Shear Behavior of High Strength Self-Compacting Concrete with Lower Transverse Reinforcement Index

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Received: Sept. 29, 2021; Accepted: Oct. 17, 2021

Self-Compacting Concrete (SCC) generally has lesser coarse aggregate contents and also the maximum size of aggregates is limited as compared to Normal Vibrating Concrete (NVC) for the same class of strength. This results in reduced aggregate interlock in Self-Compacting concrete as against NVC, which affects the shear strength of slender beams and thus, SCC might have lower shear strength. In this article, an experimental programme which includes six slender beams of High-Strength Self Compacting Concrete (HSSCC) with compressive strength more of than 90 MPa and with different stirrup spacing is presented. Experimental test results of shear strength of HSSCC beams are compared with high strength NVC beams for different stirrups spacing. The results showed the ultimate shear stress of HSSCC beams is lower than NVC beams and increase in transverse reinforcement index, $\rho_w f_y$, in HSSCC beams decreases this difference. The results are also compared with different code provisions. 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.

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

http://dx.doi.org/10.6180/10.6180/jase.202208_25(4).0010

1. Introduction

Rapidly increasing use of chemical and mineral admixtures, developments in the area of construction technology and a better understanding of the behavior of fresh and hardened concrete have contributed to our ability and confidence in using concrete in more and more challenging conditions. It has led to the development of special concretes, special construction methods and improvement in concrete properties. Given the dense reinforcement around which concrete is required to move, or the complicated geometry of the formwork, and the distances over which concrete needs to be pumped, makes a high demand on the workability of the concrete, and practically "flowing" concrete is required [1]. In order that the concrete should not segregate, the workability and flowability of concrete plays an important role to carry denser aggregate fraction without segregation [2]. Self-Compacting Concrete (SCC) provides a solution by overcoming these problems as it can flow, compact by itself without any need of vibration or another means of compaction and fills completely into the formwork with no segregation [3, 4].

High Strength SCC (HSSCC) requires lower water to binder ratio with higher cement content and limiting the size of coarse aggregates [3]. The production of HSSCC also requires suitable chemical admixture to reduce water content by decreasing interparticle friction but maintaining required workability and also mineral admixtures, to fill the voids to make the concrete denser thereby increasing its compressive strength [4].

Much work has been done on the properties of SCC but very limited literature is available on shear properties of

HSSCC. Among the available research, results are quite contradictory, wherein, some shows that SCC and NVC have similar shear properties [5] and others state SCC has lesser shear strength [6, 7]. This might be mainly because of various parameters which affect the shear properties of beams and also because of various SCC composition, the researchers have used to make the concrete more flowable by opting increased powder content with different mineral admixtures and superplasticizer. Reduced coarse aggregate content and maximum aggregate size results in reduced aggregate interlock between fracture surfaces as compared to NVC.

Aggregate interlock, strength of concrete, steel reinforcement ratio and effective depth are important parameters which affect the ultimate nominal shear stress of beam without stirrups [8]. Aggregate interlock is influenced by the texture of cracks, its width which is depending upon the size and type of aggregates used [9].

Cracks in the higher strength concrete beams generally do not propagate around the aggregates but pass through them resulting in reduced roughness on crack interfaces, which in turn reduces the interlocking capacities [10, 11]. Thus, when using higher strength concrete, some international codes limit the concrete strength and maximum aggregate sizes which are to be considered in shear strength equations. For instance, Eurocode 2 [12] restricts the concrete strength to 50MPa and fib Model Code [13] takes the maximum aggregate size as zero if the strength reaches 70 MPa.

Beams having higher longitudinal reinforcement will have high shear capacities which are mainly because of additional dowel action along with small crack width resulting in improved aggregate interlock with a bigger compression zone. A larger beam will have wide crack and aggregate interlock becomes less effective for the same longitudinal reinforcing ratio and aggregate size. Stirrups increase the shear strength and improves shear transfer mechanism and limits the propagation of shear cracks and may minimize, but not eliminate, the size effect on shear strength of beam [14]. Resende [15] analysed the research work done by other authors who experimentally carried out investigations on shear behaviour of self compacting concrete beams with shear span to effective depth ratio (a/d)geq2 [7, 16–27] and found most of the beam depths were lesser than normal with h≤300mm. Resende [15] compared the shear strength VU of these beams with strengths calculated by different code provisions [13, 28–30] and not much difference was found between means and medians of V_U/V values for SCC and NVC beams. A total of 95 SCC beams (60 beams without stirrups and 35 with stirrups) and 35 NVC beams were analysed and found a high co-efficient of variation V_R in SCC beams which might be because of differences in number of beams. Beams (SCC and NVC) with stirrups does not had any V_U/V_R value less than 1, however, most of the SCC beams without stirrups had V_U/V_R values less than 1.

