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Research Article

Flexural behavior of sustainable high-strength RC beams with GGBS and iron filings incorporation

Sawsan Akram HASSAN[1], Saif Luay ALTAI*[2]

[1]*Department of Civil Engineering, Mustansiriyah University, College of Engineering, Baghdad, Iraq*
[2]*University of Babylon, College of Engineering, Babylon, Iraq*

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ABSTRACT

This experimental study investigates the behavior of sustainable high-strength reinforced concrete (HSRC) beams when cement is partially replaced with ground granulated blast furnace slag (GGBS) and sand with iron filings (IF). Eight rectangular HSRC beams were experienced to four-point loading to examine the effects of these substitutions. The cement was replaced with GGBS at three percentages (10%, 30%, and 50%), with and without a 10% substitution of sand by IF. The results showed that substituting 30% GGBS caused a minor reduction in beam strength, while higher GGBS percentages (above 30%) led to a more significant decrease. However, adding 10% IF improved the beams' strength, demonstrating its potential as a reinforcing material. All beams exhibited similar failure patterns under peak loads. Similarly, the load-deflection behavior of all beams showed consistent patterns across different configurations. However, beams of an optimum replacement consisting of 30% GGBS and 10% IF can support larger values of load-carrying capacity, moment-resisting capacity, and energy absorption than those with other mixtures. The study shows that while GGBS could enhance sustainability, it should be judiciously adopted to maintain structural integrity. Contrariwise, IF shows excellent potential in improving the HSRC beams with improvement in sustainability. It tends to create a balance in material substitution to optimize performance and environmental impacts in concrete structures.

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1. INTRODUCTION

Applications of waste material in RC beams have been developed as a relatively new research area to increase construction sustainability and tackle some environmental problems originating from conventional concrete production. Past research has investigated various waste materials that can be partially used to substitute conventional aggregates or cement in RC beams. In this connection, the clean coal bottom ash and coal fly ash replacement of fine and coarse aggregates demonstrate higher ultimate load and deflection capacities for RC beams [1]. Similarly, researchers have also made attempts to utilize spent garnet as a replacement for fine aggregate, exhibiting enhanced material behavior and reduced failure under impact loads in RC beams [2]. In minor uses, ceramic waste powder tends to decrease environmental impacts and, with that, even CO_2 emissions in higher percentages, almost invariably affecting compressive strength and load-carrying capacity negatively [3]. Other wastes used in tests were granular plastic, crumbed

*Corresponding author.
*E-mail address: eng.saif.hadi@uobabylon.edu.iq

rubber, waste newspaper, and crushed bricks—all of which decreased compressive strength but are still possibly useful for minor structural uses [4, 5]. Recycled concrete aggregate has also shown some strength in maintaining and even improving the mechanical properties of RC beams, obtaining higher compressive strength compared to the ones using natural aggregates [6]. Waste glass and agricultural by-products like rice husk ash have also been applied; these materials give some advantages regarding ductility and sustainability [7, 8]. The addition of fibers, namely polypropylene glass fibers and waste aggregates, further developed the flexural capacity and ductility of the RC beams [9]. All these studies reflect the potentiality of waste materials for reducing environmental impacts and enhancing the RC beams' structural performance, thus promoting greener construction methodologies.

As industrial waste production rises, factory and mechanical plant byproducts are recognized for construction applications. One example is ground granulated blast furnace slag (GGBS), a by-product of blast furnaces in the steel and iron industries. Researchers have explored ways to reduce the environmental footprint of GGBS, enabling its use in concrete structures as a partial or complete replacement for traditional cement. Consequently, depending on the size of the concrete structure and the quantity of GGBS employed, a significant amount of this by-product can be removed from the environment, along with its economic advantages. The partial substitution of GGBS for cement substantially improves the strength of concrete in comparison to normal concrete [10–14]. The compressive strength of concrete rises with an increase in the proportion of GGBS up to a specific limit, i.e., the optimal substitution of GGBS, after which compressive strength diminishes [15–18]. The optimal substitution of GGBS was found to be 55%, according to [15], and [16] reported it to be 10%. However, [17] observed that GGBS exhibits no influence on the concrete strength up to a replacement level of 20%, after which the concrete strength declines. This manifestation is attributed to unreacted GGBS functioning as a filler material.

Furthermore, when utilized in place of some of the cement, GGBS slows down the hydration process, causing a decrease in the strength of the concrete [19]. The compressive strength of a concrete mixture containing cement, fine and coarse aggregates with partial replacement with GGBS, fly ash, and recycled aggregates demonstrates improved results compared to conventional concrete mixes [20]. The flexural behavior of RC beams and the ones with GGBS is comparable [21, 22]. However, the flexural strength of concrete with 60% GGBS content significantly increased compared to 0% GGBS. In comparison, a minor decrease was observed at 40% replacement, and a substantial decrease occurred at 80% replacement [23]. The characteristics of the beams without GGBS closely resemble those in which 70% of the cement is substituted with GGBS [24]. However, for beam specimens with GGBS of 90%, both stiffness and strength were lower than those without GGBS by 16% and 6%, respectively. In RC beams, GGBS as a complete replacement for cement was experimentally examined [25]. The ultimate load of RC beams with GGBS that failed in flexure was 83% of those without GGBS. Recent studies highlight that GGBS significantly enhances the sustainability performance, engineering properties, and life cycle assessment of high-strength self-compacting geopolymer concrete composites, making it an optimal choice for sustainable construction [26–33]. Experimental research has also shown that GGBS enhances the performance of previous concrete, particularly in terms of chloride resistance and sustainability benefits [34].

Iron filing (IF) is another by-product of the milling, filing, or grinding of finished iron products. Numerous studies have investigated replacing sand with fly ash, stone powder, and copper slag. IF is among the waste products that can effectively replace sand in concrete. Iron-containing waste materials were first explored for manufacturing heavy concrete in 2011 [35]. The compressive strength of concrete produced with IF as sand replacement exhibited a 3.5% increase for the 10% replacement level and a 13.5% increase for the 20% replacement level. However, at the 30% replacement level, there was a decrease of 8% [36]. The concrete achieved optimal strength with a 20% substitution of sand with IF and particles of waste glass[37]. The compressive and flexural strength decreased after replacing sand with IF by 20%, which was suggested to be the optimal amount for sand replacement with IF. The highest compressive strength of concrete can be attained with IF at 12%, after which it begins to decline [22]. A previous study [36] found that when sand is replaced with IF, the compressive strength overperforms by 30%. A considerable improvement in compressive strength was attained when the sand was entirely replaced with IF [38].

