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A Parametric Study on the Flexural Behaviour of High Performance Concrete Beams by Industrial by-Products

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ABSTRACT

The use of industrial by-products in concrete is becoming more popular for producing high performance concrete. Industrial by-products act as pozzolanic reaction and hydration reaction as well as micro fillers in concrete. Industrial by-products such as silica fume, bottom ash and steel slag aggregate are introduced to enhance the overall performance of concrete. Their use in high performance concrete (HPC) enhances its properties of strength and durability. The scope of the present study is to investigate the effect of industrial by-products of silica fume, bottom ash and steel slag aggregate replaced by cement, fine aggregate and coarse aggregate respectively towards the functioning performance of HPC. An effort has been made to focus on the influence of industrial by-products on strength properties and load carrying capacities of RC beams. The need for the present study arises from the requirements to improve the overall utilization of combination of industrial by-products in correct proportions in concrete particularly in aggressive environment depending upon the requirements. The effect of those industrial by-products towards the enhancement of the strength and durability of HPC needs to be researched.

Introduction

With this background, the objectives of the present study can be summarized as follows:

- To arrive at the mix design for M30 grade concrete using IS 10262:2009 and to evaluate the workability by slump cone test.
- To find the optimum mix proportions for the conventional concrete by trial mixes and high performance concrete with proper selection of industrial by-products by trial mixes.
- To study the material properties of replacement concrete and to examine the physical and chemical properties of the industrial by-products.
- To conduct the feasibility study on material replacement concrete with the selected industrial by-products: silica fume, bottom ash and steel slag aggregate.
- To study the mechanical properties of Compressive Strength, Split Tensile Strength, and Flexural Strength at the age of 28 days for optimum replacement level of single combination of replacement material concrete mixes.
- To study the flexural behaviour of reinforced concrete beams subjected to bending on HPC mixes with industrial by-products materials.
- To formulate an analytical modelling using Artificial Neural Network (ANN) software.
- To compare the predicted results with that of experimental and theoretical values.
- To develop a linear regression model using statistical analysis for various properties of HPC mixes.

Mechanical Strength Properties

Four combinations of silica fume concrete (SFC) mixes, five combinations of bottom ash concrete (BAC) mixes and five combination of steel slag aggregate concrete (SSAC) mixes were made by replacing cement, fine aggregate and coarse aggregate with the replacement level of 5%, 10%, 15% and 20% for SF and for BA and SSA 10%, 20%, 30%, 40% and 50% by volume. The mix SFC1 attained higher compressive strength value of 36.42 MPa at 28 days which was 4.68 % higher with respect to CC. The mix BAC1 attained higher compressive strength value of 35.32 MPa at 28 days which was 1.523 % higher with respect to CC. The mix SSAC1 obtained higher compressive strength value of 39.55MPa at 28 days which was 13.68 % with respect to CC. The mix SFC1 attained higher split tensile strength value of 3.64 MPa at 28 days which was 31.40 % with respect to CC. The mix BAC1 attained higher split tensile strength value of 3.80 MPa at 28 days which was 37.18 % with respect to CC. The mix SSAC1 attained higher split tensile strength value of 3.88 MPa at 28 days which was 40.07 % with respect to CC. The mix SFC1 attained higher flexural strength value of 9.05 MPa at 28 days which was 27.28 % with respect to CC. The mix BAC1 attained higher flexural strength value of 8.94 MPa at 28 days which was 25.73 % with respect to CC. The mix SSAC1 attained higher flexural strength value of 8.67 MPa at 28 days which was 21.94 % with respect to CC. The other SFC mixes the compressive strength obtained maximum of 8.16 % decreases in SFC4, the split tensile strength obtained maximum of 20.93 % increases in SFC2, the flexural strength obtained maximum of 6.43 % decreases in SFC4. The other BAC mixes the compressive strength obtained maximum of 15.46 % decreases in BAC5, the split tensile strength obtained maximum of 13.71 % and 14.07 % decreases in BAC4 and BAC5, the flexural strength obtained maximum of 22.16 % decreases in BAC5. The other SSAC mixes the compressive strength obtained maximum of 5.28 %

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Table 1. Experimental Load and Deflection Behaviour.

