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Enhancement of Flexural Behavior Using Minimal Reinforced Concrete and Steel Slag as Fine Aggregate Replacement

M. F. Sofianto[1*], M. Wulandari[2], Y. B. Nugroho[3], M.T. Heryanto[4]

[1*,2,3,4] *Civil Engineering Department, Faculty of Engineering, Universitas Negeri Surabaya, Surabaya, Indonesia*

Email: [1] mochamadfirmansyah@unesa.ac.id, [2] meitywulandari@unesa.ac.id, [3] yanuar.19026@mhs.unesa.ac.id, [4] muhammadtitho.19004@mhs.unesa.ac.id*

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ABSTRACT

The ductility capacity of structural elements is influenced not only by the reinforcement steel but also by the quality of the concrete material. Recent mix designs increasingly consider the incorporation of industrial by-products such as steel slag. Therefore, steel slag waste can be utilized as an alternative material in the reinforced concrete, especially for simple beam elements. This study aims to determine the effectiveness of steel slag as a fine aggregate replacement for beams as simple structural elements. The replacement ratios of steel slag were 1%, 3%, 5%, and 7% by weight of fine aggregates. The specimens included cylindrical samples for compressive strength testing and rectangular beam with 100 cm in span, for flexural testing. Beam elements conducted with two points of loading and recorded the deflection in middle and draw the crack pattern on beam element. The results revealed that the highest compressive strength, 33.24 MPa, was achieved with a 7% steel slag substitution. A higher proportion of steel slag affected the deflection behavior and internal force capacity. Initial cracking occurred at an external load of approximately 800 kg, while reinforcement yielding was observed at around 2500 kg, leading to ultimate failure. The maximum deflection of 9.25 mm was recorded for the 7% mixture, which also demonstrated the highest moment capacity. Overall, the findings confirm that partial substitution of sand with steel slag significantly enhances the flexural performance of concrete beams, thus providing a sustainable material solution.

1. Introduction

In concrete structural planning, the design must consider safety aspects and regulatory compliance. Flexural strength should be ensured in the reinforced concrete calculation design for the model span [1], [2]. A reinforced concrete beam functions as an element that resists bending, with minimum reinforcement determined from calculations based on the assumed span and service loads. This situation is designed to ensure that the beam exhibits ductile behavior, prioritizing flexural failure over shear failure [3]. The flexural capacity ensures the minimum reinforced steel bar reaches yield stress before first cracking on the beam; hence, its calculation depends on the effective depth of the beam. Experimental analysis of beams is a simple approach to measure the flexural capacity and to understand the failure pattern that occurs on a simple beam [4]. The material strength and beam design dimensions will determine the flexural capacity and failure patterns created [5], [6]. A simple beam depends on its length and the types of loads that act on it above [7]. The design of a simple beam is determined according to its failure target and field condition target [8], [9]. Therefore, developing a beam structure depends on the material construction and its reinforcement, to discover the impact of its material and its reinforcement on deflection value and internal forces [10].

Concrete, as a basic material in construction, can be developed by using waste material as a substitute properly and in order to overcome environmental issues. Steel slag is a byproduct of separating molten steel from impurities in the steel industry. Chemical compositions of steel slag are dominated by Silica (SiO2) and Beso (Fe2O3) [11]. Steel slag grows as an economical commodity in cement production as a raw material or a material substituted in concrete as aggregate [12]. Several steel slag waste materials depend on the raw material used in their production. Indonesian home industry of steel mixes the raw material of steel with other compounds, which affects the steel's performance and its waste material [13]. In an odd moment, the steel waste material is classified as a dangerous material and disposed of in the designated place [5]. In other conditions, waste materials are thrown away without any processing and can be reused in material construction [14]. Therefore, developing reinforced concrete materials using steel slag from small-scale industries needs to be further explored to improve the material's performance in concrete structures and enhance its capacity, primarily in simple beam structures.

In previous studies, steel slag was mainly used as a replacement for coarse aggregate, yielding quite significant results [5]. The compressive strength tests achieved maximum values of 58.1 and 75.6 MPa, while the split tensile tests showed ratios ranging from 0.9% to 4.3%. Beam tests with this mixture demonstrated good ductility, with the tensile reinforcement ratio reaching 3.6%. The deformation capacity of the reinforcement, combined with the steel slag mixture, indicated an interaction between them that enhanced strain capacity up to the maximum limit under flexural loading. Another investigation explored the influence of steel slag on beam properties and durability [14]. Steel slag was used as an additive in concrete mixtures with a target strength at 28 days, maintaining a constant water-to-binder ratio of 0.5.

