilience (0.52) under proper curing. These outcomes confirm that high GGBFS levels are advantageous in marine or sulphate-rich environments, consistent with Elchalakani et al. (2015), Heikal et al. (2023), and Al-Hamrani et al. (2021) [2, 6, 8].

Strength-prioritized criteria (α = 0.60, β = 0.40).

The highest PI (0.64) was found at 20% and 60% GGBFS. At 20%, clinker dominates hydration, ensuring rapid early strength. At 60%, slag's contribution to long-term C–S–H formation offsets clinker dilution, particularly under thermal or mild chemical activation. This dual mechanism supports the findings of Yang et al. (2020) and Kim & Jun (2018) [13, 29].

TABLE 5. PI Analysis based on composite criteria's

GGBFS (%)	0	10	20	30	40	45	50	55	60	70	80
PI for Balanced Condition	0.38	0.50	0.55	0.57	0.75	0.60	0.56	0.32	0.63	0.59	0.17
PI for Durability Prioritized	0.35	0.46	0.62	0.47	0.60	0.51	0.41	0.55	0.62	0.62	0.52
PI for Strength Prioritized	0.41	0.44	0.64	0.48	0.61	0.49	0.44	0.53	0.64	0.60	0.52

Note: PI values calculated using normalized compressive strength data extracted from 16 peer-reviewed studies published between 2006 and 2025.

The integration of these composite indices, as shown in Figure 3, demonstrates that no single slag dosage universally optimizes all performance criteria. However, a 40% GGBFS replacement consistently ranks among the top across all environmental scenarios, confirming its flexibility and robustness. 60–70% GGBFS is optimal for durability-driven applications, provided curing or activation is carefully controlled. These outcomes reinforce the principle that mix design must be context-specific, with dosage tailored to the structural function and exposure class, an approach supported by Richardson (2006), Karri et al. (2015), and Dewi et al. (2019) [5, 11, 21].

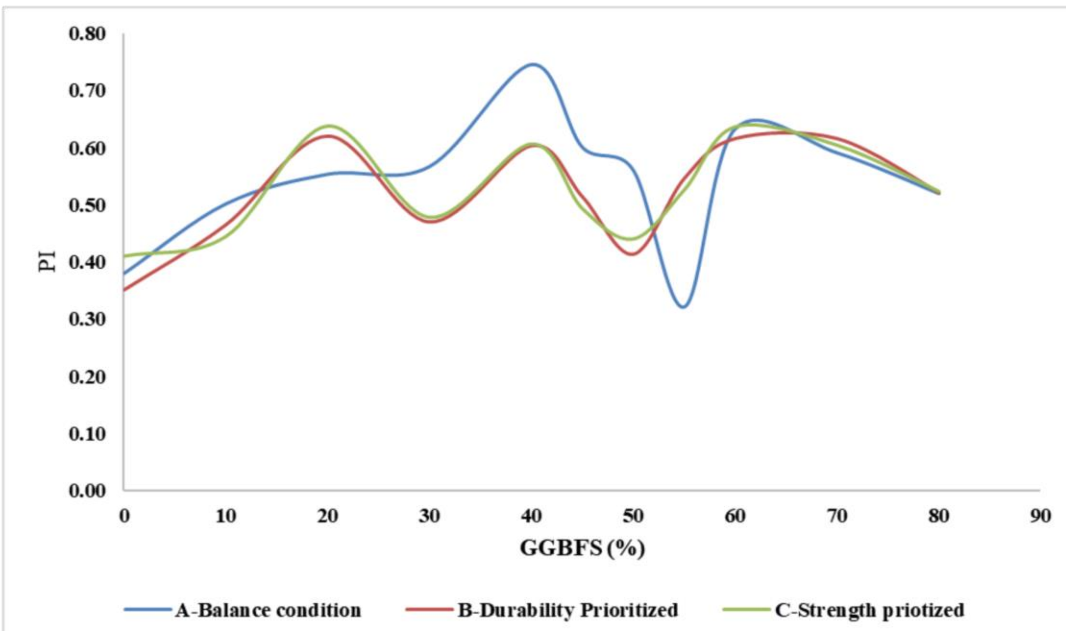

FIGURE 3. Performance index at different criteria with varying proportions of GGBFS

