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# Flexural Behaviour of Reinforced High Performance Concrete Beams Subjected to Bending

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***ABSTRACT:*** *This paper presents the findings of the comprehensive experimental investigation on the use of industrial by-products like silica fume, bottom ash and steel slag aggregate for making reinforced high performance concrete beams for enhancing the flexural strength. Based on the encouraging results of the preliminary experimental work conducted by the authors, a comprehensive experimental investigation was carried out by testing ten numbers of RC beams with varying mix ratio of industrial by-products in order to further explore the viability of this technique. Data presented include the parameters such as load-deflection behaviour, moment - curvature relationship, ductility and energy absorption capacity. A reinforced high performance concrete beam proves to be effective at controlling cracks and exhibits ductility with a ductility ratio. The investigation revealed that the flexural behaviour of reinforced high performance concrete beams was comparable to that of control beams. The results of this study provide valuable data that can be used in further studies on the development of computational models of the deflection and flexural of HPC.*

***Keywords:*** *High performance concrete (HPC), Flexural, Load-Deflection, and Moment-curvature.*

## I. INTRODUCTION

Concrete is currently the most widely used building material. Although many structures are built of concrete, there are still some limitations related to the use of usual concrete such as low compressive strength, tensile strength and almost no ductility. Reinforced high performance concrete may be able to overcome these types of limitations. The study of reinforced high performance concrete with industrial by-products has been an area where significant effort is focussed. A considerable amount of work has been devoted to the study of various material properties of high performance concrete. In this regards, the evolving technology of using industrial by-products for making reinforced high performance concrete beams has attracted attention in recent years. In particular, their practical implementation in flexural has been numerous [1-12] and has resulted in tremendous improvement in their application. As HPC can offer solutions for specific concrete construction which heretofore were not possible, attempts are being made to utilize HPC for innovative applications. Flexural behaviour of Reinforced high performance concrete beams made with steel slag coarse aggregate beams has been studied and observed that the RHPC-SSA beams can give satisfactory structural performance according to American and Egyptian building codes [13]. However, few experimental test results are available on the flexural capacity and deflection of HPC beams at the structural level. Samir A Ashour [14] carried out a feasibility study of effect of compressive strength and tensile reinforcement ratio on flexural behaviour of high-strength concrete beams and investigated about displacement ductility. The addition of fly ash coarse aggregate increase the ductility and deflection behaviour of reinforced concrete beams in a study by R. N. Swamy et al [15]. Abdul K. Azad et al [16] studied ultra-high performance concrete bars made with hybrid steel fiber reinforced beams and developed flexural tensile strength at the peak load without any bond slip. Lee T. K [17] investigated that the estimating the relationship between tension reinforcement and ductility of RC beam section and they proved that the ductility increases. Ibrahim et al [18] studied the flexural behaviour of reinforced and prestressed solite structural lightweight concrete beams and possessed adequate ductility characteristics. Ali chahrour et al [19] carried out to investigate the flexural response of reinforced concrete beams strengthened with end-anchored partially bonded carbon fiber-reinforced polymer strips. Prabhat et al [20] presented the flexural behaviour of damaged RC beams strengthened with ultra high performance concrete.

### 1.1 Research Background

The purpose of this paper is to examine the basic al properties of reinforced high performance concrete beams with industrial by-products. The experimental parameters included the use of industrial by-products and the method of placing HPC. The reinforced high performance concrete beams used in this study had five mix ratios of combination of industrial by-products. The experimental test results from static loading of the reinforced high performance concrete beams revealed the characteristics of flexural. Flexural included load-deflection characteristics, moment-curvature characteristics and ductility. The test results from this study provide more information to help establish a prediction model for the flexural capacity and deflection of HPC beams under bending conditions.

## II. EXPERIMENTAL INVESTIGATIONS

### 2.1 Beam specimens

The experimental program included tests on a total of 10 beam specimens with rectangular cross sections. Two for each mix were prepared and tested. The specimen dimension of 250 mm (depth) x125 mm (width) with an effective span of 3000 mm were cast, damp cured for 28 days and tested for four point bending. Of these, two beams were reference beams (CB) without having industrial by-products and other eight beams were four combination of silica fume, bottom ash and steel slag aggregate of by-products are added (SF+BA, SF+SSA, BA+SSA, SF+BA+SSA). The mechanical property of concrete used in beam as given in Table 1.

