Shear behaviour of high strength self-compacting concrete with varying stirrup spacing

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Abstract: One of the most important advantages of using self-compacting concrete (SCC) in construction over normal concrete (NC) is the flowability. High strength self-compacting concrete (HSSCC) have less coarse aggregate content and also the maximum size of aggregate is limited as compared to NC for the same class of strength. And hence, there is a reduction in aggregate interlock in SCC compared to NC, affecting the shear capacity of slender beams and thus, SCC might have lower shear strength. In the present research work, a total of 18 numbers of HSSCC slender beams, six beams for each grade, i.e., 70 MPa, 80 MPa and 90 MPa, with transverse reinforcement were tested to understand the shear behaviour. All the beams were provided with stirrups at a spacing of 75 mm, 100 mm, 125 mm, 150 mm, 175 mm and 200 mm. Shear reinforcement index, $\rho_w f_y$, were selected such that they are in the range of $\rho_{w,min} f_y$ as per international codes. Experimental test results of HSSCC beams are compared with NC beams for different stirrups spacing. The results are also compared with different code provisions.

Keywords: self-compacting concrete; SCC; stirrups; shear stress; experiment testing; slender beams; high strength self-compacting concrete; HSSCC.

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1 Introduction

One of the most important development in the field of concrete in the last few decades was the development of self-compacting concrete (SCC) by Okamura in the year 1986. It was developed to overcome the problems of compaction and improve the durability of concrete. Since its development in the 1980s, it was used in tunnels, bridge constructions, silos, etc. (Ouchi, 2001; Bennenk, 2001). Şahmaran et al. (2005) defined SCC as "a concrete which has little resistance to flow so that it can be placed and compacted under its own weight with little or no vibration effort, yet possesses enough viscosity to be handled without segregation or bleeding". One of the most important advantages of using SCC in construction over normal concrete (NC) is the flowability. And also, using

HSSCC, it can reduce the considerable number of the skilled workforce and need for good quality control; thereby it reduces the time of construction. It was also reported that HSSCC is more economical than conventional concrete (Fikas, 2017). However, because of its requirement of 'highly flowing nature', proper care should be taken so as to achieve filling and passing ability without any segregation (Sonebi et al., 2007). HSSCC requires lower water to binder ratio with higher cement content and limiting the size of coarse aggregates (CAs) (Safiuddin, 2008). The production of HSSCC also requires suitable chemical admixtures to reduce water content by decreasing interparticle friction but maintaining required workability and also supplementary cementitious materials so as to fill the voids to make the concrete denser increasing its compressive strength (Safiuddin et al., 2009; Hossain and Lachemi, 2010).

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.

Normally, when the beams without or little transverse reinforcement are subjected to moments and shear forces, they fail mainly because of shear even before reaching its full flexural capacity. This failure should be avoided since it is a sudden and catastrophic failure. To prevent this shear failure, beams are provided with transverse reinforcement. This increases labour cost required for installation. Also, casting beams with the transverse reinforcement at closed spacing will increase the voids in the concrete and affects the bond between the steel and concrete.

The important parameters which resist the shear are – the strength of the uncracked region (20%–40%), dowel action of longitudinal steel (15%–25%) and the aggregate interlock mechanism (35%–50%) (Taylor, 1974). The aggregate interlock mechanism, 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 behaviour of HSSCC is necessary.

Previously, many researchers (Hassan et al., 2008, 2010; Lachemi et al., 2005) have carried out studies on the shear behaviour of SCC by varying the CA contents and comparing it with NC beams. The results showed that the shear capacity of NC beams is higher than SCC beams. Thus, many other researchers (Safan, 2012; Biolzi et al., 2014) 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 (Fritih et al., 2013; Kumari et al., 2020; Cholker and Tantray, 2021) have also suggested the use of fibres like steel and polypropylene for improving the cracking behaviour and ductility.

SCC having higher compressive strength (more than 70 MPa), solves problems of filling the voids and increasing the bond between the steel and concrete. But, 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 (Hashemi et al., 2020). 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.

