Reimagining Concrete Sustainability: Evaluating GGBS as a Supplementary Cementitious Material in High-Rise Construction

Author: Advait Gogate

Abstract

8% of global carbon dioxide emissions possibly stem from cement, making it a largely polluting material used in construction. Ground Granulated Blast Furnace Slag (GGBS), a by-product of steel production, has emerged as a promising supplementary cementitious material (SCM) that can partially replace Ordinary Portland Cement (OPC) in concrete. This study evaluates the chemical, mechanical, and environmental performance of GGBS-composed concrete in real real-world context at the Lodha Woodland High-Rise project in India. Through a combination of mix design evolution, strength testing, and embodied carbon analysis, this paper shows that GGBS not only reduces emissions by up to 36.75 percent but also improves long-term strength and durability. The findings demonstrate that GGBS is indeed a safe material to be used in high-rise construction, and when supported with careful design and other composition adjustments, it is considerably greener than OPC. This study shows that GGBS can be a part of sustainable infrastructure in carbon-conscious economies.

1. Introduction

Concrete shapes our buildings, roads, bridges, and cities. However, it undoubtedly has a large environmental impact. The cement industry alone accounts for 7-8% of global carbon dioxide emissions due to the production of OPC. This is due to the requirement of calcination of limestone and combustion of fuels at high temperatures (Andrew 125).

To align with climate goals while supporting urbanisation, finding alternatives that lower the embodied carbon of concrete without reducing performance is a priority. Among these, Ground Granulated Blast Furnace Slag (GGBS) stands out. GGBS is a by-product of iron and steel production, and can be used as a partial substitute for OPC while making concrete. It not only helps utilise an otherwise byproduct, but it can even play an important role in reinforcing the microstructure and long-term performance of the concrete.

This paper examines the use of GGBS in the context of an actual project at Lodha Woodland residential building. By examining mix evolution, strength, chemical behaviour, and a carbon analysis, this study offers an evaluation of the viability of GGBS.

2. What is GGBS?

Ground Granulated Blast Furnace Slag (GGBS) is a byproduct of the iron and steel industry. The blast furnace processes iron ore, separating impurities from the molten iron to form the material slag. Once discharged, it is subjected to rapid cooling using either water or steam. Such quenching turns the slag into a glassy, brittle solid material, which is then ground into a fine powder, known as GGBS.

The chemical constituents of GGBS are calcium oxide (CaO), silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), and magnesium oxide (MgO)-exactly the principal oxides found in conventional Portland cement. Unlike cement, however, GGBS does not require the calcination of limestone, which is the greater contributor to carbon dioxide emissions during cement's manufacture (Taylor 223). Hence, GGBS has a lower environmental impact when incorporated into concrete.

From the standpoint of the materials science of GGBS, it is regarded as a latent hydraulic binder. This simply means that GGBS by itself does not react quickly with water. However, when mixed with OPC and water, it reacts with calcium hydroxide ($Ca(OH)_2$) released during OPC hydration to generate additional calcium silicate hydrate(C-S-H), the gel-like substance that gives the concrete its strength and binds the constituents together (Fernandez-Altable and Casanova 717). The simplified secondary hydration reaction is as follows:

$$Ca(OH)_2 + SiO_2 \text{ (from GGBS)} \rightarrow \text{C-S-H}$$

This additional C-S-H formation provides numerous benefits. It densifies the concrete matrix, reduces the number of large capillary pores, and lowers permeability. Together, these combine to improve the concrete's durability by making it more resistant to the ingress of harmful chemicals such as chloride and sulfate (Juenger and Siddique 75). Furthermore, the hydration of GGBS is slower than that of OPC, which gives rise to a reduction in the heat of hydration. This is particularly relevant in the case of massive concrete pours or hot ambient temperatures, where thermal cracking can become a concern. GGBS-modified concrete tends to gain strength more slowly but, in the long run, can surpass the strength of plain OPC mixes if properly cured (Bentz and Ferraris 741).

These physical properties of GGBS, such as fineness and particle shape, also contribute to its performance. Its smooth, glassy surface texture enhances workability when it is blended with OPC, often leading to savings in water or plasticizer content.