Previous studies have extensively explored the use of waste materials in RC beams to enhance sustainability and structural performance. However, there are notable gaps in understanding the optimal use of these materials. While materials like coal bottom ash, fly ash, spent garnet, and ceramic waste powder have been investigated, their effects on compressive strength at high replacement levels remain a concern, as they can lead to strength reductions. Using fibers such as polypropylene and glass has also improved flexural capacity and ductility. Still, the specific interactions between these fibers and other waste materials like GGBS and IF are not fully understood. GGBS is recognized as a viable cement substitute, with research indicating that a 55% replacement level optimizes concrete strength. However, too much GGBS can diminish strength, and the ideal balance for strength and sustainability remains unclear. Likewise, while IF has shown promise as a sand replacement, especially in boosting compressive strength, the long-term impacts and ideal replacement ratios to sustain structural integrity need further investigation.

This study seeks to bridge existing gaps by examining the combined influence of GGBS and IF on high-strength reinforced concrete (HSRC) beams, particularly their effects on flexural behavior, crack patterns, energy absorption, and overall structural performance. The research aims to offer deeper insights into the optimal use of these materials to enhance the sustainability and functionality of concrete structures.

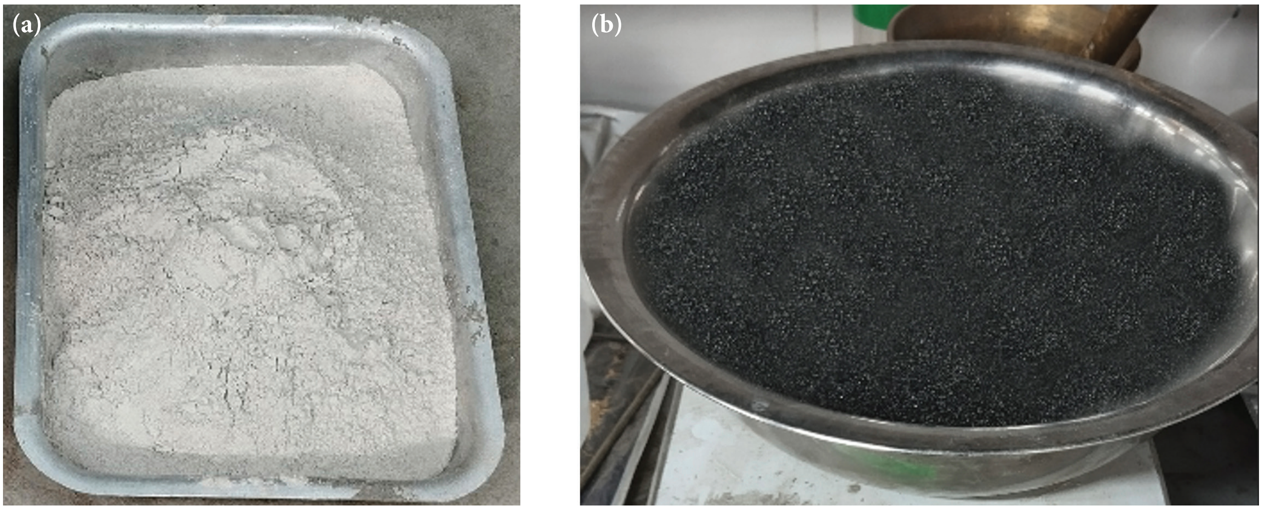

Figure 1. Materials used in the experiments. **(a)** GGBS, **(b)** IF.

Table 1. Materials used in the mixture of each specimen

Specimen ID*	Cement (kg/m³)	GGBS (kg/m³)	GGBS/cement (%)	Sand (kg/m³)	IF (kg/m³)	IF/sand (%)
BG0F0	570	0	0 %	640	–	–
BG10F0	513	57	10 %	640	–	–
BG30F0	399	171	30 %	640	–	–
BG50F0	285	285	50 %	640	–	–
BG0F10	560	0	0 %	576	64	10 %
BG10F10	504	56	10 %	576	64	10 %
BG30F10	392	168	30 %	576	64	10 %
BG50F10	280	280	50 %	576	64	10 %

*B refers to beam, G (0,10,30,50) refers to GGBS content percentage of cement replacement, and F (0,10) refers to IF percentage of replacement of the sand. GGBS: Ground granulated blast furnace slag; IF: Iron filings.

2. EXPERIMENTAL PROGRAM

2.1. Materials

Cement (Portland cement type I), aggregate, superplasticizer, and various other materials (such as GGBS and IF) were the components used to produce the concrete mixture. The sand and gravel were washed to remove any dust deemed to be unwelcome, after which they were dried and placed in a container prepared for use later. In Figure 1, the GGBS and IF were utilized in the experiments—the use of GGBS and IF were implemented as partial replacements for cement and sand, respectively. Table 1 shows the usage of GGBS and IF as a partial replacement. As shown in Table 1, the following quantities of materials were employed to achieve one cubic of mixing. The amount of water used was 125 kg/m³. The amount of sand used was 640 kg/m³, while the amount of gravel used was 1075 kg/m³. The amount of superplasticizers (EUNIFLOW 260) was 6 kg/m³. It was determined that the reinforcing bars used in the experiments were made of 45-grade steel (i.e., yield stress 450 MPa) after they were put through the testing procedures outlined in ASTM A370.

2.2. Test Beam Specimens

Eight HSRC beams were cast and tested. The HSRC beams were cast in two sets (four in each). In the first set, HSRC beams were cast to investigate the impact of varying GGBS content percentages on beam strength. In contrast, the second set consists of beams with IF and the exact varying GGBS content percentages as in the first set. After placing the steel frame inside the formwork, which was cleaned and oiled earlier, the concrete was poured into it. The concrete was left inside the formwork for two days to ensure it had enough strength to be unmolded. Beams were constantly sprayed with water and covered with a plastic sheet to keep them as moist as possible. Reinforcing bars of 16mm diameter were used as flexural rebars, while reinforcing bars of 6 mm were used as stirrups. Figure 2 shows the layout of the HSRC beams designed according to the ACI code [39] with flexural reinforcing bars of 2ϕ16 mm and stirrups of 12ϕ6 mm at a spacing of 150mm. Two ϕ 6mm rebars were used at the top to hold the stirrups in place during casting. At 35 days of age, the beams were tested, during which measurements were taken for load in kN and midspan deflection in mm, as well as observations of the mode of failure and crack pattern. Figure 3 shows the beam molded and curing. Three 150 mm by 300 mm cylinders were cast for each beam tested to determine its compressive strength.