### 2.2 Ingredients of concrete

A good quality of cement 43 grade ordinary Portland cement were preferred in this study, river sand passing through 4.75 mm IS sieve with specific gravity of 2.65, fineness modulus 2.97, falling in grading zone II as fine aggregate and coarse aggregate used in this study had a maximum size of 20 mm and specific gravity of 2.75 as per IS: 383 [21] were used as ingredients of concrete. Potable water free from impurities and chemical substances was used for mixing of concrete. The targeted concrete cube compressive strength of 30 MPa was planned and the proportions of the concrete mixture are summarized in Table1. Three numbers of 150 mm cube specimens were cast, kept beside the specimen, subjected to the same curing conditions. The cubes were tested for compressive strength at the time of conducting the test on the beam specimens.

**Table 1** Mechanical properties of concrete

| Beam Designation | $f_c$ | $f_s$ | $f_r$ |
|---|---|---|---|
| CB 1 | 27.78 | 3.12 | 7.18 |
| CB 2 | 30.17 | 3.14 | 7.20 |
| HPC 1 | 27.98 | 3.16 | 7.62 |
| HPC 2 | 35.91 | 3.81 | 7.20 |
| HPC 3 | 37.82 | 3.29 | 8.13 |
| HPC 4 | 37.37 | 3.74 | 8.92 |
| HPC 5 | 37.82 | 3.33 | 7.90 |
| HPC 6 | 35.55 | 3.95 | 7.26 |
| HPC 7 | 27.11 | 3.27 | 7.49 |
| HPC 8 | 29.82 | 3.83 | 7.62 |

$f_{cr}$= compressive strength of concrete (MPa)
$f_s$= split tensile strength of concrete (MPa)
$f_r$= flexural strength of concrete (MPa)

### 2.3 Fabricating the beam specimens

The beam specimens were fabricated through the following process. Five numbers of formwork were fabricated with clear dimensions of 3200 mm x 125 mm x 250 mm using plywood and reinforcement cages were made with two numbers of 12 mm diameter lifting hooks. Commercially available concrete cover blocks of size 25 mm were used at the bottom and sides of the beam. Concrete was properly mixed, placed properly. Specimens were demoulded after 24 hours, and cured for 28 days by sprinkling and spraying water method periodically. After 28 days of moist curing, specimens were air cured in the laboratory till the day of testing. The experimental set-up for the beam specimens were shown in figure 1.

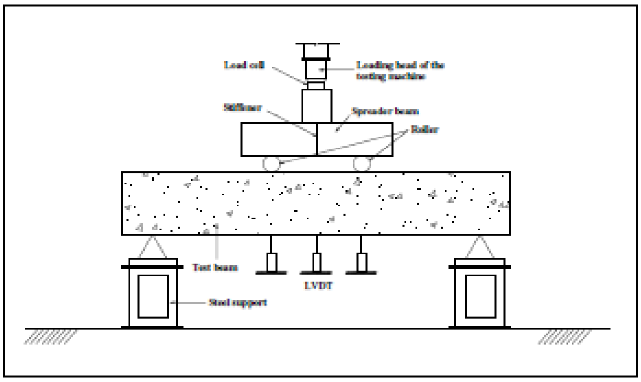


**Fig 1** Experimental set-up for the beam specimens

### 2.4 Test setup and procedure

The instrumentation plan for the beam test setup and the loads were applied to the beams at the top face using hydraulically actuated jacks of capacities 500 kN via the two-point loading methods. A loading steel frame was installed between the beams. Beam support rollers were installed at a distance of 100 mm both ends of the beam. The strain variations along the depth of the beam were measured using demounted mechanical (Demec) strain gauge at the mid-span. The loading was measured using 50 ton load cell. The beams were cleaned, white washing, dried and grid lines were drawn at 50 mm to identify mapping of the crack patterns. Visual inspection and marking of the cracks were carried out up to the failure load. Load at the formation of first crack was also observed. During the process of loading, developments of cracks were observed at every 5 kN load increment and the crack pattern was drawn on the beam. The beams were loaded up to till the crushing of concrete at the compression face. This procedure continued until the beam was observed to be softened. The reinforcement details for the test specimens were shown in figure 2.

