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# Comprehensive Study of High Strength Concrete Beams with Confinement Shear Reinforcement under Cyclic Loads

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**Abstract :** Concrete off late has transcended into many forms depending upon the application. In the present paper, the flexural and the shear resistance of high strength reinforced concrete (HSC) beams with longitudinal bars and confinement of transverse stirrups [1] is analyzed both theoretically and experimentally. An experimental program has been made in order to study the confined concrete behaviour when its strength changes from traditional values to high strength values. Six HSC beams of span 3m with constant width 150 mm and depth 250 mm by varying (i) transverse shear reinforcement spacing -100 and 200mm c/c and (ii) the longitudinal reinforcement ratio (1.0%, 1.25% and 1.5%) were casted and tested under cyclic loading to understand the flexural behavior of the beams. The details of the beam specimens, material properties, instrumentation and the testing procedure used are carefully described in this paper. Furthermore, mathematical modeling using regression equations are proposed to study the effect of confinement reinforcement obtained from the experimental results. Test results are also compared with predicted results for various reinforcement ratios and finally, conclusions are drawn.
**Keywords**: High strength concrete, reinforcement ratio, cyclic loads, confinement.

## 1. Introduction

[2]High strength concrete (HSC) has compressive strength of up to 100 MPa as against conventional concrete which has compressive strength of less than 50 MPa. [3]& [4] The ingredients of high strength concrete [14-26] are the same as those used in conventional concrete with the addition of one or two admixtures, both chemical and mineral. However, there are two crucial aspects to be considered while deciding upon the ingredients to be used. The first relates to the use of an extremely low water-cement ratio and the second to the use of a proper mix in order to produce concrete with minimum or no voids. Generally, water-reducing admixtures (WRA's) are used. The mix requires high paste volume, which often leads to shrinkage and high evolution of heat of hydration, besides increasing the cost. The substitution of cement by supplementary cementitious materials (mineral admixtures) that are commonly used are fly ash, ground granulated blast-furnace slag, silica fume, rice husk ash, and metakaolin. The use of such material not only improves the properties of fresh concrete but also enhances the long term durability characteristics. Although the compressive strength of concrete has been steadily improving in recent times, the potential to increase it further has become evident with its use in columns of high-rise buildings and long span bridge girders all over the world. The provision of confinement improves the flexural ductility of a beam section in two ways. First, it increases the uniaxial strength of the concrete which results in a higher balanced steel proportion (pmax). Second, it increases the flexural ductility of the beam due the increased ductility of the triaxially stressed concrete. [5]& [6]

Bai Z.Z, Francis T. K. Au & A. K. H. Kwan (2007) [7] carried out a study on the complete nonlinear behavior of RC beams under both non-reversed and reversed cyclic loading based on the moment–curvature relationship that employs the actual stress–strain curves and takes into account the stress-path dependence of concrete and steel reinforcement. Generally, the response under cyclic loading was found to be dependent on the loading path in bending. The variation of neutral axis depth is different for under- and over-reinforced sections during cyclic loading. The Bauschinger effect of steel reinforcement is insignificant for non-reversed cyclic loading but notable for reversed cyclic loading, especially when the loading extends into the post-peak stage. The beneficial effects of concrete tension stiffening were only observed at the service stage and were more significant for under-reinforced RC beams than over-reinforced ones.

Dr. Bayar Jaafer Al sulayfani, Muna Mubarak Abdullah (2007) [8] studied the bending behavior of reinforced concrete sections and frames subjected to cyclic loads, such as wind loads or earthquake loads. The authors presented a numerical model which is capable of predicting the behavior of a reinforced concrete beam, frame and joint subjected to cyclic loading. The effect of axial force on the structure is also considered and concluded that the effect of axial force in the structural members is to decrease the energy absorption by these members and increases their failure loads.

M.N.S. Hadi (2008) [9] investigated the effectiveness of utilising confining reinforcement, to achieve ductile behaviour in high-strength reinforced concrete beams. The advantages of using confining reinforcement to achieve ductility in reinforced concrete beams, as opposed to the conventional method of reducing the neutral axis depth were investigated. Five beams, 4000 mm long, 200mm wide and 300 mm deep were constructed from 85 MPa concrete. Three of the beams were designed to be over-reinforced and the other two under-reinforced. The three over reinforced beams incorporated confining reinforcing, in the form of stirrups, figure 8 stirrups and a helix in the compression zone. The under reinforced beams included the use of compression reinforcement to limit the neutral axis depth for one of the beams. The beams were loaded to failure and the load deflection response was recorded. The results of the experimental program showed that ductility can be achieved through the use of confining reinforcement. The degree of ductility obtained was proportional to the confining pressure provided by the confining reinforcement.