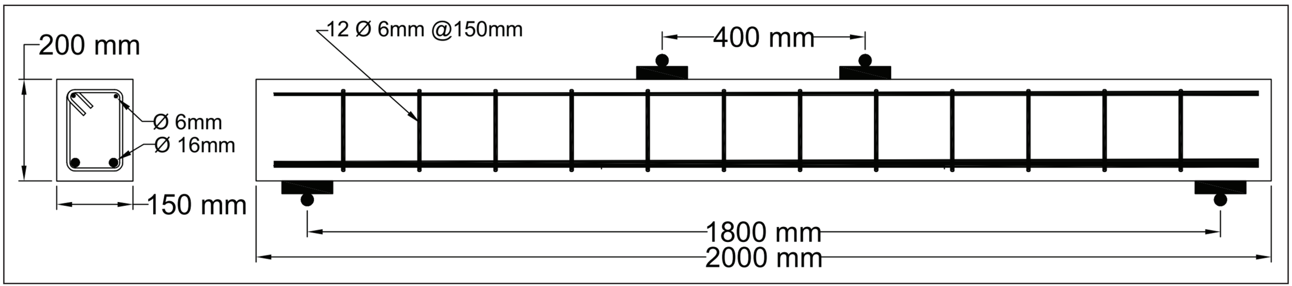

Figure 2. HSRC beam layout.

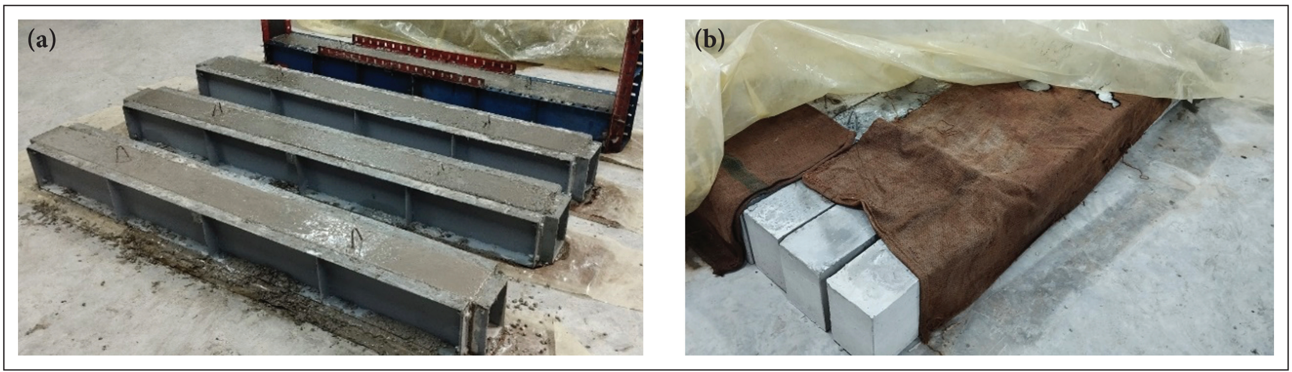

Figure 3. Beam molded and curing. **(a)** Beam molded. **(b)** Curing.

This study divided the beam specimens into two groups according to the materials' composition. In the first group, no GGBS was used, and the IF percentages were 0%, 10%, 30%, and 50% in the four beam specimens, respectively. The second group used a constant 10% GGBS across all beam specimens, with IF percentages of 0%, 10%, 30%, and 50%. GGGBS and IF partially replaced cement and sand in the concrete mix. Six HSRC beams were tested with varying compositions: three contained GGBS at 10%, 30%, and 50%, respectively, while others included 10% IF in addition to GGBS. The control beam, BG0F0, contained neither GGBS nor IF. The beam BG0F10 had 10% IF only. The beams BG10F0, BG30F0, and BG50F0 contained 10%, 30%, and 50% GGBS, respectively, without IF. Conversely, the beams BG10F10, BG30F10, and BG50F10 each included 10% IF alongside their respective GGBS percentages. The weights of cement, sand, GGBS, and IF used in the concrete batches are detailed in Table 1.

2.3. Test Setup

Utilizing a universal loading cell machine with a maximum capacity of 600 kN, a monotonic test was performed on four point-loading beams, as depicted in Figure 4. The ratio of shear span to beam depth was 3.5, which was determined by the fact that each loading point was positioned 200 millimeters away from the center of the beam to induce flexural failure. A dial gauge with an accuracy of 0.02 millimeters was attached to the bottom face of the beam being tested to measure the midspan deflection. Once the tested beam could no longer support additional loads, the testing was terminated because of failure. While the beam was being loaded, the crack pattern was recorded on the surface of the beam that was being tested. A rate of one kilonewton per second was applied to the load. During the process of loading the beam, the load and deflection were measured, and at the same time, the crack pattern was meticulously examined and marked.

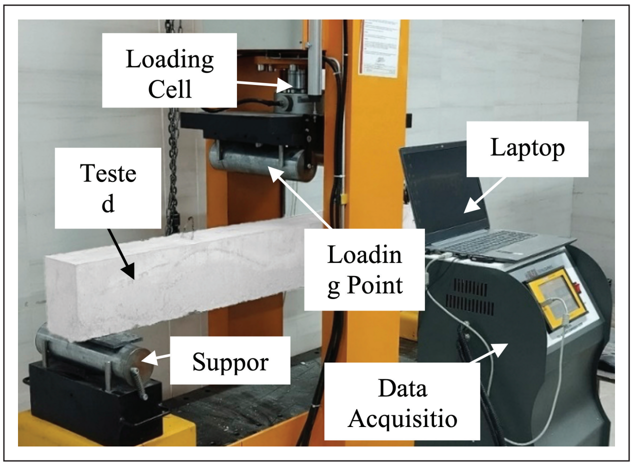

Figure 4. Test setup.

The testing procedure for determining the stress-strain behavior of a concrete cylinder involves using a universal compressive testing machine that applies a compressive load to the cylinder. A dial gauge is attached to measure the longitudinal deformation, as shown in Figure 5. Three cylinders measuring 150 mm by 300 mm were cast for each beam tested to capture stress-strain curves and determine peak compressive strength. This setup enables precise strain measurement, essential for evaluating the concrete's elasticity and compressive strength.

