Shear Behavior of High Strength Self-Compacting Concrete Slender Beams Without Web Reinforcement

Aijaz Ahmad Zende[1*], R.B. Khadiranaikarb[2], and Asif Iqbal. A. Momin[1]

[1] *Department of Civil Engineering, BLDEA's Vachana Pitamaha Dr. P.G Halakatti College of Engineering and Technology, Vijayapur, Affiliated to VTU, Belagavi, Karnataka, India.*
[2] *Department of Civil Engineering, Basaveshwar Engineering College, Bagalkot, Affiliated to VTU, Belagavi, Karnataka, India.*
[*] *Corresponding author. E-mail: cv.aijaz@bldeacet.ac.in, aijaz.52964@gmail.com*

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High Strength Self-Compacting Concrete (HSSCC) is known for its various advantages and becoming very common among construction industries. Because of the various advantages of HSSCC, many researchers are working on improving the overall performance of HSSCC. But, since it is quite a relatively new material, shear design guidelines for high strength are not available in major design codes. These guidelines may not even be safe and adequate to use in designing HSSCC beams. The shear behaviour of HSSCC beams differs much from normal SCC beams. Thus, a systematic analysis of the shear behaviour of HSSCC beams is very important. In this experimental program, the shear behaviour of slender HSSCC beams without web reinforcement was studied by casting 27 beams for three mixes having compressive strength 70 MPa, 80 MPa and 90 MPa and without transverse reinforcement. In the present article, the various parameters discussed includes- failure loads of the beams, shear strength and failure angles, cracking patterns and failure modes, the effect of longitudinal steel ratio and shear span to depth (a/d) ratio on the shear strength of beams and load-deflection curves.

Keywords: SCC, Shear Stress, High Strength Concrete, Experimental testing.

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1. Introduction

Shear behaviour of Reinforced Concrete (RC) structures is one of the most complex problems in concrete technology. The concept of which is not fully clear even after decades of study. Many researchers are developing methods and models to predict the shear behaviour till date [1–3]. The failure in RC due to shear indicates a rapid degradation of strength which will lead to sudden failures. Thus, shear resisting capacity of RC should be greater than any other type of failure resistance that doesn't lead to sudden failure, for instance, flexural failure. Self-Compacting Concrete (SCC) is a recent development in the field of concrete technology which has become very popular among construction industries. SCC offers advantages like better flowability than Normal Vibrating Concrete (NVC) and significantly reduces the construction time since the complete process of compaction is eliminated [4].

SCC's composition of concrete is different from NVC. It consists of lesser coarse aggregate contents and higher fine materials to achieve the required flowability [5, 6]. Taylor, H. (1974) [7] reported that the important elements of concrete which resist the shear are- aggregate interlock mechanism (35% to 50%), Strength of un cracked concrete region (20% to 40%) and dowel action due to the presence of longitudinal reinforcement (15% to 25%). Hence, the shear behaviour of SCC differs from NVC [8]. Much work has been done on SCC concerning its fresh properties and durability. However, not much work has been done on bond and shear failure of HSSCC beams. Hence, little experimental data is available for researchers to understand the shear behaviour of HSSCC. The aggregate interlock mechanism,

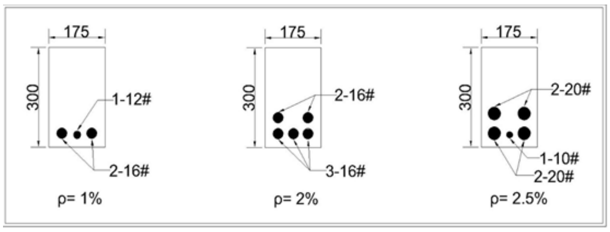


Fig. 1. Reinforcement details

which contributes maximum to shear resistance, is reduced in concrete by the type and size of CA. Thus, the production of HSSCC requires a careful selection of materials. In HSSCC, the fine content is increased and coarser content is kept minimum. This results in better flow of aggregates increasing the flowability of the concrete. Subsequently, the aggregate interlock mechanism is affected. Because of this reduction in aggregate interlock mechanism, research on shear behavior of HSSCC is necessary.

