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Research Article

Performance of structurally deficient blended RC beam

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Abstract

In this study, the flexural behavior of structurally deficient reinforced concrete (RC) beams incorporating fly ash partially replacing cement was investigated. Structural deficiencies in RC beams typically arise from causes like old age, poor design, and material deterioration. To understand the performance of these deficient beams, a series of flexure tests were conducted. Nine categories of RC beam specimens, each measuring 150mm x 150mm x 700mm, were cast and divided based on steel reinforcement percentages into three sets: 100%, 70%, and 50% of required steel. Within each set, one specimen contained 0% fly ash (100% cement), another contained 20% fly ash (80% cement), and the last one contained 30% fly ash (70% cement). The study focused on analyzing crack propagation, applied load versus mid-deflection relationships, stress-strain relationships, and normalization curve relationships. The results demonstrated that incorporating fly ash improved the flexural performance of RC beams. Beams with fly ash exhibited enhanced crack resistance and higher load-bearing capacities, particularly with 20% fly ash. Lower steel reinforcement percentages increased flexural deficiencies, but the presence of fly ash mitigated some effects. This research provides a significant understanding of optimizing RC beam design for improved durability and performance, showcasing the potential benefits of using sustainable materials such as fly ash in construction.

1. Introduction

The construction industry makes considerable use of concrete because of its many favorable qualities, such as its exceptional strength in compression and other desirable durability features [1]. Plain concrete is frequently inappropriate for a variety of building applications due to poor resistance to vibrations, wind, and tensile stress. Thus, reinforced materials like steel are embedded within concrete such that concrete's compressive strength and steel's tensile strength form a powerful bond to resist these stresses [2]. When transverse loads are applied to structural members like beams and slabs, flexure or bending usually occurs. Errors in design calculations and inadequate reinforcement detailing, subpar construction, poor construction practices, function changes in the structure that result in increased service loads, wind and seismic forces, and corrosion that diminishes or obliterates the reinforcement steel area in severe service environments are all potential causes of flexural deficiencies [3, 4]. Flexural, web shear, flexure-shear, torsion, and bond fractures are some of the ways that can cause concrete cracking. Crack development patterns and beam failure mechanisms are strongly related [5].

The total amount of CO_2 emissions (measured in kg CO_2/tonnes or kg CO_2/m^3) produced throughout the extraction, transportation, and raw materials production into the final product is called embodied CO_2 (ECO_2) [6]. To improve and lessen the environmental effect of CO_2 emissions created during the basic production processes of concrete components, numerous researchers are investigating partial or alternative replacements for concrete elements [7]. Supplementary

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Cementitious Materials (SCMs) namely, Ground Granulated Blast Furnace Slag (GGBS), Pulverized Fly Ash (PFA), Rice Husk Ash (RHA), and Silica Fumes (SF) can be used as partial replacements to reduce ECO_2 of concrete [6]. Fly ash, a fine powder generated during combustion and produced in large quantities annually harms the environment but serves as a pozzolanic cement replacement in concrete, where it reacts with calcium hydroxide and water to form finer hydration products, thereby reducing waste [7]. ECO_2 of Type 1 Portland cement is 228 times that of pulverized fly ash [6]. In order to compare high-volume fly ash concrete—which replaces 70% of cement with fly ash—with conventional concrete (CC), Arezoumandi M, et al [8] investigated experimentally full-scale RC beams to evaluate their mechanical characteristics and bending strength. It was observed that fracture shape and advancement, the behavior of beams of conventional concrete (CC) and high-volume fly ash concrete (HVFAC) are comparable. In addition, flexural strength of HVFAC beams is typically estimated conservatively in design standards. The flexural strength of both beams may be precisely predicted using the Modified Compression Field Theory (MCFT) technique. However, it was noted that MCFT overestimates the deflection of the HVFAC beam by around 14% and underestimates the deflection of the CC beam by about 9%. Also, test findings for HVFAC and the CC mixes agree with the nonlinear regression model fit of CC flexure test database within a 95% confidence interval. Raj et. al. [9] investigated the variation of fly ash proportions between 0% and 60%, binder content between 400 and 450 kg/m^3, and the water-binder ratio between 0.2 and 0.4 to do flexural studies on beams of dimension 0.1x0.2x1.2 meters. The highest load-carrying capability was shown by concrete beams reinforced with 30% fly ash; adding fly ash increased the load-bearing capacity by up to 40%.

The properties of concrete containing fly ash which partially replaces cement and the inherent structural flaws in RC have been the subject of independent investigations by several researchers. But neither of these characteristics had been investigated simultaneously up to now. This study aims to examine the behavior of blended RC beams that show flexural insufficiency by integrating research on the incorporation of fly ash as a partial cement substitute with the evaluation of intrinsic flexural deficiency in reinforced concrete. By integrating investigations on the incorporation of fly ash as a partial cement substitute with evaluation of intrinsic flexural deficiencies in reinforced concrete, this study provides a comprehensive analysis of the synergistic effects of these two factors. Fly ash (FA), by-product of coal combustion, is highly utilized in concrete to attain sustainability and improve certain properties, such as workability and long-term strength. Concurrently, the structural integrity of reinforced concrete is often compromised by intrinsic flaws, particularly in flexural performance, due to factors like inadequate reinforcement, poor material quality, and design flaws. This study addresses the critical need to understand how these flexural deficiencies interact with the modified concrete mix containing fly ash. Through experimental investigations and structural analysis, this research assesses how the integration of FA influences flexural behavior of reinforced concrete beams, particularly those with pre-existing structural weaknesses. The findings aim to reveal whether the incorporation of fly ash mitigates or exacerbates flexural deficiencies, providing valuable insights for structural engineers and construction professionals. Ultimately, the study seeks to enhance the understanding of how to optimize reinforced concrete formulations to achieve better performance and durability, considering both the benefits of fly ash and the challenges posed by intrinsic structural flaws. This dual-focused investigation promises to contribute significantly to the fields of sustainable construction and structural engineering, promoting the development of more resilient and environmentally friendly concrete structures.

