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Sustainable Concrete with GGBS and M-Sand: Experimental and Machine Learning Approach

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Abstract: This Accurate prediction of how beams deflection is a key part of designing safe and efficient structures. Traditional methods for calculating beam bending rely on manual calculations and assumptions, which may not accurately reflect the complex data from real experiments. This study looks at using a Support Vector Machine (SVM) model to predict beam deflection from experimental data on how beams bend under different loads. A dataset from beam tests was cleaned and used to train the SVM model. The model had a high coefficient of determination ($R^2 \approx 0.96$), showing it closely matches actual deflection values. However, the data came from a single beam with fixed size and material properties, which means the model fits the data well but doesn't generalize to different beams. The study shows both the promise and the limits of using machine learning in structural engineering and stresses the importance of using varied data for accurate predictions.

Index Terms - SVM, Deflection, beam, structural engineering.

I. INTRODUCTION

The construction industry is a major contributor to environmental degradation, particularly through the high consumption of Ordinary Portland Cement (OPC). With increasing concerns over sustainability, the use of supplementary cementitious materials (SCMs) such as GGBS has gained attention due to their ability to reduce the environmental footprint of concrete. These SCMs not only lower carbon emissions but also enhance the durability and strength of concrete. Reinforced concrete (RCC) structures can benefit from improved reinforcement methods. Spiral reinforcement, commonly used in columns, enhances confinement, which improves the concrete's strength and ductility. The combination of SCMs and additional spiral reinforcement could lead to more sustainable and high-performing concrete, offering both environmental and structural benefits.

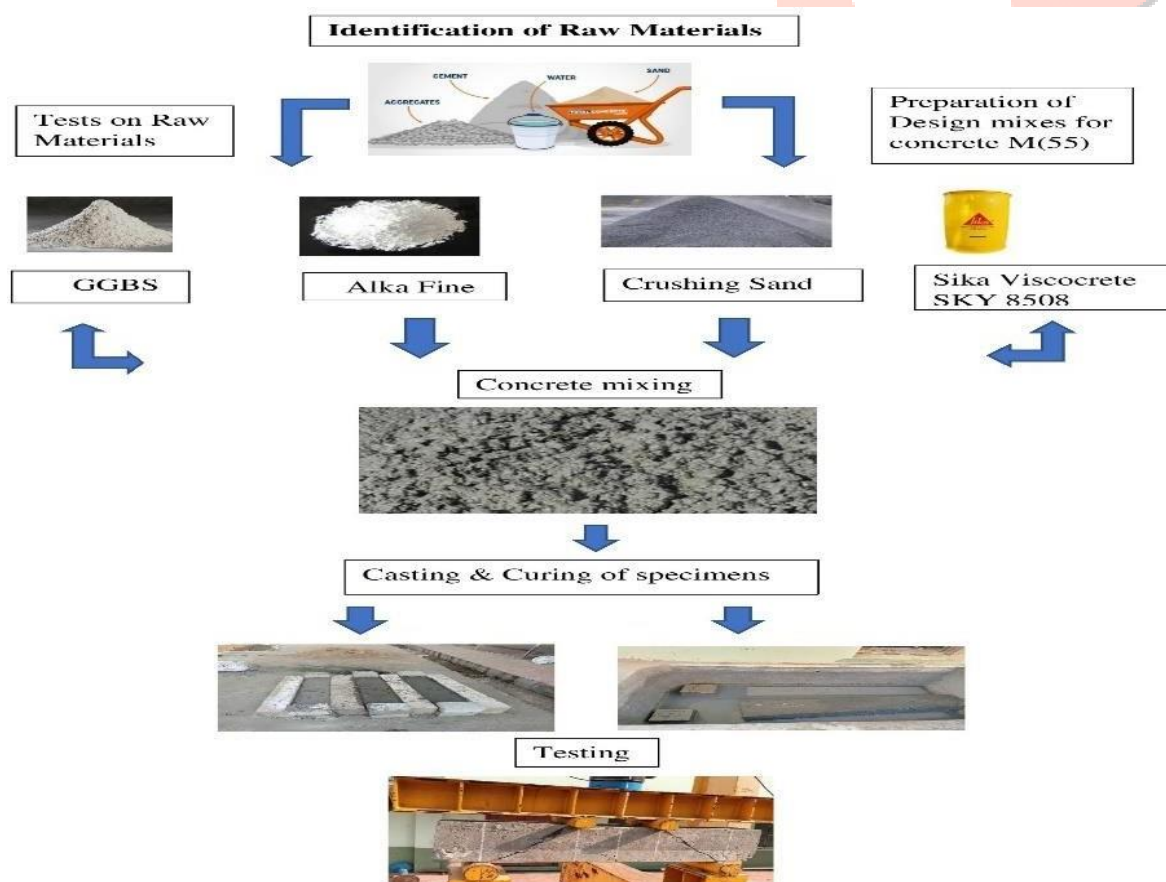
This experimental study aims to assess the performance of RCC with SCMs and added spiral reinforcement, examining key parameters such as compressive strength, durability, and overall structural behavior. The results will provide valuable insights into optimizing concrete mixes for sustainability and performance.

