A Comparative Analyses on the Ground Granulated Blast Furnace Slag (GGBS) in Temperature Control Concrete Production for Mass Concrete Structure

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Abstract:

The rapid growth of infrastructure in Indian metropolitan cities has led to an increasing demand for construction materials, particularly in the design of multi-story buildings, which now incorporate greater height and scale. This, in turn, necessitates larger and deeper foundations, resulting in the widespread use of mass concrete. However, the large casting volumes involved in mass concrete construction can generate excessive heat of hydration, leading to potential cracking if not properly managed. To address this problem and lower the significant carbon emissions linked to traditional cement production, materials like Ground Granulated Blast Furnace Slag (GGBS) and ultrafine additives are gaining attention as viable solutions. GGBS, known for its lower carbon footprint and cost efficiency, offers a sustainable solution to the challenges posed by traditional cement.

In this study, we explore the usage of GGBS as a partial replaced material with cement in mass concrete structures, going beyond the typical 25-50% replacement allowed by Indian Standards (IS) to examine the effects of substituting cement with up to 70% GGBS. The methodology includes the preparation of M60 grade concrete with varying GGBS proportions (0%, 40%, 50%, 60%, and 70%) and the use of temperature-controlled techniques such as ice concreting. Key parameters, including early-age strength and heat of hydration, are monitored and analyzed.

The findings reveal that higher GGBS content can effectively control the hydration heat in large volume concrete, while maintaining the required structural performance. This research demonstrates that with proper curing methods and a well-designed mix, temperature-controlled concrete with up to 60% GGBS can be successfully implemented, offering a more sustainable and durable solution for large-scale construction projects.

***Keywords*: Mass concrete, GGBS, Temperature Control Concrete, Temperature Monitoring, Raft Concrete, Partial Cement Replacement, Sustainable Concrete.**

1. INTRODUCTION:

Rapid urbanization in the metropolitan cities has led to population increase, creating a requirement for real estate businesses to push forward for high rise tower constructions. Mumbai, being a metropolitan city, year after year the construction of High Rise is taking a new shape, resulting in growing of mass structures and volume of concrete, grade of concrete in vital components of buildings. With the increase in multi-story buildings, the need for heavy and deeper foundations arising at the cost of development, in turn leading to massive construction practices. To provide unique foundation designs suiting to the city of Mumbai, which has evolved originally from seven islands, many designers are adopting new technologies, by use of combination of mixed shallow and deep foundations. This has led to introduction of mass concrete in congested areas without compromising the durability of the structure and timeline of the project. The scope of current study is to regulate the peak percentage of GGBS replacement with OPC in mix design for Temperature Control Concrete in Mass Structures which doesn't compromises the durability and other major parameters of mass concrete.

Mass concreting even with higher grades of concrete has become common practice in the construction industry. Mass concrete or large volume concrete can be defined as "Any volume of concrete with dimensions larger to require that measures be taken to cope with generation of heat from hydration of cement and attendant volume change to minimize cracking" as per ACI 116R [1]. Generally, structures greater than 1.22m fall into this category [2]. Earlier, mass concrete was only restricted to mega infra projects but today the scenario has completely changed. Now, since mass concreting is involved in various projects, special attentions to the concrete production and design is mandatory as it impacts the quality of construction as well as the functionality of these structures. Also, in higher grades of concrete and large volumes requirement makes the structures more uneconomical by utilizing increase cement content and other materials consumption.

The increasing demand for cement production and subsequent extraction of raw materials, such as limestone, raises concerns about depleting non-renewable resources. To mitigate the risk of shortages in cement production in the future, it is imperative to explore alternative sources that are renewable and can be produced without further depleting natural resources on the verge of extinction or depletion. To minimize the dependency on cement, alternate binding materials in production of concrete has always been a topic of research with products like rice husk, eggshell powder, palm oil fuel ash, fly ash, ground granulated blast furnace slag, silica fume, metakaolin etc. [5-7]. Using alternate cementitious material, on other hand may be practical in significantly reducing global greenhouse emissions.

In mass concrete structures, the heat generated by hydration occurs at a rate faster than it can be dissipated, especially within the core of large concrete masses, resulting in elevated internal temperatures and producing conditions that closely resemble an adiabatic environment [8]. The early-age temperature rise in concrete plays a crucial role in its long-term durability, as significant temperature differentials can induce thermal stresses, potentially leading to cracking at an early stage [2]. The temperature evolution in mass concrete is influenced by several factors, including ambient temperature, wind speed, foundation temperature, and most notably, the amount of hydration heat produced, which is largely dependent on the type and quantity of cement used [9].

