International Journal of Engineering and Advanced Technology (IJEAT)
ISSN: 2249-8958 (Online), Volume-2 Issue-5, June 2013

Study on Shear Behaviour of High Strength Concrete (HSC) Slender Beams

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Abstract: ***In this paper an experimental investigation is carried out on Twelve HSC beams with constant width (125 mm) and effective depth (100 mm) by varying (i) shear span to depth ratio, (ii) the longitudinal reinforcement ratio and (iii) the minimum web reinforcement ratio were casted and tested to understand the shear behavior of the beams with minimum web reinforcement as per IS CODE and ACI CODE and maximum web reinforcement as per IS CODE. The load-deflection behavior and the failure pattern of the beams, ultimate shear strength and reserve shear strength are studied with varying a/d ratio and longitudinal reinforcement. The results obtained are compared with the different codal equations. Based on these observations, it can be concluded that, there are many parameters influencing the shear behavior of RC beams such as shear span to depth ratio (a/d ratio>2), concrete grade, depth of the beam and the percentage of the longitudinal reinforcement The results obtained were compared with the different codal equations. The British code model is proposed for the present work.***

Key Words: High strength concrete, shear span to depth ratio. Reserve strength, failure pattern, ultimate shear capacity, codal provisions.

I. INTRODUCTION

In the past decade there has been rapid growth in high strength concrete whose compressive strength is higher than 50 MPa. Although high-strength concrete (HSC) is often considered a relatively new material, the applications of HSC have been possible as a result of recent developments in material technology and a demand for HSC [1].

The primary difference between high-strength concrete and normal-strength concrete (NSC) relates to the compressive strength that refers to the maximum resistance of a concrete sample to applied pressure. Although there is no precise point of separation between HSC and NSC, the ACI defines HSC as concrete with a compressive strength greater than 41 MPa [2].

Manufacture of HSC involves making optimal use of materials by varying the proportions of cement, water, aggregates, and admixtures also the bond between the cement paste and the aggregate, and the surface characteristics of the aggregate. Any of these properties could limit the ultimate strength of HSC. A common practice is to use a superplasticizer in combination with a water-reducing retarder for HSC. The superplasticizer gives the concrete adequate workability at low water-cement ratios, leading to concrete with greater strength.

Manuscript published on 30 June 2013.
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II. SHEAR MECHANISM

An increase in the strength of the concrete produces an increase in its brittleness and smoother shear failure surfaces, leading to some concerns about the application of HSC [16]. A brief description of the mechanism in the shear behavior involved is presented herein. The total shear force Vu is distributed between the concrete Vc and the stirrups Vs. Initially upon loading, the shear reinforcement carry only a small portion of the shear force is carried by the concrete .On the formation of the first inclined crack, redistribution of shear stresses occur, with some part of the shear being carried by concrete, and the rest being carried by stirrups. It is assumed that the total shear is resisted by concrete until the formation of diagonal cracks [3][4][5].

Increase in shear forces beyond that which causes inclined cracking results in the shear stirrups carrying increasing shear, while the contribution to shear resistance by the concrete remains nearly constant .The shear load that caused diagonal or inclined cracking Vcr is considered to be the ultimate capacity of the concrete Vuc to resist shear. The shear resisting capacity of the beam remains constant once the shear stirrups have yielded[6].

2.1 Effect of Shear on Longitudinal Reinforcement:

Accounting for the effects of shear on the longitudinal steel is necessary to ensure a safe design and to avoid the possibility of brittle failures[7][8]. The diagonal crack due o shear crosses both the transverse and tension longitudinal reinforcement at an inclined angle and causes stresses in both. Despite the relatively low bending moment across this crack, the stresses in the longitudinal reinforcement due to shear at this location are significant and therefore cannot be neglected[9][10].The longitudinal reinforcement in beams should be proportioned to resist the forces not only from bending, but also from shear. This could be critical in many cases such as near the support regions of beams, where the longitudinal stresses due to shear are significant[11].

2.2 Function and Strength of Web Reinforcement[18]:

Web Reinforcement is provided to ensure that the full flexural capacity can be developed (desired a flexural failure mode - shear failure is brittle). Acts as "clamps" to keep shear cracks from widening shown in FIG1.

Uncracked Beam - Shear is resisted by uncracked concrete.
Flexural Cracking - Shear is resisted by Vcz, Vay, Vd
Vcz – Shear in compression zone
Vay – Vertical component of Aggregate Interlock Force
Vd – Dowel Action from longitudinal bars
Shear is resisted by Vcz, Vay, Vd and Vs – Shear resisted by stirrups = $\dfrac{A_v f_y d}{s}$

Vs increases as cracks widen until yielding of stirrups till it provide constant resistance.