## 2. Experimental Programme

The experimental programme was conducted to study the flexural performance of the HSC beams. In this study, concrete of grade M 60 was used and it was designed as per the ACI Standard. [10][11]& [12] The mix was designed with a water-cement ratio (w/c) of 0.36. The concrete mix proportion used in the test program is presented in the Table 1.

**Table 1. Constituents of Concrete Mix**

| Grade of concrete | Cement | FA | CA | Water @ | Silica Fume @ | Hyperplasticizer |
|---|---|---|---|---|---|---|
| | $kg/m^3$ | $kg/m^3$ | $kg/m^3$ | $kg/m^3$ | $kg/m^3$ | $litre/m^3$ |
| M60 | 450 | 750 | 10mm=450<br>20mm=680 | 160 | 36 | 4.5 |

The research work consisted of casting a total of six rectangular beams of cross-section 150mm x 250mm and 3m long. The beams were made of concrete of strength 66.81MPa and provided with HYSD bars of yield strength 445.63 MPa. The beams were tested under four-point bending condition in a loading frame of 50Tons capacity over a simple span of 2.8m. The variables considered for the study include reinforcement percentage and stirrup spacing. For all the test beams, the study parameters included ultimate load, yield load, service load, mid span deflection, crack width, ductility and failure modes. The beams were tested under cyclic loading conditions until failure. The details of the beams are shown in Table 2 and Fig.1.

**Table 2. Details of Tested Beams**

| Beam ID | Characteristic Strength of Concrete 'fck' | Percentage of Tension Steel 'Pt' | Bottom Bar | Top Bar | 2L-8dia Stirrups Spacing 'Sv' |
|---|---|---|---|---|---|
| | N/mm$^2$ | % | | | mm c/c |
| HSC-P1 | 67.56 | 1.14 | 2-12# +1-16# | 2-12# | 100 |
| HSC-P2 | 68.44 | 1.14 | 2-12# +1-16# | 2-12# | 200 |
| HSC-Q1 | 68.00 | 1.37 | 2-16#+1-12# | 2-12# | 100 |
| HSC-Q2 | 65.77 | 1.37 | 2-16#+1-12# | 2-12# | 200 |
| HSC-R1 | 66.22 | 1.60 | 3-16# | 2-12# | 100 |
| HSC-R2 | 66.67 | 1.60 | 3-16# | 2-12# | 200 |

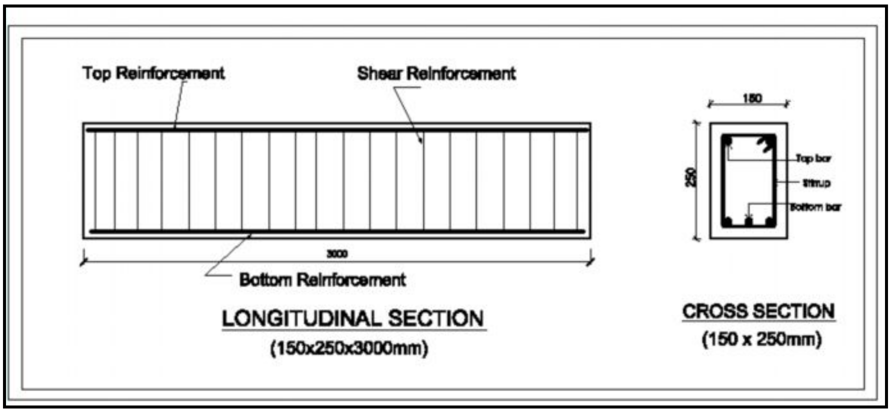



**Fig.1. Reinforcement Details of Test Beam**

**Cyclic Test Procedure**

Six beams were tested under cyclic loading using a push pull jack arrangement. The specimens were tested under four point-bending in a loading frame of 50 Tons capacity in dynamic. The details of cyclic load test set-up are in shown in Fig.2 and Fig.3. The beams were simply supported at the ends with one end hinged and roller at the other end. The beams were supported with 100mm bearing at the ends, resulting in a test span of 2.8m. Two-point loading was applied through a spreader beam. The deflection at each cycle was recorded. Crack widths, crack spacing, number of cracks and corresponding cycles were periodically measured during cyclic loading. The crack widths were measured using a crack detection microscope with a least count of 0.02mm. Crack propagation was continuously monitored during the process of testing. All the above measurements were taken until the failure of the beam.