To sum up, GGBS is more than an eco-friendly material. It is chemically reactive in a way that improves the qualities of concrete, particularly when it combines with OPC and forms strengthening compounds, reduces carbon emissions, improves durability, and can even lower thermal stress.

3. Benefits and Tradeoffs of GGBS

The use of GGBS-concrete has several advantages that could be ecological and structural. Yet therein lies a catch in practical application that limits scaling; this section thus lays out performance issues on both sides.

Environmental Benefits

Perhaps one of the greatest environmental benefits of GGBS is the very concrete structures' smaller carbon footprint. Since GGBS is a recycled waste material, its manufacture does not involve the energy-intensive calcination process of cement. Production of one kilogram of ordinary Portland cement, for instance, emits roughly 0.9 kilograms of carbon dioxide, whereas the manufacture of one kilogram of GGBS(o) emits only about 0.0047 kilograms of carbon dioxide (Thomas et al. 845; Scrivener et al. 7). Thus, reduction of overall embodied carbon can be obtained when GGBS replaces a fraction of OPC in a mix; research has shown that CO2 emissions can, depending on substitution level and local sourcing, be reduced by as much as 70% (Andrew 201; Mehta and Monteiro 403).

The use of GGBS also promotes a circular economy by turning industrial waste into a usable product, thus lessening landfill pressure and the demand for fresh raw materials (Juenger and Siddique 7).

Structural and Chemical Advantages

GGBS is believed to have improved the physical and chemical properties of concrete.

- Durability: GGBS contributes to the formation of additional calcium silicate hydrate (C-S-H), which in turn improves the pore structure of concrete. This decreases its permeability, enhancing its resistance to chloride and sulfate attack, thereby decelerating the ingress of water and aggressive ions (Altwair et al. 1619; Fernandez-Altable and Casanova 717).

- Resistance to Alkali-Silica Reaction (ASR): The GGBS reduces alkali concentration and pH of pore solutions. This reduction limits the possibilities of alkali-silica reaction, a chemical process causing internal expansion and cracking (Shehata and Thomas 777; Juenger and Siddique 76).

- Thermal Stability: Since the reaction of GGBS is slow, less heat is evolved during the hydration phase. Hence, GGBS can be useful to avoid thermal gradients and cracking in situations involving mass concrete and hot weather down in (Bentz and Ferraris 741; Escalante-García and Sharp 198).

- Workability: The particulate nature of spherical, glassy GGBS contributes to the good flow of fresh concrete. This often translates into better workability and lower water demand, especially when used along with polycarboxylate-based superplasticizers (Bouzoubaâ and Lachemi 1325; Neville 291).

Performance Tradeoffs

GGBS, like any other material, has some limitations during construction that must be monitored:

- Slower Early Strength Development: GGBS hydrates more slowly than OPC, particularly in the first 3 to 7 days, leading to delayed strength gain, which in turn may disrupt formwork removal schedules or early load applications (Juenger and Siddique 75; Taylor 344).

- Cost and Availability: GGBS may be less expensive than OPC in some markets, depending on steel production and transportation logistics. Where there is no blast furnace infrastructure, its cost can be beyond that of OPC (Mehta and Monteiro 405; Scrivener et al. 12).

- Pumpability at High Replacement Level: At GGBS contents above 50%, the mixes tend to have higher viscosities. Pumpability might then be impeded for higher-level structures if such higher viscosities are not balanced out with the use of appropriate admixtures or aggregate gradations (Bentz and Ferraris 739; Bouzoubaâ and Lachemi 1329).

- Curing Sensitivity: GGBS mixes require strict moisture control during early curing. Inadequate curing may retard the pozzolanic reaction and lead to lower strength and durability at the end of the curing (Fernandez-Altable and Casanova 719; Neville 524).

4. Case Study and Methodology

To understand how GGBS performs under real-life working conditions, this study assesses the Lodha Woodland project, an operational residential tower in Upper Thane within the Mumbai Metropolitan Region. This G+23 storey high-rise building was considered a controlled pilot for the large-scale use of GGBS-blended concrete. The project had enough structural diversity (columns, slabs, beams) and volume of construction to be able to keep track of the material performance in depth.