Previously, many researchers [9–11] have carried out studies on the shear behavior of SCC by varying Coarse Aggregate (CA) contents and comparing it with NVC beams. The results shows that the shear capacity of NVC beams is higher than SCC beams. Thus, many other researchers [12, 13] worked on improving the shear capacity of SCC beams by investigating the effect of type of CA, variation in their size and optimum proportion to be used. Many researchers [14] have also suggested the use of fibers in SCC like steel and polypropylene for improving the cracking behavior and ductility.

SCC having higher compressive strength (more than 70 MPa), solves problems of filling the voids and increases the bond between the steel and concrete. However, since it has high strength, it is brittle because the sound matrix of aggregate and cement paste provides a smooth shear failure plane leading to its sudden failure. Thus, the shear capacity of HSSCC beams will not increase in the same way as the compressive strength does. There is very little experimental research available on the shear behaviour of HSSCC beams with strength of more than 70 MPa. This makes it quite difficult to predict the shear behaviour of HSSCC beams.

The shear capacity of high strength beams is generally predicted by using the different codal provisions given in design codes. The empirical equations in these codes are derived based on experimental results of various beams tested with lower compressive strength. Hence, this raises doubt on researchers on the applicability of these equations for higher grade concrete.

Some researchers have proposed theoretical models to predict shear behaviour but these are much complex and time consuming to include it in design codes. To simplify this, simplified equations were developed and included in design codes [15, 16]. But many studies have shown that these equations either overestimates or underestimate the shear capacity of beams depending on aggregates and cross sections. Since all the design codes must cover all the possible cases, they result in conservative results. This conservativeness depends on the precisions and accuracy of predictions. Precisely predicted equations will have less scatter and dispersions which result in economical design.

Thus, to summarize, much work has been carried out on fresh and other mechanical properties like stress-strain curve, modulus of elasticity and Poisson's ratio of SCC which are considered to be important parameters to design reinforced concrete structures. But, it is very essential to understand the shear behaviour of HSSCC to prevent sudden and catastrophic failures which is only possible with experimental testing. Hence, for rationalizing and generalizing the empirical equations given by many researchers and design codes, much experimental research data is needed. The present experimental work is an effort in this direction.

2. Experimental Program

The shear behaviour of slender HSSCC beams without web reinforcement was studied by casting 27 number of beams for three mixes having compressive strength 70 MPa, 80 MPa and 90 MPa and without transverse reinforcement. Table 1 gives the details of 3 mixes studied and Table 2 gives the fresh properties of HSSCC.

After testing the beams, the following parameters were studied- Failure loads of the beams, Shear strength and failure angles of the beams, Cracking pattern and failure modes of beams, effect of longitudinal steel ratio on the shear strength of beams, effect of shear span to depth (a/d) ratio on the shear strength of beams and load-deflection curves.

2.1. Details of specimens

All the beams were having a width of 175 mm and overall depth of 300 mm. The major variable to study was the effect of longitudinal reinforcement on HSSCC beams, hence three values of ρ=1%, $\rho = 2\%$ and $\rho = 2.5\%$ were selected. Another variable to study was the effect of a/d ratio on the slender HSSCC beams. Thus, for each value of ρ, three values of a/d ratio are used i.e. a/d=3, a/d= 3.5 and a/d=4. The details of tested beams are presented in Table 3. In this table, series 1 refers to M1 mixes having grade 70 MPa, series 2 refers to M2 mixes having grade 80 MPa and series 3 refers to M3 mixes having grade 90 MPa. Since the over-

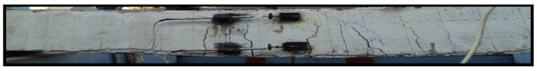
Table 1. Details of selected mix proportions

Mix Trial No	Cement Kg/m^3	W/C Ratio	Fly Ash h%	Silica fume %	Sand Kg/m^3	CA Kg/m^3	28 days' strength in MPa
M1	0.28	480	10%	10%	755	960	79.57
M2	0.26	480	20%	20%	780	945	86.93
M3	0.28	480	15%	15%	755	995	94.36

Table 2. Summary of test results on fresh SCC

Concrete designation		M1	M3	M2
Slump flow	Diameter (mm)	680	675	670
T500	Time (sec)	4.02	4.04	4.1
V-funnel test	Time (sec)	10.1	10.15	11.55
	H1 in cm	9.4	9	10.1
	H2 in cm	8.3	7.7	8.1
L- Box test	L-box test value in (H2/H1)	0.88	0.85	0.8

all depth of all the beams were 300mm, the length of the beams was varied from 1.6 m to 2 m, for each value of ρ so as to get the shear span to depth ratio of a/d=3, a/d= 3.5 and a/d=4. The length of the beams for each series were 1.6 m, 1.8 m and 2 m so as to vary the a/d ratio. The details of reinforcement used in all the beams can be seen from Fig. 1.