Beam Designation	Initial cracking Load		Service Load		Yielding stage		Ultimate stage	
	P_{cr} (kN)	Δ_{cr} (mm)	P_s (kN)	Δ_s (mm)	P_y (kN)	Δ_y (mm)	P_u (kN)	Δ_u (mm)
CB 1	10.00	0.75	40.20	9.80	50.00	18.00	60.00	54.65
CB 2	12.50	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	65.00	71.15
HPC 2	15.00	2.90	43.55	8.45	52.50	19.30	62.50	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	55.00	21.50	70.00	71.50
HPC 5	20.00	0.45	45.22	11.50	52.50	16.10	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	52.50	14.55	70.00	68.45
HPC 8	17.50	2.00	43.55	7.50	50.00	23.80	65.00	63.45

Table 2. Results for Displacement Ductility, Curvature Ductility and Ductility Ratio.

Beam designation	Deflection		Displacement Ductility	Ductility Ratio	Curvature		Curvature Ductility	Ductility Ratio
	Δ_u	Δ_y			ϕ_u	ϕ_y		
CB	60.30	13.60	4.43	1.00	$5.3X10^{-5}$	$1.3x10^{-5}$	4.12	1.00
HPC 1	71.15	14.45	4.92	1.11	$7.2X10^{-5}$	$1.3x10^{-5}$	5.60	1.35
HPC 2	76.85	19.30	3.98	0.89	$6.3X10^{-5}$	$1.3x10^{-5}$	4.86	1.17
HPC 3	77.05	17.90	4.30	0.97	$6.3X10^{-5}$	$1.3x10^{-5}$	4.89	1.18
HPC 4	71.05	21.50	3.30	0.74	$6.8X10^{-5}$	$1.3x10^{-5}$	5.26	1.27
HPC 5	68.60	16.10	5.66	1.27	$6.1X10^{-5}$	$1.3x10^{-5}$	4.69	1.13
HPC 6	73.35	23.38	3.13	0.70	$6.5X10^{-5}$	$1.3x10^{-5}$	5.01	1.21
HPC 7	68.45	14.55	4.70	1.06	$6.0X10^{-5}$	$1.4x10^{-5}$	4.34	1.05
HPC 8	63.45	23.80	5.82	1.31	$5.6X10^{-5}$	$1.3x10^{-5}$	4.33	1.05

and 9.77 % decreases in SSAC4 and SSAC5, the split tensile strength obtained maximum of 15.88 % and 20.93 % decreases in SSAC4 and SSCA5, the flexural strength obtained maximum of 2.95 % and 12.09 % decreases in SSAC4 and SSAC5. Finally, from the results the optimum replacement found that the percentage of SF was 5 %, BA was 10 % and SSA was 10% replaced which represented the maximum strength when compared with other replacement percentage and conventional concrete. Hence, finally the optimum replacement ratios were chosen for finding the mechanical properties of binary and ternary combination mixes.

Flexural Behaviour

From the results of the experimental investigations, it was observed that the initial cracking load, ultimate load and deflections were calculated. From the observation of the experimental study load-deflection behaviour, moment-curvature relationship, cracking behaviour, load-strain behaviour, ductility and energy absorption capacity and overall performance were calculated.

Ductility and Energy Capacity of the Beams

The ductility of a reinforced concrete beam could be used as a measure of the resistance of the structural member or structural system to deformation during transition from the elastic zone to the plastic zone until failure. Ductility may be defined as the ability to undergo deformation without a substantial reduction in the flexural capacity of the member. The deflection ductility and curvature ductility were calculated using the following formula

Deflection ductility, $\mu_Q = \Delta_u/\Delta_y$

Curvature ductility, $\mu_\phi = \phi_u/\phi_y$

Energy absorption capacity can be measured under the area of stress-strain curve or through load-deflection curve. The load-deflection and the moment-curvature curves showed that HPC beams positively influence the overall structural ductility with respect to control beams.

