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A Comparative Evaluation of Bio Based and Industrial Additives Based Concrete Materials as Carbon Neutral Concrete

Manisha[1], Er. Janardan Tiwari[2]

[1]M Tech Scholar, Jan Nayak Chaudhary Devi Lal Memorial College of Engineering, Sirsa, Haryana, India
[2]Guide, Jan Nayak Chaudhary Devi Lal Memorial College of Engineering, Sirsa, Haryana, India

ABSTRACT

The construction sector significantly contributes to global CO_2 emissions due to high Portland cement usage. This study comparatively analyzed bio-based (RHA) and industrial (GGBS) additives as partial cement replacements at 10, 20, and 30%. Concrete samples were tested for mechanical (compressive, split tensile, flexural), durability (water absorption, porosity, UPV), workability (slump, compact-ing factor), and environmental (CO_2 emissions, embodied energy) performance over 7, 14, 28, and 56 days. The control mix showed the highest 28-day strengths: 32MPa compressive, 3.1MPa tensile, and 4.2MPa flexural. Bio-based (B30) and industrial (I30) mixes showed gradual reductions, with compressive strengths of 25MPa and 27MPa, tensile strengths of 2.5MPa and 2.7MPa, and flexural strengths of 3.5MPa and 3.6MPa. Durability tests indicated slight increases in water absorption (6.2%) and porosity (14%), with UPV confirming good quality. Workability decreased slightly but remained practical, while 30% replacements reduced CO_2 emissions and embodied energy by 30%. Overall, 10–20% replacement offered an optimal balance between performance and sustainability.

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***KEYWORDS:** Carbon-neutral concrete, RHA, Bio-based additives, Industrial by-products, GGBS.*

1. INTRODUCTION

The construction industry, as a major user of natural resources and energy, is central to the world's sustainability and carbon neutrality agenda [1]. Cement, being the main binding material in traditional concrete, is a main source of greenhouse gas emissions, especially carbon dioxide (CO_2). It has been estimated that cement alone contributes almost 7–8% to the total CO_2 emissions in the world due to both calcination of limestone and fossil fuel combustion in cement kilns [2]. As demands for infrastructure keep growing, mitigation of the environmental impact of cement and concrete has become a pressing issue [3]. As a response, scientists, engineers, and policymakers have shifted their attention to novel solutions that focus on embodied carbon reduction in building materials while addressing sufficient strength, durability, and service life [4]. Among these, the application of bio-based and industrial additives as partial substitution for cement has become a potential avenue for the development of carbon-neutral concrete.

Bio-based additives, including ashes from rice husk, sugarcane bagasse, sawdust, and other agricultural residues, have become a attractive significant interest because they provide the dual benefit of using waste from agro-industrial activities and enhancing sustainability in concrete [5]. These bio-based materials contain large amounts of amorphous silica and exhibit pozzolanic characteristics, allowing for reaction with the calcium hydroxide released during cement hydration to create additional "calcium silicate hydrate (C-S-H)" gel [6]. This additional hydration provides both enhanced long-term strength of concrete and improved durability through pore refinement and reduced permeability [7,8]. Figure 1 presents the advantage and disadvantages of bio and industry additive based concrete material.