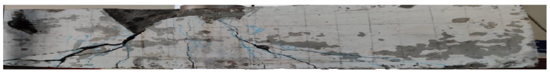

1SCC-M2 with a/d ratio= 3 and ρ=1%


2SCC -M2 with a/d ratio= 3 and ρ=2%


2SCC -M2 with a/d ratio= 3.5 and ρ=2%


1SCC-M3 with a/d ratio= 4 and ρ=1%


2SCC-M3 with a/d ratio= 4 and ρ=2%


3SCC-M3 with a/d ratio= 3.5 and ρ=2.5%

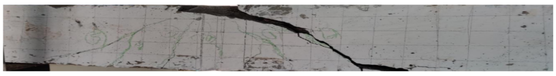

3SCC-M3 with a/d ratio= 4 and ρ=2.5%

Fig. 2. Failure mode of beams

3. Results and Discussions

3.1. Failure loads of the beams

Beams without transverse reinforcement were tested in loading frame and their failure loads, shear strength and approximate failure angles are given in Table 4. It was observed that longitudinal steel ratio and a/d ratio has a prominent effect on the ultimate shear capacity of HSSCC beams without web reinforcement. In mix 1, for constant longitudinal steel ratio of 1%, the total applied failure load decreased by 15 % as the a/d ratio increased from 3 to 4, which is also approximately same for the other two mixes. However, as the longitudinal steel ratio is increased from 1% to 2.5 %, for all the three mixes, the total applied failure load decreased by approximately 20 % as the a/d ratio increased from 3 to 4.

The reason behind this decrease in ultimate failure load can be because of the fact that, with increase in a/d ratio, the bending moment in the shear span also increases. Hence, it increases the flexural stresses thereby increasing the tensile stresses which, acts with the shear stress forming diagonal tension stress and ultimately reducing the shear capacity of beams.

3.2. Cracking pattern and failure modes

The shear strength of all the 27 beams tested experimentally is presented in Table 4.

The shear strength of the beams was taken as half of the applied failure load since the beams were simply supported. While testing the beams, the angles were also measured for the diagonal cracks causing failure to nearest 5°. The cracking patterns and failure modes of beam were monitored closely. It was observed while testing HSSCC beams without transverse reinforcement, vertical cracks were formed in mid span regions when the loading was

Table 3. Details of HSSCC beams

Sl No.	Mix	Beam	Eff. Length (mm)	Depth (mm)	a/d Ratio	Longitudinal steel ratio%
1	M1	1SCC-M$_{1,3}$	1600	300	3	1
2		1SCC-M$_{1,3.5}$	1800	300	3.5	1
3		1SCC-M$_{1,4}$	2030	300	4	1
4		1SCC-M$_{2,3}$	1600	300	3	2
5		1SCC-M$_{2,3.5}$	1800	300	3.5	2
6		1SCC-M$_{2,4}$	2030	300	4	2
7		1SCC-M$_{2.5,3}$	1600	300	3	2.5
9		1SCC-M$_{2.5,4}$	2030	300	4	2.5
10	M2	1SCC-M$_{1,3}$	1600	300	3	1
11		1SCC-M$_{1,3.5}$	1800	300	3.5	1
12		1SCC-M$_{1,4}$	2030	300	4	1
13		1SCC-M$_{2,3}$	1600	300	3	2
14		1SCC-M$_{2,3.5}$	1800	300	3.5	2
15		1SCC-M$_{2,4}$	2030	300	4	2
16		1SCC-M$_{2.5,3}$	1600	300	3	2.5
17		1SCC-M$_{2.5,3.5}$	1800	300	3.5	2.5
18		1SCC-M$_{2.5,4}$	2030	300	4	2.5
19	M3	1SCC-M$_{1,3}$	1600	300	3	1
20		1SCC-M$_{1,3.5}$	1800	300	3.5	1
21		1SCC-M$_{1,4}$	2030	300	4	1
22		1SCC-M$_{2,3}$	1600	300	3	2
23		1SCC-M$_{2,3.5}$	1800	300	3.5	2
24		1SCC-M$_{2,4}$	2030	300	4	2
25		1SCC-M$_{2.5,3}$	1600	300	3	2.5
26		1SCC-M$_{2.5,3.5}$	1800	300	3.5	2.5
27		1SCC-M$_{2.5,4}$	2030	300	4	2.5