Implications for Design and Standards

The results have direct implications for structural design and code recommendations. Current guidelines, such as ACI 233R-17 and BS EN 15167-1, recommend GGBFS replacement levels between 25% and 50% [1, 3]. The PI-based evaluation in this study confirms that 40% replacement is optimal when both strength and durability are considered simultaneously, aligning with the upper range of these recommendations. However, in exposure conditions dominated by durability concerns, such as marine or sulphate-rich environments, 50–60% replacement may be more appropriate [8]. This suggests that prescriptive replacement ranges in current standards could be complemented by performance-based approaches, where dosage is tailored to project-specific priorities. Recent pilot studies further highlight that activated GGBFS–silica fume blends offer cost savings and sustainability benefits [23]. Integrating multiple criteria, the PI framework developed here provides a robust and adaptable tool to guide such decisions.

CONCLUSIONS

This study introduces an integrated Performance Index (PI) framework to evaluate concrete incorporating Ground Granulated Blast Furnace Slag (GGBFS), combining strength and durability in a single multi-criteria assessment. Analysis of sixteen studies identified practical GGBFS replacement ranges: 20–30% for strength-driven applications, 40% for balanced performance, and 60–70% for durability-critical structures, provided appropriate curing or activation is applied. Limitations include reliance on secondary data with variable mix designs, curing regimes, and testing protocols. Future research should focus on standardized experimental datasets, broader durability metrics, and life-cycle assessment to optimize sustainable, high-performance concrete for diverse construction applications.

REFERENCE

[1] ACI Comm. 233, *ACI 233R-17: Guide to Using Slag Cement in Concrete and Mortar.* Farmington Hills, MI: American Concrete Institute, 2017.

[2] M. Al-Hamrani, W. Kucukvar, E. Alnahhal, E. Mahdi, and N. C. Onat, "Green concrete for a circular economy: A review on sustainability, durability, and structural properties," *Materials,* vol. 14, Article 351, 2021, doi:10.3390/ma14020351.

[3] British Standards Institution, *BS EN 15167-1: Ground Granulated Blast Furnace Slag for Use in Concrete, Mortar and Grout – Part 1: Definitions, Specifications and Conformity Criteria*. London: BSI, 2011.

[4] K. Dandaboina, J. S. Prasad, and S. Sohail, "Mechanical and microstructural properties of concrete with partial replacement of fine aggregate by steel slag and cement by GGBFS and metakaolin," *Discover Civil Engineering*, vol. 2, no. 16, 2025, doi:10.1007/s44290-025-00180-5.

[5] S. M. Dewi, L. Susanti, and H. Suseno, "Effects of GGBFS on compressive strength, workability, and mixing compacting time of concrete paste," *International Journal of Civil Engineering and Technology*, vol. 10, no. 3, pp. 1404–1412, 2019.

[6] M. Elchalakani, T. Aly, and E. Abu-Aisheh, "Sustainable concrete with high volume GGBFS to build Masdar City in the UAE," *Sustainable Cities and Society*, vol. 18, pp. 56–64, 2015, doi:10.1016/j.scs.2015.05.007.

[7] N. N. Ghafoori and H. Diawara, "Chloride permeability and corrosion resistance of concrete containing ground granulated blast furnace slag," *Cement and Concrete Composites*, vol. 32, no. 7, pp. 503–512, 2010, doi:10.1016/j.cemconcomp.2010.04.010.

[8] M. Heikal, M. A. Ali, D. Ghernaout, N. Elboughdiri, B. Ghernaout, and H. I. Bendary, "Prolonging the durability of maritime constructions through a sustainable and salt-resistant cement composite," *Materials*, vol. 16, Article 6876, 2023, doi:10.3390/ma16206876.

[9] J. Hosseinbor, H. Madani, and M. N. Norouzifar, "Improving the characteristics of less active geopolymer binders utilizing ground granulated blast-furnace slag under different curing conditions," *Materials*, vol. 16, no. 10, p. 3562, 2023, doi:10.3390/ma16103562.