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The test results showed that the compressive strength increased at a later age, following the 28-day concrete strength development. Future research speculates on the optimality of steel slag in flexure testing with minimum reinforcement [15].

From previous discoveries, studies using steel slag as a coarse aggregate replacement have often been conducted, and few researchers consider it as a fine aggregate. Because steel slag is obtained in the lump form, the change from coarse to fine aggregate needs more effort and time by using a machine or manually. So, the further development of this research considers the influence of using this material in fine aggregate, especially reducing the void in the beam, increasing deformation capacity, and strength. This study aims to determine the effectiveness of steel slag as a fine aggregate replacement for beams as simple structural elements. The exploration includes compressive strength, deflection, and force in beam testing. The results of this study are expected to provide a deeper understanding of the effect of fine aggregate replacement on the structural performance of beams, as well as generate experimental data that can serve as a basis for evaluation in the development of steel waste-based reinforced concrete materials. This will optimize waste from small-scale steel industries, increase the value of industrial commodities, and provide a sustainable material solution.

2. Research Method

This research conducts an experimental method with casting a concrete material in cylinder and beam specimens. All specimens are cast at the Laboratory of Materials and Concrete, Faculty of Engineering, Surabaya State University, and testing all of the specimens was carried out in the same place.

2.1 Material

The concrete design mix in this study consists of coarse aggregate in the form of crushed stone, sand aggregate predominantly sourced from the Lesti Lumajang River, type 1 cement, and steel slag obtained from a local steel processing industry located in Trosobo, Taman, Sidoarjo, as shown in **Figure 1**. Steel slag as a substitute for fine aggregate has been taken into account in the mix design calculation sheet [11]. The proportion of steel slag is 1%, 3%, 5%, and 7% in sand aggregate compositions. The details of the mix design will be explained in **Table 1**. The coarse aggregate gradation was dominated by particles with a maximum size of 20 mm, with most particles ranging between 4.75 and 9.5 mm, indicating a predominance of small-sized gravel. The fine aggregate (sand) was characterized by a fine gradation with a mud content of less than 1%. The steel slag exhibited a coarser sand gradation with a mud content

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of approximately 2%, which is close to the permissible limit. The target characteristics of normal quality concrete at 28 days are 22.5 MPa, the water-cement factor in the design mix is 0.518, and the determination of the volume weight is 2310 kg/m^3. The tensile tests on the reinforcement used are a yield stress of 506 MPa and a tensile stress of 522 MPa.

(a) (b)

Source: Author Research Results (2025).

Figure 1. Steel Slag Waste Material (a) Origin Size (b) Fine Aggregate

Table 1. Mix Design

Steel Slag Variation	Cement	Steel Slag	Sand	Coarse Aggregate	Water	Number of Cilinder	Number of Beam
	kg/m3	kg/m3	kg/m3	kg/m3	lt/m3	3	1
Normal	416.667	0	821.6665	821.6665	250	3	1
1%	416.667	8.216665	813.4498	821.6665	250	3	1
3%	416.667	24.65	797.0165	821.6665	250	3	1
5%	416.667	41.08333	780.5832	821.6665	250	3	1
7%	416.667	57.51666	764.1498	821.6665	250	3	1

Source: Author Research Results (2025).

2.2 Testing Procedure

All specimens are tested at 28 days after curing in fresh water. Beam specimens with modelling are a length size of 110 cm and a square size of 5 x 10 cm. Beam flexural testing was in accordance with ASTM C78, with the test scheme shown in **Figure 2** and **Figure 3(b).**