Overall Performance Evaluation

For computation of equivalent elastic forces for ductile structures, ductile-based design concepts use equivalence of failure deformation which is shown in figure and equivalence of failure energy in figure, between the elastic and elasto-plastic systems based on the ductile ratio is shown in figure The overall performance of the beams was evaluated by considering the equivalent elastic forces using energy and deflection approach.

Hence it is felt that, to evaluate the overall performance, the following effectiveness factors may be used. The effectiveness factors F1 and F2 may be expressed as

$F1 = Pe_1\,(HPC) / Pe_1\,(CC)$ ⟶ Energy approach

$F2 = Pe_2\,(HPC) / Pe_2\,(CC)$ ⟶ deflection approach

The effectiveness factors were evaluated using energy approach (F_1) and deflection approach (F_2) for the control beams and high performance concrete beams. For beam HPC 3 mix, the higher effectiveness factor F_1 and F_2 varies between 1.33 and 1.55 with reference to control beams and other HPC beams.

Table 3. Effectiveness Factor for CC and HPC Beams.

Beam Designation	P_y	Δ_y	Δ_u	A_e	Pe_1	Pe_2	F_1	F_2
CB 1	50	18	54.65	1825.66	100.71	151.80	1.00	1.00
HPC 1	52.5	14.45	71.15	1094.26	89.1705	258.50	0.88	1.70
HPC 2	52.5	19.3	76.85	2247.25	110.571	209.04	1.09	1.37
HPC 3	55	17.90	77.05	2945.50	134.539	236.74	1.33	1.55
HPC 4	52.5	21.50	71.50	2386.20	107.952	174.59	1.07	1.15
HPC 5	50	16.1	68.6	2018.75	111.977	213.04	1.11	1.40
HPC 6	52.5	23.38	73.35	2169.99	98.7191	164.70	0.98	1.08
HPC 7	52.5	14.55	68.45	2449.28	132.948	246.98	1.32	1.52
HPC 8	50	23.8	63.45	2009.22	91.8809	133.29	0.91	0.87

Conclusions

1. Concrete with 5 % silica fume replacement of cement had higher compressive strength on an average of 36.42 MPa at 28 curing days which was almost 4.46% higher with respect to CC. Concrete with 10 % bottom ash replacement of fine aggregate attained higher compressive strength on an average of 35.32 MPa at 28 curing days which was almost 1.486 % higher when compared with CC. Similarly, concrete with 10 % steel slag aggregate replacement of coarse aggregate obtained higher compressive strength value on an average of 39.55MPa at 28 curing days which was almost 12.02 % with respect to CC.
2. For SFC, it was observed that the there was maximum increase in the tensile strength and flexural strength of nearly 23.9 % and 21.43 % respectively. It was also understood that the split tensile strength increases in 5% SF content and beyond that the strength decreases. For BAC, there was a maximum increase in tensile strength and flexural strength of nearly 27.10 % and 20.46 % with respect to CC. For SSAC, it was observed that the maximum increase was in tensile strength and flexural strength of nearly 28.6 % and 17.99% with respect to CC.
3. From the experimental results, the reinforced high performance concrete beams showed an increased value of load and deflection caused by the industrial by-products. The flexural behaviour of ultimate load and deflection got better results in mix SFBAC when compared with control beams and other HPC beams. The rate of increase in load carrying capacity for flexural behaviour of reinforced high performance concrete beams resulted that the mix SFBAC obtained higher load carrying capacity, 75 kN which was about 25 % with respect to CC and comparatively increased. The higher deflection attained higher in high performance concrete beams found in the mix SFBAC with respect to CC.
4. In flexural performances, the number of cracks was reduced in high performance concrete beams due to incorporation of industrial by-products and crack widths were reduced at serviceability stage and ultimate stage.

As a limitation it could be seen that the industrial by-products of silica fume, bottom ash and steel slag aggregate in high performance concrete have been studied for their performance. Further, this study is valid for high strength and high performance with the addition of fibres.

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