[10] S. Y. Jang, S. Karthick, and S. J. Kwon, "Investigation on durability performance in early aged high-performance concrete containing GGBFS and FA," *Advances in Materials Science and Engineering*, vol. 2017, article 3214696, 2017, doi:10.1155/2017/3214696.

[11] S. K. Karri, G. V. R. Rao, and P. M. Raju, "Strength and durability studies on GGBS concrete," *SSRG International Journal of Civil Engineering*, vol. 2, no. 10, pp. 34–41, 2015.

[12] J. M. Khatib and J. J. Hibbert, "Selected engineering properties of concrete incorporating slag and metakaolin," *Construction and Building Material*s, vol. 19, no. 6, pp. 460–472, 2005, doi:10.1016/j.conbuildmat.2004.07.017.

[13] T. Kim and Y. Jun, "Mechanical properties of Na_2CO_3-activated high-volume GGBFS cement paste," *Advances in Civil Engineering*, vol. 2018, article 8905194, 2018, doi:10.1155/2018/8905194.

[14] W. Kubissa, R. Jaskulski, J. Chen, and P. L. Ng, "Evaluation of ecological concrete using multi-criteria ecological index and performance index approach," *Architecture, Civil Engineering, Environment*, vol. 12, no. 1, pp. 105–112, 2019, doi:10.21307/ACEE-2019-010.

[15] J. Lee and T. Lee, "Durability and engineering performance evaluation of CaO content and ratio of binary blended concrete containing ground granulated blast-furnace slag," *Applied Sciences*, vol. 10, p. 2504, 2020, doi:10.3390/app10172504.

[16] A. T. Mashuri, A. Yudi, and A. S. Aprilia, "Comparative analysis of concrete compressive strength using GGBFS as a cement substitute for normal concrete," *J Civil Eng Planning*, vol. 5, no. 2, pp. 239–250, 2024.
[17] M. M. Maske, S. S. Sayyed, S. K. More, S. N. Patil, and P. G. Chandak, "Influence of partial replacement of ordinary Portland cement with ground granulated blast furnace slag (GGBFS) on concrete strength and durability," *Research Square* preprint, 2024.
[18] M. J. Miah, R. Huaping, S. C. Paul, A. J. Babafemi, and Y. Li, "Long-term strength and durability performance of eco-friendly concrete with supplementary cementitious materials," *Innovative Infrastructure Solutions*, vol. 8, pp. 255, 2023, doi:10.1007/s41062-023-01192-4.
[19] B. Omer, "Evaluating the long-term strength of GGBFS-blended cement composites," *PLOS ONE*, vol. 20, no. 4, e0319923, 2025, doi:10.1371/journal.pone.0319923.
[20] S. Paruthi, I. Rahman, A. H. Khan, N. Sharma, and A. Alyaseen, "Strength, durability, and economic analysis of GGBS-based geopolymer concrete with silica fume under harsh conditions," *Scientific Reports*, vol. 14, Article 31572, 2024, doi:10.1038/s41598-024-31572-0.
[21] D. N. Richardson, *Strength and durability characteristics of a 70% ground granulated blast furnace slag (GGBFS) concrete mix*, Missouri Department of Transportation Report RI99-035, 2006.
[22] S. Samad, A. Shah, and M. C. Limbachiya, "Strength development characteristics of concrete produced with blended cement using ground granulated blast furnace slag (GGBFS) under various curing conditions," *Sādhanā*, vol. 42, no. 7, pp. 1203–1213, 2017, doi:10.1007/s12046-017-0621-x.
[23] A. Sengupta, "A pilot study on cost-effective utilization of activated GGBFS and silica fume as cement substitutes," arXiv preprint arXiv:2305.12288, 2023.
[24] C. Shi, A. F. Jiménez, and A. Palomo, "New cements for the 21st century: The pursuit of an alternative to Portland cement," *Cement and Concrete Research*, vol. 41, no. 7, pp. 750–763, 2011, doi:10.1016/j.cemconres.2011.03.005.
[25] H.-W. Song and R. Saraswathy, "Studies on the corrosion resistance of reinforced steel in concrete with ground granulated blast-furnace slag—An overview," *Journal of Hazardous Materials*, vol. 138, no. 2, pp. 226–233, 2006, doi:10.1016/j.jhazmat.2006.05.024.
[26] M. D. A. Thomas, "The effect of supplementary cementing materials on alkali–silica reaction: A review," *Cement and Concrete Research*, vol. 41, no. 12, pp. 1224–1231, 2011, doi:10.1016/j.cemconres.2011.08.001.
[27] J. Torkaman, S. A. Zareei, and B. A. Tayeh, "Performance assessment of alkali-activated materials using multicriteria decision-making techniques," *Construction and Building Materials*, vol. 279, article 122455, 2021, doi:10.1016/j.conbuildmat.2021.122455.
[28] G. Turuallo, "Kinerja ground granulated blast furnace slag (GGBS) sebagai bahan pengganti sebagian semen untuk sustainable development," in Proc. *Seminar Nasional, Inovasi Teknologi Berwawasan Lingkungan Dalam Pembangunan Infrastruktur Wilayah dan Industri*, Universitas Tadulako, Palu, Indonesia, 2013.
[29] H.-M. Yang, S.-J. Kwon, N. V. Myung, J. K. Singh, H.-S. Lee, and S. Mandal, "Evaluation of strength development in concrete with ground granulated blast furnace slag using apparent activation energy," *Materials*, vol. 13, p. 442, 2020, doi:10.3390/ma13020442.