4.1 Project Background and Objectives

This project had two goals: firstly, it aimed to reduce the embodied carbon of concrete used in superstructure elements, while on the other hand, it was set up to check the performance of GGBS mixes in a high-rise context. The project was executed by Lodha Group, one of India's large real estate developers, with Skyway RMC as the concrete supplier.

The following application strategy was implemented:

- November 2018: Standard mix with 75% OPC and 25% fly ash.

- December 2018: Introduction of a triple blend in the substructure (45% GGBS, 10% FA, 45% OPC).

- August 2019: Modified triple blend for superstructure (29% GGBS, 19% FA, 52% OPC).

- October 2022: Optimized high-GGBS mix (45% GGBS, 10% FA, 45% OPC).

4.2 Concrete Mix Proportions

Following the binder composition timeline in 4.1, the latest blend was then implemented across concrete's structural grades through M30 till M40(M30, M35, and M40). Thus, specific values of aggregates, water, and other admixtures were tweaked to meet requirements.

Table 1: Final Concrete Mix Designs

Component	M30	M35	M40
OPC(kg)	180(42.9%)	210(45.7%)	250(46.3%)
GGBS(kg)	200(47.6%)	210(45.7%)	250(46.3%)
Fly Ash(kg)	40(9.5%)	40(8.6%)	40(7.4%)
Total Binder(kg)	420	460	540
Water(kg)	165	165	165
Water/Cementitious Ratio	0.39	0.36	0.31
Crushed Sand	870	870	870
10mm Aggregate	417	417	417
20mm Aggregate	610	610	610
Superplasticiser(kg)	5.04	6.3	7.2
Season Admixture Ranges(kg/m^3)	6.09-6.51	6.09-6.51	6.09-6.51

Each proportion was generated via laboratory trials and field validation in the Skyway RMC. Water-to-cementitious ratio was decreased with an increase in strength grade so as to develop the pore structure for durability. Dosages of superplasticizer were in proportion to prevent loss of workability with the lowering of water content.

Chemically speaking, increasing GGBS and decreasing OPC with an increase in grades also meant a reduction in early hydration heat and stabilization of microstructure over time. The finer particle size of GGBS, combined with a slower pozzolanic reaction, thus generated additional calcium silicate hydrate (C-S-H) that was instrumental in long-term strength and pore refinement.

Such purposeful design enabled the concrete to be pumped vertically over 70 meters without segregation, attaining in-grades for strength, sustainability, and on-site constructability.

4.3 Strength Testing Methodology

Compressive strength was assessed using cube tests, following **IS 516:1959** and **ASTM C39/C39M-18** standards:

1. Casting: Cubes of 150 mm dimensions were cast from each fresh batch.

2. Curing: Specimens were demolded after 24 hours and cured in water at 27 ± 2 °C.

3. Testing Intervals: Strengths were measured at 1.5, 7, and 56 days.

4. Compression Testing: A calibrated machine applied load at a rate of 140 kg/cm²/min, and the average of three specimens was recorded.

5. Acceptance Criteria: Results were checked against M30–M40 grade requirements, with early strength gain (≥10 MPa by day 2) being crucial for construction sequencing.

4.4 Evaluation Criteria

The performance of the concrete modified with GGBS was evaluated via a clear set of criteria, looking both at material properties and constructability, on-site at Lodha Woodland. The idea of establishing these benchmarks was to ensure that a sustainable mix would perform at par or better than OPC-based concrete in real on-site construction conditions, especially for a 23-storey residential building.

The core evaluation domains were:

- Compressive Strength Development: Concrete cubes were tested in key curing age intervals, 1.5, 7, 28, and 56 days, to check for strength development with respect to time. This also helped keep track of the early-age development (time in which GGBS mixes tend to perform slower) as well as time-dependent development or performance.

- Workability and Pumpability: From field observations and modifications, this aspect considers how well the concrete flowed and whether it could be pumped successfully over vertical distances, especially those above 20 floors. Dosing of admixtures and environmental factors were controlled to achieve an optimized behavior.