Note. Beam Designation example- 1SCC-M$_{1,3}$ -1 denote mix 1 with grade 70 MPa, Subscript 1 denotes longitudinal reinforcement ratio and Subscript 3 denotes a/d ratio.

applied. At first, the cracks were smaller, mostly in mid-span regions with angles almost vertical. When the loads were further increased, the crack widths and depth also increased. With the increase in load, the angle of cracks was becoming shallower and diagonal.

These changes in angles of crack could be because of the cantilever action of the concrete in the cracked zone which is restrained by longitudinal reinforcement. After further increase in load, depth of few diagonal cracks increased again and crossed into compression zone of beams causing eventually beam failure since the cracks prolonged near the point of application of load. Fig. 2 shows the shear failure of beams tested. This type of failure is also known as “diagonal tension failure”.

It was also observed for the beams with a/d ratio of 4, the dominating failure was shear flexure failure since flexural cracks appeared while loading. The flexural cracks were governing in the middle third regions with large angles of failure. Thus, it can be said that the beams were near to achieving the flexural strength before failing in shear on the upper boundary of “Kani’s shear valley”. The theoretical values of flexural and shear strength of these beams are very near to each other in these regions. For beams having longitudinal reinforcement of 2 % or more, it was observed that failure was mainly due to shear failure. But, the shear crack pattern differs much as the longitudinal reinforcement and a/d ratio increases. Beams having lower a/d ratio, failed due to pure shear failure like arch action compression failure. For these beams, the cracks originated from the support and propagated towards the mid-span region with angles being more or less shallower (between 40°-50°). When the loading is further increased, the cracks extended further towards the mid span region and a clear shear crack was observed. This type of failure is generally seen in HSC beams having higher longitudinal reinforcement. Table 5 shows the failure mode for all the 27 tested beams.

3.3. Effect of longitudinal steel ratio

ncrease in longitudinal reinforcement in HSSCC beams from 1 % to 2.5 % increased the shear strength for all three mixes by approximately 30 % for constant a/d ratio. This increase in shear strength in the beams is also referred as “Dowel Action” which increases with an increase in longitudinal reinforcement. Moreover, it also increased the tensile strength resisting the tensile stress in surrounding concrete. Also, the formation of cracks depends on the intensities of shear stress and then the principal stress nearby the

Table 4. Failure load and shear strength

Beam	Total applied load at failure in (kN)	Shear at the failure Vtest (kN)	Failure angle. (degrees)
1SCC-$M_{1,3}$	168.04	84.02	40-55
1SCC-$M_{1,3.5}$	151.06	75.53	40-55
1SCC-$M_{1,4}$	142.36	71.18	45-65
1SCC-$M_{2,3}$	201.32	100.66	30-505
1SCC-$M_{2,3.5}$	191.36	95.68	30-50
1SCC-$M_{2,4}$	182.36	91.18	30-50
1SCC -$M_{2.5,3}$	236.63	118.315	30-50
1SCC-$M_{2.5,3.5}$	215.24	107.62	30-50
1SCC-$M_{2.5,4}$	191.23	95.615	30-50
2SCC-$M_{1,3}$	179.34	89.67	40-55
2SCC-$M_{1,3.5}$	162.36	81.18	40-55
2SCC-$M_{1,4}$	153.66	76.83	45-65
2SCC-$M_{2,3}$	212.62	106.31	30-50
2SCC-$M_{2,3.5}$	202.66	101.33	30-50
2SCC-$M_{2,4}$	193.66	96.83	30-50
2SCC-$M_{2.5,3}$	247.93	123.965	30-50
2SCC-$M_{2.5,3.5}$	226.54	113.27	30-50
2SCC-$M_{2.5,4}$	202.53	101.265	30-50
3SCC-$M_{1,3}$	192.7	96.35	40-55
3SCC-$M_{1,3.5}$	175.72	87.86	40-55
3SCC-$M_{1,4}$	167.02	83.51	45-65
3SCC-$M_{2,3}$	225.98	112.99	35-55
3SCC-$M_{2,3.5}$	216.02	108.01	30-50
3SCC-$M_{2,4}$	207.02	103.51	30-50
3SCC-$M_{2.5,3}$	261.29	130.645	30-50
3SCC-$M_{2.5,3.5}$	239.9	119.95	30-50
3SCC-$M_{2.5,4}$	215.89	107.945	35-50