Hassan et al. [7, 17] and Arezoumandi and Volz [26] used beams with depth >350 mm and the beams were without stirrups. Hassan et al. [7, 17] in their experimental programme used 20% less coarse aggregates in SCC beams than in NVC beams and the SCC beams showed less shear strength as compared to NVC beams. Arezoumandi and Volz [26] used same size coarse aggregate but achieved the SCC characteristics by using superplasticizers and Viscosity Modifying Agents (VMA). Cuenca et al. [19] and Lin and Chen [24] did an experimental investigation on SCC and NVC beams with depth greater than 350 mm. Cuenca et al. [19] used 10% lesser coarse aggregate for SCC beams and both beams showed similar shear properties. Lin and Chen [24] compared two types of SCC beams (one with similar coarse aggregate content and the other 14% less coarse aggregate content) with NVC beams and found that SCC beams with lesser coarse aggregate content showed lower shear capacities.

Based on the literature study on shear behaviour of SCC beams, it was found that all the researches carried out are either on low strength SCC or with lower depth beams. In this paper, we have summarized the results of experimental study on shear properties of high strength self-compacting concrete with strengths more than 90MPa and varying 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 programme

2.1. Properties of materials

In this experimental work, Ordinary Portland Cement (OPC) conforming to IS: 12269-1987 has been used. Fly ash and Silica Fume (SF) were incorporated as mineral admixtures. They together act as a binder in the concrete. The chemical and physical properties of OPC, fly ash and silica fume are given in Table 1. The fineness of mineral admixtures was checked by wet sieving over a 45-μm sieve every 2 hours as per ASTM C430-08 (2009a) [31]. After 20 hours, it was observed that passing was more than 90%, better than the amount of OPC passing 45-μm sieve.

Graded crushed aggregates having 12 mm downsize and fineness modulus of 6.78. and natural river sand having fineness modulus of 3.43 is used to produce HSSCC.

Table 1. Properties of materials used in concrete

Chemical composition	OPC	Fly ash	Silica Fume
SiO2 (%)	19.3	62.63	91.9
Al2O3 (%)	5.2	23.34	0.7
Fe2O3 (%)	2.4	3.93	0.3
CaO (%)	61.2	2.04	-
MgO (%)	1.25	1.3	0.1
SO3 (%)	3.2	0.6	0.1
Na2O (%)	0.069	0.63	0.06
Density (kg/m^3)	3089	2270	2260
Specific surface area BET (10^3/kg)	0.55	2.14	26.43
Fineness % Retain on 90μ sieve	3%	-	-
Initial setting time (min)	62	-	-
Final setting time (min)	370	-	-
Specific gravity	2.96	2.2	2.15
Compressive Strength(MPA)			
7-Days	45	-	-
28-days	65	-	-

Table 2. Physical and chemical properties of Master Glenium Sky 8233

Parameter	Result
Colour	Light brown
Boiling point	>100 °c
Viscosity (25 °c)	=50-150 cps
Specific gravity (25 °c)	=1.2
Soluble in water	Soluble
pH	≥ 6
Chloride ion content	< 0.2%

Specific gravity of Fine Aggregate (FA) and Coarse Aggregates (CA) was 2.62 and 2.70 respectively. Master Glenium-Sky 8233 was used as superplasticizer to increase the workability and reduce water content in the concrete. Physical and chemical properties of Master Glenium Sky 8233 are tabulated in Table 2. The viscosity modifying agent Master matrix 2 is used to make the concrete more viscous and prevent segregation. In the present work, optimum dosage of superplasticizer and VMA used is 3% and 0.5% respectively.

A series of trial mixes were prepared for achieving a target strength of more than 90 MPa by varying superplasticizer, fly ash and silica fume content to obtain optimum dosage and water-binder ratio in the range of 0.34 to 0.4. For all the mixes, fresh properties were tested as per EFNARC (2002) guidelines to satisfy the conditions of SCC. After obtaining the results, a final mix proportion was finalized.

To study the hardened properties, cubes of size 150mm × 150mm were cast along with the beams. A Revolving pan type concrete mixer was used to prepare cubes, cylinders and beams. To evaluate fresh properties, EFNARC (2002) guidelines were followed and tests like slump flow, T500, V- Funnel and L-Box were conducted to ascertain the SCC requirements. Table 3 shows the fresh and hardened properties of HSSCC. The average compressive strength and split tensile strength was 94.36 MPa and 4.25 MPa respectively. While conducting split tensile test on cylinders, it was found that some coarse aggregates fractured.

Polyethylene sheets were used to cure the cubes and cylinders on the first day and then moist cured for 28 days. After casting the beams, they were put under plastic sheets for 10 days and then formwork was removed and kept under normal conditions. Table 4 shows the properties of reinforcing steel used in the beams.