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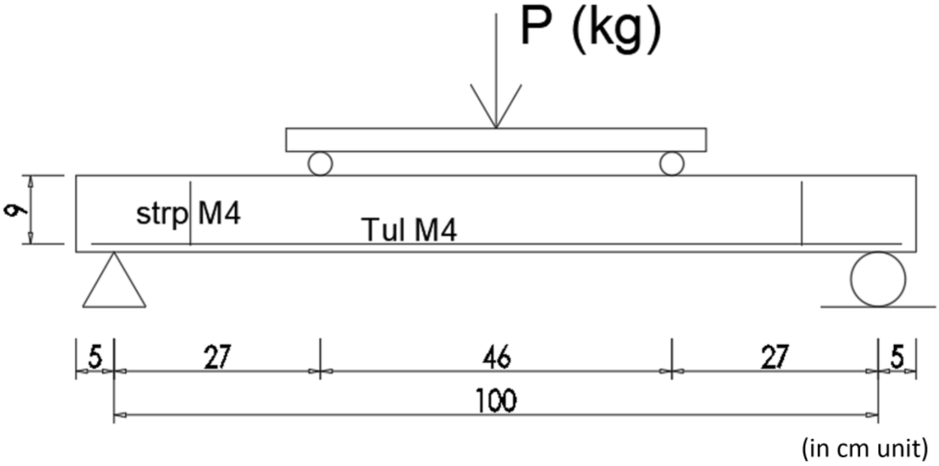

Source: Author Research Results (2025).

Figure 2. Beam Design and Reinforcement Setting

Flexural strength tests were performed using a load cell setup under two-point loading with a span-to-depth ratio (d/a) between 3 and 4, as illustrated in **Figure 2** [16]. On beam testing, the force dial uses a hydraulic load dial 10-ton capacity. This tool is set in the middle of the beam, distributed with a steel bar on two sides symmetrically. The final distance between the force distribution with support (a) is 27 cm, and the effective height of the beam concrete is determined to be 9 cm (d). According to the reinforcement setting in the Chu Kia Wang research, the ratio of the length of force to the effective depth of the beam is obtained as 3 [5]. This describes that the beam is defined on the pure flexural failure. Loading was applied on the beam using a hydraulic jack with a 10-ton capacity in the middle of it, then it was divided into two points with a pipe and a wood log distribution [7]. Deflection dial set on 2 positions, at the middle of the beam and beside the support [18]. The beam testing records force from hydraulic load for each 0.25 mm deflection in the middle of the beam, as well as dial in front of the support, and a horizontal dial was also recorded. The force value is calculated between the value of the dial hydraulic and its calibration. The first crack on the beam had been written on the note and drawn on the beam model [8]. This conduction was repeated until the beam gained its collapse. The experimental results included the relationship between the applied load and the corresponding beam deflection for each mix variation. These load–deflection data were also used to calculate the pure bending moment and beam curvature [17]. The correlation between deflection and applied flexural load describes the effect of steel slag on the flexural behavior of under-reinforced beams up to failure.

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(a) (b)

Source: Author Research Results (2025).

Figure 3. (a) Compression Strength Testing (b) Beam Test Setting

Cylinder specimens are made with a diameter of 10 cm and a height of 20 cm. Compressive strength testing uses a Universal Testing Machine (UTM) in accordance with SNI 1974: 2023 or ASTM C39-20, IDT. Compression strength testing is shown in **Figure 3 (a)**. The result of compressive strength testing is obtained from the UTM Dial, and it times the calibration ratio, then divided by the sectional area of the cylinder concrete for each specimen. All the values will be compared with each proportion of steel slag [19]. Meanwhile, the compressive strength values of each mix variation served as parameters for theoretical calculations of concrete capacity. Accordingly, the relationship between compressive and flexural strength can be clearly established to evaluate the mechanical performance of steel slag concrete beams.

3. Results and Discussions

3.1 Compressive Strength

The results of the compressive strength test can be shown in **Figure 4.** The figure describes the comparison between compressive strength values with the variation of steel slag. From that graph, the variation of steel slag in 1% proportion results in a reduction from the normal concrete strength. Because the amount of steel slag is not enough to substitute for sand aggregate. Compressive strength results for 3% and 5% proportions is close to the strength target, even if their values are still under specimen control. To achieve the same concrete with normal quality, a substitution of 5% is recommended. Meanwhile, at a proportion of 7%, the highest compressive strength results are shown, and are higher than the control concrete. This finding shows a slight difference compared to previous research that showed a decrease in compressive strength with the use of steel slag [11].