II. LITERATURE SURVEY

Sl. No.	Title of the Paper	Objective	Tools / Methods Used	Limitations
[1]	A comprehensive experimental study on the performance of pumice powder in self-compacting concrete (SCC)	To evaluate the effect of pumice powder as a partial cement replacement in self-compacting concrete	Experimental study: slump flow, compressive strength, durability tests	Limited to SCC; does not address structural elements like beams
[2]	Effect of SF and GGBS on pore structure and transport properties of concrete. Materials	To study the influence of silica fume (SF) and GGBS on pore structure and transport properties	Microstructural analysis (SEM), porosity tests, permeability tests	Focuses on micro-level properties; lacks structural performance evaluation
[3]	A comprehensive experimental study on the performance of pumice powder in self-compacting concrete (SCC)	To assess the impact of using pumice powder as a partial replacement for cement in self-compacting concrete.	Experimental investigation involving slump flow, compressive strength, and durability tests.	Duplicate reference; no additional findings
[4]	Supplementary cementitious materials. <i>Reviews in mineralogy and geochemistry</i>	To provide a comprehensive review of SCMs and their role in cement hydration	Literature review, mineralogical analysis	Theoretical; lacks experimental validation
[5]	A comprehensive review on the ground granulated blast furnace slag (GGBS) in concrete production. <i>Sustainability</i> ,	To review the properties and applications of GGBS in concrete production	Review of experimental studies, comparative analysis	No original experimental data
[6]	Adhesive characteristics of novel greener engineered cementitious composite with conventional concrete substrate. <i>Construction and Building Materials</i>	To study bonding behavior between engineered cementitious composites and conventional concrete	Adhesion tests, mechanical strength tests	Limited to bonding properties; not focused on shear or beam behavior
[7]	Behaviour of high-strength concrete columns confined by spiral reinforcement under uniaxial compression. <i>Constru</i>	To investigate behavior of high-strength concrete columns with spiral confinement	Uniaxial compression tests, stress-strain analysis	Focus on columns only; not applicable directly to beam behavior

	ction and Building Materials			
[8]	Bond-slip response of ultrahigh-strength steel bars with spiral grooves embedded in reinforced concrete	To analyze bond-slip behavior of steel bars with spiral grooves in concrete	Pull-out tests, bond-slip modeling	Focus on bond behavior; does not address overall structural performance
[9]	Glass fibre-reinforced polymer circular alkali-activated fly ash/slag concrete members under combined loading	To study performance of FRP-confined alkali-activated concrete under combined loading	Experimental loading tests, stress-strain analysis	Uses alternative materials (FRP, AAFS); limited relevance to conventional RCC
[10]	Fresh and hardened properties of GGBS-contained cementitious composites using graphene and graphene oxide.	To examine the effect of graphene and GGBS on fresh and hardened properties	Rheology tests, compressive strength, microstructure analysis	High-cost materials (graphene) limit practical applicability

III. METHODOLOGY



This flowchart describing experimental flow of a concrete study. It starts with the purchase and testing of raw materials and then it prepares design mixes with different percentages. This is followed by a process of casting cubes, cylinders and beams and curing them over stipulated periods. After curing, destructive testing is carried out on the specimens.