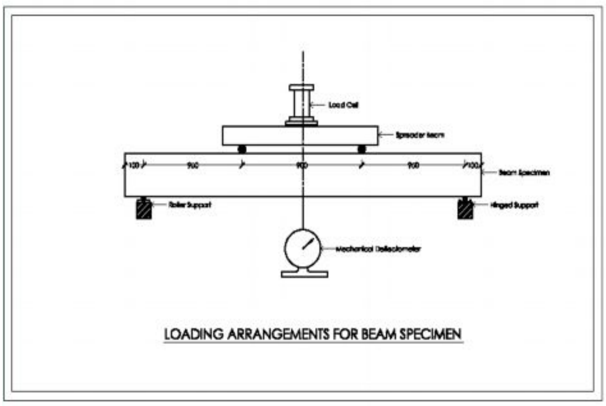




**Fig. 2. Cyclic Load test set-up of Loading Frame**

**Fig. 3. View of Cyclic Load Test of Beam**

## 3. Test Results and Discussions

[7]Cyclic test results of high strength concrete beams with varying reinforcement percentage and shear reinforcement spacing and the results pertaining to the objectives of the study are discussed and presented in table.3

**Table 3. Cyclic Test Results of Beams**

| Beam ID | Ultimate Load | No. of Cycles | Deflection | Stiffness | Energy Absorption |
|---|---|---|---|---|---|
| | kN | Nos | mm | kN/mm | kNmm |
| HSC-P1 | 84.6 | 9 | 4.5 | 18.80 | 156.87 |
| HSC-P2 | 84.6 | 9 | 4.5 | 18.80 | 152.39 |
| HSC-Q1 | 91.1 | 11 | 5.5 | 16.56 | 251.40 |
| HSC-Q2 | 91.1 | 11 | 5.5 | 16.56 | 235.75 |
| HSC-R1 | 97.6 | 10 | 5.0 | 19.52 | 233.68 |
| HSC-R2 | 104.1 | 10 | 5.0 | 20.82 | 216.19 |

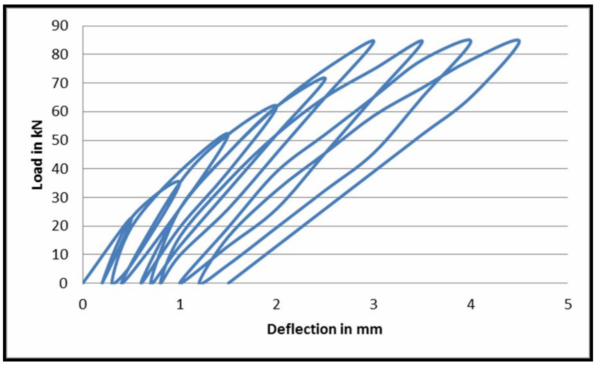
### Effect on Cyclic Test Parameters

In beams with reinforcement percentage, Pt=1.14% and with stirrup spacing's of 100mm and 200mm, the maximum number of cycles went up to 9 and there is no significant variation in deflection and stiffness. The energy absorption increased by 2.94% in beams with 100mm stirrup spacing when compared to beams with 200mm stirrup spacing.

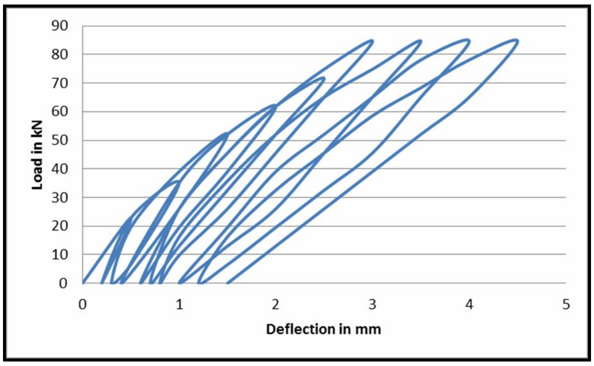
In beams with reinforcement percentage, Pt=1.37% and with stirrup spacing's of 100mm and 200mm, the maximum number of cycles went up to 11, and there was no significant variation in deflection and stiffness. The energy absorption increased by 6.64% in beams with 100mm stirrup spacing when compared to beams with 200mm stirrup spacing.