The flexural behavior of beams incorporated with fly ash partially replacing cement has been an area of interest due to significant benefits in both performance and sustainability. When FA is used in concrete beams, it can positively influence their flexural performance up to a certain degree by contributing to the formation of a denser and more cohesive microstructure. This densification can lead to improved load-bearing capacity and higher resistance against cracking under flexural stresses [9]. Studies have shown that beams with FA exhibit higher ultimate flexural strength and increased ductility in comparison to beams made with only ordinary Portland cement alone. The pozzolanic reactions of FA also contribute to the gradual strength gain over time, enhancing the durability and lifespan of concrete beams. Moreover, the decreased heat of hydration in fly ash-modified concrete minimizes thermal cracking, further supporting structural integrity under flexural loads. These findings underscore the viability of incorporating fly ash in reinforced concrete beams not only as a sustainable practice but also to enhance flexural behavior and overall structural performance.

2. Theoretical Analysis

The theoretical capacity was computed by analyzing theoretical calculations on specimens that measured 150mm x 150mm x 700mm and had different balanced steel reinforcement ratios of 100%, 70%, and 50%. As per IS 456:2000[10] prescriptions, these specimens were specifically made not to fail under shearing but rather for study in flexural collapse.

2.1. Calculation of Steel Reinforcement

As per Indian Standard IS 456: 2000[10], Ultimate Moment without applying the factor of safety (M_u) as calculated.

$$M_u = f_y A_{st}(d - 0.42x_{umax}) \tag{1}$$

Where f_y, A_{st}, d, and x_{umax} are the characteristic strength of the reinforcement, area of tension reinforcement, effective depth, and depth of the neutral axis. A balanced section is achieved as the beam reinforcement is designed using three 12 mm diameter reinforcing bars made of Fe500 grade steel.

Table 1. Total reinforcement quantity

Specimen	Diameter	Number of bars	Number of specimens	Length of bar (mm)
100% steel (ρ = 1.5)	12 mm	3	3	660
	10 mm	2	3	660
70% steel (ρ = 1.05)	10 mm	5	3	660
50% steel (ρ = 0.79)	8 mm	2	3	660
	10 mm	3	3	660

Table 1 shows the total quantity of reinforcement for all nine specimens. Each tensile reinforcement and hangar bar is 660 mm long. For 70% of the calculated reinforcement area beam, 3 members of 10mm diameter were used. This gives 69.44% of the original reinforcement. For 50% of the calculated reinforcement area beam, 1 member of 10mm diameter, and 2 members of 8mm diameter were used. This gives 52.7 % of original reinforcement. 8 mm diameter stirrups at 100 mm c/c spacing were used in each beam.

2.2. Mix Design Calculation

Using concrete with characteristics compressive strength of 25 N/mm^2 and a water-cement ratio of 0.42, the design mix for the quantity of concrete materials required for a 150mm x 150mm x 700mm specimen with 100% OPC, the one with 20% and 30% replacement of cement with fly ash were calculated as per IS 10262:2019 [11]. The design values are summarized in Table 2.

Table 2. Mix design constituent quantities

Material	Quantity (kg)		
	For 100% OPC	For 20% Fly Ash Replacement	For 30% fly ash replacement
Cement	400	320	280
Fine aggregate	728	713.6	705.17
Coarse aggregate	1213	1188.5	1174.48
Water	168	168	168
Fly ash		80	120

3. Experimental Investigations

Tests were performed to determine the specific gravity of fine aggregate, coarse aggregate, cement, and fly ash. Fly ash's specific gravity was experimentally checked to verify the value provided by the source factory. And sieve analysis was performed for the fine aggregate to classify the grading zone of sand. Validating calculated values involved the performance of compressive-strength tests on concrete cubes.

This study used cement, fly ash, fine and coarse aggregates, water, and steel rods, with a focus on how the fly ash amount along with the variation of reinforcement affects the strength of the beam. OPC 53 grade cement as specified in IS 12269:2013[12] was used. The aggregates were obtained locally, and the FA is of type F sourced from Vijayawada Thermal Power Station (VTPS). Fig 1 shows the constituent materials of concrete after batching.

Fig. 1. Batching of material

Fig. 2. Sieve analysis

The specific gravity of cement and the aggregates were tested according to Indian standard code[13, 14]. The sieve analysis was also done to determine the zone of fine aggregate as presented in Fig. 2[15]. The specific gravity of FA was obtained from the factory and tested using the density bottle method to check for any variation.