Table 2. Compressive strength of cylinders

Specimen ID	Compressive strength (MPa)
BG0F0	60
BG10F0	64
BG30F0	73
BG50F0	70
BG0F10	61
BG10F10	67
BG30F10	73
BG50F10	71

3. RESULTS AND DISCUSSION

These experiments were conducted to gain a deeper understanding of the sustainability-related behavior of HSRC beams. The following sections detail the experimental results, including crack patterns, load capacity, and deflection curves. These findings are presented in the following sections. Additionally, an explanation is provided for how these results behave.

3.1. Cylinder Specimens

The compressive strength of the average value of the compressive strength of three (150x300) mm cylinders of all the tested beams is shown in Table 2. The baseline specimen (BG0F0) demonstrates a compressive strength of 60 MPa. As additive levels of (GGBS and IF) increase, compressive strength rises notably, peaking at 73 MPa for BG30F0 and BG30F10. This increase suggests enhanced load-bearing capacity due to a denser and more robust concrete matrix. However, when additives (GGBS and IF) reach a higher concentration in both groups, as seen in BG50F0 and BG50F10, the compressive strength declines slightly to 70 MPa and 71 MPa, respectively. This reduction indicates that excessive additives may lead to brittleness, limiting the concrete's overall stability under load.

Regarding the stress-strain response shown in Figure 6, all cylinder specimens initially behave similarly up to around 15 MPa, showing a linear increase in stress as strain is applied, indicating stable load-bearing capacity across mixtures. Beyond this point, however, the effects of additives become more pronounced. Cylinder specimens with 10-30% additives continue to gain compressive strength, peaking around 73 MPa, while those with 0% or excessive additives start to plateau.

3.2. Beam Specimens

3.2.1. Crack Patterns

The HSRC beams, after failure, depicted in Figure 7, show distinct cracking patterns influenced by varying IF ratios and GGBS content. The analysis of these beams revealed that cracks typically initiated at loads between 24 kN and 29 kN, depending on the material composition. Beam Specimens without GGBS, like BG0F0 and BG0F10, began cracking at around 24 kN and 26 kN, respectively. The cracks were closely spaced and propagated quickly, indicating a lower resistance to crack formation and growth. However, the addition of IF in BG0F10 slightly improved crack resistance, delaying the onset of cracking and slightly controlling crack propagation.

Figure 5. Measuring the stress-strain curve (left image is before testing, right image is after testing).

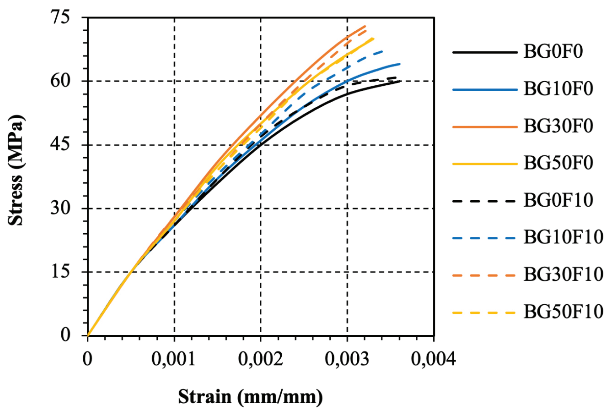

Figure 6. Stress-strain curves of tested cylinders.

Beams incorporating GGBS exhibited enhanced crack resistance, with BG10F0 and BG30F0 showing crack initiation at 27 and 26 kN, respectively. The cracks in these beams were spaced wider apart, reflecting the beneficial effects of GGBS in improving the concrete's microstructure and delaying crack propagation. 30% GGBS optimizes crack resistance by enhancing the microstructure through improved particle packing and reducing voids. This level maintains a balance between cementitious properties and filler effect, which prevents excessive cracking. In contrast, 50% GGBS delays crack initiation further due to enhanced packing but compromises overall strength as the cement matrix becomes overly diluted. When combined with IF, as seen in BG10F10 and BG30F10, the cracking load increased to approximately 28 kN and 29 kN, with the cracks being more controlled and evenly spaced, demonstrating a synergistic effect of the two materials.