In beams with reinforcement percentage, Pt=1.6% and with stirrup spacing's of 100mm and 200mm, the maximum number of cycles went up to 10, and there was no significant variation in deflection. But the stiffness increased by 6.14% in beams with 200mm stirrup spacing when compared to beams with 100mm stirrup spacing. The energy absorption increased by 8.09% in beams with 100mm stirrup spacing when compared to beams with 200mm stirrup spacing.

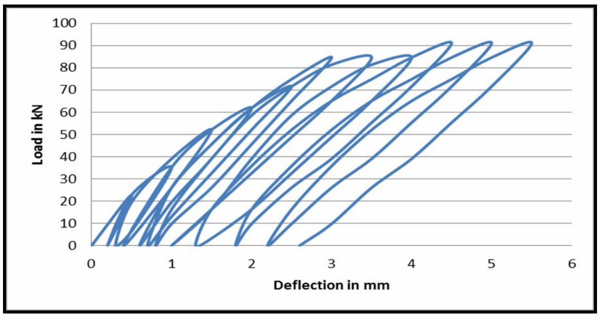
The Load Vs deflection behavior of all the beams under Cyclic loading is shown in Fig. 4a to 4f. The behaviour of deflection Vs number of cycles, stiffness Vs number of cycles, and energy absorption Vs number of cycles, for beams with 100mm c/c confinement shear reinforcement and 200 mm c/c shear reinforcement were analyzed and are presented in Fig. 5a to 5b, Fig. 6a to 6b, Fig. 7a to 7b respectively.