Materials Used:

- Ordinary Portland Cement (OPC)
- River sand
- Manufacture sand (M-sand)
- Ground Granulated Blast Furnace Slag (GGBS)
- Micro Silica
- Reinforcement
- Sika Visco Crete SKY 8508

Ensure all materials meet relevant standards and specifications through proper certifications or preliminary checks.

Testing on Materials:

Conduct basic tests to determine material properties:

Cement: Fineness, consistency, initial and final setting time. Aggregates (River Sand and M-sand): Specific gravity, fineness modulus, and particle size distribution. GGBS: Specific gravity, Fineness and consistency

Mix Design (M55):

Develop a concrete mix for M55 grade, adhering to IS 10262 standards, ensuring the desired workability and compressive strength. Optimize proportions of cement, GGBS, sand, and aggregates.

Classify materials based on their properties (e.g., fine and coarse aggregates, pozzolanic material like GGBS) and document mix components for efficient batch production.

Casting and Curing:

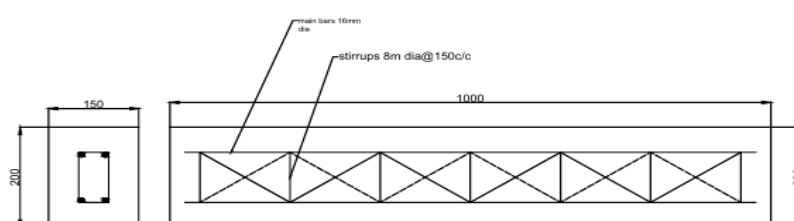
Use spiral reinforcement in structural specimens for shear performance evaluation. Cure the specimens under standard water-curing conditions for the required duration (28, and 56 days).

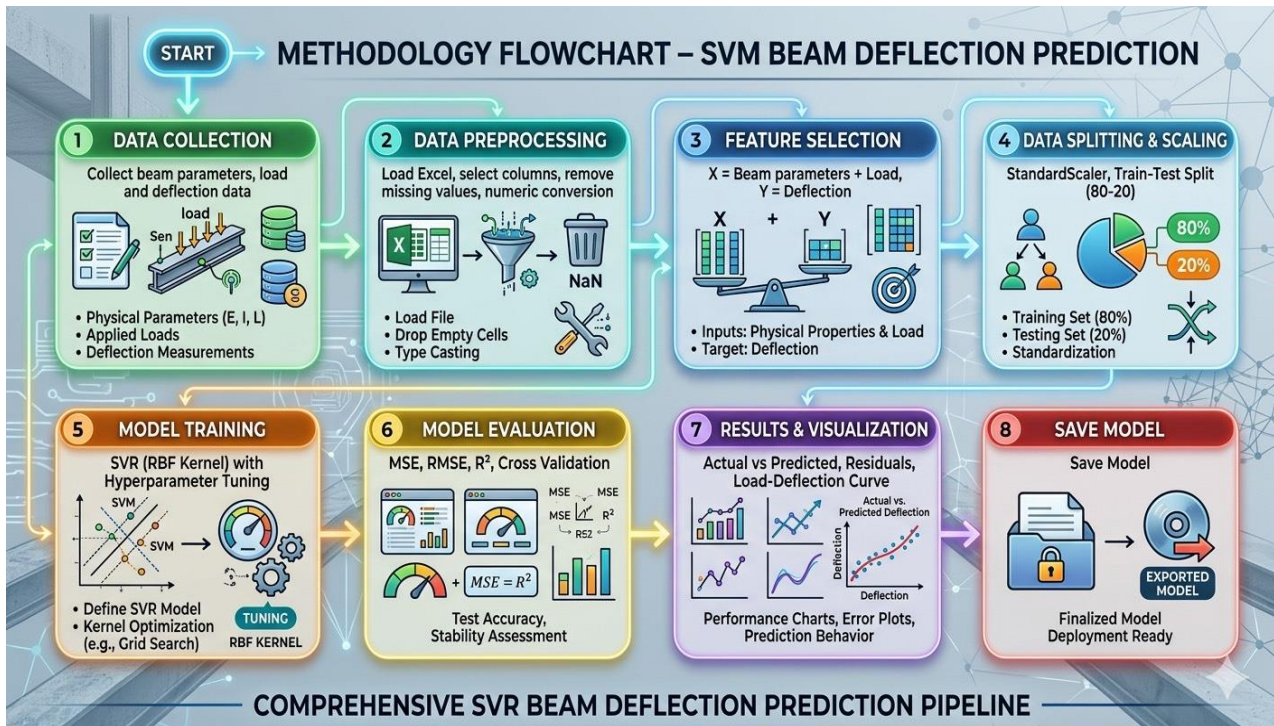
Tests on Specimens:

Shear Tests: Evaluate performance & stiffness of rcc beams, particularly for specimens with spiral reinforcement

Fig. 1. Load Vs Deflection for Conventional Beam

In Fig.2 a structural drawing of a reinforced concrete beam with both cross-sectional and longitudinal views. The cross-section on the left shows the size of the beam and where the reinforcement bars are placed. The longitudinal section in the right shows the length of the beam (1000 mm) and how the stirrups are placed on the beam. The stirrups are indicated to be 8 mm diameter with a spacing of 150 mm between them. Moreover, there are main reinforcement bars of 16 mm diameter depicted running along the beam length.





1. Data Collection:

The engineering pipeline initiates with the critical task of gathering raw empirical and structural data. The foundational purpose of this stage is to systematically collect beam architectural parameters, load vectors, and resultant physical deflections to establish a high-fidelity ground truth dataset.

Physical Parameters: Sourcing structural and material engineering properties vital to performance, including Young's Modulus (E), Moment of Inertia (I), and the total geometric Beam Length (L).

Applied Loads: Quantifying and documenting the external forces, point weights, and distributed stress configurations structurally acting upon the beam system.

Deflection Measurements: Capturing the actual, physically verified displacement or deformation metrics under known loads, serving as the target labels for future machine learning optimization.

2. Data Preprocessing:

Raw physical data is inherently susceptible to recording discrepancies, missing fields, and varied file formats. The preprocessing sequence formats, cleans, and standardizes structural entries into uniform numerical matrix layers.

Load File: Infecting and extracting tabular datasets from administrative spreadsheet environments, such as Microsoft Excel (.xlsx format), into the central computational workspace.

Drop Empty Cells: Isolating and dropping null observations, missing attributes, or NaN (Not a Number) rows to prevent matrix invalidation during linear algebra executions.

Type Casting & Column Selection: Filtering structural noise by filtering out descriptive metadata text columns, parsing values into high-precision floating-point formats, and verifying index consistency.

3. Feature Selection :

Feature selection segregates multidimensional database columns into mathematically independent input matrices and targeted dependent vectors, ensuring optimal mapping clarity for the regression algorithm.

Inputs (X Matrix): Aggregating the structural geometry variables (E, I, L) and operational constraints (Applied Load) into a combined multidimensional input tensor.

Target (Y Vector): Isolating the critical continuous mechanical output element—the total structural Beam Deflection—to act as the singular target vector.

4.Data Splitting & Scaling:

To protect against model overfitting and ensure authentic validation, data is divided into separate, insulated subsets and standard normalized across standard units.

Train-Test Split (80-20 Ratio): The core matrix is algorithmically parsed to guarantee strict out-of-sample checking:

Training Set (80%): Allocated to fit, optimize, and construct the SVR boundaries.

Testing Set (20%): Held completely independent to gauge final accuracy metrics.

Standardization (StandardScaler): Physical features operate in fundamentally different units (e.g., Pascals vs. Meters). Applying a StandardScaler shifts values to a mean of zero and standard deviation of one, preventing high-magnitude columns from artificially biasing model weights.

5. Model Training :

This operational step centers on training a Support Vector Regression (SVR) network capable of handling non-linear stress-strain relationships by lifting spatial dimensions.

SVR Model with RBF Kernel: Implementing an advanced Support Vector Regression framework using a Radial Basis Function (RBF) kernel. The RBF kernel allows the pipeline to implicitly project non-linear structural engineering phenomena into higher-dimensional spaces where hyperplanes can be linearly fit.