cracks. These stresses decrease with a decrease in penetration depths of flexural crack by increasing the longitudinal steel area.

It was also observed that, at same a/d ratio, when the longitudinal steel is increased, the cracks and its widths were reduced. The angle of failures was also seen to be decreased. Thus, it confirms the bond between concrete and longitudinal reinforcement as stated in "Kani tooth model".

The bond force between the cracked concrete at cantilever ends too increased when the longitudinal reinforcement is increased from 1 % to 2.5 %, thus, applying additional action at the free end of crack and reducing the failure angles. This is well explained in Modified Compression Field Theory [17], in which the longitudinal reinforcement provided at the tension side of the beam plays an important role in reducing the cracks and thereby, improving the shear capacity of beams. For high strength concrete beams, the widths of shear cracks and their spacing are considered as dominating factors for shear failures. Fig. 3 shows the effect of longitudinal steel ratio on shear capacity of beams for all the three mixes. Aggregate interlock, un-cracked concrete in compression zone and dowel action are the important factors affecting the shear transfer. Thus, beams having high tension steel exhibits post crack shear resistance because of dowel action and uncracked concrete in compression zone.

3.4. Effect of a/d Ratio

Similarly to the NVC beams or normal strength beams, in HSSCC too, the shear span to depth ratio plays an important role in the overall shear behaviour of beams. In beams without transverse reinforcement, it was observed that the shear capacity of beams decreases with increase in shear span to depth ratio. While testing, it was observed that, beams having shear span to depth ratio of 4 were having larger no of cracks and hence, larger cantilever action is applied at cracked concrete resulting in reduction of shear strength of HSSCC beams. Fig. 4 shows the effect of a/d ratio for same longitudinal ratio for all the three mixes. It can be seen that the shear strength of M1 mix decreased by 15%, 10% and 20% approximately when the a/d ratio increased from 3 to 4 for a longitudinal reinforcement ratio of 1%, 2 % and 2.5 % respectively. Similarly, for M2 mix, the shear strength decreased by 15%, 9% and 18 % approximately when the a/d ratio increased from 3 to 4 for a longitudinal reinforcement ratio of 1 %, 2 % and 2.5 % respectively. For M3 mix, the shear strength decreased by 13%, 8% and 18