3.1. Mix Design Calculation

Three categories of cubes were cast each using M25 mix design calculation values. The first category was without fly ash (FA), the second with 20% FA, and the last category with 30% fly ash to partially replace cement. In each of the three categories, three cube specimens were cast making a total of nine cubes. The cubes were placed in a water curing tank and tested after 28 days to find their compressive strength. The test was performed as per IS 516 (1959) [16]. Fig 3 shows the concrete cubes immediately after casting them into cubes.

Fig. 3. Wet concrete cubes after casting

3.2. Mix Design Calculation

The arrangement of rebars in the cage was done per the design calculations while taking care of all the necessary cautions. The stirrups bent of 135^0 was maintained. The beam molds were then tightened, and lubricated (greased), and the reinforcement cage was set in the molds using cover blocks of 20mm. Proper compaction was done using a needle vibration, the cast beams were covered using gunny bags after about an hour and allowed to harden for 24 hours. Demolding was then done, and the specimens were marked and then placed in the curing water tank for 56 days to ensure that blended specimens acquired enough strength. Fig 4 shows the reinforcement detail after arranging the rebar in the cage. The beam specimen ready for testing is shown in Fig 5. Table 3 depicts the nomenclature of the specimens.

Fig. 4. Rebar arrangement in the cage

Fig. 5. Beam specimen in use

Table 3. Labelling and identification of the specimens

Identification mark	Description
A1	100% steel with 100% cement (0% fly ash)
A2	100% steel with 80% cement (20% fly ash)
A3	100% steel with 70% cement (30% fly ash)
B1	70% steel with 100% cement (0% fly ash)
B2	70% steel with 80% cement (20% fly ash)

B3	70% steel with 70% cement (30% fly ash)
C1	50% steel with 100% cement (0% fly ash)
C2	50% steel with 80% cement (20% fly ash)
C3	50% steel with 70% cement (30% fly ash)

3.3. Mechanical Testing

The heart of this research involved mechanical testing of the cast beam specimens. The beams were subjected to flexure tests to evaluate load-carrying capacity, deflection characteristics, and crack propagation. For this, state-of-the-art equipment and testing methodologies were employed while high precision recording the data using UTM (Universal Testing Machine). A four-point load method was used. The beams were taken out from the curing tank, dried and the surfaces whitewashed to allow clear visualization of crack patterns and then marked before placing it in the UTM.

The middle third of the beam will experience pure bending as the monotonic flexure loading increases. If the load is within the elastic limit, then any one section will develop a moment that does not exceed the cracking moment and this, in turn, results in tensile stress which is less than the flexural strength of concrete. After the cracking moment has been passed, the maximum tensile stress in concrete surpasses the flexural strength of concrete. Non-linear behavior can be observed after passing the cracking moment. As the load continues to rise, concrete has less ability to carry more load and so reinforcement begins to take part of it [9]. Fig 6 shows the specimen subjected to loading in the UTM in use.

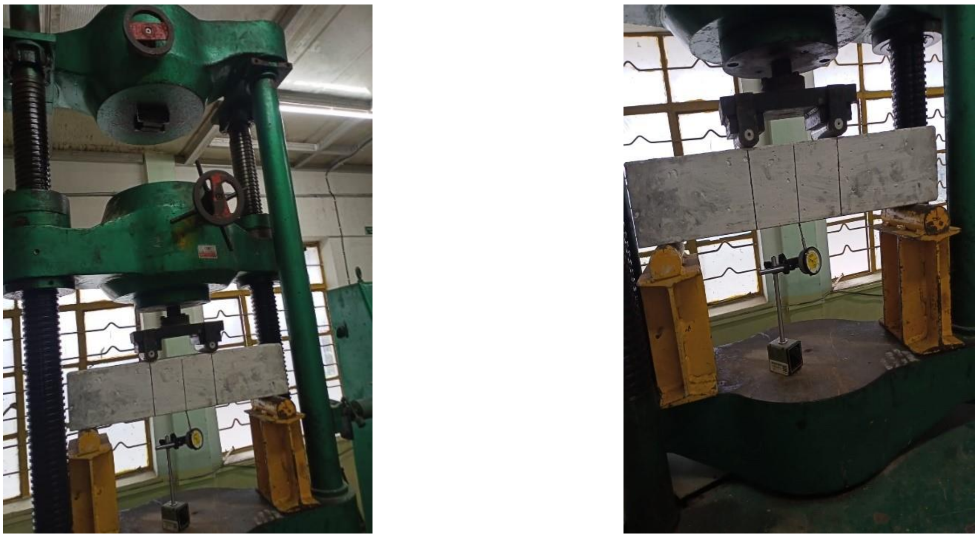

Fig. 6. Flexure test setup of specimen in use

4. Results

The specific gravity of cement used was found to be 3.05 which is approximate to the limit specific gravity of cement which is 3.15. The specific gravity of fly ash was experimentally found to be 1.95, which conforms to the value provided by the manufacturer. The specific gravity of fine aggregate and coarse aggregate was found to be 2.61 and 2.95 respectively. After the sieve analysis, the fine aggregate was found to belong to zone III as per the IS 383-2016[15] method as shown in Table 4 below and its gradation curve is shown in Fig 7 below.