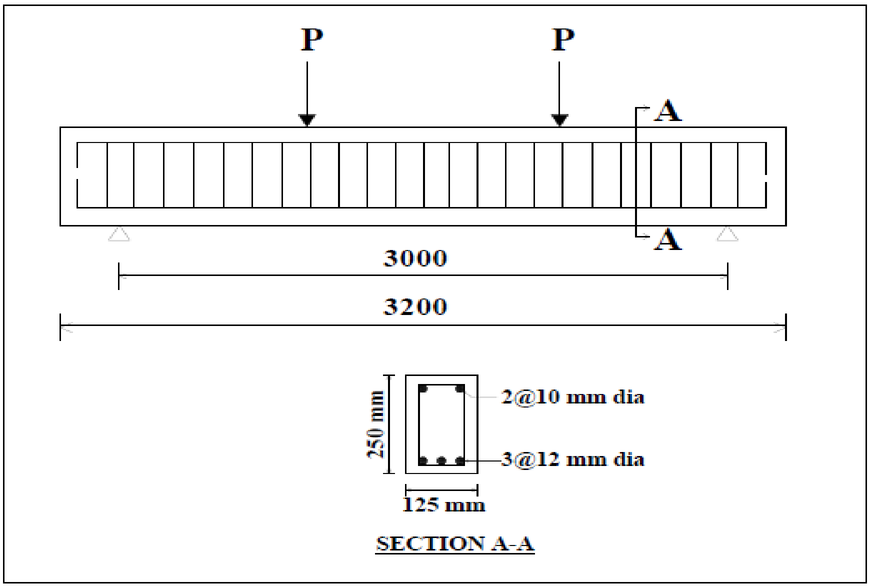


**Fig 2** Reinforcement details for the test specimens

## III. TEST RESULTS AND DISCUSSION

### 3.1 Load-deflection behaviour

The HPC beams resulted in higher ultimate loads as compared to the control beams. The beam specimen HPC 3 had the maximum ultimate load carrying capacity of 75 kN under flexure. This is 25 % higher than the load carrying capacity of control beam which carried a load of 60.00 kN. It was observed that the HPC beams showed higher load carrying capacities. The results of load and deflection at various stages are mentioned in the Table 2.

**Table 2** Experimental Load and deflection at four stages

| Beam Designation | Initial cracking Load | | Service Load | | Yielding stage | | Ultimate stage | |
|---|---|---|---|---|---|---|---|---|
| | $P_{cr}$ (kN) | □$_{cr}$ (mm) | $P_s$ (kN) | □$_s$ (mm) | $P_y$ (kN) | □$_y$ (mm) | $P_u$ (kN) | □$_u$ (mm) |
| CB 1 | 10.00 | 0.75 | 40.20 | 9.80 | 50.00 | 18.00 | 60.00 | 54.65 |
| CB 2 | 12.5 | 0.90 | 41.87 | 9.50 | 50.00 | 13.60 | 62.50 | 60.30 |
| HPC 1 | 17.50 | 1.70 | 41.87 | 7.95 | 52.50 | 14.45 | 62.50 | 71.15 |
| HPC 2 | 15.00 | 2.90 | 43.55 | 8.45 | 50.00 | 19.30 | 65.00 | 76.85 |
| HPC 3 | 20.00 | 1.95 | 47.90 | 16.90 | 55.00 | 17.90 | 75.00 | 77.05 |
| HPC 4 | 17.50 | 3.15 | 46.90 | 18.50 | 50.00 | 21.50 | 70.00 | 71.50 |
| HPC 5 | 20.00 | 0.45 | 45.22 | 11.50 | 47.50 | 12.10 | 67.50 | 68.60 |
| HPC 6 | 17.50 | 6.50 | 46.90 | 22.10 | 50.00 | 23.38 | 70.00 | 73.35 |
| HPC 7 | 15.00 | 2.47 | 46.90 | 19.25 | 45.00 | 14.55 | 70.00 | 68.45 |
| HPC 8 | 17.50 | 2.00 | 43.55 | 7.50 | 50.00 | 23.80 | 65.00 | 63.45 |