In the present experimental work, the shear capacity of HSSCC slender beams for three different grades, i.e., M70, M80 and M90 designated as M1, M2 and M3 respectively is studied. All the 18 beams were having different stirrup spacing and its effect on shear behaviour is discussed. Not much work has been done on beams with lower transverse reinforcement index, $\rho_w f_y$ and in the present work, $\rho_w f_y$ ranges between 0.276 to 0.80.

2 Experimental program

2.1 Properties of materials

Proportioning of concrete constituents like cement, fine aggregates (FAs), CAs, mineral and chemical admixtures and water is very important in producing SCC. To achieve the desired qualities of SCC, it is essential to understand the influence of each constituent material on flow behaviour at the paste scale. Producing high strength SCC needs materials of good quality. Along with cement, water and aggregate, constituents like mineral and chemical admixture is a must for producing SCC. Chemical admixtures in SCC controls the properties like slump and flow, while, mineral admixtures in SCC enhance the compressive strength. Selection of cement is of utmost importance in HSSCC production as the chemical and physical characteristics of cement affects the compressive strength of concrete more than any other single material. In the present experimental work, ordinary Portland cement (OPC) 53 grade was used. FA was obtained from the bed of Krishna River, Karnataka which was locally available. The sand was black in colour and conforms to zone II grade as per IS code specification [IS: 383-1970]. CAs were obtained from locally available stone crushers which were crushed basalt stones having a specific gravity of 2.7. To achieve high strength, fly ash and silica fume were used as mineral admixtures which help in filling the voids (Singh and Kaur, 2022). Master Glenium-Sky 8233 was used as superplasticiser along with viscosity modifying agent (VMA) to increase the workability and reduce water content in the concrete (Mahdi and Ismael, 2021).

Table 1 Trial mix proportions

Mix trial no.	*W/B ratio*	*Cement Kg/m³*	*Fly ash %*	*Silica fume %*	*Sand Kg/m³*	*CA Kg/m³*	*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

Initially, to produce high strength SCC with strength up to 90 MPa, a series of trial mix proportions were produced by varying the cement content, CA content, FA content and w/c ratio. All the mixes were checked to satisfy the SCC characteristics as per EFNARC guidelines. A final mix proportion was finalised based on the fresh properties obtained by testing all the mixes. Variations with fly ash and silica fume were then done to achieve desired target strength of 70 MPa, 80 MPa and 90 MPa. Table 1 shows the trial mix proportions for M1, M2 and M3 mixes.

Table 2 Fresh properties of HSSCC

Concrete designation	*M1*	*M2*	*M3*
Slump flow test (diameter in mm)	680	670	675
T500 time (sec)	4.02	4.1	4.04
V-funnel test time in (sec)	10.1	11.55	10.15
L-box test value in (H2/H1)	0.88	0.8	0.85

For evaluating the fresh properties, EFNARC (2002) guidelines were followed and tests like slump flow, T500, V-funnel and L-box were conducted to ascertain the concrete is SCC. Table 2 shows the fresh properties of HSSCC.

2.2 Testing details

All the beams were having rectangular cross section with width (b_w), 175 mm, overall depth (h), 300 mm and effective depth, (d) 243 mm and length of 1.6 m. In three beams, longitudinal tensile steel ratio, ρ, used is 2.5% and in the other three beams, ρ used is 2%.

Two bars of 12 mm diameter were used on compression side, in all the beams and the stirrups used were of 6 mm diameter. Figure 1 shows the details of reinforcement and Table 3 gives the details of properties of reinforcing steel used in the experimental program. All the beams were designed in such a way that they should fail in shear only with the main variable, transverse reinforcement ratio ρ_w.