Results obtained from the flexure test are tabulated in Table 6. The flexural strength was calculated as per IS 516 [16]. The flexural strength for balanced RC specimens was highest, followed by that of 70% and then 50% reinforcement area. In each set of three specimens, the flexural strength varied in the way that 20% blended fly ash cement specimens had the highest values followed by the ones without fly ash content then lastly the ones with 30% fly ash as cement replacement. The design mix test result for nine concrete cube specimens in which three of the specimens were of 100% OPC, three were of 20% fly ash and 80% cement, and the last three were of 30% fly ash and 70% cement was also computed and tabulated in Table 5.

Table 4. Result obtained from sieve analysis

Size of sieve (mm)	Weight retained (g)	Weight retained (%)	Cumulative retained (%)	% Finer	% Passing as per IS 383-2016 Zone I	Zone II	Zone III
10	0	0	0	100	100	100	100
4.75	0	0	0	100	90-100	90-100	90-100
2.36	4	0.4	0.4	99.6	60-95	75-100	85-100
1.18	44	4.4	4.8	95.2	30-70	55-90	75-100
0.6	124	12.4	17.2	82.8	15-34	35-59	60-79
0.3	656	65.6	82.8	17.2	5-20	8-30	12-40
0.15	130	13	95.8	4.2	0-10	0-10	0-10
pan	42	4.2	100	0	Zone III		
Total	1000						

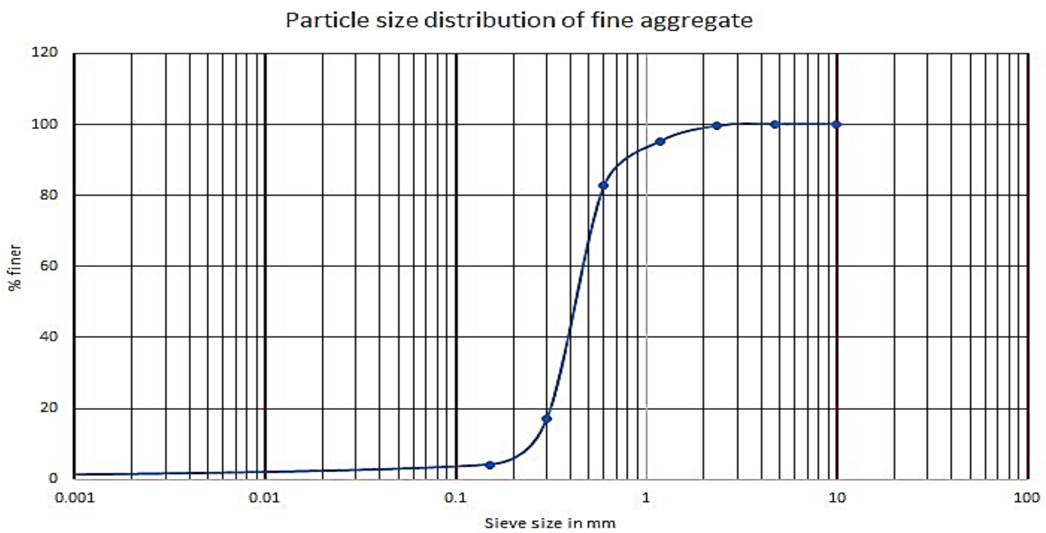

Fig. 7. Particle size distribution of fine aggregate

Table 5. Mix designs results

S. No	Mix	Load (KN)	Compressive strength (MPa)	Average strength (MPa)
1	100% OPC	960	42.67	41.93
2		930	41.33	
3		940	41.78	
4	20% fly ash replacement	890	39.56	38.37
5		860	38.22	
6		840	37.33	
7	30% fly ash replacement	780	34.67	34.52
8		800	35.56	
9		750	33.33	

Table 6. Flexure test results

Identification mark	Position of fracture in cm	Load in KN	Strength in N/mm^2
	For 100% steel specimen		
A1	20.1	200.124	4.23
A2	19.8	190.314	4.25
A3	20.2	190.314	4.02
	For 70% steel specimen		
B1	17.5	200.124	3.17
B2	20	156.96	3.32
B3	22.7	147.15	3.11
	For 50% steel specimen		
C1	27.5	141.264	2.99
C2	27.5	149.112	3.15
C3	17	137.34	2.08

4.1 Cracking Pattern and Failure Mode

For the specimens A1, A2, and A3, at failure, the cracks propagated up to between 60mm to 75mm depth from the bottom while for specimens B1, B2, and B3, it was up to 90mm to 105mm depth, and for C1, C2 and C3 specimen, the cracks propagated to the nearly full depth of the beams (above 130mm). In the test section, only flexural cracking occurred; typical bending failure leading to crushing of the compression-side concrete after the yielding of the tension reinforcement was noted, however, when the applied load exceeded the theoretical value, shear cracks were seen for specimen C towards the supports. There were more than 3-4 cracks in the test section in the C3 specimens. The shear force-generating zone between the loading points and the support points outside the test section did not show any significant shear cracks, and failure in shear did not occur until the test was finished. Fig 8 shows the crack pattern of the specimens with 100% reinforcement. Fig 9 and Fig 10 show the crack pattern for the 70% and 50% specimens respectively.