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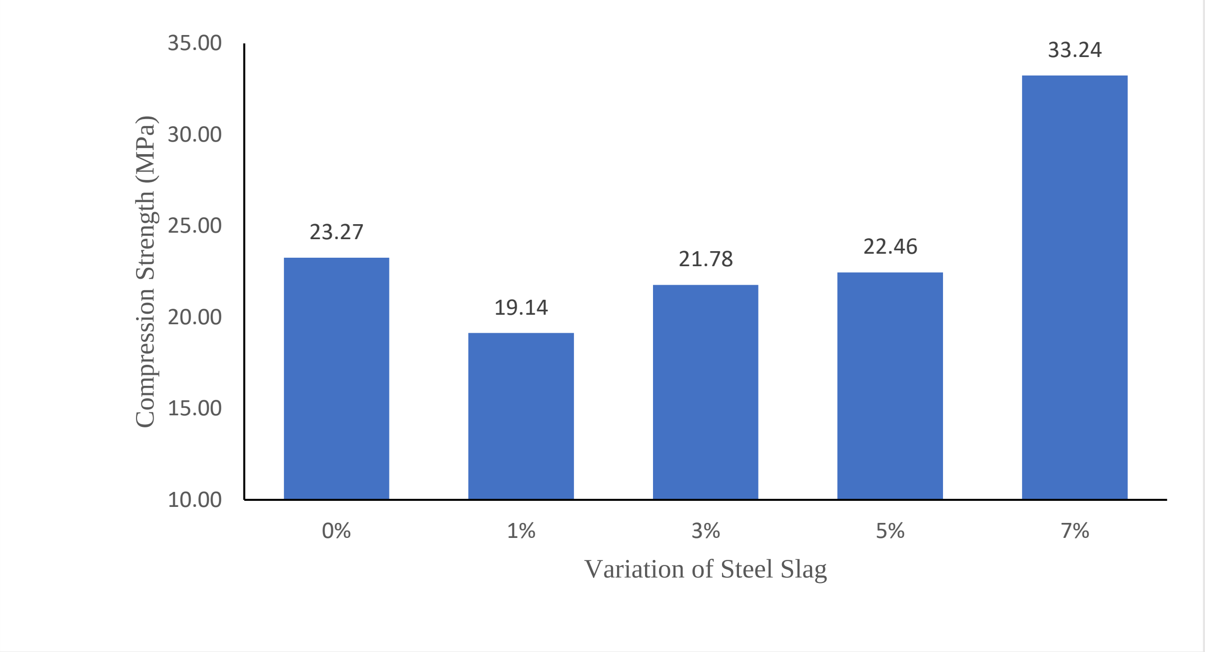

Source: Author Research Results (2025).

Figure 4. Compression Strength Result

The 7% steel slag specimen provides a significant enhancement and influence on the compressive strength of the concrete. This allows an increase in the amount of steel slag, also increasing the number of compression strengths. Previous research shows that the maximum compression strength occurs with ranges of 10% - 30% of steel slag compositions [20]. Fine aggregates of steel slag will fill the gap between coarse aggregates. This makes the total area of concrete massive and rigid. Therefore, stress distribution will be divided into a large area in the internal section of cylinder specimens [14]. This situation suggests the potential for increasing the proportion of steel slag in the mixture for further studies, particularly those comparing deflection and the applied load [5].

3.2 Flexural Strength

The result of beam testing is shown in **Figure 5**. This figure illustrates the deflection versus force in a-position for each proportion of steel slag. From that graph, describe each specimens have a similar pattern with various values. Specimen control and specimen 1% proportion result have a similar pattern, and the initial crack occurs at a deflection of 3.25 mm. In addition, the proportion of steel slag increases the elongation of deflection. However, the force results are almost as similar as for 3% to 7% proportion of steel slag. This condition describes the combination strength between compression in concrete and tension in reinforcement, bringing out the maximum force with long deformation [21]. Increasing compressive strength also contributes on deformation [3].

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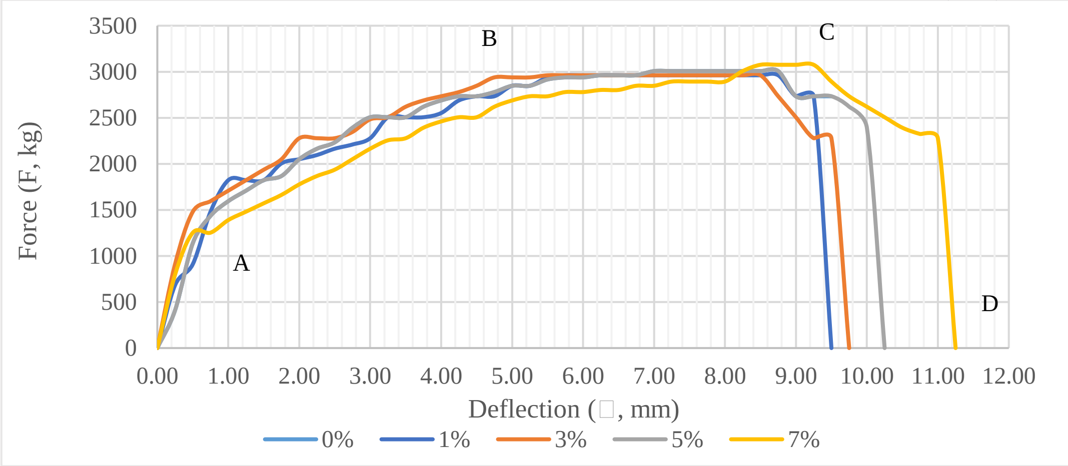