Table 3 Properties of reinforcing steel

Diameter, ϕ (mm)	*Yield stress, f_y (MPa)*	*Tensile strength, f_{st} (MPa)*	*f_{st}/f_y*
6	460	510	1.10
12	580	650	1.12
16	560	630	1.125
20	540	610	1.125
25	530	590	1.113

Figure 1 Details of reinforcement

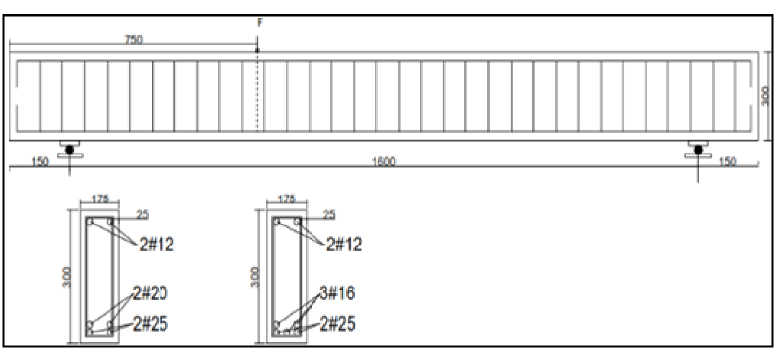


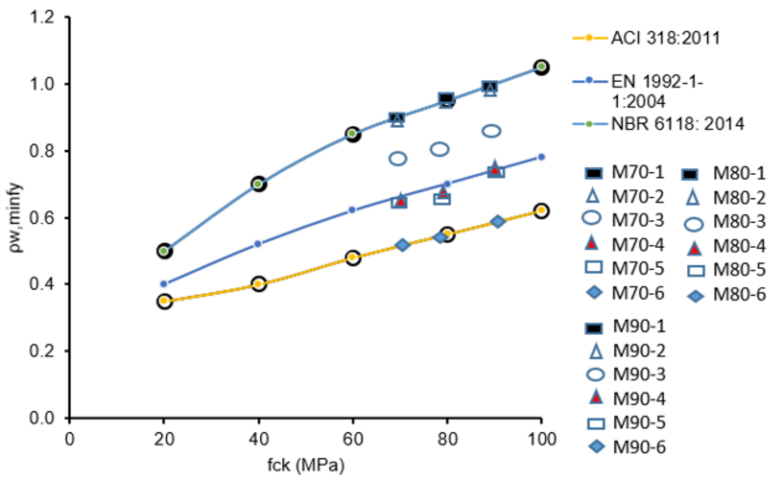
Table 4 Details of beams with transverse reinforcement

Mix	*Beam*	*Transverse reinforcement*					*Longitudinal tension reinforcement*	
		Diameter Φ (mm)	*Spacing s (mm)*	ρ_w *(%)*	$\rho_w f_y$ *(MPa)*	$\rho_w f_{st}$ *(MPa)*	*Steel*	*ρ (%)*
M1 mix	M70-1	6	75	0.18	0.82	0.882	2#25 mm + 2#20 mm	2.5
	M70-2		100	0.14	0.64	0.686	2#25 mm + 2#20 mm	2.5
	M70-3		125	0.11	0.50	0.539	2#25 mm + 2#20 mm	2.5
	M70-4		150	0.09	0.414	0.441	2#20 mm + 3#16 mm	2
	M70-5		175	0.07	0.322	0.343	2#20 mm + 3#16 mm	2
	M70-6		200	0.006	0.276	0.294	2#20 mm + 3#16 mm	2
M2 mix	M80-1	6	75	0.18	0.82	0.882	2#25 mm + 2#20 mm	2.5
	M80-2		100	0.14	0.64	0.686	2#25 mm + 2#20 mm	2.5
	M80-3		125	0.11	0.50	0.539	2#25 mm + 2#20 mm	2.5
	M80-4		150	0.09	0.414	0.441	2#20 mm + 3#16 mm	2
	M80-5		175	0.07	0.322	0.343	2#20 mm + 3#16 mm	2
	M80-6		200	0.006	0.276	0.294	2#20 mm + 3#16 mm	2
M3 mix	M90-1	6	75	0.18	0.82	0.882	2#25 mm + 2#20 mm	2.5
	M90-2		100	0.14	0.64	0.686	2#25 mm + 2#20 mm	2.5
	M90-3		125	0.11	0.50	0.539	2#25 mm + 2#20 mm	2.5
	M90-4		150	0.09	0.414	0.441	2#20 mm + 3#16 mm	2
	M90-5		175	0.07	0.322	0.343	2#20 mm + 3#16 mm	2
	M90-6		200	0.006	0.276	0.294	2#20 mm + 3#16 mm	2