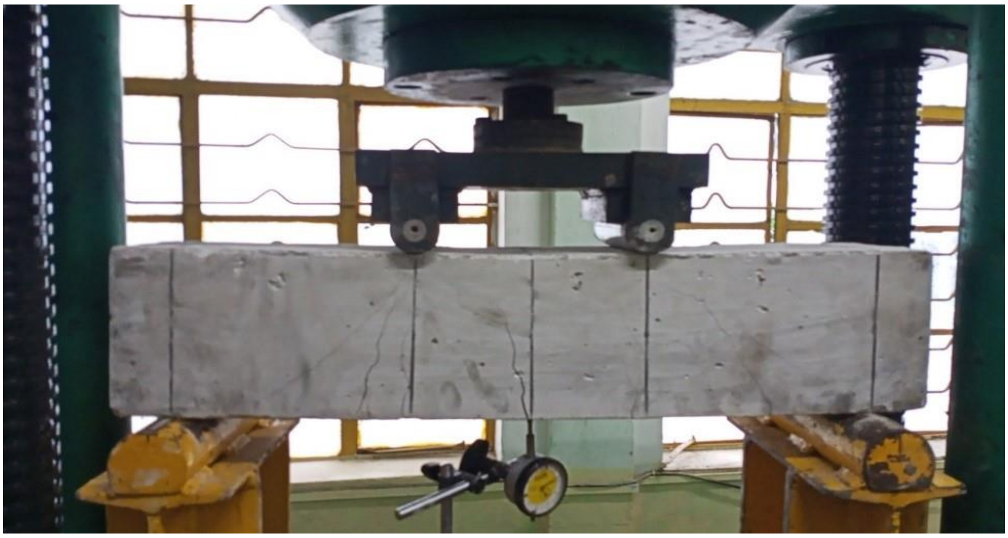

Fig. 8. Specimen crack for 100% reinforcement

Fig. 9. Specimen crack for 70% reinforcement

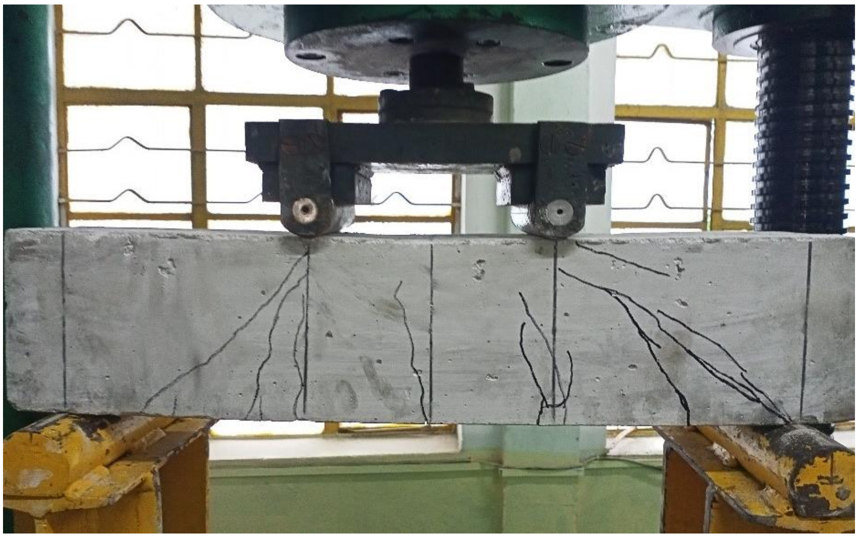

Fig. 10. Specimen crack for 50% reinforcement

4.2 Applied Load vs Mid-Deflection Relations

For specimens with 100% steel reinforcement (balanced section), the mid deflection at ultimate load for pure cement RC specimen was 3mm while that of 20% and 30% fly ash was 4mm and 3.6mm respectively. For 70% reinforcement specimens, the maximum deflections were 2.4mm, 2.9mm, and 5mm for 0%, 20%, and 30% fly ash volume respectively and for 50% reinforcement specimens, the maximum deflections were 3.7mm, 4.6mm, and 5.5mm for 0%, 20% and 30% fly ash volume respectively as shown in Fig 11, 12 and 13.