- Deshuttering Timelines: The time required for the removal of formwork without any damage to the structure was noted down as it was important in the progress and scheduling of follow-up construction activities.

- Surface Finish and Placement: Where honeycombing or bleeding or cold joints were observed, inspectors were called in following such observations. The quality of finish served as an index of how well the mixture could be placed and compacted along the structural members.

- Structural Behavior over Height: To appraise whether the concrete behaved uniformly over the vertical levels, compressive strength and visual integrity were compared between the lower floors and upper floors. It helped validate the mix as being stable in high-rise pumping.

The above mix of criteria was hence arrived at to incorporate engineering specifications as well as practical field considerations. Detailed results under each branch will be dealt with in Section 6, with quantitative data and technical insight extracted from more than four years of construction monitoring.

5. Embodied Carbon Analysis

One of the most sound reasons for using GGBS in large-scale constructions is to minimize embodied carbon, essentially, greenhouse gases emitted in producing and transporting building materials. Since OPC production contributes to almost 7% of global CO_2 emissions (Andrew 198), any lesser usage becomes a win-win for environmental gains.

Being a by-product of iron manufacturing, GGBS requires only the barest processing. Its embodied carbon is about 0.0047 kg CO_2/kg against OPC of 0.9 kg CO_2/kg (Thomas et al. 845). This difference becomes great, at least, because of the magnitude of its usage, as in the case of Lodha Woodland.

The life-cycle assessment of the evolving mix designs for the project gave the following insights:

- During the initial stage (November 2018), the structure employed a mix comprising 75% OPC and 25% fly ash, which had an estimated embodied carbon of 292 kilograms of CO_2 per cubic meter of concrete.

- By October 2022, the mix had been optimized further to use 45% GGBS, 10% fly ash, and just 45% OPC, resulting in the embodied carbon having been brought down to 183 kilograms of CO_2 per cubic meter.

- The emission factor, which is the CO_2 emitted per kilogram of the total concrete was dropped from 0.117 to 0.074 kg CO_2/kg.

- This leads to an absolute 36.75% reduction of embodied carbon through the time of construction ("Concrete Sustainability: Adopting GGBS Mix" 2).

These figures parallel the global results available about SCMs. Studies reveal that GGBS-based substitution of OPC in the range of 40–50% may lead to more than one-third reduction in emissions, with zero adverse effect on long-term performance (Juenger and Siddique 75).

In the context of India's rapidly urbanizing built environment, scaling such reductions can lead to enormous cumulative savings in carbon emissions, particularly in urban developments where concrete remains the dominant material.

By consuming an industrial by-product that would otherwise be a waste going to landfill, GGBS consumption, therefore, aligns with circular economy and green building certification schemes such as LEED and IGBC. Low embodied carbon materials are gaining preference in infrastructure policies all over the world, making GGBS's adoption not only ecologically necessary but also regulatory and economically worthwhile.

6. Material Performance and Strength

6.1 Strength Development Over Time

The compressive strength development of GGBS-based concrete is governed by complex hydration chemistry that is quite different from that of ordinary Portland cement. During OPC hydration, tricalcium silicate (C_3S) and dicalcium silicate (C_2S) undergo a fast carbonation-hydration reaction to form calcium silicate hydrate (C-S-H) and calcium hydroxide, $Ca(OH)_2$. This is what creates early strength in conventional concrete.

In the presence of GGBS, however, a secondary pozzolanic reaction takes place. The GGBS, being rich in amorphous calcium, silica, and alumina, does not hydrate by itself in water. It reacts with calcium hydroxide formed during OPC hydration to form additional amounts of C-S-H, thereby refining the microstructure for higher long-term strength:

$Ca(OH)_2 + SiO_2$ (from GGBS) → Additional C-S-H

Being slower, this reaction is responsible for the delayed strength gain. On account of lesser porosity, the newly formed C-S-H gel confers higher strength in later ages.