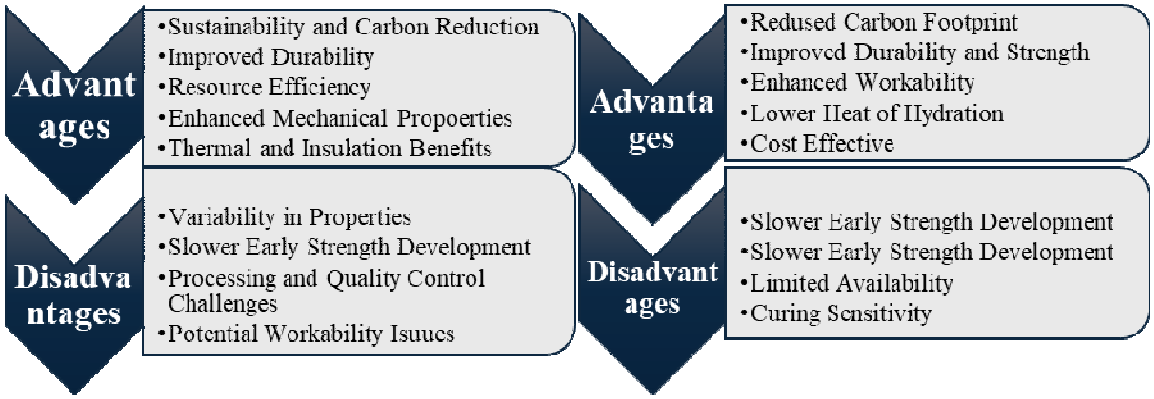

Figure 1: Advantage and disadvantages of Bio and industry additive-based concrete material

Conversely, industrial additives like "Ground Granulated Blast Furnace Slag (GGBS), fly ash, silica fume and steel slag" constitute another significant group of "Supplementary Cementitious Materials (SCMs)" [9]. These additives can be regarded as the results of high-scaled industry with many of them being the by-products of steel, power, or silicon production. The combination of the two sustainability issues in their incorporation into concrete is that first, they require less cement and second, they can be used safely and effectively to utilize the industrial waste that would otherwise, pose a serious problem of disposal [10]. Mechanical and durability properties of the concrete are well known to be improved by industrial additives especially against sulfate attack, chloride penetration, and alkali-silica reactions [11,12].

The relative research of bio-based and industrial additives in concrete offers valuable information to evaluate their relative performance, environmental advantage and cost. Though the two categories of materials are intended to reduce reliance on cement and achieve net-zero carbon emissions, its characteristics, accessibility, and permanence are quite distinct [13]. The present study, seeks to systematically analyze and compare the effects of bio-based and industrial additives on the durability, mechanical properties, and environmental performance of concrete. By examining the strengths and limitations of each additive category, this work contributes to the development of optimized, eco-friendly, and performance-driven mix designs. Here are the potential research objectives of the study follows as:

- To evaluate the mechanical properties of concrete with partial replacement of cement using RHA (bio-based additive) and GGBS (industrial by-product).
- To investigate the durability performance of modified concrete mixes through water absorption, porosity, and ultrasonic pulse velocity (UPV) tests at different curing ages.
- To assess the workability of fresh concrete incorporating varying proportions of RHA and GGBS using slump and compaction factor tests.
- To perform an environmental assessment by estimating CO_2 emissions and embodied energy of concrete mixes to determine their contribution toward carbon-neutral construction.

2. Related Work

Sudan et al., (2025) [14] compared the cradle-to-grave carbon footprint of geopolymer concrete, bamboo, recycled steel, and bio-based composites against traditional materials using ISO-compliant LCA. Results show geopolymer concrete cuts emissions by 35–45 %, bamboo and bio-based composites by 60–80 %, and recycled steel by 40–50 % compared to conventional options. These outcomes focus the potential of low-carbon materials to significantly decrease embodied emissions and support net-zero goals, offering engineers, designers, and policymakers practical guidance for sustainable material choices.

Affan et al., (2025) [15] evaluated hemp- and miscanthus-based insulation combined with low-carbon binders (NPC and CL90-S) across physical, mechanical, thermal, moisture, and durability properties. Hemp insulation with NPC (C100H) showed the best thermal ($\lambda = 0.12$ W/m·K) and mechanical performance (0.81 MPa), while miscanthus formulations, especially L100M, excelled in moisture regulation and freeze-thaw resistance. These results demonstrate the potential of bio-based materials and low-carbon binders to enhance building sustainability and reduce CO_2 emissions.

Ba et al., (2025) [16] evaluated the thermal and energy performance of bio-based materials—"Typha Australis, straw, banana fiber, Alfa fiber, peanut shells, and VSS"—against conventional concrete using COMSOL and TRNSYS simulations. Results show these materials improve insulation and cut cooling energy demand by over 30%, with banana fiber performing best. While promising for sustainable construction and CO_2 reduction, challenges such as cost, durability, and market adoption remain, highlighting the need for optimization and supportive policies for wider implementation.