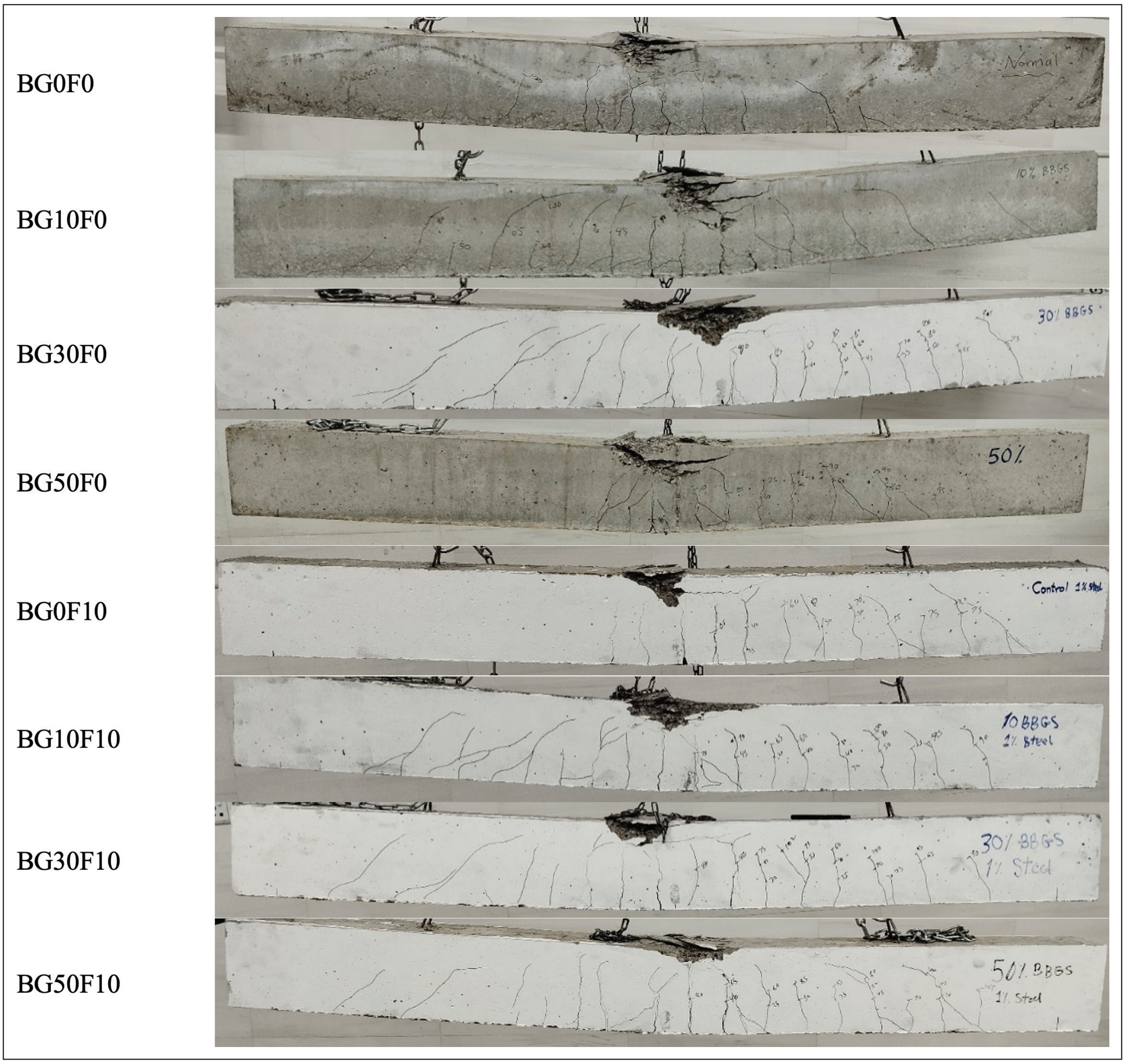

Figure 7. HSRC beams after testing.

The most significant improvement was observed in BG50F0, where the high GGBS content delayed crack initiation to around 29 kN. This specimen exhibited the widest crack spacing and the smallest crack widths, showing the highest resistance to crack propagation even at higher loads. Across all beam specimens, crack propagation slowed significantly once the load exceeded 70 kN to 75 kN, with final failure characterized by widening flexural cracks in the upper-middle span. The variations in cracking patterns across the beam specimens underscore the importance of GGBS and IF in enhancing the structural performance and durability of HSRC beams.

3.2.2. Load Capacity

One of the characteristics studied is the load capacity of the HSRC beams incorporating various GGBS content with or without IF. Table 3 illustrates the peak load results for all HSRC beams. The highest peak load recorded at 123.8 kN was noted for BG30F10, while the lowest peak load measured at 114.1 was observed for BG10F10. The compressive strength of the concrete was somehow diverse due to differences in the GGBS content percentage added to some beam specimens. However, all HSRC beams failed in flexural mode. The experimental results

Table 3. Peak load of tested beams

Specimen ID	Peak load (kN)
BG0F0	122.3
BG10F0	118.6
BG30F0	120.6
BG50F0	112.9
BG0F10	120.7
BG10F10	114.1
BG30F10	123.8
BG50F10	119.3

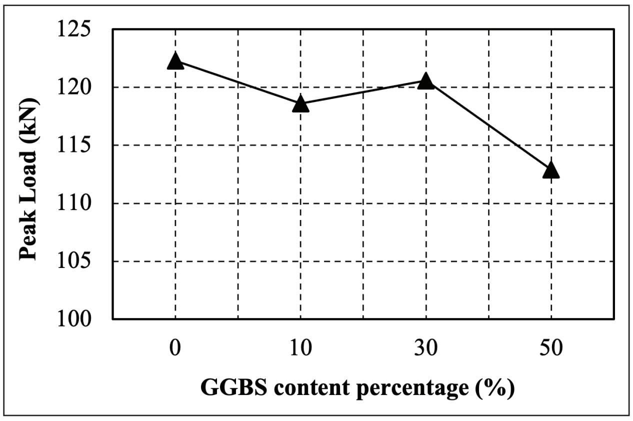

Figure 8. GGBS content percentage vs. peak load of beams with GGBS.

showed that both GGBS and IF undoubtedly influence the behavior of HSRC beams. The optimal performance of 30% GGBS is due to its ability to act as a non-reactive filler that enhances the density without significantly reducing the cement's binding capabilities. However, at 50% GGBS, the dilution of cement content reduces load-bearing capacity. Adding 10% IF further supports the load capacity by reinforcing the tensile properties, effectively distributing stresses, and reducing crack formation. Even though all HSRC beams failed in a flexural mode, loads at which HSRC beams failed were distinguishable.

Furthermore, the experiments revealed that HSRC beams with different percentages of GGBS exhibited slightly different strengths [21, 22]. GGBS is a very fine material and experiences no chemical reactivity. Hence, GGBS functions solely as a filler. Due to the fineness and lack of chemical reactivity of the GGBS, as the percentage of replacement increases, the strength of the HSRC beams gets greater until a certain percentage is reached, at which point the strength starts to decrease [15, 18]. This percentage is called the optimal percentage of replacement. However, it is very challenging to maintain this percentage practically, along with other in-situ circumstances. Suggesting a prescribed percentage that can provide the best strength is better. Three different percentages of GGBS were suggested (i.e., 10%, 30%, and 50%) of the weight of the cement. As the GGBS content percentage increases, the need for water content rises, leading to a drop in compressive strength. In addition, the cement content responsible for the chemical binding of concrete components lessens.

Moreover, the findings from the experiment indicated that when the GGBS content percentage increases, the peak load of the beams drops. The beams BG50F0 and BG10F10 were the only two with the lowest strength compared to all other beams. However, BG30F10 showed the highest strength among all beams. The peak load of the beam (BG50F0) with 50% of GGBS content percentage drops 8% of the control beam. However, the best GGBS content percentage is 30%, unlike what was found by [15, 18]. Because the strength starts to deteriorate as the GGBS content percentage increases after a certain point.

Table 4. Peak load of beams with GGBS

Specimen ID	Peak load (kN)	Compressive strength (MPa)*
BG0F0	122.3	100%
BG10F0	118.6	97%
BG30F0	120.6	99%
BG50F0	112.9	92%

*The calculated percentage relative to the control beam BG0F0. GGBS: Ground granulated blast furnace slag.

When it comes to decision-making, it all comes down to the structural designer, who may prioritize the utilization of GGBS even though it may compromise the strength of the structure.