APPENDIX 1: DATA ANALYSIS MATRIX

S/N	PAPER	PAPER RESULTS SUMMARY										NORMALIZED SCORE FOR EACH TESTS									PERFOMANCE INDEX		
	Study	%SL	CS	RCPT	UPV	WA (%)	C0_D (mm)	SO_4_A	SOR	POR	ME	CS	RCPT	UPV	WA	C0_D (mm)	SO_4_A	SOR	POR	ME	PI (50/50)	PI (40/60)	PI (60/40)
1	Samad et al. (2017)	0	70								39	1.00								0.00	0.50	0.50	0.50
		30	52								40	0.00								0.36	0.18	0.18	0.18
		40	67								40	0.80								1.00	0.90	0.90	0.90
		50	65								40	0.73								0.40	0.56	0.56	0.56
2	Mashuri et al. (2024)	0	25									0.00									0.00	0.00	0.00
		25	26									0.23									0.23	0.23	0.23
		30	26									0.31									0.31	0.31	0.31
		35	26									0.50									0.50	0.50	0.50
		40	28									1.00									1.00	1.00	1.00
		45	26									0.42									0.42	0.42	0.42
3	Maske et al. (2024)	0	30	1596			1.6		110			1.00	0			0		1			0.67	0.60	0.73
		50	28	1510			1.3		100			0.00	1			1		0			0.33	0.40	0.27
		0	70	3142			2.3		120			1.00	0			0		1			0.67	0.60	0.73
		50	65	1486			1.4		110			0.00	1			1		0			0.33	0.40	0.27
4	Elchalakani et al. (2015)	0	74	1971		1.67						1.00	0		0.00						0.50	0.40	0.60
		60	73	493		0.98						0.78	0.948		1.00						0.88	0.90	0.86
		70	68	486		1.49						0.24	0.952		0.26						0.42	0.46	0.39
		80	66	411		1.46						0.00	1.000		0.30						0.33	0.39	0.26
5	Miah et al. (2023)	0	3.5							24		0.50							0.00		0.25	0.20	0.30
		10	3							21		0.00							0.43		0.21	0.26	0.17
		20	3.5							19		0.50							0.71		0.61	0.63	0.59
		30	4							17		1.00							1.00		1.00	1.00	1.00
		45	3.7							18		0.70							0.86		0.78	0.79	0.76
		60	3.5							19		0.50							0.71		0.61	0.63	0.59
6	Al-Hamrani et al. (2021)	10	68									0.46									0.46	0.46	0.46
		20	98									1.00									1.00	1.00	1.00
		30	78									0.64									0.64	0.64	0.64
		40	75									0.59									0.59	0.59	0.59
		50	70									0.50									0.50	0.50	0.50