Fig. 11. Applied load vs mid-deflection for 100% reinforcement

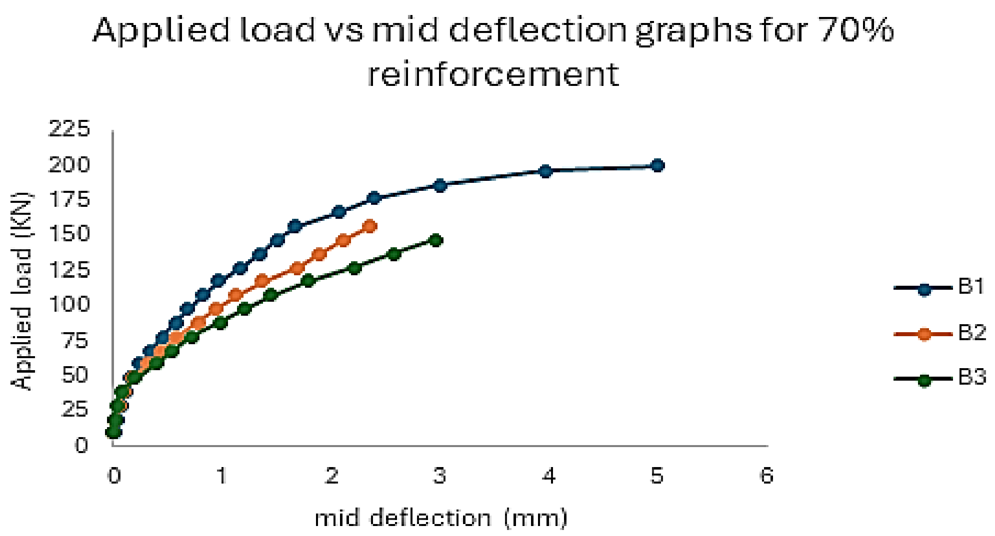

Fig. 12. Applied load vs mid-deflection for 70% reinforcement

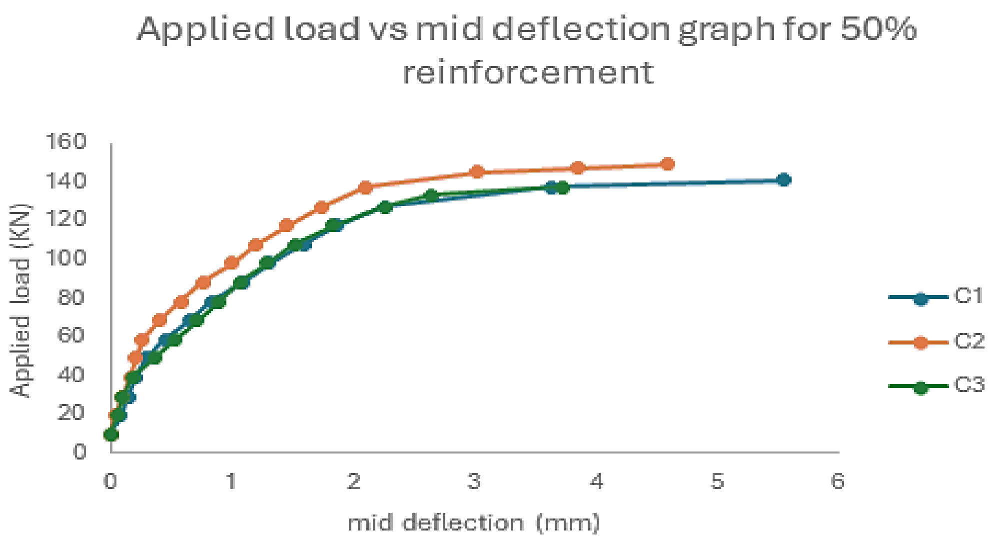

Fig. 13. Applied load vs mid-deflection for 50% reinforcement

4.3 Stress-Strain Relations

As the area of reinforcement steel is reduced to 70% (ρ = 1.05) and then 50% (ρ = 0.79), the maximum stress corresponding to maximum strain is reduced from 9 N/mm² to 8.8 N/mm², to 6.6 N/mm². For 100%, 70%, and 50% steel reinforcement specimens, the stress-strain relation for each fly ash constituent is shown respectively in Fig 14, 15, 16 below.