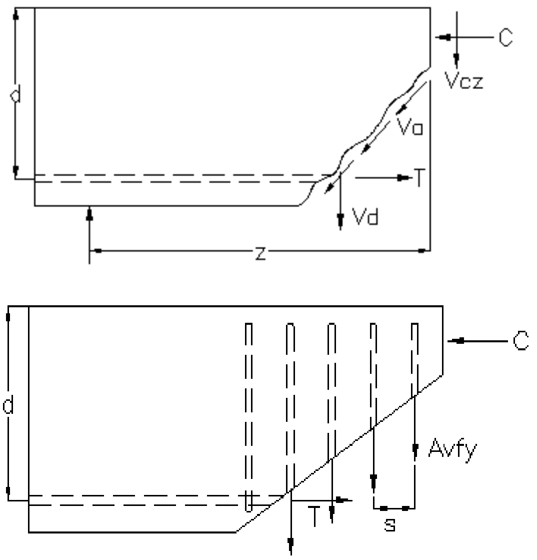

FIGURE 1 Web reinforcement contributions to shear.
Vcz – Shear in compression zone
Va – Vertical component of Aggregate Interlock Force
Vd – Dowel Action from longitudinal bars

Minimum shear reinforcement:

The reasons for providing minimum shear reinforcement in Reinforced Concrete beams are as follows[3]:

a) To avoid brittle shear failure after diagonal shear crack.
b) To provide reserve strength even after the diagonal shear crack formation.
c) To redistribute the stresses in the region of shear span.
d) To impart ductility to the beam before shear failure.
e) To limit the diagonal crack width within the limits and to provide reserve deflection.

Most of the codes gives the expressions similar based on concrete strength and yield strength of web reinforcement neglecting the important parameters such as a/d ratio, longitudinal steel (p) etc. Understanding the strength and deformational behaviour of beams with HSC provided with minimum reinforcement becomes very important before it is put in to practice, that shear reinforcement must prevent sudden shear failure on the formation of first diagonal tension cracking. To prevent a brittle failure, adequate reserve of strength must be provided by the shear reinforcement after diagonal cracking of reinforced concrete beams. The provision of an appropriate amount of minimum shear reinforcement also helps to control bond splitting cracks that otherwise could lead to brittle shear-bond failures[12]. The required minimum shear reinforcement should be made as a function of concrete strength (f'_c), longitudinal steel, axial load, (a/d) ratio and small amount of web reinforcement on the shear strength of HSC beams The increase in web reinforcement and (f'_c) without insuring an adequate amount of longitudinal steel could make this reinforcement the weak link in the member strength [3]. The minimum amount of shear reinforcement can produce a shear resistance equal to that provided by effective aggregate interlock along shear cracks[4]. Tests on beams with HSC indicated that reserve strength beyond diagonal cracking strength decreased as concrete strength increased [13]. Current ACI shear design procedures could be unconservative if applied to thick one-way slabs or large beams containing only minimum stirrups[14][15]. The minimum shear reinforcement was found to increase as the compressive strength was increased[10][11].

Minimum shear reinforcement given by different codes:

1.IS 456-2000[16]

$$A_{V,\min} = \frac{0.4 b_w s}{0.87 f_y}$$

[$s \le 0.75d \cdot or \cdot 300mm$,least]…**(1)**

2. ACI 318-02 [17]

$$A_{V,\min} = 0.0625 \frac{\sqrt{f'_c}}{f_y} b_w s \qquad \text{……………..} \quad (2)$$

$A_{v,\min}$ = Minimum required cross-sectional area of shear reinforcement.

b_w = Web width of the beam section.

s = Spacing of the shear reinforcement.

f'_c = Cylinder compressive strength of the concrete.

f_{cu} = Cube compressive strength of the concrete.

f_y = Yield strength of shear reinforcement.