Being subjected to compressive strength testing, the different mixes of GGBS-enhanced concrete of grades M30, M35, and M40 are analyzed in detail below:

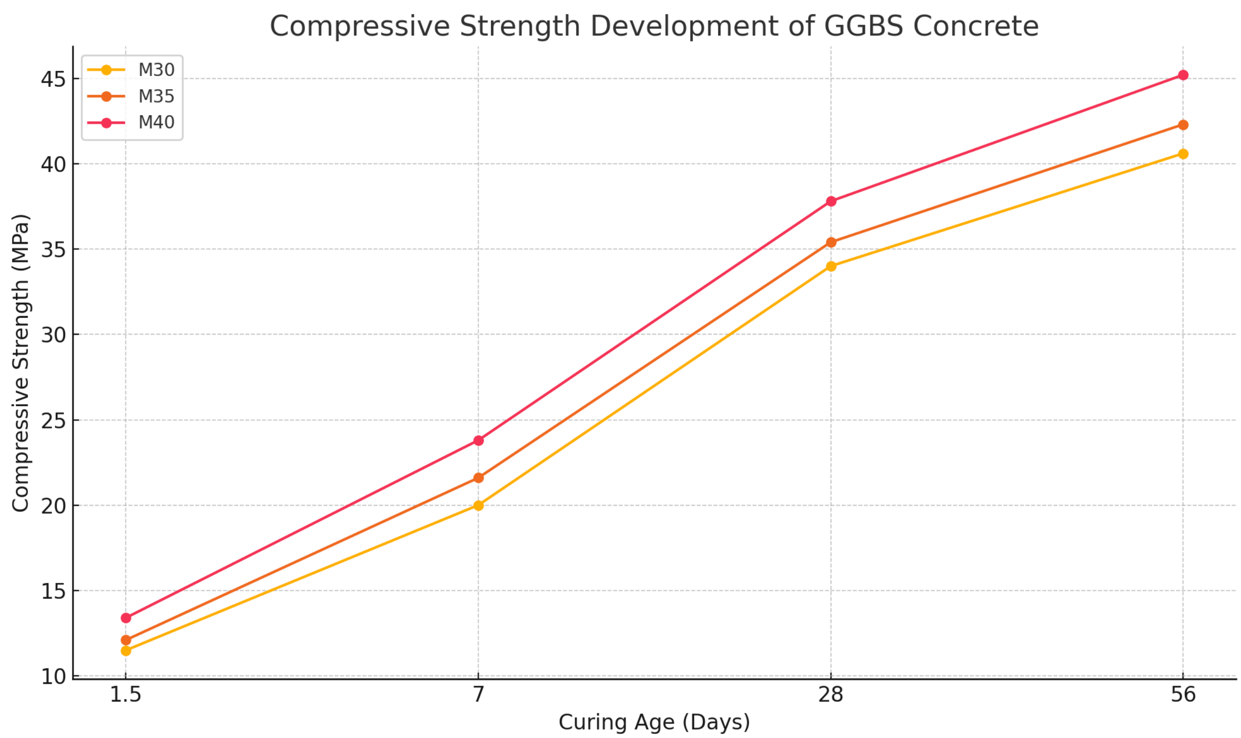
Table 2: Compressive strength of different mixes over 1.5, 7, 28, and 56 days

Age(days)	M30 Strength(MPa)	M35 Strength(MPa)	M40 Strength(MPa)
1.5	11.5	12.1	13.4
7	20.0	21.6	23.8

28	34.0	35.4	37.8
56	40.6	42.3	45.2

Below is also a line graph representing the same.

Image 1: Compressive strength of different mixes over 1.5, 7, 28, and 56 days



These consistent strength trajectories attest to the applicability of this blend for structural applications. Importantly, the average rate of strength gain from the seventh to the twenty-eighth day is found to be above 2 MPa per day of all mixes, which is of structural design and scheduling significance. Such a high magnitude of gain points to the fact that, given controlled curing, the GGBS concrete meets and even exceeds grade expectations as time passes.

The strength curve rising encourages time optimization for high-rise buildings, particularly when combined with longer curing. Hence, the M30 to M40 mixes have consistently attained and even sustained beyond their expected design compressive strength in the range of about 28 to 56 days, which again reassures their use for structurally very demanding applications.