The increase in ultimate load carrying capacity for other beams when compared with control beams were 4.16 %, 8.33 %, 25.00 %, 16.66 %, 12.50 %, 16.66 %, 16.66 % and 8.33 % for beams HPC 1 to HPC 8 respectively. The control beams resulted with an initial cracking load of 10 kN and 12.5 kN. The beams HPC 1 and 2 had 17.5 kN and 15 kN which was higher than control beams.This showed that the strength of concrete had influenced the initiation of the first crack. The load-deflection plots of control beams and HPC beams were shown in figure 3 and the load deflection curve for left, middle and right as shown in figure 4 and the graph represents similar pattern for all beams.

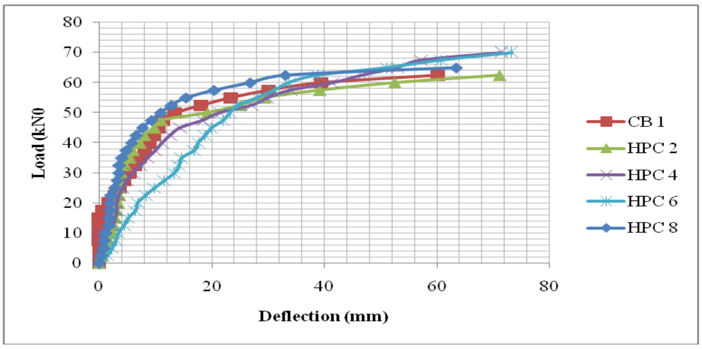


**Fig. 3** Load & deflection relationship

Similarly the beams HPC 3, HPC 4, HPC 5 and HPC 6 got 20 kN and 17.5 kN higher than the beams control beams and other HPC beams. Meanwhile the beams HPC 7 and 8 having 15 kN and 17.5 kN which was higher than control beam. With the further loading, the cracks occurred in the pure bending zone. Up to the service loads, the load-deflection of the beam was proportional to the applied load which indicated the stiffness of the beams.

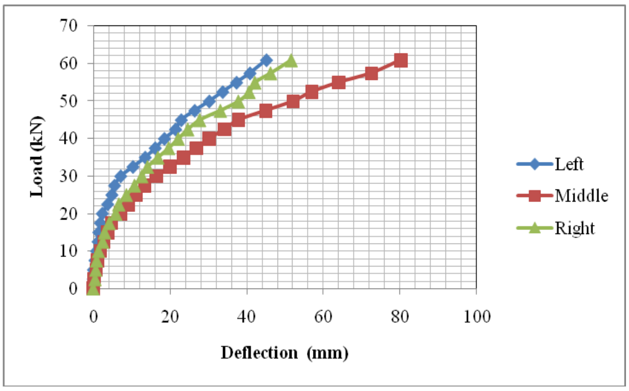


**Fig. 4** Load-deflection curve for left, middle and right

The service load was calculated by 67% of ultimate load. The maximum service load attained in the mix HPC 3 and HPC 4 of 47.90 kN and 46.90 kN than control beams. Then the beam HPC 1 and HPC 3 resulted with a minimum service load of 41.87 kN and 43.55 kN when compared with HPC beams. Then the yield load values were found from graph. The beam HPC 3 and HPC 4 had higher yield load 55 kN and 50 kN when compared with control beams and HPC beams. Majority of the beams yielded at same stage. Similarly the beam HPC 7 and HPC 8 got 45 kN and 50 kN got lower yield load. Finally at the ultimate stage, the ultimate load was recorded. The maximum ultimate load presents in the mix HPC 3 and 4 had 75 kN and 70 kN which was higher than all beams. The beam HPC 3 exhibits higher load carrying capacity in terms of percentage which was 25 % than other beams.