1.1. Ground Granulated Blast Furnace Slag (GGBS)

Ground Granulated Blast Furnace Slag (GGBS) being an manufacturing byproduct extracted from the steel and iron engineering process in blast furnaces. The working temperatures of these furnaces are around 1,500°C and results with a precisely controlled blend of iron ore, coke, and limestone. While processing in the furnace, the iron ore are separated from raw iron, whereas the other materials that transforms into slag that floats above the liquid iron. This slag is regularly detached in its molten state, and washed for GGBS production, it must be rapidly quenched in large volumes of water. The slag's cementitious properties are enhanced by smothering process, resulting in granules that resemble coarse sand. These granulated particles are then dried and finely ground into a powder. Approximately 65% of the global GGBS production, out of a total of 530 million tonnes, is utilized within the construction sector.

Due to its high content of shapeless calcium, silica, and alumina, GGBS serves as an effective binder, making it a widely adopted substitute for cement. In addition to being cost-effective and environmentally sustainable, GGBS demonstrates strength and durability properties comparable to those of traditional cement. Its status as an industrial byproduct further enhances its environmental benefits when used as a cement alternative [7]. The chemical properties of different cementitious materials are highlighted it Table 1:

Table 1 : Chemical Properties of Different Cementitious Materials [7][14]:

Chemical	Cement	Flyash	GGBS
SiO2	26.9	54.22	37.5
CaO	66.7	1.24	34.6
Al2O3	6.4	31.18	6.4
Fe2O3	4.7	2.63	0.51
MgO	4.5	0.47	8.6
Na2O	0.2 2	0.49	0.3
K2O	1.4	1.34	-

1.2. Advantages with GGBS

The mean global carbon emission factor for producing one ton of cement, including its transportation to ready-mixed concrete facilities, is 0.91 t CO2-e/ton, whereas for GGBS, this figure significantly decreases to 0.143 t CO2-e/ton [10]. In concrete mixtures containing GGBS, the overall heat of hydration decreases as the proportion of GGBS increases. This is due to the gradual progression of the pozzolanic reaction, which occurs alongside cement hydration, resulting in a reduction in heat, particularly in the initial stages of hydration [11]. The heat generated during hydration diminishes with the substitution of GGBS for cement. Previous research indicates that up to 20% replacement of cement by GGBS improves the compressive strength of concrete at all curing ages. However, further increases in GGBS content may lead to a reduction in compressive strength. While early strength development in GGBS concrete mixes is delayed due to the slower pozzolanic reaction compared to Ordinary Portland Cement (OPC), the strength gain in later stages shows substantial improvements [12].

1.3. Project Details

The Government of Maharashtra (GoM) has proposed a rehabilitation scheme, facilitated by the Development Control Rule 33/7 of DC Regulation 2034, to address the housing needs of Project Affected Persons in and around Mumbai regions. This redevelopment initiative stands as a testament to GoM's commitment to integrating innovative and sustainable solutions into urban development practices.

The High-Rise building, situated in south Mumbai division is proposed as a multi-faceted structure comprising three basements, a ground floor, seven commercial floors, two service floors (8th and 9th), and an impressive 39 residential floors (10th to 48th). Additionally, a distinct wing of the building features ten commercial floors, contributing to the overall functionality and urban aesthetic of city's ancillary building.

The initial concrete mixture utilized for the raft construction of building consisted of a proportion of traditional mix design for M60 with Cement and Flyash. However, this combination could lead to the development of surface cracks due to the elevated heat of hydration during pouring and setting in rafts with depth more than 2 meters. Considering the raft depth (in this case 3m) with concrete grade of M60, prompted the exploration of alternative options by the designers and concrete experts to mitigate the heat of hydration during the concrete placement process. Subsequently, the team investigated a modified concrete mixture design and conducted trial mixes using Grade M60 concrete, wherein the proportion of GGBS varying from 0%, 40%, 50%, 60% to 70% were conducted. Additionally, cold concreting techniques were employed, incorporating ice into the concrete mixture to diminish the initial heat of hydration.

1.4. Project Methodology

For selecting one such design, as per IS there are some parameters which needs to be set for deriving the optimum mix design. For mass cold concrete, the major criteria would be its heat of hydration, following its durability, permeability and chloride penetration.