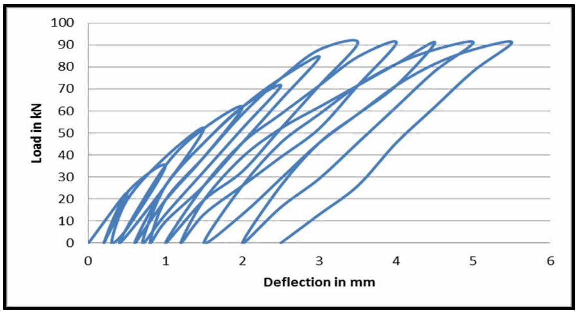

**a. HSC-P1 Beam**



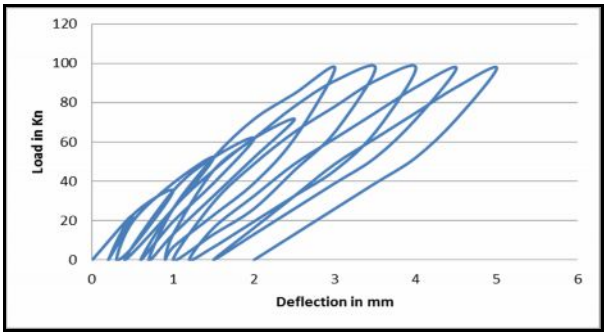

**b. HSC-P2 Beam**



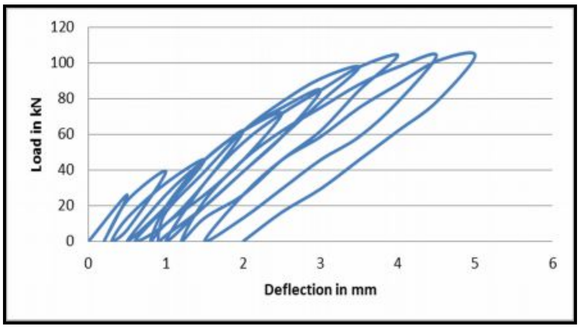

c. **HSC-Q1 Beam**




d. **HSC-Q2 Beam**

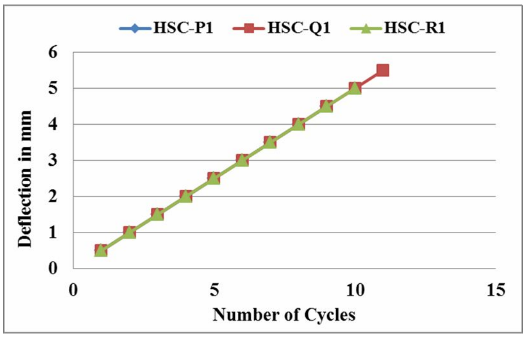



e. **HSC-R1 Beam**

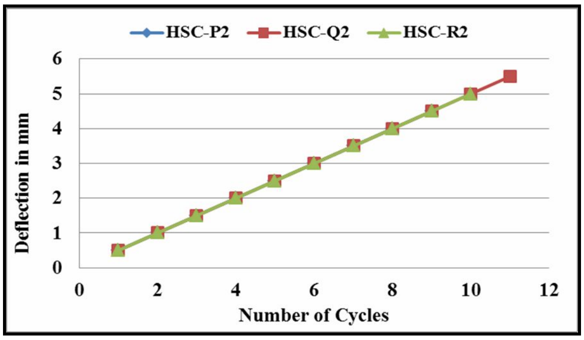



f. **HSC-R2 Beam**

**Fig.4. Load Vs Deflection**

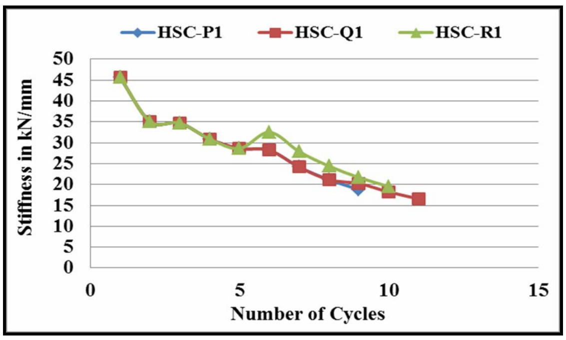



**a. 100 mm stirrup spacing beams**

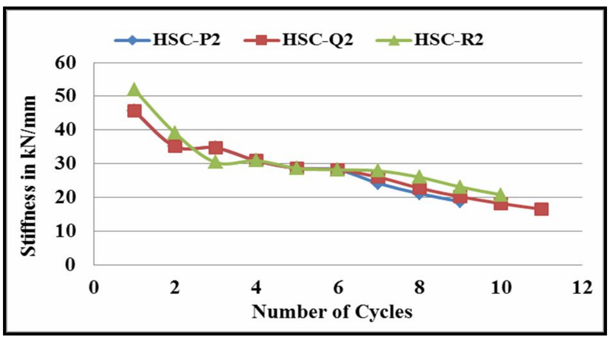



**b. 200 mm stirrup spacing beams**

**Fig. 5. Deflection Vs Number of Cycles**

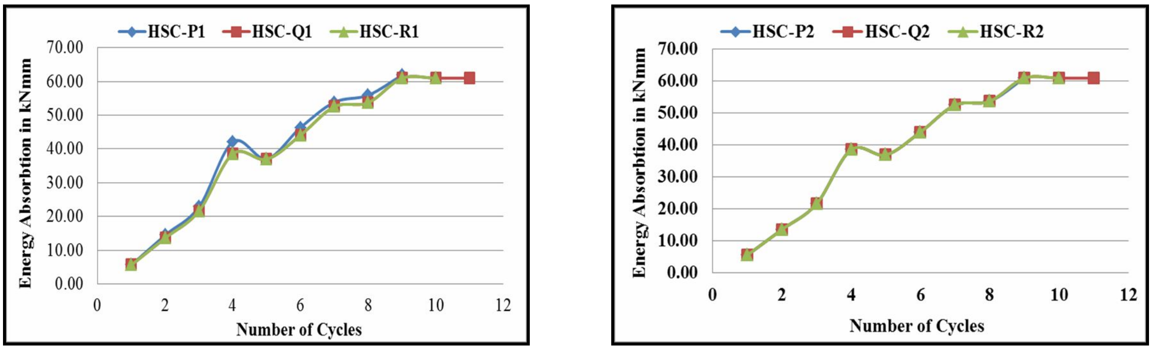



**a. 100 mm stirrup spacing beams**




**b. 200 mm stirrup spacing beams**

**Fig. 6. Stiffness Vs Number of Cycles**




**a. 100 mm stirrup spacing beams** **b. 200 mm stirrup spacing beams**

**Fig. 7. Energy Absorbtion Vs Number of Cycles**

### Effect on Crack Width

The beams experienced considerable flexural cracking and vertical deflection near to failure. Well distributed closely spaced cracking was observed. Flexural cracks were initiated in the constant moment region as the tensile strength of concrete was reached. The cracks propagated upwards as loading progressed but remained very narrow throughout the loading period. The crack pattern, average crack width and failure modes of high strength concrete beams are presented in Table 4.