Source: Author Research Results (2025).

Figure 5. Load and Deflection Relationship

From **Figure 5**, the ratio force-displacement shows the stiffness of each beam. From The graph is divided to be 4 situations, there are points A through D. Point A is a turning point F/Δ from higher to smaller. The first crack occurred at this point, which is explained that concrete reaches maximum compression strength [16], [22]. The effect of steel slag reduced of force capacity than other additions. For 0% addition, obtain F/Δ with 40,8 kN/mm, increase at 5% proportion with 45,9 kN/mm, then drop drastically at 7% proportion with 37,29 kN/mm. This finding is similar to previous Research that steel slag does not significant effect on flexural strength [5]. After that, in the point A to point B situation, the form of F/Δ for all specimens is are similar pattern and a similar gradient of the graph. Its situation indicates that the minimum reinforcement work is required until it reaches its yield strength at point B [14]. In the last situation between point B and point C, the stiffness is decreased as the deformation of the beam increases. The maximum F/Δ for each specimen is obtained at 13,28 kN/mm for no addition and 1% proportion of steel slag. It increases to 13,67 kN/mm on 3% and 13,49 of 5% addition of steel slag, then it drops to 13,05 kN/mm for 7% proportion because deformation of 7% reaches 9,5 mm, with maximum force and maximum deformation is about 11 mm. This result is opposite to the first situation at point A. The last form of F/Δ indicates that the material of steel slag gives some effect on the long elongation of deflection and stiffness before the beam element reaches collapse. In that position, all specimens have a similar value of stiffness with a range of 3,32 kNm until 3,37 kNm, then reinforced concrete will collapse, except that the maximum elongation will reach a very long distance of deformation. Steel slag 7% proportion brings more elongation, about 11 mm, with a maximum force of around 29,43 kN (3000 kg). This concluded that steel slag gives enhanced ductility and also elongation of deformation.

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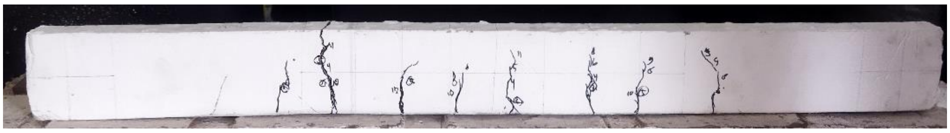
3.3 Crack Pattern

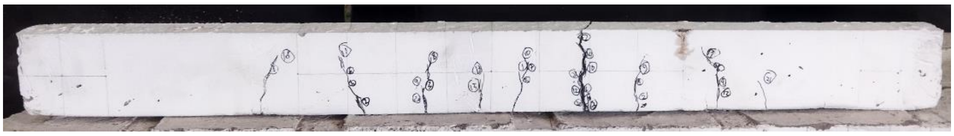
From **Figure 6**, all of the specimens had crack on a vertical pattern. The first crack occurred in the middle, or between the force loading, and the following crack was identified under P force and pure bending area. The length of the first cracking appeared with a force of around 16.76 kN for all specimens, and the deformations were 40 mm, 48 mm, 66 mm, 52 mm, and 52 mm with a crack width of less than 0.01 mm. The subsequent crack spread and got longer with following the increasing force of each step of the Hydraulic Jack and to support of the beams. The earlier cracking on the beam was caused by the minimum reinforcement. The longest crack for all specimens is 100 mm, 100 mm, 98.7 mm, 98.5 mm, and 100 mm, with the maximum crack is the depth of the beam section, and the widest crack being around 0.1 mm. The results showed that all specimen was successfully collapsed in the bending situation, according to the concrete design, a/d ratio is 3 to 4. From all specimens' total collapse on flexural crack, is not on the shear cracks.