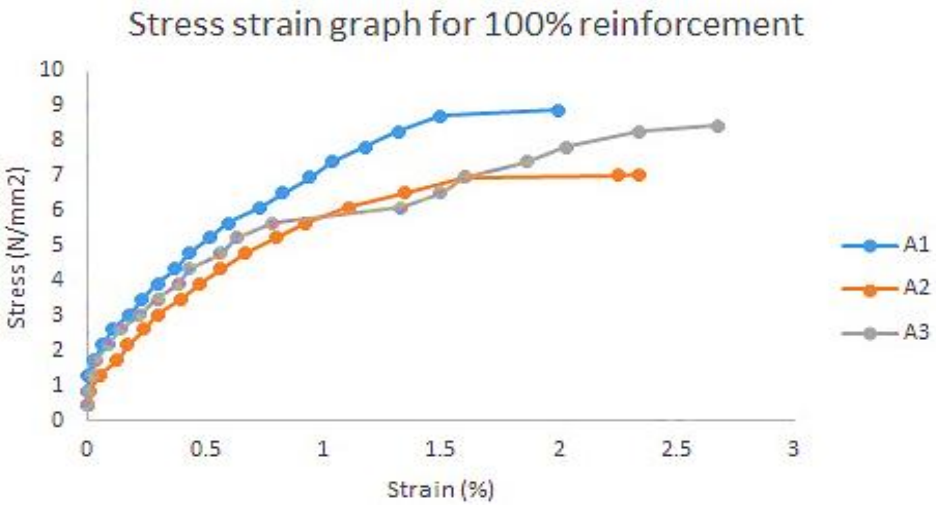

Fig. 14. Stress vs strain for 100% reinforcement

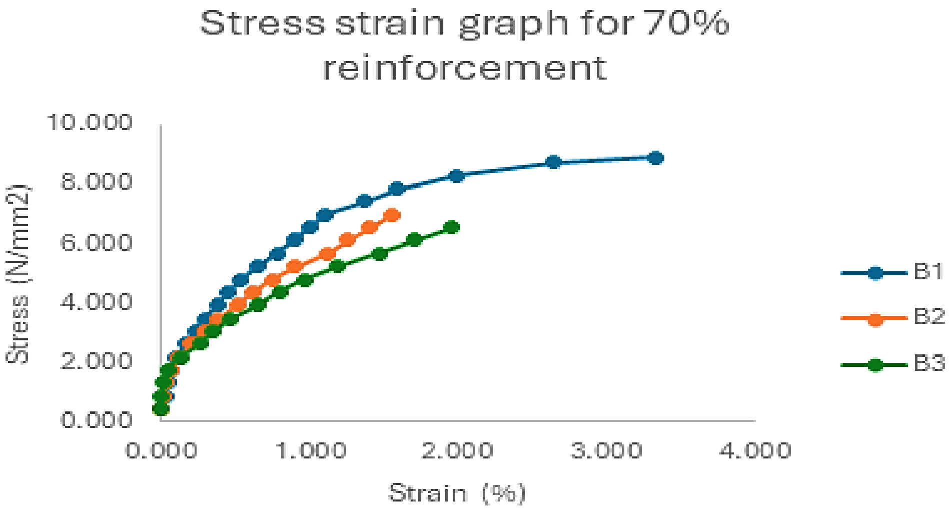

Fig. 15. Stress vs strain for 70% reinforcement

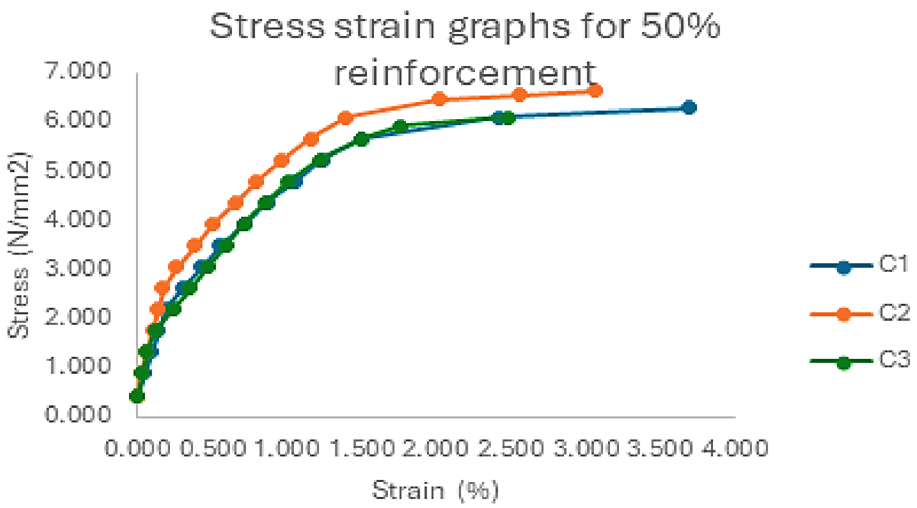

Fig. 16. Stress vs strain for 50% reinforcement

4.4 Normalization Curve

The $\frac{p_u}{f_{Ck}bD}$ for the beams decreased with a decrease in the percentage of the area of reinforcement. This was indicated by the downward shift in the $\frac{p_u}{f_{Ck}bD}$ against strain curve as from the 100% reinforcement specimens to 70% and 50% respectively.