Hyperparameter Optimization (Grid Search): Executing an exhaustive automated tuning pass over operational parameters (such as Regularization Cost 'C', Gamma scale, and Epsilon margins) to isolate the ultimate architecture minimizing geometric training loss.

6.Model Evaluation:

Once trained, the candidate mathematical model must undergo structural stress-testing to prove its validity against unknown physical loads using independent metrics.

Key Performance Metrics: Calculating standardized precision evaluations from testing performance:

Mean Squared Error (MSE): Penalizes large error outliers to verify variance safety.

Root Mean Squared Error (RMSE): Brings error metrics back directly to real physical units (meters/millimeters).

Coefficient of Determination (R^2): Defines the total proportion of deflection variance explained perfectly by the SVR.

Cross-Validation: Utilizing iterative data folds to guarantee stability, validating that model predictability is generalized and resistant to local sampling anomalies.

7. Results & Visualization :

Numerical metrics are translated into engineering visual plots to examine regression behavior, structural trend continuity, and model error distributions.

Actual vs. Predicted Deflection: Plotting true experimental results directly against SVR predictions to check for alignment along a 45-degree perfect-fit trajectory.

Residual Analysis & Error Plots: Tracking remaining data variances to confirm that error terms are randomly distributed, ruling out systemic algorithmic underfitting.

Load-Deflection Curves: Mapping continuous load increases against structural deflection outputs to guarantee that predictions honor foundational laws of solid mechanics.

8. Save Model :

The conclusion of the methodology pipeline establishes physical portability for the optimized machine learning system, enabling runtime application execution.

Finalized Model Asset: Serializing the optimized SVR framework parameters, scaler weights, and metadata matrices into a protected, compressed binary asset file.

Production Deployment Ready: Packaging the exported file into real-time engineering infrastructure, enabling instantaneous, sensor-driven structural deflection monitoring without requiring repetitive model training overhead.

IV. RESULTS AND DISCUSSION

TABLE I. LOAD AND DEFLECTION VALUES FOR 28 DAYS

LOAD (KN)	DEFLECTION (MM)	LOAD (KN)	DEFLECTION (MM)	
0	0	70	0.7	
5	0.1	75	0.75	
10	0.12	80	0.81	
15	0.19	85	0.89	
20	0.2	90	0.95	
25	0.25	95	1	
30	0.3	100	1.1	
35	0.32	105	1.17	
40	0.36	110	1.25	
45	0.38	115	1.33	
50	0.45	120	1.45	
55	0.48	125	1.55	
60	0.55	130	1.95	
65	0.6	135	2	
25	0.25	95	1	
30	0.3	100	1.1	
35	0.32	105	1.17	
40	0.36	110	1.25	
45	0.38	115	1.33	
50	0.45	120	1.45	
55	0.48	125	1.55	

In Table-I indicates the correlation between load applied and deflection and this shows that deflection rises with increase in load. It indicates the structural behavior of the specimen under loading with a smooth increase in the deflection and steeper increase at higher loads.

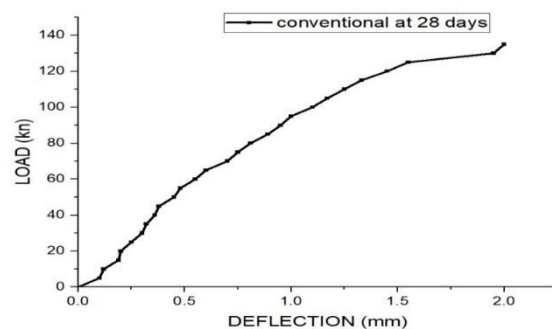


Fig. 2. Load Vs Deflection for Conventional Beam

In Fig.3 the graph demonstrates the load deflection characteristics of a conventional specimen at 28 days where the load is rising constantly as the deflection is rising. It shows a nonlinear reaction, which becomes gradually more and more deflected as the load level increases until it reaches the final stage.