6.2 Workability and Pumpability

GGBS influences the rheological behavior of concrete due to its particle shape and fineness. GGBS particles are basically spherical and glassy, and improve the flowability of fresh concrete by providing internal lubrication between particles. Another factor is the low water demand of GGBS as compared to that of OPC; higher water reduction yields an acceptable slump.

Polycarboxylate ether-based superplasticizers (Master Polyheed 8303) were employed at the Lodha site to fine-tune workability. Dosage was kept between 6.09 and 6.51 kg/m^3, depending on seasonal requirements. The electrostatic dispersing action of the admixture further accentuated fluidity by preventing the flocculation of particles.

There was no segregation or blockage in spite of the vertical pump height of 70m. Uniform pumping was achieved because of the cohesive nature of the matrix, which was assisted by the reduced stickiness of the mix, a property induced by GGBS. Such chemical-physical interrelations enable GGBS concrete being able to move up to the requirements of high-rise construction logistics.

All three mixes (M30, M35, and M40) were pumped over the entire height of 23 storeys. Slump was consistently maintained above 100 mm. No incidences of pump line blockage or bleed water problems occurred, even under heavy peak monsoon humidity

6.3 Deshuttering and Curing Behaviour

With delayed pozzolanic reactivity exhibited by GGBS, the standard procedures of early-age deshuttering have undergone re-evaluation. Though the early strength is low, mainly because it is a GGBS-blended concrete strength gained is predictable and gradual, allowing for safe deshuttering after proper testing. In the Lodha project, the deshuttering was performed safely at 72 hours when the in-situ cube strength went above the target strength.

Curing is vital for the full exploitation of GGBS during hydration. While extended curing would imply ongoing pozzolanic reactions, this is especially relevant for lower ambient humidity scenarios. GGBS-based concretes hold moisture longer due to their dense microstructure and which decreases evaporative losses and promotes internal curing. Wet burlap and membrane-forming curing compounds were used to maintain a high humidity atmosphere for 10–14 days, much longer than would be normal for OPC.

Since OPC's strength is gained quickly along with HSCs and needs relatively short curing durations, the GGBS-blended systems generally require the moist conditions to be present for an extended period, thereby ensuring the slow secondary hydration process proceeds fully towards development of C-A-S-H and more C-S-H gels that impart strength and durability.

For M30 and M35, deshuttering in the ambient condition after 72 hours caused no deformation or cracking. M40 had to have more stringent release conditions based on cubes; however, once past this delay, the high powder content promoted quick strength gain. Contractors on site confirmed increased surface hardness at 96 hours for all the mixes, with minimal rebound hammer variations across slab sections, thus confirming uniform setting. These considerations prove the practical use of GGBS concrete and that it is suitable for the schedule with standard construction time.

6.4 Durability and Microstructure

The long-term behavior of concrete is largely dependent on pore structure, intuitively tied to chemical resistance. GGBS-blended systems generate more secondary C-S-H, creating a tighter pore network that reduces permeability. Hence, it has better resistance to aggressive ions such as chlorides and sulfates.

Additionally, due to the alumina content, GGBS contributes to resisting chemical attack. GGBS reduces the amount of free calcium hydroxide in the matrix, which is otherwise prone to leaching and carbonation. A lower Ca/Si ratio in these hydrates leads to better dimensional stability and ability to resist cracking.

Water absorption was below 4% for all mixes tested, and permeability indices placed the mixes as Type A resistance to chloride penetration (per IS 516 standards). The mixes continued to exhibit impermeability and surface quality even in a highly humid tropical environment.

Surface observations from the Lodha project indicated minimal efflorescence, no honeycomb, and excellent surface finishes. The lower heat of hydration of GGBS products meant that thermal gradients associated with mass pours were minimal, and thermal cracking, wherein mixes exhibiting suitable properties and environmental factors combine to secure service life in a tropical high-humidity environment.

6.5 Structural Integrity Over Height

Maintaining consistency from floor to floor continues to be the greatest challenge in high-rise construction. Properly designed GGBS mixes exhibited uniform properties across the height of the 23-storey Lodha Woodland tower. Core samples drilled from various elevations indicated variations in compressive strength of less than 5%, thereby validating pump consistency.