Shoukat et al., (2025) [17] explored bio-stabilization of earthen materials using Opuntia Ficus-Indica (OFI) and other bio-based polymers to enhance thermal performance and reduce reliance on high-energy building materials. Experimental analysis of various mix designs (S-30, S-40, D-30, D-40, OFI-30, OFI-40) under dry conditions, supported by SEM imaging and statistical evaluation (ANOVA and Tukey test), shows that OFI-30, D-40, and S-40 mixtures achieve strong bonding and superior thermal conductivity. These findings highlight the potential of natural biopolymers in sustainable, energy-efficient earthen construction.

Zuaiter et al., (2025) [18] examined the mechanical properties of geopolymer concrete using GGBS and silica fume (SF) binders with sodium silicate-to-sodium hydroxide ratios of 1.5 and 2.0. Mechanical properties at 1, 7, and 28 days showed that adding up to 50 % SF with a 1.5 ratio increased 28-day CS by 50%, while higher SF content reduced strength. Raising the solution ratio to 2.0 improved CS for GGBS-rich mixes but reduced it for SF-rich mixes. Slag-only mixes achieved the highest modulus (18.7 GPa), and balanced GGBS-SF blends developed tensile strength compared to SF-rich mixes.

Paruthi et al., (2024) [19] evaluates the effect of 5–15 % silica fume (SF) on geopolymer concrete (GPC) cured at 60 °C for 24 h. Specimens were immersed for 62 days in sodium sulfate, sodium chloride, sulfuric acid, and hydrochloric acid to assess durability through water absorption, sorptivity, and CS loss. Incorporating 10 % SF yielded maximum CS (48.35 MPa), STS (4.91 MPa), and FS (5.01 MPa) at 28 days, and the highest rebound number and ultrasonic pulse velocity at 90 days. Results show that 10 % SF significantly enhances GPC's mechanical and durability properties, with an economic analysis confirming its viability as a sustainable, cement-free alternative.

3. Methods and Material

The research framework assessing bio-based and industrial additive concrete as carbon-neutral material (see Figure 2).