The below parameters define the best mix design:

1. **Compressive strength test on cubes:** This test determined the competence of the concrete mix to withstand compressive forces, providing insights into its structural integrity and load-bearing capacity.
2. **Water permeability test:** This examination assessed the concrete's resistance to water penetration, crucial for evaluating its durability and resistance to deterioration caused by moisture ingress.
3. **Rapid chloride penetration test:** This test assesses the concrete's resistance to chloride ion penetration, a vital indicator of its durability, particularly in environments prone to chloride exposure, such as marine or de-icing salt environments.
4. **Temperature Monitoring test:** This test evaluates the concrete’s heat of hydration dissipated from the concrete for the duration of 07 days. The important criteria for the temperature control concrete in mass structures is determine from this test result. The maximum heat and differential temperature between top and middle of concrete can be examined from this test.

Using different variations of GGBS in total cementitious content of M60 grade concrete in the mentioned above parameters, we will inspect the result based on which the optimum mix design for temperature control concrete for mass concrete structure would be concluded.

1.5. Experimental Work

By providing a comprehensive analysis, the paper aims to contribute valuable insights into the broader discourse on sustainable construction methodologies, using the building as exemplary case studies. In this study, the methodology involved assessing the comparative analyses of the proposed mix design incorporating a proportion of 0%, 40%, 50%, 60% & 70% Ground Granulated Blast Furnace Slag (GGBS) and Ultrafine to the proportionate percentage of cement as the total cementitious material for concrete. To evaluate its suitability, a series of tests were conducted to measure workability, durability, and overall performance throughout the building's lifespan.

Additionally, GGBS have shown great results in normal temperature concrete, but it’s still under explored for temperature control concrete specially for mass concrete structures. Now, IS 16700 2023[15] has set a benchmark value of peak temperature and differential of core temperature, according to this code the maximum peak temperature should be 70 degrees Celsius and differential core temperature shall not exceed 20 degrees Celsius.

Also, as per IS 10262 2019[16], the recommended dosages of GGBS by percentage by mass of total cementitious materials shall be between 25 % - 50%. Considering at both these above IS restrictions, we will study our iterations and find out which iteration works suitably with temperature requirement of cold concrete for mass structure.

The expert study shows that, to maintain the peak temperature and differential core temperature of any design we need to restrict our initial pour temperature to 27 ± 2 degrees Celsius to obtain our desired results.

1.6. Temperature Monitoring

Temperature control is a critical aspect in mass concrete construction, particularly in large volumes and under hot weather conditions [refer Figure 1]. Its importance becomes even more pronounced in such conditions. This study was conducted in the Mumbai region during April, where daily temperatures can reach as high as 36°C. As a result, appropriate temperature control measures were implemented to mitigate the effects of elevated ambient temperatures.

Figure 1 : Concreting of M60 TCC (Mock)

To ensure optimal temperature control during the mass concrete work, several key measures were implemented: (i) During material selection, Cement (OPC) 53 grade was replaced with a 60% blend of GGBS and ultrafine additives, resulting in reduced heat of hydration. (ii) Cold water was sprayed on the aggregates to lower their temperature. (iii) Using ice flakes the water was cooled which were mixed in the concrete. (iv) The mixers were wrapped with wet hessain cloth while transporting concrete from the batching plant to the site, this helped to lower the concrete temperature during transit. (v) Concrete placement was scheduled post sunset as much as possible to minimize the risk of shrinkage and thermal cracking. (vi) Shortest distance routes were directed for dispatch of concrete in-efforts to reduce transportation and pumping time, ensuring the concrete was placed within the stipulated retention period for slump. (vii) Post achieveing final setting time, the concrete was protected with 100-micron transparent polythene sheets to prevent moisture loss. (viii) Over the polythene sheets, 50 mm thick thermocol sheets were placed to prevent heat dissipation. The formwork was left in place for seven days, as illustrated in Figure 02. The temperature differences between the core and top surface, and the surface adjacent to the core in a rectangular mass concrete raft are critical for assessing the potential for thermal cracking. It is essential to monitor temperature variations at these three points. This part of study entails about the equipment used, such as thermal loggers and sensors,

Figure 2: Insulation of Concrete (Mockup)

Figure 3: Temperature Monitoring

and describes the positioning of the sensors along with the temperature data collected during the study, as illustrated in Figure 3.