**Table 4. Details of Cracks**

| Beam ID | Ultimate Load | Number of Cracks | Average Spacing of Cracks | Average Crack Width |
|---|---|---|---|---|
| | kN | No's | mm | mm |
| HSC-P1 | 84.6 | 18 | 84 | 0.14 |
| HSC-P2 | 84.6 | 20 | 67 | 0.18 |
| HSC-Q1 | 91.1 | 8 | 78 | 0.18 |
| HSC-Q2 | 91.1 | 10 | 82 | 0.22 |
| HSC-R1 | 97.6 | 12 | 90 | 0.22 |
| HSC-R2 | 104.1 | 9 | 94 | 0.28 |

In beams with 1.14% of reinforcement, the crack width decreased by 22.22% in 100 mm spacing of shear reinforcement when compared to 200 mm spacing of shear reinforcement. In beams with 1.37% of reinforcement, the crack width decreased by 18.18% in 100 mm spacing of shear reinforcement when compared to 200 mm spacing of shear reinforcement. In beams with 1.6% of reinforcement, the crack width decreased by 21.43% in 100 mm spacing of shear reinforcement when compared to 200 mm spacing of shear reinforcement. The variation of crack width for 1.14%, 1.37% and 1.6% of reinforcement with 100 and 200 mm spacing of shear reinforcement is shown in Fig-8.

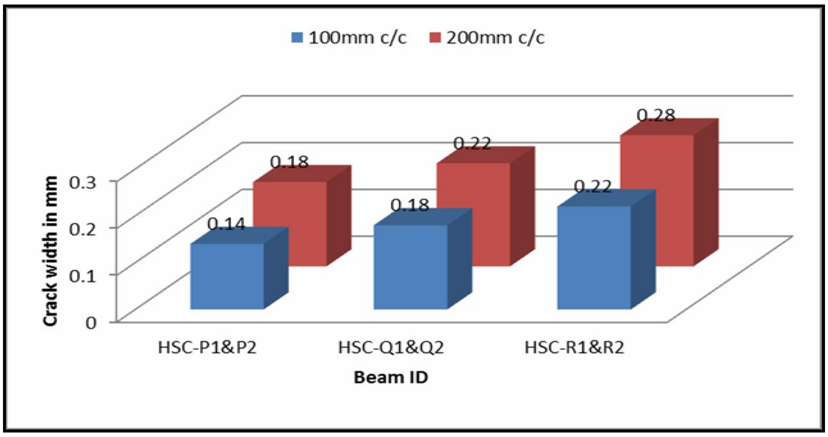



**Fig. 8. Crack Width at Ultimate stage**

## 4. Analytical Prediction

The data obtained from experimental study are used for calibrating the values of unknown regression co-efficients in such a way that the difference between the predicted values and experimental values remains a minimum. In this regression analysis, the independent parameters considered to frame regression equation are variables like No. of cycles, deflection, stiffness, Energy absorption, crack width. The dependent parameters which are known only after prediction are compressive strength of concrete, steel percentage, spacing of shear reinforcement.

Minitab 16 Statistical Software is a Windows statistical software package developed and published by Minitab, Inc. It is used for different statistical analysis and data management. The program was originally designed as a light edition of OMNITAB until it was released as a standalone statistical package. The application is also used together with the implementation of CMMI, Six Sigma, and other statistics-based improvement methods.

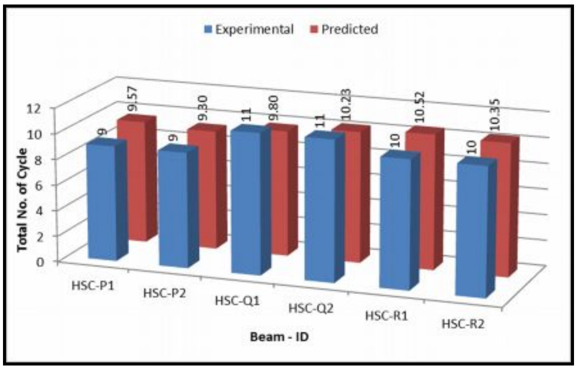
The regression equations have been proposed for predicting the study parameters. Regression equations for tested beams are presented in Table-5. Predictions from the regression equations were compared against experimental results and are presented in Table 6 and Fig. 9a to 9f.