**3.2 Moment-Curvature relationship**

The control beams resulted with ultimate load of 60.00 kN and 62.5 kN. The beams HPC 1 and 2 obtained 62.5 kN and 65.00 kN which was same and higher than control beams. This showed that the strength of concrete had influenced the ultimate load. Similarly the beams HPC 3 and HPC 4 obtained 75.00 kN and 70.00 kN higher than the beams control beams and HPC 5 and HPC 6 obtained 67.5 kN and 70.00 kN.

Meanwhile the beams HPC 7 and 8 obtained 70.00 kN and 65.00 kN which was higher than control beam. The increase in ultimate moment for other beams when compared with control beams were 0 %, 4.00 %, 7.69 %, 15.38 %, 3.84 %, 7.69%, 0% and 7.69 % for beams HPC 1 to HPC 8 respectively. The results of ultimate load and moment with curvatures of demec and deflections are mentioned in the Table 3.

The moment curvature relationships based on deflection demec as shown in figure 5 and deflection for curvature and demec as shown in figure 6 and the graph represents similar pattern for all beams.

**Table 3** Experimental Moment-Curvature at ultimate stage

| Sl. No. | Beam Designation | Ultimate Load (kN) | Ultimate Moment (kNm) | Curvature (rad/mm) | |
|---|---|---|---|---|---|
| | | | | Demec | Deflection |
| 1 | CB 1 | 60.00 | 32.50 | $5.70 \times 10^{-5}$ | $6.23 \times 10^{-5}$ |
| 2 | CB 2 | 62.50 | 31.25 | $6.17 \times 10^{-5}$ | $5.36 \times 10^{-5}$ |
| 3 | HPC 1 | 62.50 | 32.50 | $6.84 \times 10^{-5}$ | $7.28 \times 10^{-5}$ |
| 4 | HPC 2 | 65.00 | 31.25 | $6.42 \times 10^{-5}$ | $6.32 \times 10^{-5}$ |
| 5 | HPC 3 | 75.00 | 35.00 | $5.76 \times 10^{-5}$ | $6.36 \times 10^{-5}$ |
| 6 | HPC 4 | 70.00 | 37.50 | $6.73 \times 10^{-5}$ | $6.85 \times 10^{-5}$ |
| 7 | HPC 5 | 67.50 | 37.50 | $6.07 \times 10^{-5}$ | $6.10 \times 10^{-5}$ |
| 8 | HPC 6 | 70.00 | 35.00 | $6.70 \times 10^{-5}$ | $6.52 \times 10^{-5}$ |
| 9 | HPC 7 | 70.00 | 32.50 | $5.18 \times 10^{-5}$ | $6.08 \times 10^{-5}$ |
| 10 | HPC 8 | 65.00 | 35.00 | $6.21 \times 10^{-5}$ | $5.64 \times 10^{-5}$ |