1.7. Location of sensors

A temperature monitoring study was supervised during the concrete pour for a raft measuring 2.4m x 2.4m x 3m. The monitoring was carried out at two key locations in the raft: (i) the center (L1) and (ii) edge 1 (L2). At each location, three sensors were inserted at different depths: the top sensor at 150mm, the middle sensor at 1500mm, and the bottom sensor at 2850mm from the top surface of the raft. A total of seven thermal sensors were used in the study, with six implanted in the concrete as mentioned and one placed externally to record ambient temperature. Figure 4 presents the plan and sectional view of the thermal sensor placements, while Table 2 provides details on the sensor distribution.

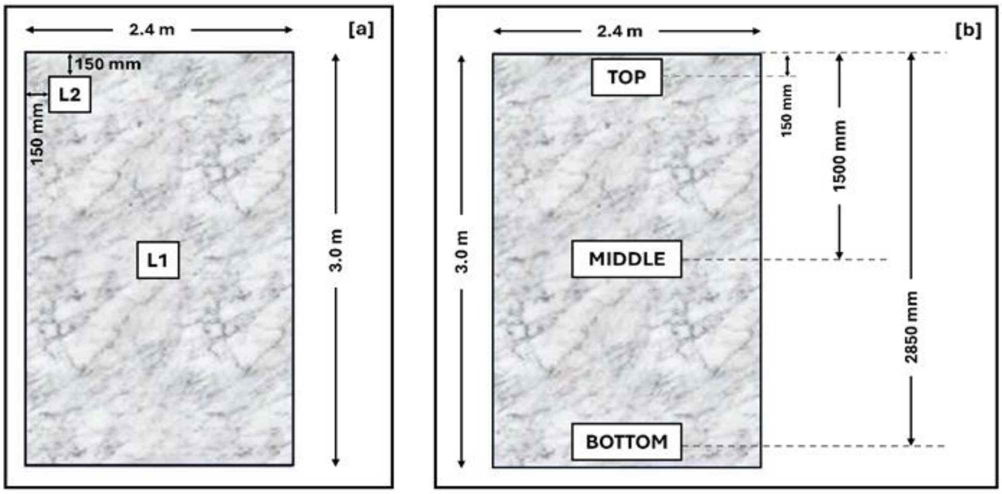

Figure 1 : Location of Sensors

Table 2 : Distribution of Sensors

Channel No	Location	Channel Placed at Location
Channel-0	Ambient	Top Outside Concrete
Channel-1	Location V1	Bottom
Channel-2	Location V1	Middle
Channel-3	Location V1	Top
Channel-4	Location V2	Bottom
Channel-5	Location V2	Middle
Channel-6	Location V2	Top

1.8. Mix Designs

The above iterations of mix design were conducted conforming IS 10262, as per design table mentioned below. The specific gravities of fine aggregate, coarse aggregate and admixtures were same for all iterations of M60 grade concrete.

Table 3 : Concrete Mix Design

SSD in KG / %GGBS	0%	40%	50%	60%	70%
Cement	440	374	320	210	180
Flyash	140	0	0	0	0
GGBS	0	372	360	370	500
Ultrafine	70	34	40	40	40
Crush Sand	692	647	629	775	708
M-1	338	436	424	545	498
M-2	644	612	596	437	400
Water	150	156	15	150	165
Admixture	7.55	7.88	7.92	6.20	6.12

Based on the initial temperature recordings and compressive strength results, further test like rapid chloride penetration test and permeability test were conducted on M60 60% GGBS replacement iteration to finalise the mock concrete. The size of the mock concrete was 2.4m x 2.4m x 3m. A total of 17.28 cum of concrete was done. The grade M60 with 60% GGBS replacement was used as per Table no. 3.