Table 5. Details of selected mix proportions

Sl No	Beam	Failure mode
1	1SCC-M$_{1,3}$	Shear Compression failure
2	1SCC-M$_{1,3.5}$	Arch failure/Compression shear failure
3	1SCC-M$_{1,4}$	Beam failure/Diagonal tension failure
4	1SCC-M$_{2,3}$	Arch failure/Compression shear failure
5	1SCC-M$_{2,3.5}$	Arch failure/Compression shear failure
6	1SCC-M$_{2,4}$	Beam failure/Diagonal tension failure
7	1SCC-M$_{2.5,3}$	Arch failure/Compression shear failure
8	1SCC-M4$_{2.5,3.5}$	Arch failure/Compression shear failure
9	1SCC-M$_{2.5,4}$	Arch failure/Compression shear failure
10	2SCC-M$_{1,3}$	Arch failure/Compression shear failure
11	2SCC-M$_{1,3.5}$	Arch failure/Compression shear failure
12	2SCC-M$_{1,4}$	Arch failure/Compression shear failure
13	2SCC-M$_{2,3}$	Arch failure/Compression shear failure
14	2SCC-M$_{2,3.5}$	Arch failure/Compression shear failure
15	2SCC-M$_{2,4}$	Arch failure/Compression shear failure
16	2SCC-M$_{2.5,3}$	Arch failure/Compression shear failure
17	2SCC-M$_{2.5,3.5}$	Arch failure/Compression shear failure
18	2SCC-M$_{2.5,4}$	Arch failure/Compression shear failure
19	3SCC-M$_{1,3}$	Arch failure/Compression shear failure
20	3SCC-M$_{1,3.5}$	Arch failure/Compression shear failure
21	3SCC-M$_{1,4}$	Arch failure/Compression shear failure
22	3SCC-M$_{2,3}$	Arch failure/Compression shear failure
23	3SCC-M$_{2,3.5}$	Arch failure/Compression shear failure
24	3SCC-M$_{2,4}$	Arch failure/Compression shear failure
25	3SCC-M$_{2.5,3}$	Arch failure/Compression shear failure
26	3SCC-M$_{2.5,3.5}$	Arch failure/Compression shear failure
27	3SCC-M$_{2.5,4}$	Arch failure/Compression shear failure

% approximately when the a/d ratio increased from 3 to 4 for a longitudinal reinforcement ratio of 1 %, 2 % and 2.5 % respectively. Increase in shear span increases the deflection when it is subjected to loading and thereby flexural cracks are developed even at a smaller amount of loads.

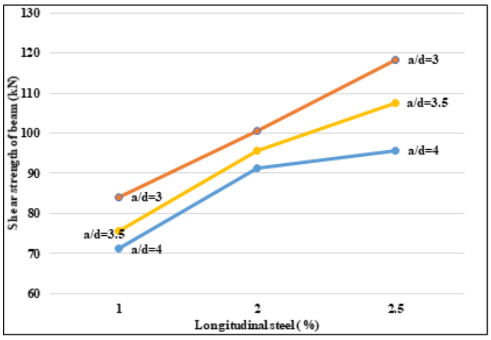
Subsequently, the width of cracks is increased resulting in reduction of interface shear transfer forming larger cracks. These cracks reduce the depth of compression zone which resists tensile stress in un cracked region. This mechanism can also be described in cracked regions, i.e. with the increase in load, the deflection of the beam also increases resulting in larger depth of cracks. This results in increase in the lever arm of cracked concrete cantilever which leads to a larger diagonal force on un-cracked concrete web. Hence, the beam failure takes place even at smaller amount of loads. Thus, “Tooth model of Kani” and “Failure of Compression zone” of Kosovo explains this mechanism. Effect of shear span to depth ratio is more dominating in beams having lower longitudinal reinforcement. The number of flexural cracks are more in these beams because of early failure of bond and larger deflection as compared to beams having higher longitudinal reinforcement. Hence, lower longitudinal reinforcement induces higher tensile strains which reduces the shear capacity HSSCC beams without transverse reinforcement.

3.5. Load vs Deflection

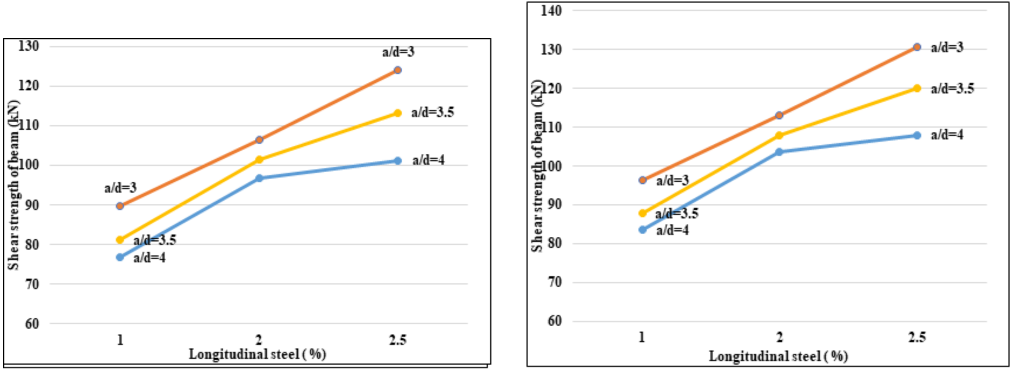
The load vs deflection graphs for all the 27 beams without transverse reinforcement is presented in Fig. 5 for constant a/d ratio and different longitudinal reinforcement. The load deflection curves normally can be categorized in to 2 different stages i.e. pre cracking and post cracking stages. In pre cracking stage, most of the beams does not show any significant deflections. But, increase in deflection was observed after the development of first flexural cracks. Once the post cracking stage was initiated, the flexural stiffness of all the beams decreased due to formation of additional cracks. After this, the behaviour of the beam becomes almost linear till the failure. It was also observed that increase in longitudinal steel ratio and increase in compressive strength increased the post cracking flexural stiffness since the deflection is reduced for a given load level.