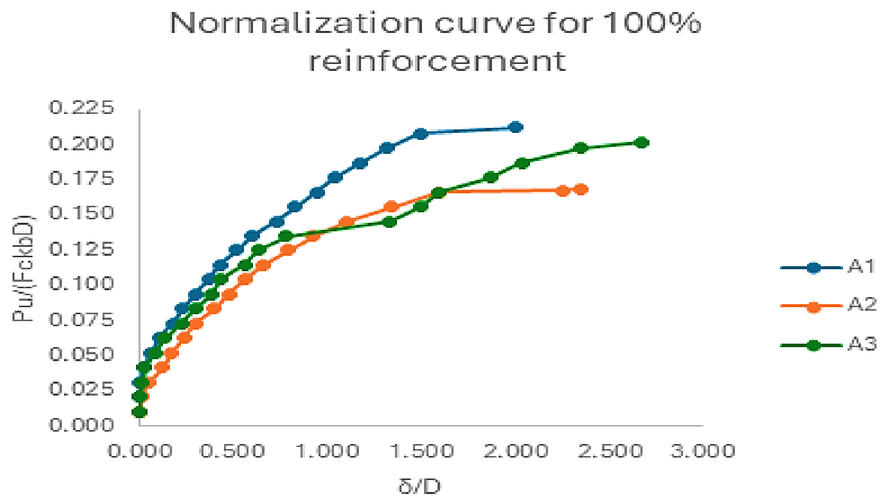

Fig. 17. Normalization curve for 100% reinforcement

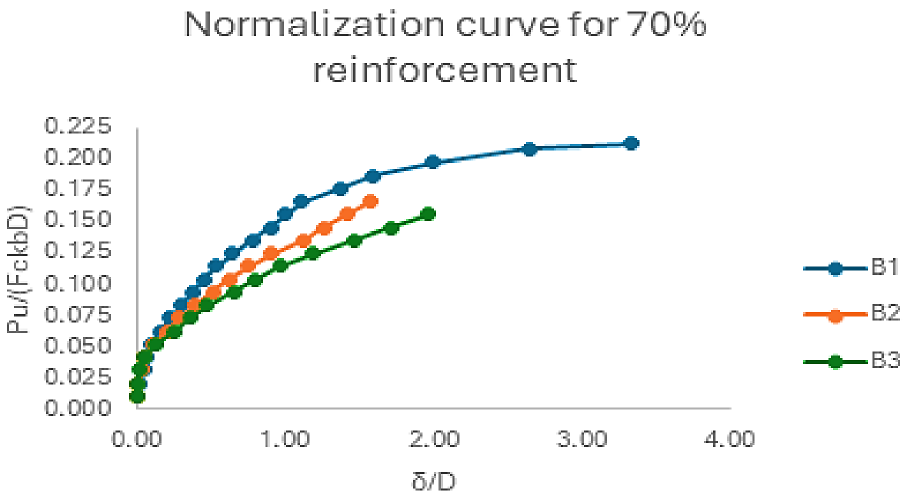

Fig. 18. Normalization curve for 70% reinforcement

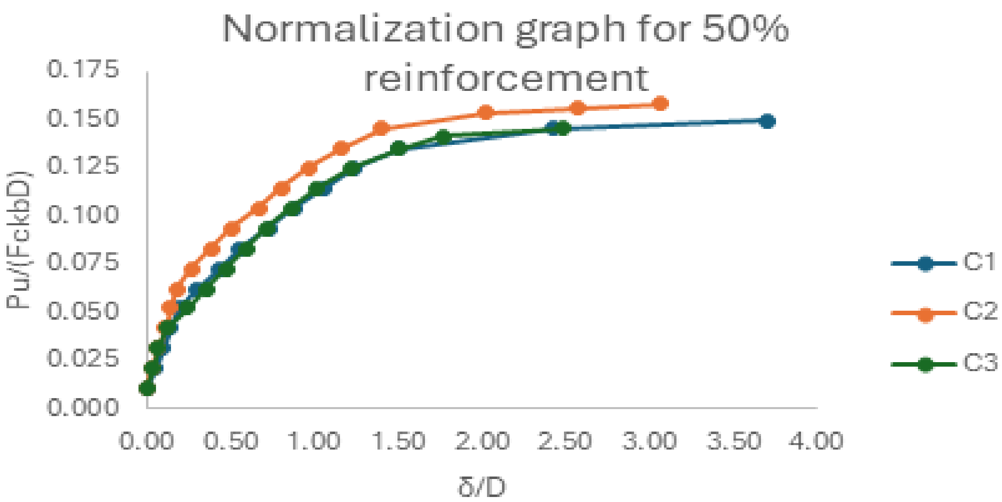

Fig. 19. Normalization curve for 50% reinforcement

Normalization curve relation for 0%, 20%, and 30% FA as replacement of cement for each specimen with varying reinforcement area is as shown below in Fig 17, 18 and 19 respectively.

5. Conclusion

The mix design produced an average strength of 41.93 MPa, 38.37 MPa, and 34.52 MPa for the concrete containing 0%, 20%, and 30% fly ash respectively. This means that all the specimens passed the required value and so the mix designs were used to cast the beams. The cubes in which cement is partially replaced with fly ash showed less compressive strength compared to those with 100% OPC after a 28-day curing period. Fly ash was found not to significantly affect flexural strength of RC beam, however, there was a slight reduction in flexural capacity with an increment in the amount of fly ash to 30%. But for all reinforcement categories, beams with 20% fly ash displayed the highest strength. As the area of reinforcement steel is reduced to 70% (ρ = 1.05) and then 50% (ρ = 0.79), the overall tensile strength decreased this was because the stress at a given strain level was lowest for 50% (ρ = 0.79), and lower for 70% (ρ = 1.05) compared to 100% (ρ = 1.5) reinforcement specimens.

The beams first deformed elastically, showing that the deformations were directly proportional to the applied load. With an increase in the load, the materials attained their yield point, entering plastic deformation. For some of the materials, this was followed by a strengthening phase of strain hardening, whereby further resistance is built up due to internal structural changes. The stress-strain relationships developed conformed to the usual trend for material behavior: a linear elastic region progressing into a plastic region and finally ending at the material's ultimate strength. The failure modes included flexural failure, whereby beams experienced a crack under tensile stress, particularly in the tension zone. For beams with 50% tensile reinforcement and 8 mm diameter bars at 100 mm Centre to Centre, theoretically maximum load that the beam can take before it fails in shear is 76.6 KN. But in our test, the beams were tested beyond this loading which led to shear cracks.

The normalized ultimate flexure capacity vs δ/D curve shifts downward and the peak shifts to the right as the percentage of the steel is reduced to 70% and 50% of the designed reinforcement area. Hence the ductility and the ultimate strength reduced along with the trend. However, the C specimens can be best used in non-critical structure design and lightly loaded members. For the normalization curves, A specimens with a high reinforcement ratio are ideal for seismic-resistant constructions or strongly loaded members because they have a high ultimate strength and significant ductility. B specimens fit well for normal building construction or moderately loaded structural elements because they have a medium reinforcement ratio and good ultimate strength and ductility. C specimens are a cost-effective option for lightly loaded members or non-critical constructions because of their low reinforcement ratio, moderate ultimate strength, and moderate ductility.

List of Abbreviations

Abbreviation	Full form
FA	Fly Ash
RC	Reinforced Concrete
SCMs	Supplementary Cementitious Materials
CO2	Carbon dioxide
ρ	Tensile reinforcement ratio
ECO2	Embodied Carbon dioxide
CC	Conventional Concrete
HVFAC	High Volume Fly Ash Concrete
IS	Indian Standard
OPC	Ordinary Portland cement
UTM	Universal Testing Machine

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