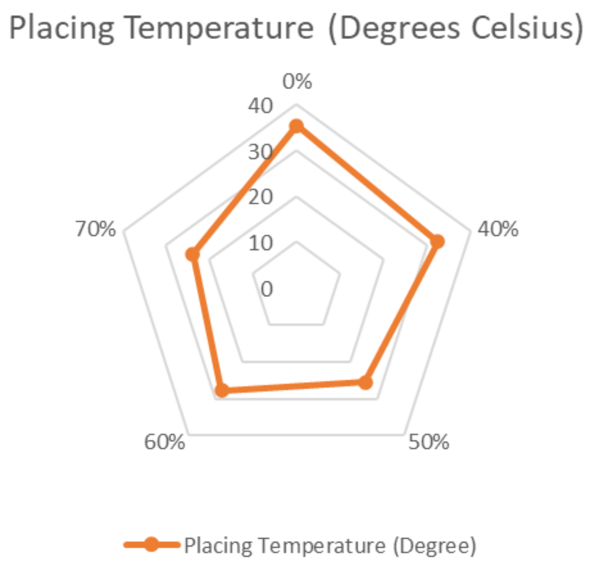

Chart 1: Placing Temperature for Different Iteration of Mix Designs

2. OBSERVATIONS & RESULTS

The GGBS proportions was increased based on the observations on temperature during the experiment and observations are tabulated below in table 4:

Table 4 : Analyses of different parameters of M60

SSD Intake (GGBS)	**0%**	**40%**	**50%**	**60%**	**70%**
Initial Temperature (ºC)	34	27.4	26.8	23.4	22.3
Flow (mm)	680	680	700	710	700
28 days strength (N/ mm^2)	48.59	65.29	55.48	64.47	46.13
56 days strength (N/ mm^2)	74.22	79.47	73.08	72.22	61.50

As per the above readings, the initial temperature, workability and compressive strengths for M60 grade replaced by 60% GGBS was found acceptable, it was further explored to Rapid Chloride Ion Penetration Test and Water Permeability Test. The results of Rapid Chloride Penetration Test (RCPT) were recorded very low as per ASTM C1202 2022 [19] and Water Permeability Test (WPT) were recorded within conforming limits IS 516 Part 2 Sec 1 2018 [18].

As per mock up study the temperature monitoring results were recorded as follows:

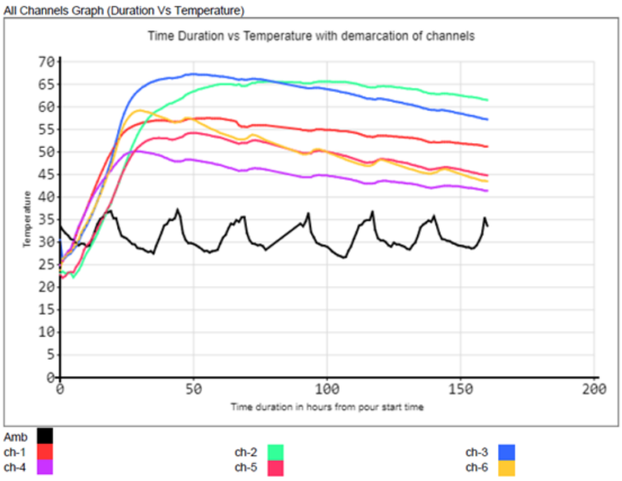

Chart 2: Temperature Recording for Mock up

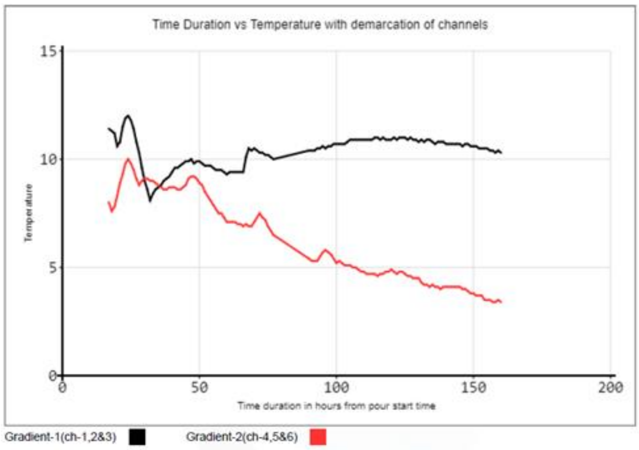

Chart 3: Differential Core Temperature Recording

The results of these tests were analysed to gauge the effectiveness of the proposed mix design in meeting the desired criteria for workability, durability, and functionality. Additionally, the findings contribute to understanding the concrete's overall performance over its anticipated lifespan in the building structure. Detailed results of these tests are provided in the attached documentation for reference and validation.

After conducting laboratory testing on various mix designs incorporating partial replacement of cement with GGBS, the most suitable design for the raft of the high-rise building was identified. Among the tested designs, those with 0%, 40%, and 50% GGBS replacement, alongside Ultrafine, were deemed unsuitable due to elevated temperature readings during concrete placement.