3.2.2.1. Effect of GGBS Replacement

A comparison in terms of load capacity between the HSRC beams utilizing GGBS and those without GGBS is presented in this section. GGBS, acting as a non-reactive fine material, functions as a filler in concrete [17]. The strength increases or stays unchanged as GGBS content percentage rises until reaching a certain point, after which the strength declines [15–18] (Table 3). For HSRC beams, this behavior is noticeable in Figure 8. In addition, replacing the cement with GGBS partially underperforms the beam in terms of peak load. The peak load for beams BG10F0 and BG30F0 is 118.6 and 120.6, respectively, approximately 1-3% less than the control beam (Table 4). However, when utilizing a GGBS content percentage of 50%, the peak load of the beam BG50F0 drops by 8%. This behavior is predicted as the GGBS content percentage increases due to the chemical non-reactivity of the GGBS. This behavior suggests that as the GGBS content percentage exceeds 50%, the load capacity may drop proportionally. The performance at 30% GGBS is near-optimal because it improves the concrete's microstructure without significantly compromising the chemical binding provided by the cement. Exceeding this threshold leads to performance declines as the cement matrix weakens, highlighting the critical balance needed in GGBS content.

3.2.2.2. Effect of IF Replacement

One of the main aims of this experiment is to examine the effect of IF content percentage on the behavior of the HSRC beams. The results showed that utilizing IF in the concrete impacted the behavior of the HSRC beams, as shown in Figure 9. Table 5 shows that the peak load of the beam BG0F10 is within only 1% compared to the control beam, even though the compressive strength of the beam BG0F10 was 1% higher than the control beam. The addition of IF shows some improvement in gaining extra strength in comparison to the control beam, even though the control beam with 10% of IF (BG0F10) failed at a load of 1% lower than the control beam (i.e., 120.7 kN) but almost the same displacement (i.e., 33.4 mm). Incorporating 10% IF is particularly beneficial as it enhances tensile properties and reinforces the matrix, helping to control cracks. Unlike higher percentages, which can introduce inconsistencies, this lev-

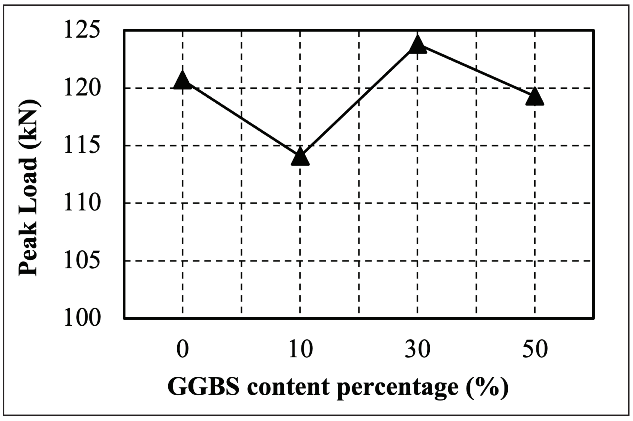

Figure 9. GGBS content percentage vs. peak load of beams with and without IF.

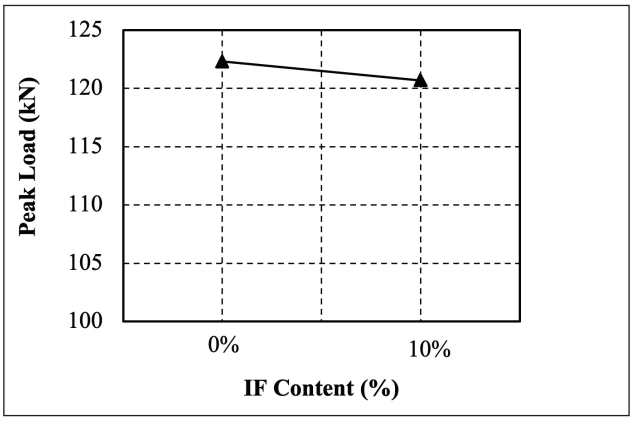

Figure 10. Peak load of beams with IF.

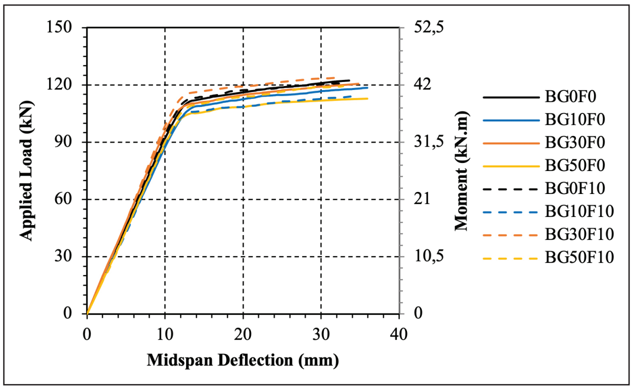

Figure 11. Load-deflection and moment-deflection curves of all HSRC beams.

el provides the best results without disrupting the overall structural integrity. The beams (BG30F10 and BG50F10) gained strength of around 2% and 6%, respectively, compared to corresponding beams without IF. The insignificant margin of strength reduction implies the potential advantage of utilizing IF as a partial replacement for sand.

3.2.2.3. Composite Effect of GGBS and IF Replacement

Studying the behavior of HSRC beams with both GGBS and IF is one of the main subjective. The combined effect of GGBS and IF may seem somewhat challenging since it

Table 5. Peak load of beams with GGBS

Specimen ID	Peak load (kN)	Specimen/BG0F0*
BG0F0	122.3	100%
BG0F10	120.7	99%

*The calculated percentage relative to the control beam BG0F0. GGBS: Ground granulated blast furnace slag.