TABLE II. LOAD AND DEFLECTION VALUES FOR 28 DAYS

LOAD (KN)	DEFLECTION (MM)	LOAD (KN)	DEFLECTION (MM)
0	0	110	1.12
5	0.015	115	1.2
10	0.02	120	1.35
15	0.05	125	1.42
20	0.1	130	1.5
25	0.15		
30	0.19		
35	0.22		
40	0.28		
45	0.3		
50	0.4		
55	0.45	165	2.25
60	0.49	170	2.3
65	0.54	175	2.4
70	0.6	180	2.58
50	0.4		
55	0.45		
60	0.49		
65	0.54		
70	0.6		
75	0.64	185	2.7
80	0.7	190	2.82
85	0.75	195	3.23
90	0.83	200	4.1
95	0.9	205	4.1
100	1	210	4.1
105	1.05		

In Table-II it presents the load–deflection relationship of the specimen, showing a steady increase in deflection with increasing load. It also indicates a sharper rise in deflection at higher loads, suggesting the onset of structural yielding or failure behavior.

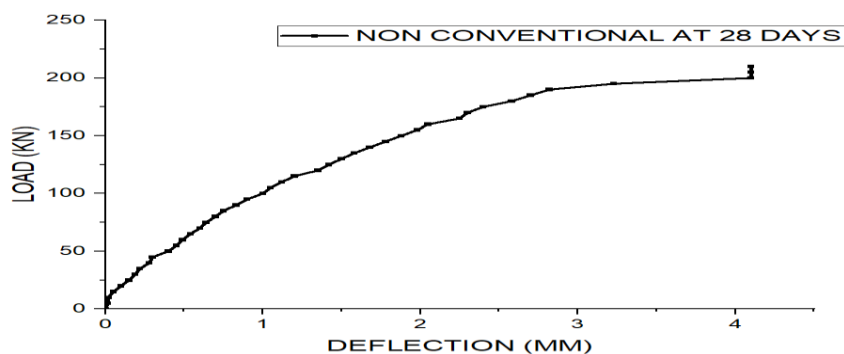


Fig. 3. Load Vs Deflection for Non Conventional Beam

In Fig.4 the graph illustrates the load–deflection behavior of a non-conventional specimen at 28 days, showing a higher load-carrying capacity compared to typical results. It demonstrates a gradual increase in deflection with load, followed by a slight plateau at higher loads, indicating improved ductility and strength.

LOAD (KN)	DEFLECTION (MM)	LOAD (KN)	DEFLECTION (MM)
0	0	125	0.98
5	0.03	130	1.03
10	0.05	135	1.08
15	0.12	140	1.13
20	0.14	145	1.16
25	0.18	150	1.21
30	0.22	155	1.25
35	0.24	160	1.32
40	0.27	165	1.35
45	0.3	170	1.43
50	0.34	175	1.47
55	0.37	180	1.53
60	0.39	185	1.59
65	0.43	190	1.69
70	0.47	195	1.72
75	0.52	200	1.78
80	0.56	205	1.8
85	0.6	210	1.89
90	0.64	215	1.9
95	0.69	220	2
100	0.72	225	2.1
105	0.8	230	2.15
110	0.84	235	2.18
115	0.89	240	2.28
120	0.94	245	2.38
		250	2.6
		255	2.8

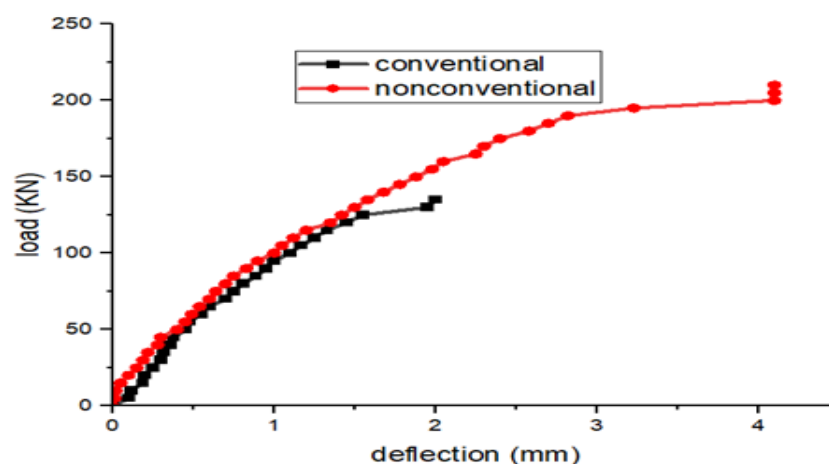


Fig. 4. Load VS Deflection combined value

In Fig.5 the graph compares the load–deflection behavior of conventional and non-conventional specimens at 28 days. It shows that the non-conventional specimen sustains higher loads and exhibits greater deflection, indicating improved strength and ductility.