(a)



(b)

(c)



(d)

Source: Author Research Results (2025).

Figure 6. Crack Pattern on Beam with Steel Slag Ratio, (a) 1%, (b) 3%, (c) 5%, and (d) 7%

Comparison between force at the first crack and the maximum crack explains the initial proportion from the maximum capacity. Value of Pcr/Pult are 32.5%, 29.55%, 29.74%, 32.2%,

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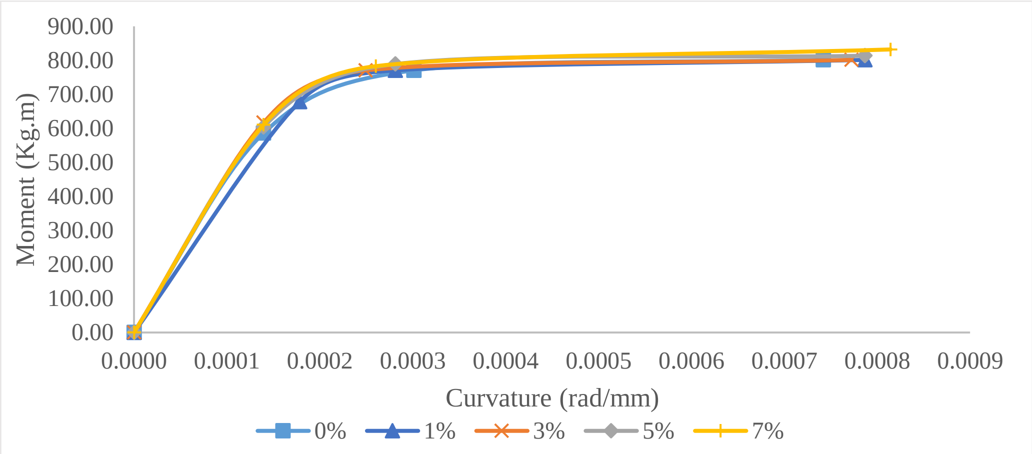
and 34.99%. The proportion model has a ductile capacity which is given by minimum reinforcement, and the ability to maintain the beam's capacity around 70%. Beam capacity is given from concrete with steel slag and steel reinforcement [23]. From the Pcr/Pult value, increasing steel slag on concrete decreases stiffness, and it causes the earlier cracking of steel slag to occur longer than half of the depth. From above result describes that the impact of steel slag as a sand substitute on concrete still gives a good impression on the ductility of the beam structure [23]. Similar results from a previous study describe that the effect of steel slag is to reduce the compression and flexural strength [24][22]. So this shows that increasing the concrete's compressive strength enhances the beam's capacity to absorb deflection, as indicated by a longer deflection period before failure.



Source: Author Research Results (2025).

Figure 7. Moment vs Curvature Relationship

Flexural capacity analysis of concrete beams with a proportion of steel slag as waste material is shown in **Figure 7**. The moment of the beam element was obtained from the calculation between the data force and position on the beam testing and deformation curvature between force position [10]. The moment maximum of each proportion, respectively, was 801.29 kgm, 801.29 kgm, 813.59 kgm, 832.04 kgm. The curvature maximum reaches 0.000815 rad/mm by 7% proportion of steel slag. This curvature is the highest for all beam specimens, which explains that steel slag with 7% proportion gives the ability to deform longer, around 8% than the beam without steel slag.

4. Conclusion

The research findings indicate that the use of steel slag increases the compressive strength of concrete, with the highest value of 33.24 MPa achieved at a 7% substitution level, thus indicating that steel slag from small-scale steel industries has potential as a viable

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alternative material. In beam testing, higher steel slag proportions influenced both deflection behaviour and internal force capacity, where initial cracking occurred at approximately 800 kg of external load and reinforcement yielding appeared at around 2500 kg before reaching ultimate failure. Specimens with steel slag also showed increased deformation capacity and improved stiffness, while the failure pattern remained consistent with a flexural mechanism. The design agreement between the experimental results and the analytical design is demonstrated by the crack pattern, which was intentionally designed to fail in flexure. These findings demonstrate that steel slag can be effectively used in small-scale concrete beams to improve mechanical performance. Therefore, this can form the basis for developing the use of steel slag as a substitute for fine aggregate in structural elements, thereby providing a sustainable material solution. Future research should further examine various steel slag proportions for use in both normal-strength and high-performance concrete.

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