Table 4 gives the details of test specimens for all the three grades of M1, M2 and M3 HSSCC beams. All the beams are roller supported and the beams were placed on rectangular steel plates of size 90 mm × 150 mm × 12.5 mm as shown in Figure 1. Loadings were applied at a shear span of 600 mm with shear span to depth ratio (a/d) of 2.5. To measure the deflection at cross-section of maximum bending moment and to record loads, displacement and strains, LVDTs along with 24-channel data acquisition system was used. Beams were loaded until failure.

Shear reinforcement index, $\rho_w f_y$, are selected such that they are in the range of $\rho_{w,min} f_{yk}$ as per international codes. Figure 2 shows the graph comparing $\rho_w f_y$ values for the beams tested and $\rho_{w,min} f_{yk}$ given by different codes. It can be seen that the values of all the codes are quite different. Spacing of stirrups in this experimental program approximately ranges between 0.3 d to 0.8 d.

Figure 2 Comparison of $\rho_{w,min} f_{yk}$ with f_{ck} (see online version for colours)



3 Results and discussion

3.1 Failure of beams

The failure in all 18 beams occurred due to the shear failure and yielding of tension steel was not observed. It was also observed that in beams having lower values of $\rho_w f_y$ with less than 0.5, the failure occurred due to rupture of stirrups and diagonal cracks were seen. In beams, M70-1, M70-2, M80-1, M80-2, M90-1 and M90-2, which were having $\rho_w f_y$ of 0.82 and 0.64 respectively, failure occurred due to shear but rupture of stirrups was not seen since the spacing of transverse reinforcement was close, i.e., 75 mm and 100 mm.

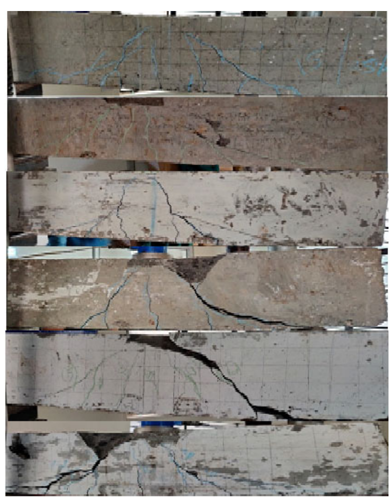
When the loading was applied initially the flexural cracks formed which were smaller, mostly in mid-span regions with angles almost vertical. When the loads were further increased, the crack widths and depth also increased. With the increase in load, the angle of cracks was becoming shallower and diagonal cracks formed. Table 5 shows the details of loads at first crack V_{CR} and shear strength V_U for all the three mixes. Cracking patterns can be seen in Figure 3.

Figure 4 shows the shear strength with respect to the $\rho_w f_y$ for different mixes. It can be observed from the figure that, as the transverse reinforcement in the beams increases, the shear capacity of the beams also increases. In addition, the longitudinal reinforcement also plays an important role in the shear carrying capacity of HSSCC beams.

Table 5 Critical diagonal cracks and shear forces

Beam	$\rho_w f_y$ *(MPa)*	ρ *(%)*	V_{CR} *(kN)*	V_U *(kN)*
M70-1	0.82	2.5	90	186
M70-2	0.64	2.5	99	156
M70-3	0.50	2.5	92	146
M70-4	0.414	2	90	131
M70-5	0.322	2	82	108
M70-6	0.276	2	78	92
M80-1	0.82	2.5	98	196
M80-2	0.64	2.5	107	166
M80-3	0.50	2.5	100	156
M80-4	0.414	2	98	141
M80-5	0.322	2	90	118
M80-6	0.276	2	86	102
M90-1	0.82	2.5	106	210
M90-2	0.64	2.5	115	180
M90-3	0.50	2.5	108	170
M90-4	0.414	2	106	155
M90-5	0.322	2	98	132
M90-6	0.276	2	94	116

Figure 3 Crack patterns after testing (see online version for colours)