III. OBJECTIVE OF INVESTIGATION

1. Twelve HSC beams with constant width (125 mm) and effective depth (100 mm) were tested to understand the shear behavior of the beams with minimum and maximum shear reinforcement under four-point loading.
2. The beams were divided into 6 series A, B, C, D, E and F, series A , C and E with a/d ratio 3, series B, D and F with a/d ratio 5. Series A, B, Series C, D and series E, F with percentage of longitudinal reinforcement ratio 0.8, 1.8 and 3.2 respectively.
3. To evaluate shear behaviour with minimum shear reinforcement, two beams in each series having minimum shear reinforcement calculated using IS code[16] and ACI code[17], maximum shear reinforcement as per IS code were cast and tested.
4. To study the Load versus Deflection characteristics of the beams
5. To determine the effect of a/d ratio, longitudinal reinforcement ratio and high-strength concrete of 65 MPa on minimum amount of shear reinforcement.
6. To determine the influence of effect of longitudinal reinforcement ratio, a/d ratio and shear reinforcement ratio on the shear strength of HSC beams.
7. To evaluate the Ultimate Shear Strength Capacity of Beams.
8. To evaluate the Reserve Shear Strength of the Beams.
9. Compare the Ultimate Shear Strength with various Codes and suggest a Model Code for Design for Shear.

IV. EXPERIMENTAL PROGRAMME

There is no single branded procedure available for Mix Proportion for HSC, therefore careful selection of the materials is also effective in production of HSC[17].

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Materials Used:

Cement: Cement used in this project was an OPC of 53 grade confirming to IS 12269 – 1987.

Fine Aggregate: Locally available river sand with Specific Gravity =2.6, Bulk density=1740 Kg/m^3 belonging to Zone II is used for the present work.

Coarse Aggregate: Crushed basalt stone aggregates of 12 mm down size with Specific Gravity =2.61, Bulk density=1702 Kg/m^3 is used for the present work.

Water: Potable tap water.

Superplasticizer: High range water-reducing admixture (HRWA Conplast SP-430 which is based on Sulphonated naphthalene polymers, a brown liquid instantly dispersible in water, having Specific gravity as 1.220 to 1.225 @ 35^{0}c.

Mix Proportion: The mix proportion for M65 grade concrete by using IS: 10262- 1982[19] and the quantities of materials required in Kg. for one Cubic Metre of concrete are:

	Cement	Fine aggregate	Coarse Aggregate	Water
Quantities (Kg)	650	397.35	1060.81	195
Mix Proportion	1	0.61	1.63	0.3

Experimental Investigation:

Twelve HSC M65 grade slender beams with minimum web reinforcement as per IS Code[16] and ACI Code[2] and maximum web reinforcement as per IS Code were casted in 6 series, each series had 2 beams. The details of the specimens are shown in Table 1. The first, second, third and fourth letters indicates the name of the beam, longitudinal reinforcement ratio, the a/d ratio and the spacing of the shear reinforcement. To conduct the experiment beams of size width=125mm, effective depth=100mm and length=1000mm) and another set of size (125 mmx100mmx1600 mm) were casted.

Table 1 – Details of Specimens:

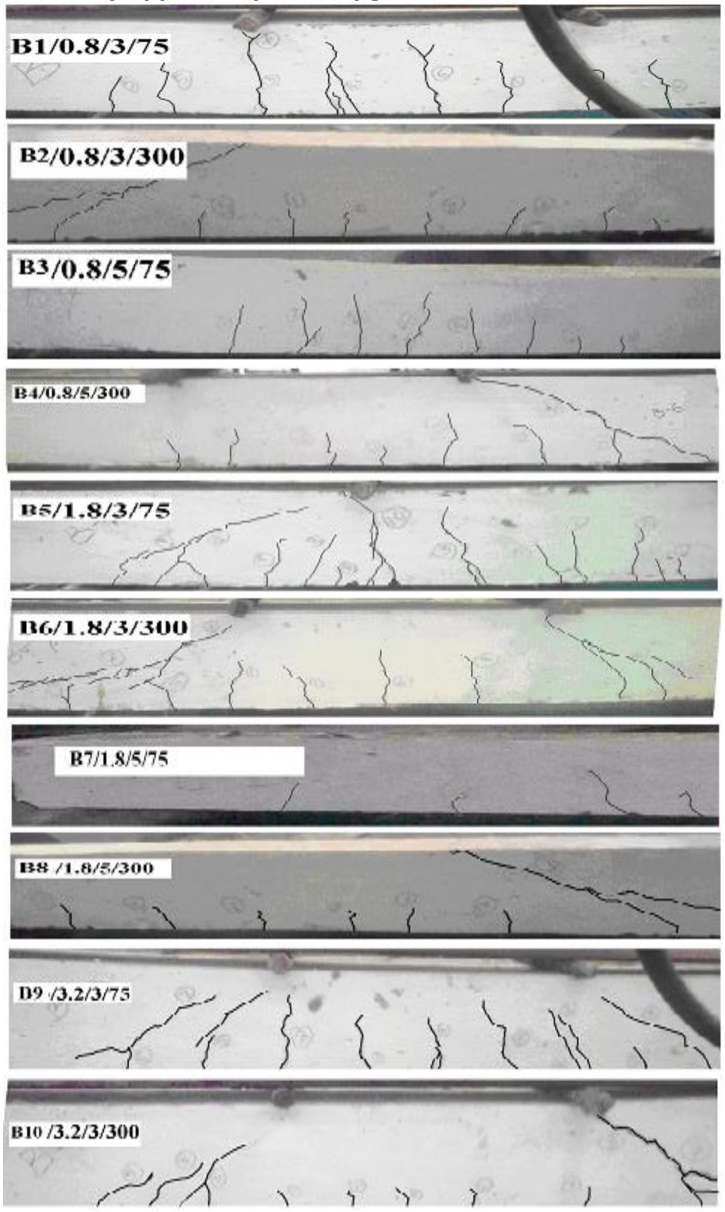
SERIES	BEAM	a/d rato	% long. steel(ρ)	stirrups spacing(s)
A	B1/0.8/3/75	3	0.8	75
	B2/0.8/3/300	3	0.8	300
B	B3/0.8/5/75	5	0.8	75
	B4/0.8/5/300	5	0.8	300
C	B5/1.8/3/75	3	1.8	75
	B6/1.8/3/300	3	1.8	300
D	B7/1.8/5/75	5	1.8	75
	B8/1.8/5/300	5	1.8	300
E	B9/3.2/3/75	3	3.2	75
	B10/3.2/3/300	3	3.2	300
F	B11/3.2/5/75	5	3.2	75
	B12/3.2/5/300	5	3.2	300

Table 2. Test Results

Beam	P_{cr}	$v_{cr} = \frac{P_{cr}}{2bd}$	P_u	$v_u = \frac{P_u}{2bd}$	Failure Mode
B1/0.8/3/75	16	0.64	60	2.4	FLEXURE
B2/0.8/3/300	12	0.48	36	1.44	SHEAR
B3/0.8/5/75	12	0.48	68	2.72	FLEXURE
B4/0.8/5/300	8	0.32	32	1.28	SHEAR
B5/1.8/3/75	16	0.64	88	3.52	FLEXURE
B6/1.8/3/300	12	0.48	48	1.92	SHEAR
B7/1.8/5/75	16	0.64	96	3.84	FLEXURE
B8/1.8/5/300	12	0.48	36	1.44	SHEAR
B9/3.2/3/75	20	0.8	116	4.64	FLEXURE
B10/3.2/3/300	12	0.48	52	2.08	SHEAR
B11/3.2/5/75	32	1.28	128	5.12	FLEXURE
B12/3.2/5/300	16	0.64	48	1.92	SHEAR

V. RESULTS AND DISCUSSION

5.1 History of failure of beams: fig 4



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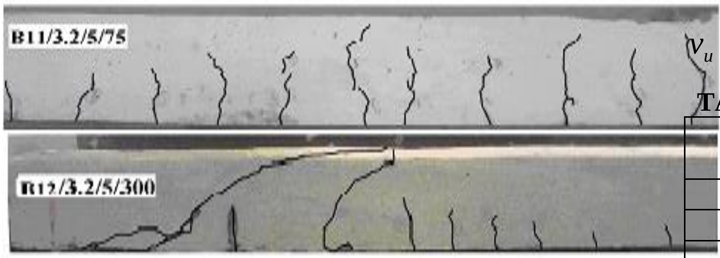


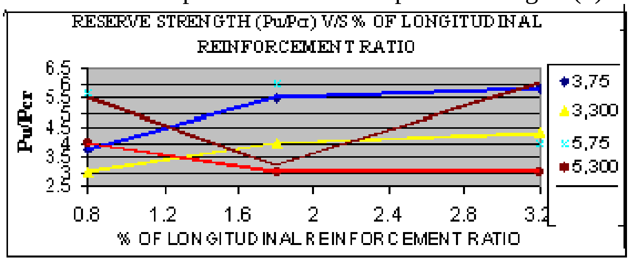
5.2. RESERVE STRENGTH

Reserve strength is taken as the ratio of ultimate load to the cracking load. The reserve strength of the tested beams are given in **table 4.**