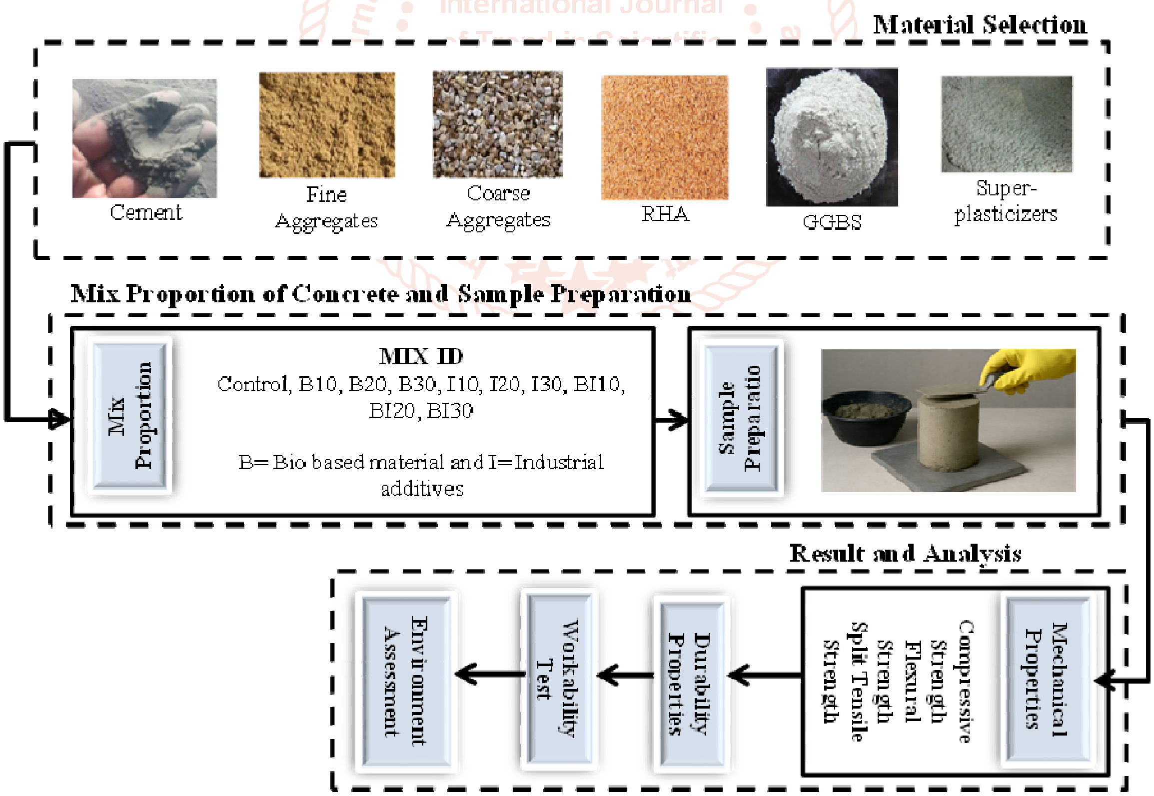

Figure 2: Flow diagram of suggested work

3.1. Material Selection

A. Cement

The project work makes use of Pozzolana Portland cement (PPC), which is easily accessible in the local market. The cement that was used for the project has been subjected to testing in accordance with IS: 4031-1988 and has been determined to meet several requirements outlined in IS: 1489-1991. Particular gravity was 3.6.

B. Fine and Coarse aggregate
River sand that is readily accessible in the area and meets the requirements of IS: 383-1970 Grade 2. The clean local river sand that is accessible would be used. For the casting of all specimens, sand would be passed through an IS 4.75mm sieve. Aggregate for the project was crushed annular granite that was mined in the area. The coarse aggregate used in the project work consisted of 60% for 20mm aggregate, with a specific gravity of 2.7.

C. Bio-based additives
Bio-based additives are renewable materials from agricultural, forestry, or organic waste and are being considered to partially replace cement in concrete to minimize its carbon content. RHA is a very reactive pozzolanic material that comes from the incineration of rice husks, a cheap agricultural by-product. It is amorphous silica rich, and this amorphous silica reacts with released calcium hydroxide from cement hydration to produce extra C–S–H gel, which strengthens the concrete microstructure.

D. Industrial by-product
Industrial by-products are products formed through industrial processes, which can improve concrete characteristics with minimal environmental effect. GGBS is an iron production by-product retrieved through quenching molten blast furnace slag and grinding it into a powder. It is generally applied as cement partial replacement due to its latent hydraulicity. When combined with cement, GGBS slowly reacts with water to create more C–S–H gel, enhancing long-term strength and lowering permeability.

E. Mix Proportion of Concrete
In concrete research, Mix ID refers to the unique identification assigned to each concrete mix, representing its specific composition and proportion of materials. It provides a systematic way to differentiate between mixes containing varying percentages of cement replacement with additives such as bio-based materials (e.g., RHA), industrial by-products (e.g., GGBS), or their combinations.

Table 1: Sample mix design

Mix ID	Cement (kg/m³)	Bio-based Additive (kg/m³)	Industrial Additive (kg/m³)	Fine Aggregate (kg/m³)	Coarse Aggregate (kg/m³)	Water (kg/m³)	Admixture (%)
Control	400	0	0	700	1150	180	0.5
B10	360	40	0	700	1150	180	0.5
B20	320	80	0	700	1150	180	0.5
B30	280	120	0	700	1150	180	0.5
I10	360	0	40	700	1150	180	0.5
I20	320	0	80	700	1150	180	0.5
I30	280	0	120	700	1150	180	0.5
BI10	360	20	20	700	1150	180	0.5
BI20	320	40	40	700	1150	180	0.5
BI30	280	60	60	700	1150	180	0.5

3.2. Key Parameters
The comparative evaluation of bio-based and industrial additives in carbon-neutral concrete considers several key parameters. Mechanical properties such as "compressive, tensile, and flexural strength" assess structural performance, while durability parameters like chloride resistance, sulphate resistance, carbonation depth, and water permeability ensure long-term stability. Workability indicators, including slump and setting time, evaluate ease of handling. Density, porosity, and microstructural characteristics such as hydration products and pore refinement are also examined.