Beams M70-6, M80-6 and M90-6 have lower shear strength since the amount of transverse and longitudinal reinforcement is less as compared to other beams. For a constant longitudinal ratio of 2%, the shear strength of M70-6, M80-6 and M90-6 beams was 92 kN, 102kN and 116kN respectively which was reduced by approximately 25% to 30% as compared to M70-4, M80-4 and M90-4 beams. These beams had shear strength of 131 kN, 141 kN and 155 kN respectively and longitudinal reinforcement of 2% which is much less than beams M70-1, M80-2 and M90-3 beams which were having longitudinal reinforcement of 2.5%. Thus, longitudinal reinforcement also affects the shear capacity of beams which is also proved by many other researchers (Dashlejeh and Arabzadeh, 2019). But most of the codes consider only the effect of transverse reinforcement and depth of the beam in equations and ignore the effect of longitudinal reinforcement.

Figure 4 Shear strength as a function of $\rho_w f_y$ (see online version for colours)

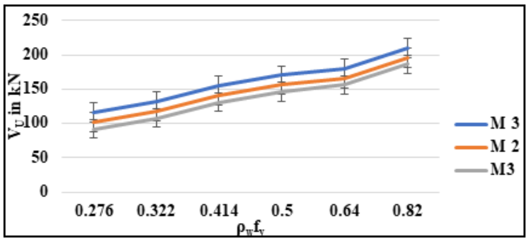
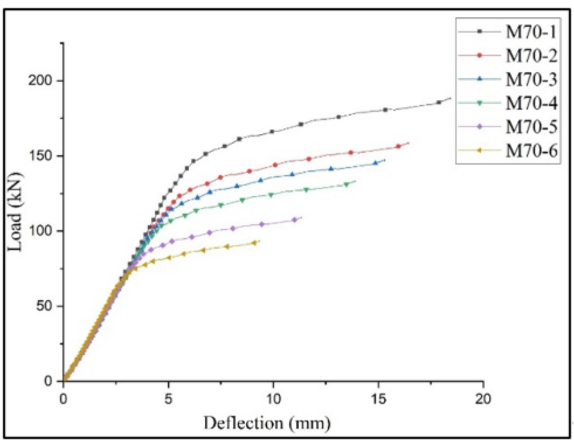


Figure 5 Load vs. deflection for M1 mix (see online version for colours)



3.2 Load vs. deflection

Figure 5 to Figure 7 shows the load vs. deflection graphs for M1, M2 and M3 mixes respectively. Deflection was not much significant in beams having lower $\rho_w f_y$ values in the initial stages and for most of the beams even after first cracking. The beams having higher $\rho_w f_y$ values showed higher deflections as well as shear strength. For beams having lower values of $\rho_w f_y$, i.e., 0.414, 0.322 and 0.276 (beams – M70-4, M70-5, M70-6, M80-4, M80-5, M80-6and M90-4, M90-5, M90-6), there was not much difference in deflection since the variation in $\rho_w f_y$ is less in comparison with other beams. 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 which was also observed by Momin et al. (2021).

Figure 6 Load vs. deflection for M2 mix (see online version for colours)

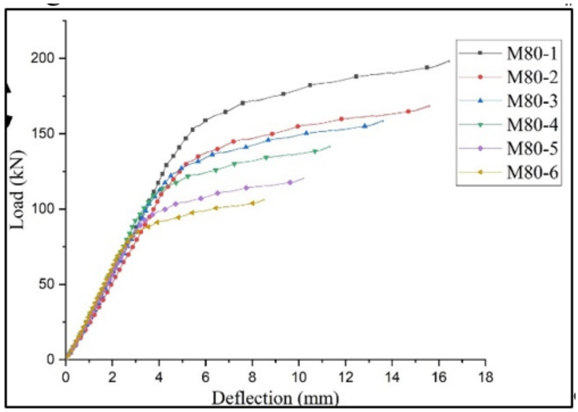
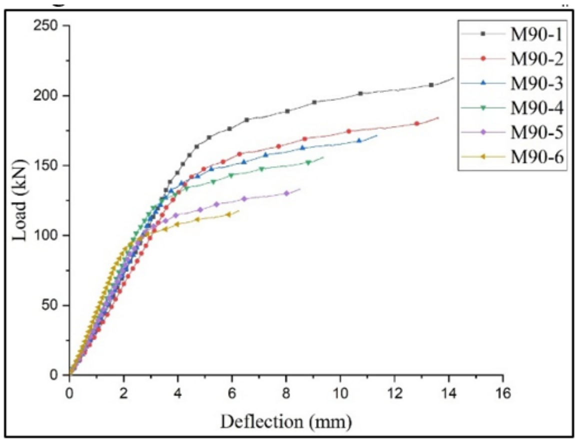