4. Conclusion

A total of 27 slender beams without transverse reinforcement and 18 slender beams with transverse reinforcement were tested experimentally to study the behaviour for different grades i.e. M1, M2 and M3 mixes. Following conclu-

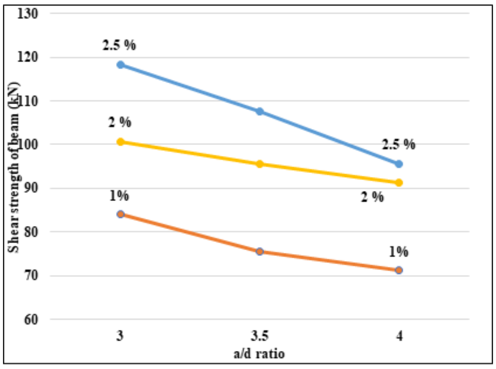


(a) Effect of longitudinal steel ratio for M1 Mi

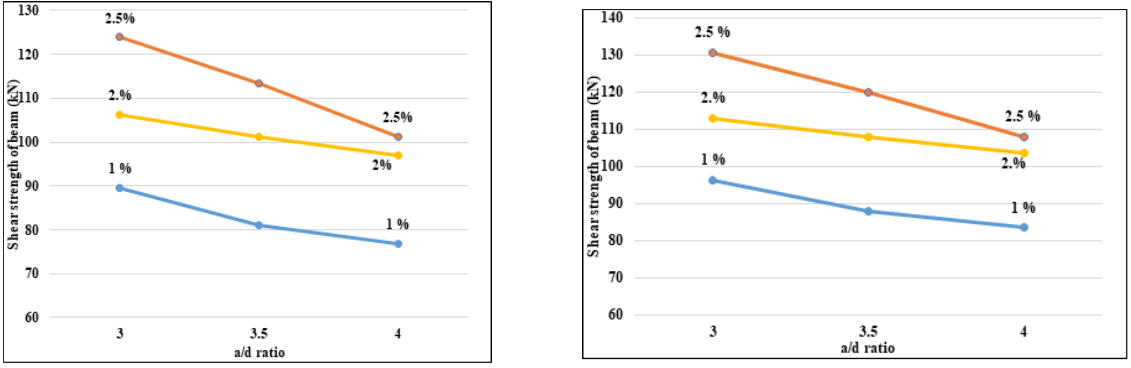


(b) Effect of longitudinal steel ratio for M2 Mix (c) Effect of longitudinal steel ratio for M3 Mix