S/N	PAPER	PAPER RESULTS SUMMARY										NORMALIZED SCORE FOR EACH TESTS									PERFOMANCE INDEX		
	Study	%SL	CS	RCPT	UPV	WA (%)	C0_D (mm)	SO_4_A	SOR	POR	ME	CS	RCPT	UPV	WA	C0_D (mm)	SO_4_A	SOR	POR	ME	PI (50/50)	PI (40/60)	PI (60/40)
	Al-Hamrani et al. (2021)	55	60									0.32									0.32	0.32	0.32
		60	65									0.41									0.41	0.41	0.41
		70	55									0.23									0.23	0.23	0.23
		80	42									0.00									0.00	0.00	0.00
7	Turuallo (2013)	0	64									0.86									0.86	0.86	0.86
		20	58									0.00									0.00	0.00	0.00
		35	60									0.29									0.29	0.29	0.29
		50	62									0.57									0.57	0.57	0.57
		70	65									1.00									1.00	1.00	1.00
8	Kim & Jun (2018)	50	143		4350	8.7						0.36		1.0	1.00						0.68	0.74	0.61
		60	160		4150	9						1.00		0.6	0.70						0.83	0.79	0.86
		70	158		4000	9.3						0.95		0.3	0.40						0.65	0.59	0.71
		80	139		3900	9.5						0.21		0.1	0.20						0.18	0.18	0.19
		90	134		3850	9.7						0.00		0.0	0.00						0.00	0.00	0.00
9	Karri et al. (2015)	0	35									0.00									0.00	0.00	0.00
		10	39									0.39									0.39	0.39	0.39
		30	41									0.60									0.60	0.60	0.60
		50	46									1.00									1.00	1.00	1.00
	Yang et al. (2020)	0	43									1.00									1.00	1.00	1.00
		10	42									0.88									0.88	0.88	0.88
		30	39									0.50									0.50	0.50	0.50
		50	35									0.00									0.00	0.00	0.00
10	Heikal et al. (2023)	40	32	0.32 %				1.63		32		0.00	0.00				0.000		0.000		0.00	0.00	0.00
		60	33	0.28 %				1.62		33		0.59	0.31				0.167		0.588		0.47	0.45	0.49
		70	33	0.19 %				1.57		33		1.00	1.00				1.000		1.000		1.00	1.00	1.00
11	Lee and Lee (2020)	0	37	25								1.00	0.00								0.50	0.40	0.60
		10	36	20								0.87	0.26								0.56	0.50	0.63
		20	36	10								0.74	0.78								0.76	0.76	0.75

S/N	PAPER	PAPER RESULTS SUMMARY										NORMALIZED SCORE FOR EACH TESTS									PERFOMANCE INDEX		
	Study	%SL	CS	RCPT	UPV	WA (%)	C0_D (mm)	SO_4_A	SOR	POR	ME	CS	RCPT	UPV	WA	C0_D (mm)	SO_4_A	SOR	POR	ME	PI (50/50)	PI (40/60)	PI (60/40)
	Lee and Lee (2020)	30	35	8								0.61	0.88								0.74	0.77	0.72
		40	34	6								0.48	0.98								0.73	0.78	0.68
		50	33	5.7								0.35	1.00								0.67	0.74	0.61
		60	32	5.7								0.22	1.00								0.61	0.69	0.53
		70	30	5.7								0.00	1.00								0.50	0.60	0.40
12	Dewi et al. (2019)	0	29									0.00									0.00	0.00	0.00
		10	31									0.50									0.50	0.50	0.50
		40	32									1.00									1.00	1.00	1.00
		70	30									0.33									0.33	0.33	0.33
13	Dandaboina et al. (2025)	0	38									0.00									0.00	0.00	0.00
		20	46									0.40									0.40	0.40	0.40
		40	58									1.00									1.00	1.00	1.00
		50	48									0.51									0.51	0.51	0.51
14	Jang et al. (2017)	0	38									0.00									0.00	0.00	0.00
		50	50									1.00									1.00	1.00	1.00

Where:

CS – Compressive strength

SL – Ground Granulated Blast Furnace slag

RCPT – Rapid Chloride Permeability test

UPV- Ultrasonic Pulse Velocity

WA – Water Absorption

C0_D – Carbonation Depth

SO_4 _A – Sulphate Attack

POR - Porosity

ME – Modulus of Elasticity