TABLE III. LOAD AND DEFLECTION VALUES FOR 56 DAYS

In Table-III the behavior of load-deflection is given in the table where we can see that the deflection is steadily increasing with increasing load. It implies that there is enhanced carrying capacity as it deforms slowly and reflects a stable structural performance to a higher load.

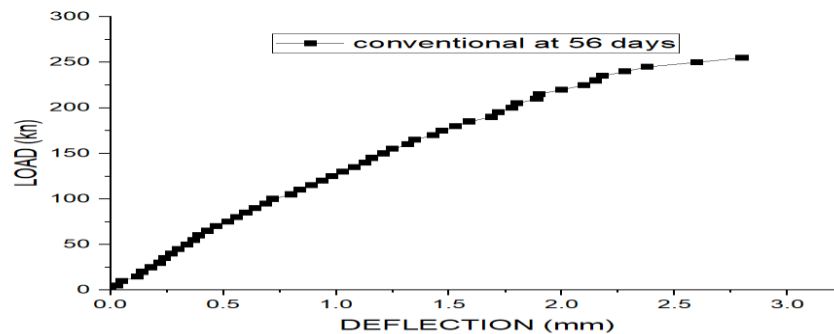


Fig. 5. Load VS Deflection for conventional beam

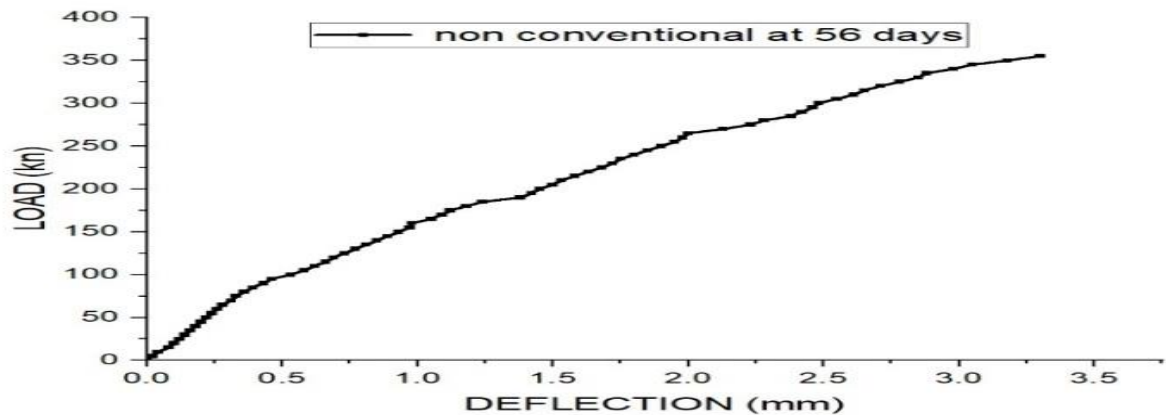
In Fig.6 the graph shows that load increases steadily with deflection for the conventional specimen at 56 days, indicating a strong positive relationship. At higher deflections, the rate of load increase slows down, suggesting the material is approaching its maximum load-carrying capacity.