Table 4 – Reserve Strength of Beams

BEAM	Pu/Pcr	BEAM	Pu/Pcr
B1/0.8/3/75	3.75	B7/1.8/5/75	6
B2/0.8/3/300	3	B8/1.8/5/300	3
B3/0.8/5/75	5.66	B9/3.2/3/75	5.8
B4/0.8/5/300	4	B10/3.2/3/300	4.33
B5/1.8/3/75	5.5	B11/3.2/5/75	4
B6/1.8/3/300	4	B12/3.2/5/300	3

The reserve strength variation with respect to the longitudinal reinforcement ratio And the reserve strength variation with respect to a/d ratio are plotted in Figure(5)



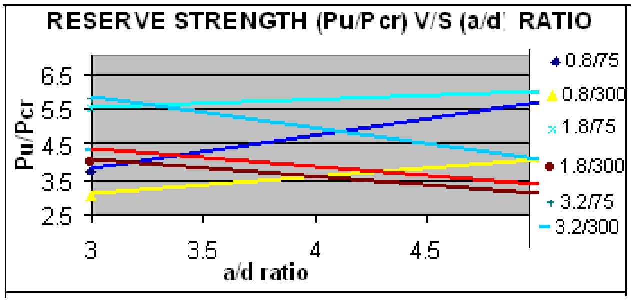


Figure (5) Reserve Strength of Beams

It was observed that the reserve strength increases with the increase in longitudinal reinforcement ratio for all the beams, except for the beams with a/d ratio 5 where reserve strength decreased with the increase of longitudinal reinforcement ratio. The graph shows that, there was an considerable variation in the reserve strength as the a/d ratio increases for the beams with 0.8 percent longitudinal reinforcement ratio, shear reinforcement spacing above 280 mm and beams with 3.2 percent longitudinal reinforcement ratio, shear reinforcement spacing 135 mm respectively and for all other beams there was no significant change in the reserve strength as the a/d ratio increases**.**

Ultimate Shear Stress of Tested Beams

The ultimate shear stress is very important in the shear behavior of HSC. The ultimate shear stress of the tested beams are calculated by the **EQ 3.** and shown in table **5.**

$$V_u = \frac{P_u}{2bd} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

TABLE 5 – ULTIMATE SHEAR STRESS OF BEAMS

BEAM	Vu (MPa)	BEAM	Vu (MPa)
B1/0.8/3/75	2.4	**B7/1.8/3/75**	3.52
B3/0.8/3/300	1.44	**B9/1.8/3/300**	1.92
B4/0.8/5/75	2.72	**B10/1.8/5/75**	3.84
B6/0.8/5/300	1.28	**B12/1.8/5/300**	1.44

It was observed that, as the a/d ratio increases there is no considerable change in the ultimate shear stress, except for the beams with 0.8, 1.8 and 3.2 % longitudinal reinforcement ratio and 300 mm shear spacing in which there is decrease in ultimate shear stress.

Ultimate Shear Strength by different Codes.

The ultimate shear strength of the beams has been predicted using the different codes. The codal equations used are shown from Equations 4 to 9.

1. INDIAN CODE OF PRACTICE [19]

$$V_u = \frac{b_w d\, 0.85\sqrt{0.8 f_{ck}}\left(\sqrt{(1+5\beta)}-1\right)}{6\beta} + \frac{A_v f_{sv} d}{s}$$

Where, $\beta = \left[\frac{0.8 f_{ck}}{689 A_s / b_w d}\right] \ge 1.0 \ldots\ldots\ldots\ldots \quad (4)$

2. ACI CODE 318 (1989) [19,23]

$$V_u = \left(0.158\sqrt{f'_c} + 17.45\rho\frac{V_u d}{M_u}\right) b_w d + \frac{A_v f_{sv} d}{s}$$

$(l/d \ge 2.5) \ldots\ldots\ldots\ldots\ldots\ldots (5)$

3. BS 8110 [19]

$$V_u = \left(\frac{0.79}{\gamma_m}\right)\left(\frac{100A_s}{bd}\right)^{1/3}\left(\frac{400}{d}\right)^{1/4}\left(\frac{f_{cu}}{25}\right)^{1/3} b_w d + \frac{A_v f_{sv} d}{s} \; for, (a/d) \ge 2$$

$\ldots\ldots\ldots\ldots (6)$

$$V_u = (2.0\, d/a)\left(\frac{0.79}{\gamma_m}\right)\left(\frac{100A_s}{bd}\right)^{1/3}\left(\frac{400}{d}\right)^{1/4}\left(\frac{f_{cu}}{25}\right)^{1/3} b_w d + \frac{A_v f_{sv} d}{s} \; for, (a/d) < 2$$

$\ldots\ldots\ldots\ldots (7)$

Where, f_{cu} = cube compressive strength.