Figure 7 Load vs. deflection for M3 mix (see online version for colours)



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.

3.3 Shear provisions in different codes

Since many last decades, much work has been carried out on understanding the shear behaviour of RC beams and has produced several formulae to predict the shear capacities but till date, there is still difference of opinion. Different codes use different formulae which are either based on only concrete or both concrete and steel and thus the results differ from one another. In this research work, to understand the shear behaviour of HSSCC beams experimental testing was carried out and the results were compared with four international codes:

1 level I and III approximation of fib model code

2 ACI 318-11

3 EN 1992-11:2004

4 ABNT NBR 6118:2014.

Among the above four codes, the level III approximation of fib model code (International Federation for Structural Concrete, 2013), ACI 318:2011 (American Concrete Institute: ACI 318-11, 2011) and ABNT NBR 6118:2014 (Associação Brasileira de Normas Técnicas: ABNT NBR 6118:2014, 2014) takes in to account the effect of both concrete, V_C and stirrups, V_S to predict the shear strength of beams. Level I approximation of fib model code (International Federation for Structural Concrete, 2013) and EN 1992-1-1:2004 (European Committee for Standardization: EN 1992-11:2004, 2004) considers only the effect of stirrups, i.e., $V_{pred} = V_S$. The values of $\rho_{w,min}f_y$ and V_C are more as per ABNT NBR 6118:2014 (Associação Brasileira de Normas Técnicas: ABNT NBR 6118:2014, 2014) in comparison with the level III approximation of fib model code 2010 (International Federation for Structural Concrete, 2013) and ACI 318:2011 (American Concrete Institute: ACI 318-11, 2011). Table 6 shows the details of ratios of V_U/V_{pred} for all the three mixes. Comparison of experimentally tested results is made with codal provisions. The numbers in the bracket indicate $\rho_{w,min}f_y > \rho_w f_y$.

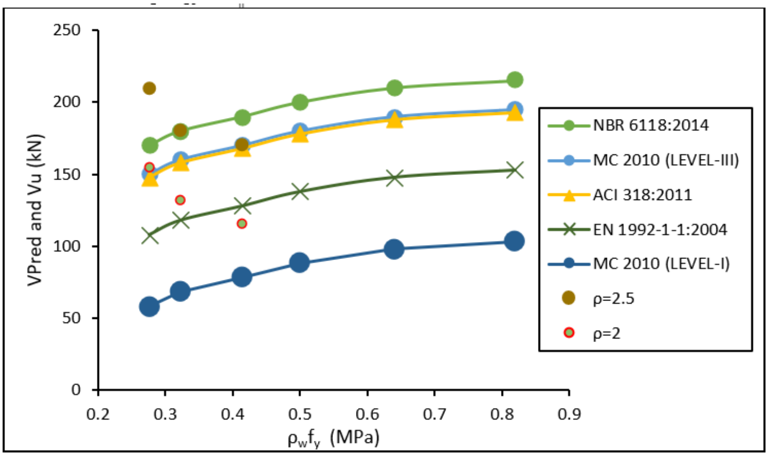
Table 6 Comparison of ratios of V_U/V_{pred}