TABLE IV. LOAD AND DEFLECTION VALUES FOR 56 DAYS

LOAD (KN)	DEFLECTION (MM)	LOAD (KN)	DEFLECTION (MM)	LOAD (KN)	DEFLECTION (MM)
0	0	120	0.69	240	1.8
5	0.02	125	0.73	245	1.85
10	0.04	130	0.77	250	1.9
15	0.08	135	0.81	255	1.95
20	0.1	140	0.85	260	1.98
25	0.12	145	0.89	265	2
30	0.14	150	0.93	270	2.13
35	0.16	155	0.97	275	2.23
40	0.18	160	0.98	280	2.28
45	0.2	165	1.05	285	2.38
50	0.22	170	1.09	290	2.42
55	0.24	175	1.12	295	2.46
60	0.26	180	1.18	300	2.48
65	0.28	185	1.24	305	2.55
70	0.31	190	1.38	310	2.61
75	0.33	195	1.42	315	2.65
80	0.36	200	1.45	320	2.71
85	0.39	205	1.5	325	2.78
90	0.43	210	1.53	330	2.85
95	0.46	215	1.58	335	2.88
100	0.53	220	1.63	340	2.98
105	0.58	225	1.68	345	3.05
110	0.62	230	1.72	350	3.18

115	0.66	235	1.75	355	3.3
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In Table- IV it indicates a steady rise in load as the deflection increases, which means that there is a positive relationship between load and deflection with specimen. Beyond a certain load (around 250 kN),

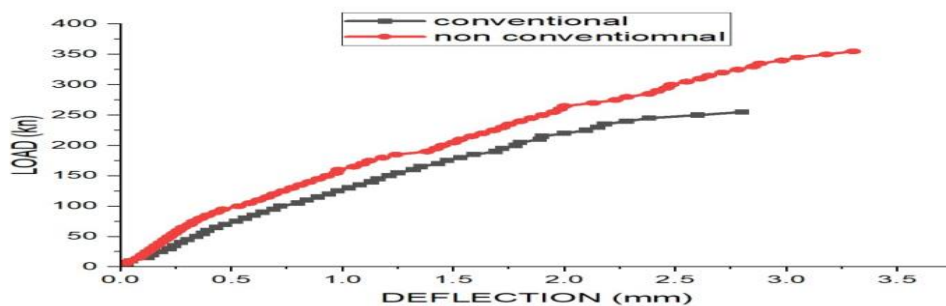


the rate of deflection becomes steeper and indicates less stiffness and nears structural failure.

Fig. 6. Load VS Deflection for non conventional beam

In Fig.7 the graph indicates that the non-conventional specimen at 56 days sustains higher loads with increasing deflection, showing improved load-carrying capacity. Compared to typical behavior, it demonstrates greater ductility, as the load continues to rise steadily even at higher deflections.

Fig. 7. Load VS Deflection for combined values



In Fig.8 it is evident in the graph that the non-conventional specimen always has higher loads than the conventional one at the same deflection, thus, better strength. It is also more ductile, being able to maintain increasing load within a higher range of deflection than the traditional specimen.

IV. CONCLUSION

1. Lower deflection: The non-conventional beam exhibited a deflection of 1.58 mm at 28 days under an applied load of 135 kN, whereas the conventional beam showed a deflection of 2 mm under the identical load, resulting in a deflection reduction of 21% and demonstrating improved flexural stiffness in the non-conventional beam.
2. At 56 days, the non-conventional beam demonstrated a deflection of 1.95 mm under a load of 255 kN, compared to a deflection of 2.8 mm in the conventional beam under the same load, indicating a 30.36% decrease in deflection and showcasing enhanced stiffness and structural performance in the non-conventional beam.
3. Enhanced flexural & Deflection : The non-conventional beam exhibited improved flexural stiffness.
4. Superior shear resistance: Initial shear cracking occurred at a higher load (210 kN) compared to the conventional beam (175 kN) at 28days .Superior shear resistance: Initial shear cracking occurred at a higher load (355 kN) compared to the conventional beam (255kN) at 56 days .
5. This study uses Support Vector Machine (SVM) regression to predict mid-span deflection of a reinforced concrete beam when a load is applied. The model uses information about the beam's properties and the load it carries as input. Before training the SVM model, the experimental data were cleaned, scaled, and split into training and testing groups. To make the model more reliable, adjusted its parameters and used cross-validation. The model performed very well, achieving an R^2 score of around 0.96 with minimal prediction errors. Visual comparisons like Actual vs. Predicted plots and Load-Deflection curves showed that the predictions were accurate. The results show that SVM is a good data-driven method for predicting deflection in structural engineering.

V. ACKNOWLEDGMENT

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