γ_m = Material Partial safety factor as 1.25;

4. NEW ZEALAND CODE NZS 3101(1982)[19]

$$V_u = (0.07 + 10\rho_w)\sqrt{f'_c}\, b_w d + \frac{A_v f_{sv} d}{s} \quad \ldots\ldots\ldots (8)$$

VI. EUROCODE EC 2 FINAL DRAFT (2002)[19]

$$V_{RD} = \left[0.18k(100\rho_l f_{ck})^{1/3}\right] b_w d + \frac{A_{sw} z f_{ywd} \cot\theta}{s}$$

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$$(k = 1 + \sqrt{\frac{200}{d}} \leq 2.0 \; ; z = 0.9d \;) \ldots\ldots (9)$$

θ = the angle between inclined concrete struts and the main tension chord.

Using the above Code equations, the ultimate shear strength of the beams, the ratio of the experimental shear to the calculated shear was worked out. The mean, standard deviation and the coefficient of variation was worked out and it is shown in Table 6.

BEAM	EXP/ ACI	EXP/ EURO	EXP/ BS	EXP/ NZS	EXP/ IS	AVG
B1/0.8/3/75	0.89	0.88	0.9	0.88	1.11	0.96
B3/0.8/3/300	0.92	0.85	0.94	0.91	1.41	1.07
B4/0.8/5/75	1.01	1.00	1.03	1	1.26	1.13
B6/0.8/5/300	0.82	0.76	0.84	0.81	1.25	1.03
B7/1.8/3/75	1.28	1.13	1.17	1	1.46	1.27
B9/1.8/3/300	1.17	0.91	1.02	0.80	1.51	1.18
B10/1.8/5/75	1.39	1.23	1.28	1.09	1.6	1.43
B12/1.8/5/300	0.88	0.68	0.77	0.60	1.13	0.95
B13/3.2/3/75	1.63	1.33	1.39	0.99	1.77	1.52
B15/3.2/3/300	1.21	0.84	0.95	0.59	1.39	1.1
B16/3.2/5/75	1.80	1.47	1.54	1.1	1.95	1.74
B18/3.2/5/300	1.12	0.77	0.88	0.54	1.28	1.1
MEAN	1.18	0.92	1.06	0.86	1.43	
SD	0.28	0.26	0.22	0.22	0.22	
CV	0.24	0.28	0.18	0.25	0.15	

Table (6)Comparison of Ult. Shear Strength with codes

It is observed from Table No: 6 that, the BS 8110 MODEL[19] predicted the values much better with a mean of 1.06, standard deviation of 0.19 and coefficient of variation of 0.18.

VII. CONCLUSIONS

1. HSC beams tested in the present investigations showed bursting type of failure at the ultimate loads.
2. It was observed that the reserve strength, increases with increase in the percentage of longitudinal reinforcement ratio. Therefore the percentage of longitudinal reinforcement ratio of the beam has definite influence on the reserve strength of HSC slender beams with minimum web reinforcement.
3. As the longitudinal reinforcement ratio increases, the ultimate shear stress increases.
4. It has been found that as the shear span to depth ratio (a/d) increases, the reserve strength the ultimate shear stress decreased. Therefore the shear span to depth ratio (a/d) of the beam has definite influence on the reserve strength, the cracking shear stress and the ultimate shear stress of HSC slender beams with minimum web reinforcement.
5. It has been observed from the **TABLE 6** that the **BS 8110 MODEL[19]** predicted the values much better when compared to other codes. The following points may be observed from the results obtained.
   - It was observed that the predictions for the beams 3, 6, 9, 15 and 18 are better when compared to the other beams.
   - The codal predictions underestimate the values of shear strength for beams with 3.2 and 1.8 percent of longitudinal reinforcement ratio and overestimate the values of shear strength with 0.8 percent of longitudinal reinforcement ratio.
   - The effect of longitudinal steel ratio and a/d ratio in the shear strength formulae given by the codal equations is to be modified.
6. From the above points we can conclude that the longitudinal reinforcement ratio, strength of the concrete, shear span to depth ratio, value and depth of the beam are the most influencing parameters in the deformational and shear behaviour of the HSC slender beams with web reinforcement.

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