4. Result and Discussion
In this section, the authors present the results corresponding to Mechanical Properties, Durability Properties, Workability Tests, and Environmental Assessment.

4.1. Compressive Strength Analysis
CS results indicated distinct trends for bio-based, industrial, and combined additives over time. The control mix (100% OPC) achieved the highest strength, 32 MPa at 28 days and 35 MPa at 56 days, serving as a benchmark. Bio-based mixes (B10–B30) showed decreasing strength with higher replacement, e.g., B10 at 30 MPa and B30 at 25 MPa at 28 days. Industrial mixes (I10–I30) maintained moderate strength, with I10 at 31 MPa and I30 at 27 MPa. Combined bio-industrial mixes (BI10–BI30) performed intermediately. All mixes gained strength from

7 to 56 days, confirming proper hydration. Replacements of 10–20% balanced strength, durability, and sustainability.

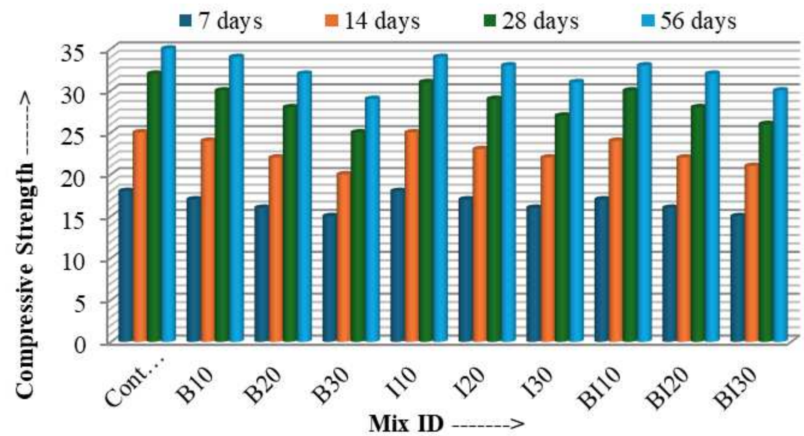

Figure 3: Graph of CS at 7 and 14 days

4.2. Split Tensile Strength

STS results highlight the influence of additives on tensile performance over time. The control mix achieved the highest values, reaching 3.1 MPa at 28 days and 3.5 MPa at 56 days. Bio-based mixes (B10–B30) showed a decline with increasing replacement, where B10 recorded 3.0 MPa and B30 dropped to 2.5 MPa at 28 days, reflecting reduced cement content and weaker binder cohesion. Industrial mixes (I10–I30) retained fair strength, ranging from 3.0 to 2.7 MPa, suggesting adequate tensile capacity with FA or slag substitution. Combined bio-industrial blends (BI10–BI30) gave intermediate values, indicating synergistic effects. All mixes gained strength from 7 to 56 days, with 10–20% replacement levels providing a balance between tensile performance and sustainability.

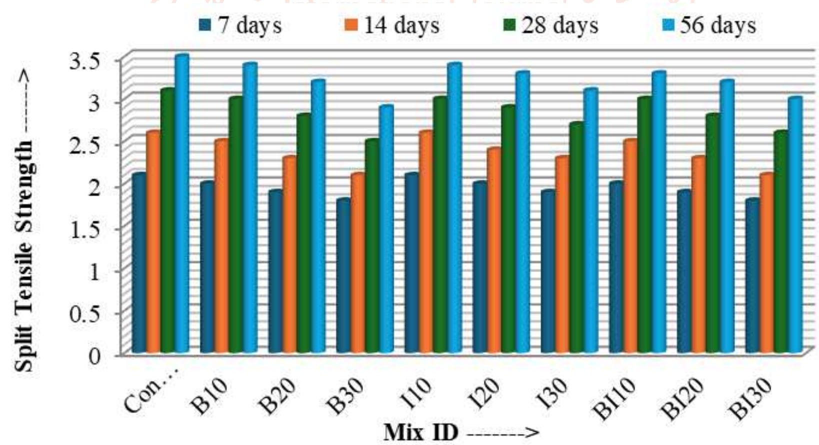

Figure 4: Graph of STS at 7 and 14 days.