**Table 5. Proposed Regression Equations for Tested Beams**

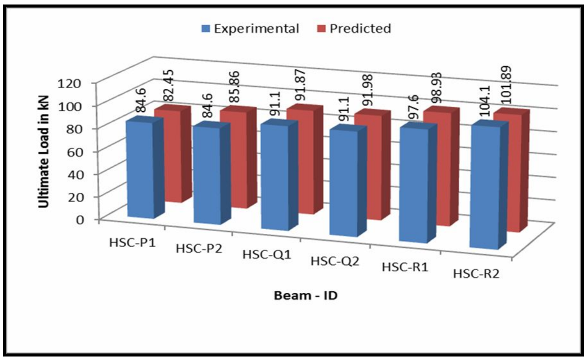
| Parameter | Regression Equation | RMS Error | Fitness |
|---|---|---|---|
| Total Number of Cycles | 23.3 + 1.41 (Pt) - 0.226 (fck) - 0.00068 (Sv) | 1.193 | 0.687 |
| Ultimate Load | -36 + 38.91 (Pt) + 1.06 (fck) + 0.0248 (Sv) | 2.669 | 0.778 |
| Ultimate Deflection | 11.7 + 0.71 (Pt) - 0.113 (fck) - 0.00034 (Sv) | 0.596 | 0.687 |
| Ultimate Stiffness | -29.7 + 5.02 (Pt) + 0.60 (fck) + 0.0061 (Sv) | 2.332 | 0.789 |
| Total Energy absorption | 327 + 138 (Pt) - 4.4 (fck) - 0.109 (Sv) | 4.444 | 0.877 |
| Crack width at Ultimate load | -0.370 + 0.2067 (Pt) + 0.00326 (fck) + 0.000476(sv) | 0.008 | 0.017 |

**Table 6. Comparison of Experimental and Predicted Results of Tested Beams**

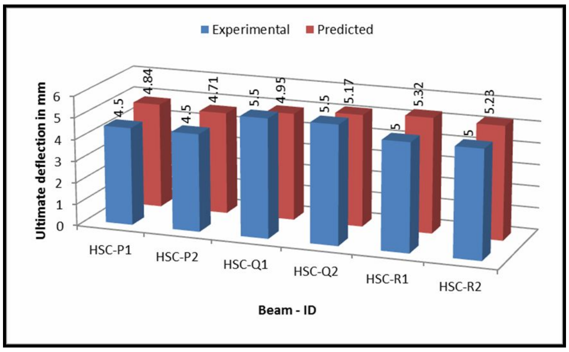
| Sl. No | Parameter | Unit | Beam ID | Experimental | Predicted | % Variation |
|---|---|---|---|---|---|---|
| 1 | Total Number of Cycles | no's | HSC-P1 | 9 | 9.57 | 6.34 |
| | | | HSC-P2 | 9 | 9.30 | 3.38 |
| | | | HSC-Q1 | 11 | 9.80 | -10.95 |
| | | | HSC-Q2 | 11 | 10.23 | -6.98 |
| | | | HSC-R1 | 10 | 10.52 | 5.22 |
| | | | HSC-R2 | 10 | 10.35 | 3.53 |
| 2 | Ultimate Load | kN | HSC-P1 | 84.6 | 82.45 | -2.54 |
| | | | HSC-P2 | 84.6 | 85.86 | 1.49 |
| | | | HSC-Q1 | 91.1 | 91.87 | 0.84 |
| | | | HSC-Q2 | 91.1 | 91.98 | 0.97 |
| | | | HSC-R1 | 97.6 | 98.93 | 1.36 |
| | | | HSC-R2 | 104.1 | 101.89 | -2.13 |
| 3 | Ultimate Deflection | mm | HSC-P1 | 4.5 | 4.84 | 7.58 |
| | | | HSC-P2 | 4.5 | 4.71 | 4.62 |
| | | | HSC-Q1 | 5.5 | 4.95 | -9.91 |
| | | | HSC-Q2 | 5.5 | 5.17 | -5.95 |
| | | | HSC-R1 | 5 | 5.32 | 6.38 |
| | | | HSC-R2 | 5 | 5.23 | 4.69 |
| 4 | Ultimate Stiffness | kN/mm | HSC-P1 | 18.80 | 17.17 | -8.68 |
| | | | HSC-P2 | 18.80 | 18.31 | -2.62 |
| | | | HSC-Q1 | 16.56 | 18.59 | 12.24 |
| | | | HSC-Q2 | 16.56 | 17.86 | 7.85 |
| | | | HSC-R1 | 19.52 | 18.67 | -4.33 |
| | | | HSC-R2 | 20.82 | 19.55 | -6.08 |
| 5 | Total Energy Absorption | kN/ $mm^2$ | HSC-P1 | 156.87 | 176.16 | 12.29 |
| | | | HSC-P2 | 152.39 | 161.38 | 5.90 |
| | | | HSC-Q1 | 251.4 | 205.96 | -18.07 |
| | | | HSC-Q2 | 235.75 | 204.87 | -13.10 |
| | | | HSC-R1 | 233.68 | 245.53 | 5.07 |
| | | | HSC-R2 | 216.19 | 232.65 | 7.61 |
| 6 | Crack Width at Ultimate Load | mm | HSC-P1 | 0.14 | 0.13 | -7.14 |
| | | | HSC-P2 | 0.18 | 0.18 | 0.00 |
| | | | HSC-Q1 | 0.18 | 0.18 | 0.00 |
| | | | HSC-Q2 | 0.22 | 0.22 | 0.00 |
| | | | HSC-R1 | 0.22 | 0.22 | 0.00 |
| | | | HSC-R2 | 0.28 | 0.27 | -3.57 |