However, the compositions with 60% and 70% GGBS, combined with Ultrafine, exhibited temperature readings within acceptable limits. Subsequent laboratory tests focused on compressive strength, permeability, and Rapid Chloride Ion Penetration tests. Results showed that the design utilizing 60% GGBS and Ultrafine displayed superior compressive strength compared to the 70% GGBS counterpart, while also meeting specified limits for permeability and rapid chloride content as per relevant codes. Furthermore, a mock trial of the M60 grade with 60% GGBS and Ultrafine, recorded temperature readings during the initial 0-7 days, confirming peak hydration temperatures within permissible levels. Thus, it was concluded that the M60 grade with 60% GGBS and Ultrafine, within the total cementitious composition, proved optimal in terms of temperature, strength, permeability and rapid chloride content. The same design of M60 grade temperature control concrete with 60% GGBS replaced with OPC were tested with another brand of admixture which yielded about same result proving that irrespective of raw materials used, this design was found to be optimum in temperature control concrete for mass structures. The analysis of compressive strength for M60 Grade of Concrete is highlighted in the Chart 4 below:

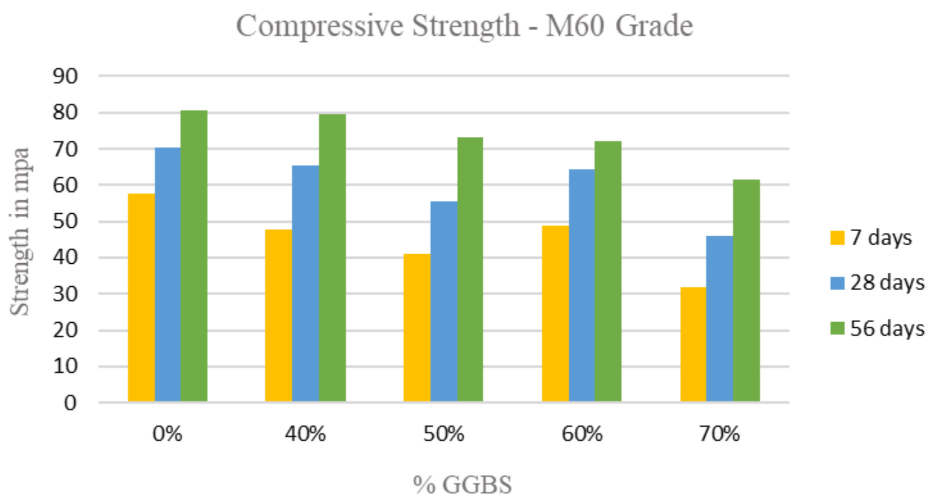

Chart 4: Analysis of Compressive Strength

3. CONCLUSION

This research has explored the potential of Ground Granulated Blast Furnace Slag (GGBS) as a sustainable and effective substitute to traditional Ordinary Portland Cement (OPC) in mass concrete structures. Through a detailed analysis of various GGBS replacement proportions—ranging from 0% to 70%—the study focused on controlling the heat of hydration, which is critical in preventing thermal cracking in large concrete pours, especially in dense urban areas like Mumbai. The findings demonstrate that a mix incorporating 60% GGBS provides optimal results in terms of temperature control, durability, and compressive strength, making it a viable solution for large-scale construction projects that prioritize both sustainability and structural integrity.

The ideal percentage of GGBS replacement was found to be up to 60% in temperature-controlled concrete without compromising the durability of the structure, adhering to the guidelines outlined in IS 456:2000. The results from the rapid chloride penetration test and permeability test are within the acceptable limits set by ASTM C1202:2022 and IS 516 Part 2 Section 1, respectively. Additionally, temperature monitoring indicated that the peak and core differential readings remained within the specified limits of IS 16700:2023.

The use of a GGBS-enhanced design mix not only facilitates easier temperature control methods but also makes the process more practical and pouring-friendly compared to traditional temperature control methods, regardless of site logistics. Furthermore, the carbon footprint associated with this temperature-controlled concrete is significantly lower than that of traditional designs, reinforcing the suitability of GGBS for future mass concrete structures.

In conclusion, this research validates the use of higher GGBS proportions in temperature-controlled concrete as a sustainable and effective strategy for mass concrete structures. It offers significant environmental benefits while maintaining durability and performance, advocating for the wider adoption of GGBS in urban high-rise developments, contributing to more eco-friendly and durable construction practices.

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