Table 6. Peak load of beams with GGBS

Specimen ID	Peak load (kN)	Specimen/BG0F0*
BG0F0	120.7	100%
BG10F10	114.1	95%
BG30F10	123.8	103%
BG50F10	119.3	99%
BG0F0	120.7	100%

*The calculated percentage relative to the control beam BG0F0. GGBS: Ground granulated blast furnace slag.

deals with two different materials with different mechanical and physical properties. The combination of 30% GGBS and 10% IF demonstrated the best structural performance due to the complementary effects of improved microstructure and enhanced crack resistance. Higher GGBS percentages, while beneficial for crack delay, slightly reduced overall beam strength, confirming that a balanced approach is necessary for optimal results. Unlike the beams without IF shown in Figure 8, where beams with a higher GGBS content percentage experience a higher drop in peak load than that of the control beam, beams with IF shown in Figure 10 exhibit slightly different behavior. Table 6 illustrates that the peak load of beam BG10F10 drops 5% compared to the control beam. However, with a GGBS content percentage of 30% and an IF content percentage of 10%, the peak load rises by 3% compared to the control beam. When the GGBS content percentage was changed to 50%, the beam BG50F10 failed at a rate of 1% lower than the control beam. The more content of GGBS and IF with less compromise in the strength of the HSRC beams is the most favorable. Hence, HSRC beams with a GGBS content percentage of 50% and an IF content percentage of 10% with a drop in strength of only 1% may appear to be the better choice to keep the strength and utilize as much GGBS and IF as a partial replacement as possible.

3.2.3. Load-Deflection Curves

The relationship between load and moment versus midspan deflection of all eight HSRC beams drawn in Figure 11 reflects the overall behavior of the beams subjected to external loads. The moment is calculated as half of the total load multiplied by the shear span, which is 0.7 m. All HSRC beams exhibit two slopes of stiffness, which is the slope of the tangent. The first steep stiffness characterizes the elastic behavior, whereas the second shallow stiffness denotes the plastic behavior. HSRC beams carry loads during the initial stiffness while experiencing deformations approximately linearly. However, as the beam experiences plastic behavior in the concrete, steel, or both, its ability to sustain loads

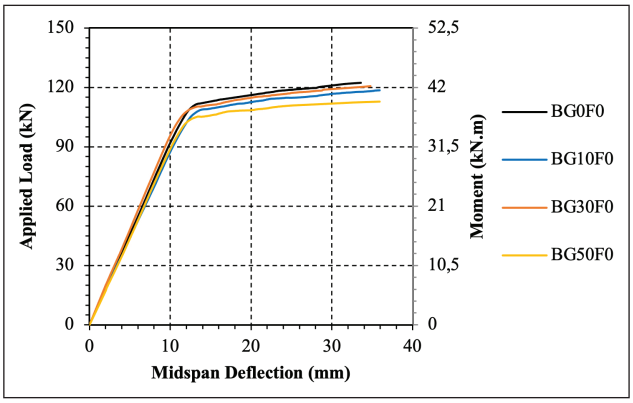

Figure 12. Load-deflection and moment-deflection curves of beams with GGBS.

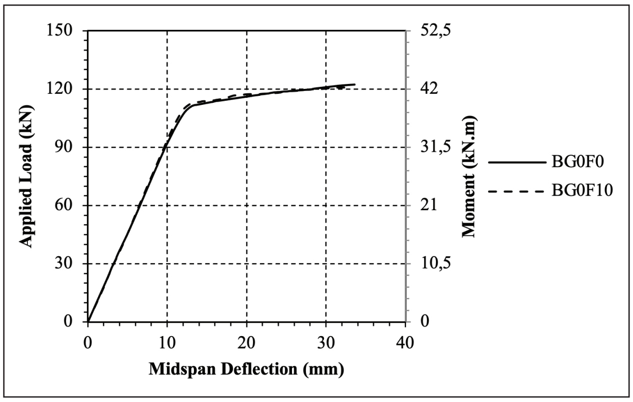

Figure 13. Load-deflection and moment-deflection curves of beams with and without IF.

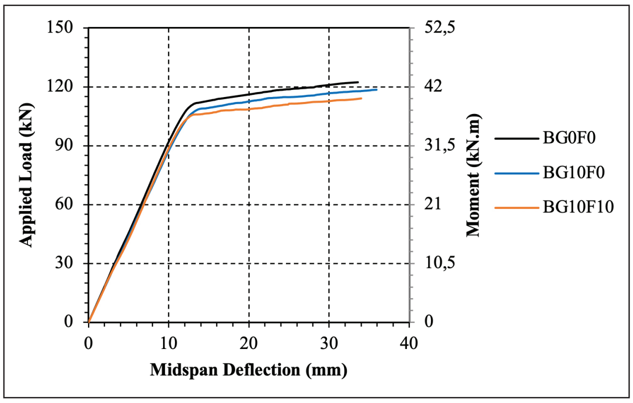

Figure 14. Load-deflection and moment-deflection curves of beams with 10% of GGBS.

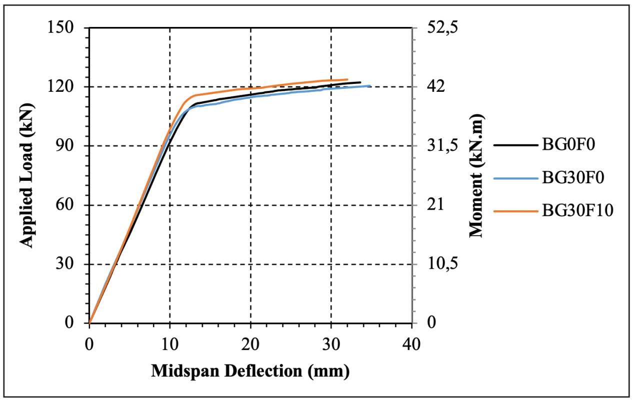

Figure 15. Load-deflection and moment-deflection curves of beams with 30% of GGBS.

uniformly diminishes, significantly reducing beam stiffness. All HSRC beams showed the same behavior, gradually increasing strength up to failure. The following sections present the deflection curves in detail.

3.2.3.1. Effect of GGBS Replacement

The load-deflection curves of the beams BG0F0, BG10F0, BG30F0, and BG50F0 are shown in Figure 12. Partial replacing the cement with GGBS can slightly change the overall behavior of the beams. The results show that the control beam has the highest plastic stiffness compared with other beams. Meanwhile, the beam BG50F0 experiences the lowest stiffness. The considerable proportion of GGBS content results in a decline in compressive strength, thereby contributing to the reduced overall beam strength observed. The plastic stiffness of the beam BG30F0 is higher than the other two beams, BG10F0 and BG50F0.

3.2.3.2. Effect of GGBS Replacement

The load and deflection of the control beam and BG0F10 are shown in Figure 13, which illustrates the relationship between the two. On the whole, the two beams behave in a virtually identical manner. The peak load, on the other hand, varies by one percent. Even though the compressive strength of the beam BG0F10 increases, the beam's behavior does not change due to the 10% IF content percentage. Additionally, due to the similarity in behavior, the engineering community may be encouraged to use the IF as a partial replacement for the sand.