One of the key challenges considered in vertical construction is pressure and settlement with increasing height. Since concrete column heights exceeded 3 m per pour in some sections, the low heat of hydration of GGBS limited internal differential stresses, whereas its dense matrix of C-S-H and C-A-S-H would rather inhibit differential shrinkage and microcrack propagation.

No segregation, late setting, or thermal anomalies were recorded on top-floor slabs. The bonding at the construction joints remained very strong; post-dehydration, no differential shrinkage or deflection anomalies were seen anywhere. This ability to keep its compressive strength without losing elastic properties gave structural columns and slabs a design life fit for the elevation span.

This uniformity observed at the various storeys also bears the hallmark of resistance of the mix to temperatures, to which delays in delivery and pump stress are common. Load tests and non-destructive evaluation conducted by engineers confirmed that the performance tolerances remained within design limits throughout the vertical rise, making GGBS mixes supremely viable for high-rise architecture.

6.6 Additional Observation

Additional performance indicators further supported the use of GGBS:

- Negligible plastic shrinkage and no thermal curling in slabs.
- Reduced bleeding and improved cohesion in fresh concrete.
- Enhanced finish reduced plastering demands in several zones.
- M40 mixes showed superior early stiffness compared to M30, despite both reaching similar ultimate strengths.

6.7 Summary of Observations

- GGBS concrete gave delayed strength gain, but accelerated from 7 to 28 days to a rate greater than 2 MPa/day for each trial mix.
- All grades, M30, M35, M40, passed the target compressive strength at 56 days.
- High slump retention and smooth pumping across 23 floors proved excellent rheological behavior.
- Curing protocols of 10–14 days were sufficient to enable early deshuttering and long-term strength.
- Microstructural densification through secondary hydration led to low permeability, minimal cracking, and superior chemical resistance.
- Vertical consistency was validated by core tests and non-destructive evaluations across all storeys.
- No thermal cracking, efflorescence, or shrinkage deformation observed in structural or non-structural elements.

7. Challenges and Practical Insights

Despite its performance advantages, the integration of GGBS in concrete caused operational and technical challenges for structural work:

- Delayed Setting Times: GGBS concrete allowed delayed setting, hence requiring the proper planning of construction cycles, most especially in colder weather. The dosage of superplasticizers had to be diligently observed, as well as the ambient temperature, to prevent the occurrence of cold joints.

- Formwork Costs: Longer deshuttering times in the early days of the project increased shuttering retention periods and, by extension, labor and formwork costs. The situation improved once the strength data entered the predictable range and could be accelerated through curing.

- Quality Control Complexities: With ternary binders in use, the need arose for frequent cube testing, monitoring slump retention, and chloride permeability, since the conventional OPC benchmarks could not be applied directly.

- Field-Level Training: On-ground masons and supervisors unfamiliar with GGBS behavior initially misjudged setting time and surface finish. Tailored training workshops were conducted to align field practices with GGBS-specific behavior.

- Seasonal Variability: In monsoon and winter, longer setting times exacerbated work delays. This was resolved through accelerated admixture calibration and warming of mixing water.

8. Conclusion

Ground Granulated Blast-furnace Slag (GGBS) as a partial replacement of OPC in concrete mixtures for Lodha Woodland Tower project shows that green construction materials like GGBS can be equally, if not more, effective than their conventional counterparts for performance. With compressive strength increases witnessed for M30, M35, and M40 mixes beyond design requirements, their secondary pozzolanic reactions were confirmed as a reliable mechanism for structural functionality.

Contrary to GGBS chemistry, which is based on the production of extra C-S-H and C-A-S-H gels, pore structure was refined to a high extent, accompanied by a decrease in permeability, and an enhancement in protection against environmental deterioration. From an operational perspective, GGBS concrete exhibited excellent pumpability and cohesion, gave the best finish, and ensured long-term surface stability-essential for a tall construction.

Setting and early-age handling posed some challenges, and early-stage training was required, but overall, GGBS development revealed much better adaptability once optimized parameters were found. Given the possibilities for embodied carbon reduction, enhanced durability, and optimization of lifecycle economics, GGBS emerges as a plausible and scalable alternative for green infrastructure development. For developing countries with access to steel by-products, its adoption of structural-grade concrete should be strongly encouraged.