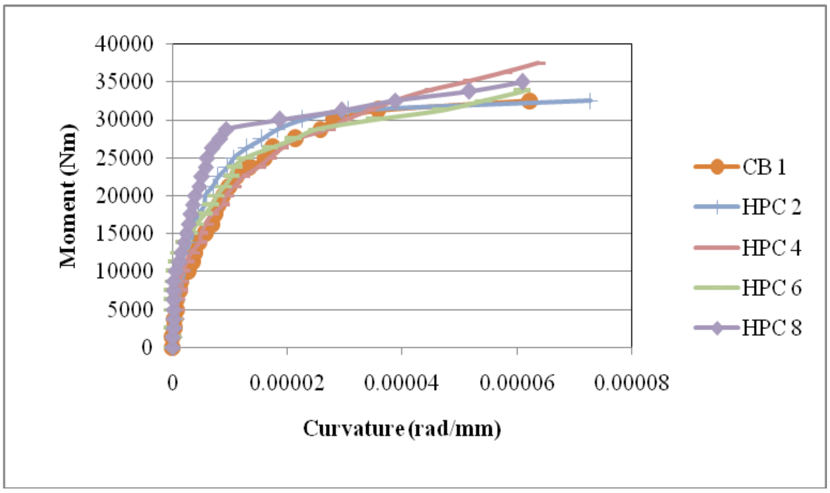


**Fig. 5** Moment-curvature relationship

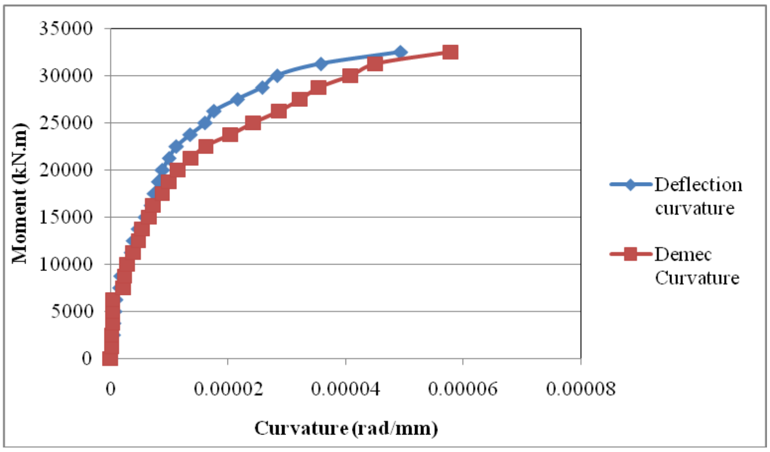


**Fig. 6** Moment-curvature for Deflection and Demec for control beam

### 3.4 Cracking behaviour

Crack widths were measured at every load interval at the tension steel level and the crack formations were marked on the beam. The crack width at the tensile face and the crack spacing were measured at every load stage in all the tests, and the cracks marked on the beams. The cracks forming on the surface of the beams were mostly vertical, suggesting failure in flexure.The mode of failure for all beams was flexure failure. In most codes of practice, the maximum allowable crack widths lie in the range of 0.10 to about 0.40 mm, depending upon the exposure condition. The maximum crack width obtained in the mix HPC 1 and HPC 7 which was 1.42 than other HPC mixes. The crack width obtained in HPC 1 which was 9.85 % lower with respect to CC. All the experimental data on maximum crack width and crack spacing at the design load are tabulated in Table 4.

**Table 4** Crack width and Crack spacing for HPC mixes

| Beam Designation | Ultimate Crack Width (mm) | No of cracks between loading points |
|---|---|---|
| CB 1 | 1.56 | 21 |
| CB 2 | 1.20 | 20 |
| HPC 1 | 1.42 | 14 |
| HPC 2 | 0.92 | 13 |
| HPC 3 | 0.86 | 13 |
| HPC 4 | 0.62 | 17 |
| HPC 5 | 1.00 | 11 |
| HPC 6 | 1.16 | 15 |
| HPC 7 | 1.42 | 18 |
| HPC 8 | 1.38 | 19 |

## IV. CONCLUSIONS AND SUGGESTIONS

Based on the results of the experimental investigation of 10 number of beam specimens, the following conclusions were arrived.

- From the experimental investigations, it was concluded that all the beams showed an increased value of load and deflection due to the ductile and flexural behaviour of HPC beams especially HPC 3 and HPC 4 beams obtained higher load carrying capacity with respect to control beams.
- For load-deflection behaviour, the maximum ultimate load presents in the mix HPC 3 and 4 had 75 kN and 70 kN which was higher than all beams. The beam HPC 3 exhibits higher load carrying capacity in terms of percentage which was 25 % than other beams.
- For moment-curvature relationship, the maximum moment obtained in the mix HPC 3 and HPC 4 with respect of CC and the maximum curvature obtained in the mix HPC 1 which was 6.84 x $10^{-05}$ rad/mm.
- The ductility of those beams with admixtures increased, when compared to the control beam. It is evident from this study that reinforced high performance concrete beams made with silica fume, bottom ash and steel slag aggregate as replaced with cement, fine aggregate and coarse aggregate can improve structural performances.
- HPC beams with industrial by-products shows improved performance with respect to initial cracking behaviour, reduction in crack width during the ultimate stage.

- The improvements in performance of the HPC beams with additions of industrial by-products were achieved due to pozzolanic reaction and hydration process and provide better structural performance than control beams.

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