3.2.3.3. Composite Effect of GGBS and IF Replacement

The results demonstrate a subtle variation between the combined influence of GGBS and IF compared to utilizing either material independently. Figure 14 shows the load-deflection curves of the control beam, BG0F10 and BG10F10. The control beam shows higher plastic stiffness than the other two beams. Adding 10% GGBS and IF underperforms the beam, while the beam with only 10% GGBS becomes stiffer. Figure 15 shows the load-deflection of the control beam, BG30F0 and BG30F10. The beam BG30F0 shows a drop in plastic stiffness compared to the control beam. However, an improvement in the plastic stiffness of the HSRC beams was noticed when a 30% GGBS and a 10% IF were utilized. The load-deflection curves of the control beam, BG50F0 and BG50F10, are drawn in Figure 16. The beam BG50F0 shows a distinguishable decrease in plastic stiffness compared to the other two beams. However, the plastic stiffness of beam BG50F10 is greater than BG50F0. This type of response may be due to the interaction of the IF with the concrete, which may improve the overall strength of the beam. It can be concluded that the overall strength of the HSRC beams can be improved by substituting GGBS and IF with a certain percentage.

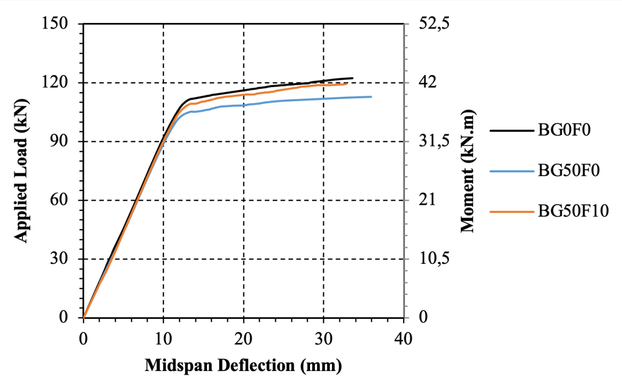

Figure 16. Load-deflection and moment-deflection curves of beams with 50% of GGBS.

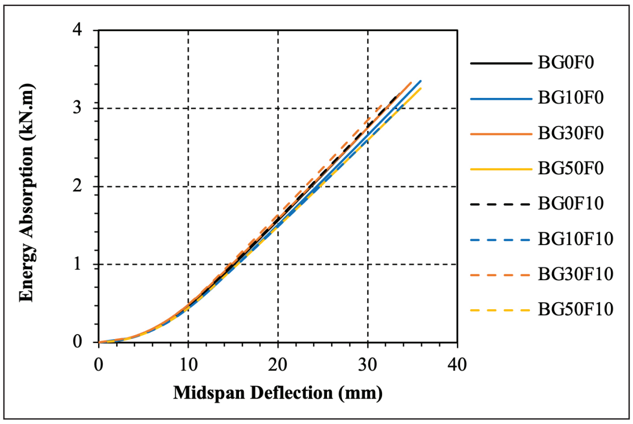

Figure 17. Energy absorption versus deflection curves of all HSRC beams.

3.2.4. Energy Absorption

The energy absorption versus midspan deflection curves for all tested beams, illustrated in Figure 17, offer valuable insights into the energy dissipation capabilities of beams with varied levels of GGBS and IF as partial replacements. Initially, all beams show a linear increase in energy absorption with rising midspan deflection, reflecting a consistent elastic response up to about 10 mm. Beyond this point, energy absorption rises slower as deflection increases, indicating a shift to plastic deformation.

Beams with a 30% GGBS substitution (BG30F0 and BG30F10) demonstrate slightly higher energy absorption at more significant deflections than the control beam (BG0F0) and other specimens. This trend suggests that 30% GGBS optimally enhances energy absorption, potentially due to better microstructural packing and material density. On the other hand, beams with a higher GGBS content (BG50F0 and BG50F10) show a slight decrease in energy absorption, indicating that an excessive GGBS percentage might reduce the material's energy dissipation effectiveness.

The addition of 10% IF in beams shows marginal improvement in energy absorption over the deflection range in beams like BG10F10 and BG30F10, which indicates some reinforcing effects. This is especially the case for the BG30F10, where 30% GGBS combined with 10% IF improves the energy absorption capacity compared to other formulations. All these results suggest that, for a balance between GGBS and IF contents, an optimum allows HSRC beams to dissipate more energy when subjected to loads and to be more deformation-resistant. The best overall performance is achieved by combining the highest percentage of GGBS with 10% IF, showing the possibility of these eco-friendly binders for structural applications requiring high energy dissipation and durability.

4. CONCLUSIONS

This study described the flexural performance of some HSRC beams manufactured to incorporate GGBS and IF as different binders. Extensive experiments were conducted to test conventional and modified HSRC beams due to various treatments to obtain important information about material performance on compressive strength and flexural behaviors. The experimental results indicated that the replacement of cement by 30% GGBS yielded a minimum loss in strength, around 1–3%, compared to the control beam—within the limit for use in structural applications. On the contrary, higher cement replacement by 50% GGBS resulted in a peak load reduction of approximately 8%, which evidenced the adverse effects of the content of GGBS in high percentages. Adding 10% IF to beams with 30% GGBS content increased the peak load by 3% and showed that an interaction between GGBS and IF leads to improved performance of RVA beams. The beams without GGBS (BG0F0) had the highest capacity among all the tested beams.

In contrast, the beams containing 50% GGBS resulted in the most significant reduction, emphasizing the importance of optimizing GGBS content to maintain beam strength. The beams, on the other hand, with a combination of GGBS and IF, showed characteristic resistance to the appearance of cracks and controlled the propagation of cracks to ensure further durability. Indeed, 30% GGBS and 10% IF gave the optimum performance that balanced sustainable issues with strength. Actual results underline that GGBS should not be higher than the optimum 30% replacement to maintain optimum structural integrity, and additional reinforcement benefits could be realized with IF when incorporation was at 10%. Other recommendations for the future include studying the durability of the HSRC beams with GGBS and IF under extreme environmental conditions of high temperature and moisture. A follow-up study may also establish the economic feasibility of using such materials in large-scale building projects, ensuring that GGBS and IF will positively contribute to the environment and be cost-effective when put into practical use.

ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

The authors declared that this study has received no financial support.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

PEER-REVIEW

Externally peer-reviewed.

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