Fig. 3. Effect of longitudinal steel ratio

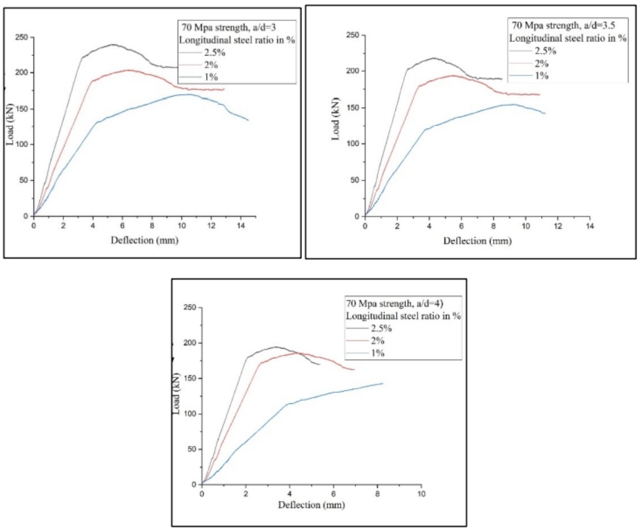


(a) Effect of shear span to depth (a/d) ratio for M1 Mix

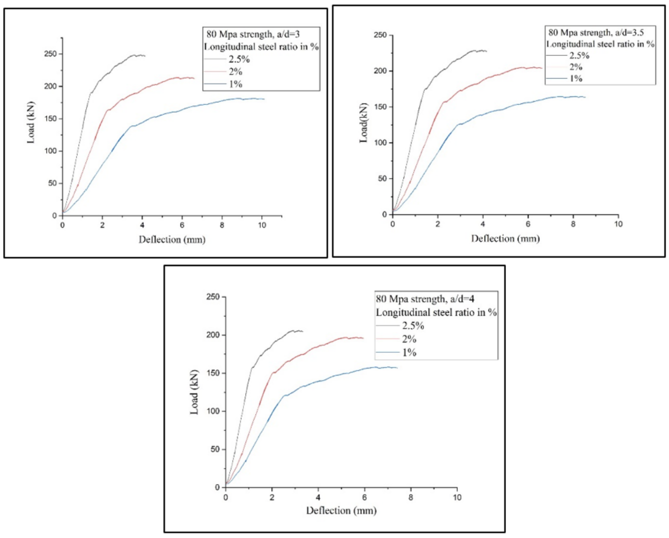


(b) Effect of shear span to depth (a/d) ratio for M2 Mix (c) Effect of shear span to depth (a/d) ratio for M3 Mix

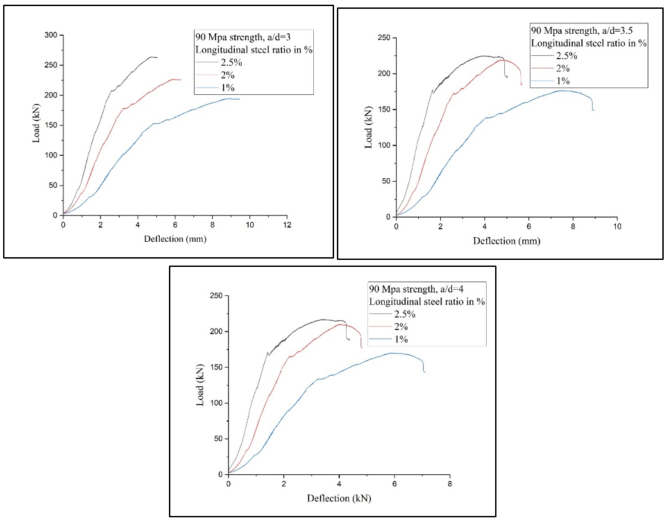
Fig. 4. Effect of shear span to depth (a/d) ratio



(a) Load Vs Deflection curves for M1 mix



(b) Load Vs Deflection curves for M2 mix



(c) Load Vs Deflection curves for M3 mix

Fig. 5. Effect of shear span to depth (a/d) ratio

sions are drawn from the present experimental work:

1. The ultimate failure load decreases with increase in a/d ratio since the bending moment in the shear span also increases.
2. At first, the cracks were smaller, mostly in mid-span regions with angles almost vertical. When the loads were further increased, the crack widths and depth also increased. With the increase in load, the angle of cracks was becoming shallower and diagonal.
3. Increase in longitudinal reinforcement in HSSCC beams from 1 % to 2.5 % increased the shear strength for all the three mixes by approximately 30 % for constant a/d ratio.
4. At same a/d ratio, when the longitudinal steel is increased, the cracks and its widths were reduced. The angle of failures was also seen to be decreased.
5. Aggregate interlock, un-cracked concrete in compression zone and dowel action are the important factors affecting the shear transfer. Thus, beams having higher longitudinal steel exhibits post crack shear resistance because of dowel action and un-cracked concrete in compression zone.
6. Increase in shear span increases the deflection when it is subjected to loading and thereby flexural cracks are developed even at smaller amounts of loads.

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