4.3. Flexural Strength

FS results show the influence of bio-based, industrial, and combined additives on concrete bending performance. The control mix had the highest FS, reaching 4.2 MPa at 28 days and 4.5 MPa at 56 days, serving as the benchmark. Bio-based mixes (B10–B30) showed a gradual decline with higher replacement; B10 achieved 4.0 MPa, while B30 dropped to 3.5 MPa at 28 days, due to reduced cement content and weaker paste cohesion. Industrial mixes (I10–I30) retained moderate FS, ranging from 4.1 MPa at 10% to 3.6 MPa at 30% replacement, showing FA and slag could partially replace cement with modest reductions. Combined bio-industrial mixes (BI10–BI30) showed intermediate results. All mixes gained FS with curing, and 10–20% replacement offered the best balance between strength and sustainability.

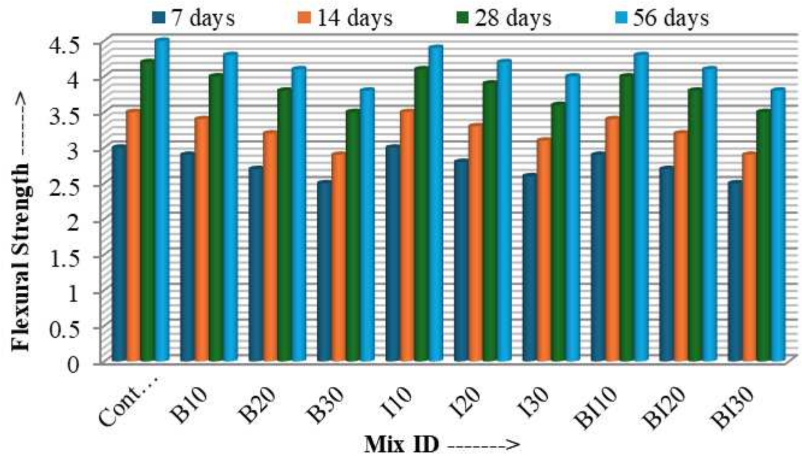

Figure 5: Graph of FS at 7 and 14 days.

4.4. Durability Properties

The durability of concrete mixes was assessed through water absorption, porosity, and UPV tests after 28 and 56 days of curing. The control mix, with 100% cement, showed the lowest water absorption (5.2%) and porosity (12.5%), indicating a dense and durable microstructure. Bio-based additive mixes (B10–B30) exhibited slightly higher absorption and porosity values, with B30 reaching 6.2% and 14.0%, reflecting increased pore connectivity though still within acceptable durability limits. Industrial additive mixes (I10–I30) showed moderate increases, with I30 performing best at 5.9% and 13.7%, suggesting minimal negative impact on microstructure. The combined bio-industrial blends (BI10–BI30) showed intermediate values, indicating a balanced influence of both additives on pore structure and long-term durability (Figures 6).