Code	*V_U/V_R*					
	M70-1	*M70-2*	*M70-3*	*M70-4*	*M70-5*	*M70-6*
fib MC2010 (level I)	2.09	2.08	1.69	1.81	1.52	(2.49)
fib MC2010 (level III)	1.14	1.13	0.79	0.78	0.71	(1.12)
ACI 318:2011	1.18	1.17	0.89	0.81	0.68	0.93
EN 1992-1-1:2004	1.49	1.44	1.19	1.27	1.08	(1.69)
NBR 6118:2014	1.01	0.98	(0.86)	(0.83)	(0.74)	(0.89)
	M80-1	*M80-2*	*M80-3*	*M80-4*	*M80-5*	*M80-6*
fib MC2010 (level I)	2.09	2.08	1.69	1.81	1.52	(2.49)
fib MC2010 (level III)	1.18	1.17	0.81	0.82	0.74	(1.09)
ACI 318:2011	1.22	1.21	0.93	0.84	0.71	0.98
EN 1992-1-1:2004	1.49	1.44	1.19	1.27	1.08	(1.69)
NBR 6118:2014	1.07	1.03	(0.83)	(0.79)	(0.69)	(0.84)
	M90-1	*M90-2*	*M90-3*	*M90-4*	*M90-5*	*M90-6*
fib MC2010 (level I)	2.09	2.08	1.69	1.81	1.52	(2.49)
fib MC2010 (level III)	1.26	1.24	0.89	0.88	0.79	(1.02)
ACI 318:2011	1.29	1.28	0.99	0.91	0.76	1.03
EN 1992-1-1:2004	1.49	1.44	1.19	1.27	1.08	(1.69)
NBR 6118:2014	1.13	1.09	(0.79)	(0.74)	(0.63)	(0.78)

In Table 6, to find the values of V_{pred}, materials and shear resistance factors are taken as 1 and for characteristics strength, mean values of compressive strength and steel strength is considered. For calculating the shear strength using level I approximation of fib model code (International Federation for Structural Concrete, 2013) and EN 1992-1-1:2004 (European Committee for Standardization: EN 1992-11:2004, 2004), least permissible angle among concrete compression strut and beam axis of the truss models was used.

Figure 8 shows the experimentally tested shear strength and predicted shear strengths using different codes. It can be seen that level I approximation of fib model code (International Federation for Structural Concrete, 2013) and EN 1992-1-1:2004 (European Committee for Standardization: EN 1992-11:2004, 2004) provided conservative results as compared to other codes since they do not consider the effect of compressive strength of concrete while calculating the shear strength. Similar values of shear strength were obtained using level III approximation of fib model code 2010 (International Federation for Structural Concrete, 2013) and ACI 318:2011 for the beams with lower tensile reinforcement even though $\rho_{w,min}f_y$ were nearly equal to $\rho_w f_y$. It can also be seen that beams with $\rho_{w,min}f_y < \rho_w f_y$, no code provided the value of $V_U/V_R < 1$.

Figure 8 Experimentally tested vs. predicted shear strength (see online version for colours)



4 Conclusions

A total of 18 number of HSSCC slender beams, six beams for each mix, i.e., M1, M2 and M3 with transverse reinforcement were tested with different spacing. Following conclusions are drawn from the present experimental program:

1 High deformability is seen in HSSCC as compared to NC beams which are primarily because of higher paste content and aggregates are less deformable.

2 Beams with $\rho_w f_y$ values less than 0.5, the failure occurred due to rupture of stirrups and diagonal cracks were seen.

3 For a constant longitudinal ratio of 2%, the shear strength of M70-6, M80-6 and M90-6 beams was 92 kN, 102kN and 116kN respectively which was reduced by approximately 25% to 30% as compared to M70-4, M80-4 and M90-4 beams.

4 Longitudinal reinforcement affects the shear capacity of beams, but most of the codes, consider only the effect of transverse reinforcement and depth of the beam in equations.

5 Increase in longitudinal steel ratio and increase in compressive strength increased the post cracking flexural stiffness.

6 Level I approximation of fib model code and EN 1992-1-1:2004 provided conservative results as compared to other codes since they do not consider the effect of compressive strength of concrete.

7 Most of the codal provisions do not safely predict the shear capacity of beams with lower $\rho_w f_y$ values even when $\rho_{w,min} f_y > \rho_w f_y$.

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