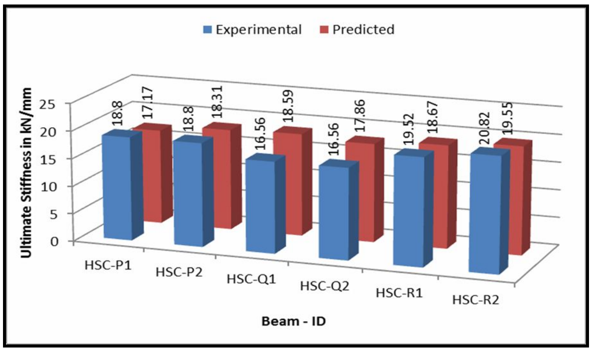

**a. Total Number of Cycles**



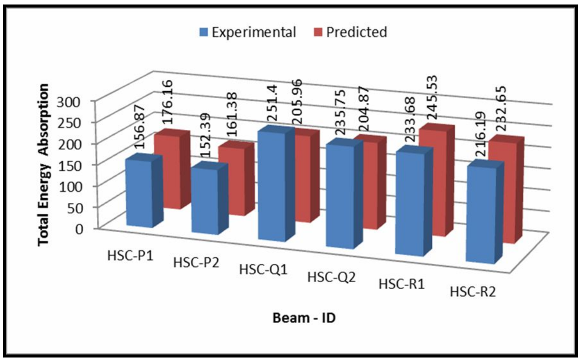

**b. Ultimate Load**



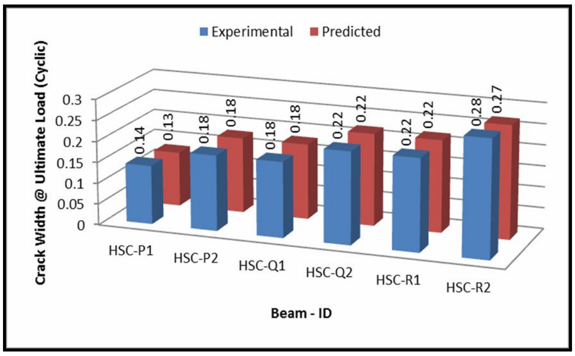

**c. Ultimate Deflection**




**d. Ultimate Stiffness**




**e. Total Energy Absorption**




**f. Crack Width at Ultimate Load**

**Fig. 9. Experimental Vs Predicted**

## 5. Conclusion

1. The current study has shown that the high strength concrete beams with various percentages of tension steel and with confinement shear reinforcement have a greater effect on the ductility in terms of crack resistance.
2. The study also reveals that all the above concrete beams with tension reinforcement percentage Pt=1.14%,1.37%&1.60% with confinement shear reinforcement spacing (100mm c/c) exhibits high energy absorption, when compared to beams with conventional shear reinforcement spacing (200mm c/c).
3. The stiffness of beams with Pt = 1.37% is found to be low when compared to beams with other tension reinforcement percentages.
4. The effect of crack propagation and crack width is minimized to a moderate level in confined shear reinforcement beams.
5. By the use of confinement shear reinforcement, there is no significant reduction in deflection and also there is no increase in load levels.

6. It has been found that the multivariate linear regression can make a reasonable estimate on the prediction values with reasonable levels of accuracy for Ultimate load, Ultimate deflection, Stiffness, Energy absorption and Crack width. A close agreement has been obtained between the predicted and experimental results.

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