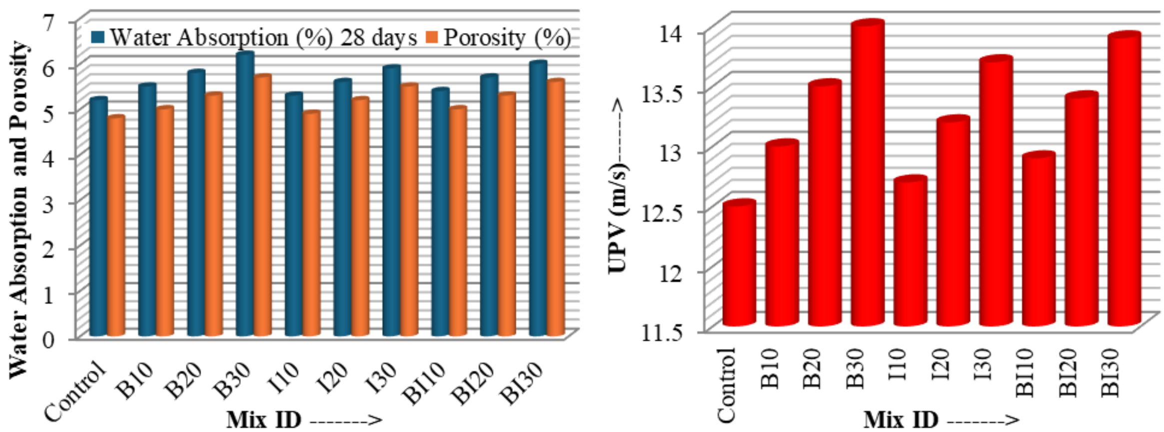

Figure 6: Graph of Duability properties

The UVP measurements showed that the internal quality of all mixes was good, and the replacement level was slightly lower with high porosity. Altogether, these findings prove that with the additive replacement of concrete at 10-20%, it can be possible to retain the good durability, as well as provide sustainability and carbon neutrality.

4.5. Workability Test

The workability of fresh concrete mixes was evaluated using slump and compacting factor tests. The control mix recorded the highest values, with a 75 mm slump and 0.92 compacting factor, indicating high consistency and ease of placement due to full cement content. Bio-based mixes (B10–B30) showed a gradual decline in workability, with B30 reaching 60 mm slump and 0.88 compacting factor, attributed to higher fineness and water absorption. Industrial mixes (I10–I30) demonstrated moderate reductions, with I30 showing 63 mm and 0.88. Combined bio-industrial mixes (BI10–BI30) yielded intermediate results. All mixes maintained workable properties, confirming that 10–20% substitution balances sustainability, mechanical performance, durability, and constructability (Figure 7).

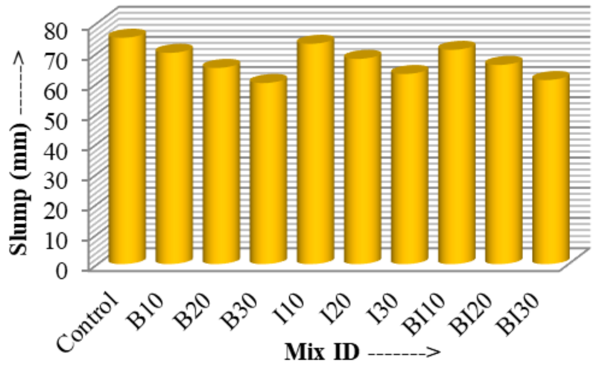

Figure 7: Graph of Slump

5. Conclusion

This research aimed to develop carbon-neutral concrete by partially replacing cement with bio-based (RHA) and industrial (GGBS) additives to reduce environmental impacts while maintaining structural performance. The methodology involved selecting OPC cement, fine and coarse aggregates, RHA, GGBS, water, and superplasticizers. Ten concrete mixes were designed (Control, B10–B30, I10–I30, BI10–BI30) with varying replacement levels of 10–30%. Mechanical properties were measured, alongside water absorption, porosity, UPV, slump, compacting factor, CO_2 emissions, and embodied energy. Numerical results showed that the control mix achieved 32MPa CS at 28 days, whereas B10 and I10 achieved 30MPa and 31MPa, respectively, indicating 10–20% replacement maintained near-control strength. Durability tests revealed slight increases in water absorption (up to 6.2%) and porosity (up to 14%), with UPV confirming good internal quality. Workability decreased with higher replacements, yet remained practical (slump 60–75 mm). Overall, 10–20% replacement offered the best balance between performance, durability, workability, and sustainability, supporting practical, low-carbon construction.

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