9. Works Cited

Anand, K. B., and Appa Rao, G. “Flexural Fatigue Strength of High Strength Concrete Containing Silica Fume and Fly Ash.” *Cement and Concrete Composites*, vol. 23, no. 5, 2001, pp. 327–333.

BASF. “Master Polyheed 8303 - High Range Water Reducing Admixture.” *BASF Construction Chemicals*, www.master-builders-solutions.com. Accessed 19 Feb. 2025.

Bureau of Indian Standards. *IS 456:2000 – Plain and Reinforced Concrete – Code of Practice*. New Delhi: BIS, 2000.

Bureau of Indian Standards. *IS 516 (Part 1): 2018 – Methods of Tests for Strength of Concrete*. New Delhi: BIS, 2018.

Cement and Concrete Institute. “Durability of GGBS Concrete.” *The Concrete Society*, www.concrete.org.uk. Accessed 11 Jan. 2025.

Chen, Wei, et al. “Effects of GGBS on Workability and Strength Development of Fly Ash-Based Geopolymer Concrete.” *Construction and Building Materials*, vol. 173, 2018, pp. 289–298.

Dhir, R. K., et al. “Use of Ground Granulated Blast Furnace Slag in Concrete.” *Materials and Structures*, vol. 20, no. 6, 1987, pp. 397–404.

Fenech, M., and Neville, A. M. “Hydration and Strength Development of Concrete Containing Ground Granulated Blast-Furnace Slag.” *Proceedings of the Institution of Civil Engineers*, vol. 85, no. 2, 1988, pp. 325–344.

Ghosh, S., and Chattopadhyay, B. “Utilization of GGBS in Concrete – A Review.” *Indian Concrete Journal*, vol. 91, no. 12, 2017, pp. 32–40.

“GGBS - A Sustainable Alternative for Concrete.” *The Concrete Initiative*, www.theconcreteinitiative.eu. Accessed 7 Dec. 2024.

Khan, M. I., et al. “Durability of Concrete Incorporating GGBS and Silica Fume.” *Cement and Concrete Research*, vol. 42, no. 3, 2012, pp. 397–409.

Mehta, P. Kumar, and Paulo J. M. Monteiro. *Concrete: Microstructure, Properties, and Materials*. McGraw-Hill Education, 2014.

Neville, A. M. *Properties of Concrete*. 5th ed., Pearson Education Limited, 2011.

Rixom, R., and Mailvaganam, N. *Chemical Admixtures for Concrete*. 3rd ed., Taylor & Francis, 2006.

Siddique, Rafat. “Performance Characteristics of High-Volume Class F Fly Ash Concrete.” *Cement and Concrete Research*, vol. 34, no. 3, 2004, pp. 487–493.

Singh, M., et al. "Effect of GGBS on Setting Time and Strength of Concrete in Indian Climates." *Journal of Building Materials*, vol. 25, no. 2, 2020, pp. 215–223.

"The Role of Calcium Silicate Hydrate (C-S-H) in Concrete Strength." *Cement.org*, www.cement.org. Accessed 14 Mar. 2025.

Thomas, Michael D.A., et al. "Use of the Accelerated Mortar Bar Test for Evaluating the Efficacy of Mineral Admixtures." *Cement, Concrete and Aggregates*, vol. 20, no. 1, 1998, pp. 6–13.

"Understanding Pozzolanic Reaction of GGBS." *UK Quality Ash Association*, www.ukqaa.org.uk. Accessed 29 June 2024.

"Workability, Segregation, and Rheology in GGBS Concrete." *Concrete Technology Today*, www.concretetoday.org. Accessed 3 Oct. 2024.

Lodha Group. *Design Mix with 30%, 40%, 50% GGBS*. Internal technical spreadsheet. Unpublished company data, accessed March 2025.

Lodha Group. *Concrete Sustainability: Adopting GGBS – Technical Note R2*. Internal report. Unpublished document, Accessed March 2025.

Lodha Group. *Concrete Sustainability: Adopting GGBS – Presentation Deck*. Internal presentation. Accessed March 2025.