2.2. Details of beams

All the beams were having rectangular cross-section with width (b_w) 175 mm, overall depth (h) 300 mm, 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 3 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. All the beams were designed in such a way that they should fail in shear only with main variable, transverse reinforcement ratio ρ_w. Shear reinforcement index, $\rho_w f_y$, are selected such that they are in the range of $\rho_{w,min} f_y$ as per international codes [13, 29, 30, 32]. Fig. 1 shows the graph comparing $\rho_w f_y$ values for the beams tested and $\rho_{w,min} f_y$ given by different codes. It can be seen that the values of all the codes are quite different. Spacing of stirrups in this experimental programme approximately ranges between 0.3d to 0.8d. Table 5 gives the details of beam reinforcement.

Table 3. Fresh and Hardened Properties of HSSCC

Fresh Properties		Hardened Properties	
Slump flow (mm)	710	Compressive strength, f_{ck} (MPa)	94.36
$T_5 00$ (Sec)	3.50	Split tensile strength, f_{ct} (MPa)	4.25
V- Funnel (Sec)	9.34	Tangent modulus of elasticity, Ec (Gpa)	31
L-Box (H_2/H_1)	0.95		

Table 4. Properties of reinforcing steel

Diameter, ϕ (mm)	Yield stress, f_y (MPa)	Tensile strength, f_{st} (MPa)	f_{st}/f_y
6	460	490	1.05
12	580	630	1.08
16	560	590	1.05
20	540	570	1.055
25	530	560	1.05

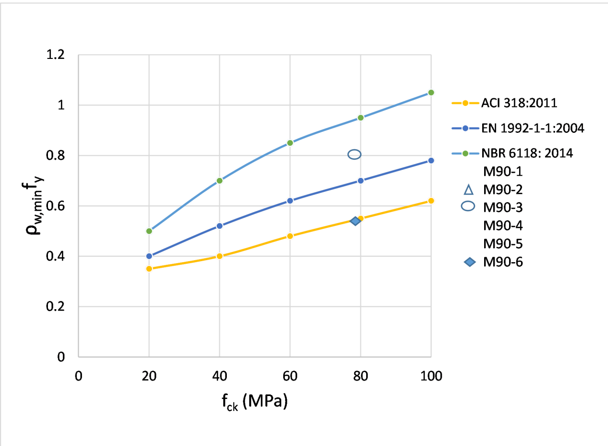

Fig. 1. Comparison of $\rho_{w,min} f_y$ with f_{ck}

2.3. Methodology and results

All the beams are roller supported and the beams were placed on rectangular steel plates of size 90×150×12.5 mm as shown in Fig. 2. Loadings were applied at a shear span of 600mm 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.

The beams failed in shear and no yielding of tension steel was observed. It was also observed by the visual inspection that all the beams except M90-1 and M90-2, were failed by rupture of transverse reinforcement with diagonal cracks. Beams M90-1 and M90-2 with $\rho_w f_y$ values of 0.82 and 0.64 respectively also failed by shear but rupture of transverse reinforcement was not observed. The reason behind this may be because of closer stirrup spacing of 75 mm and 100 mm in M90-1 and M90-2 beams respectively, while the spacing is larger in other beams. The diagonal cracks in the beams developed in the later stages as the load increased as an extension of flexure shear cracks near the support after reaching the mid-depth of beams. The load at first critical crack, VCR and ultimate shear forces, V_U for the beams tested are presented in Table 6. Crack patterns after testing are shown in Fig. 3.

Experimental values of Ultimate shear force as a function of $\rho_w f_y$ is represented graphically in Fig. 4. The beam M90-6 with $\rho_w f_y$ value 0.276 had the lowest shear strength. Beam M90-4 with tension steel reinforcement of 2% had ultimate shear force of 155kN which is around 10% less than beam M90-3 with $\rho_w f_y$ value 0.50 and tension steel reinforcement of 2.5%.

Thus, the shear strength of beams increases with increase in tension steel reinforcement which is also observed by other researchers. However, most of the codes does not consider the effect of tension steel reinforcement in their formulas but consider only the effective depth. Fig. 5 shows the deflection curves for the beams. It was observed that deflection was more noticeable after the first crack in the beams having lower $\rho_w f_y$ values. With the increase in the $\rho_w f_y$ values, the peak shear strength and deflection increased. It was also observed that for M90-4, M90-5 and M90-6 beams, the peak shear strength was almost similar since the variation of $\rho_w f_y$ values is lesser as compared to other beams. The first crack was almost 0.2 mm when it was visible to naked eye.

3. Shear provisions of different codes

In the last century, many researchers have worked on calculating the shear capacities of RC beams and developed many formulas, yet there is no consensual approach. All the codebooks providing shear provisions uses different formulas to find out the shear capacities of RC beams, which leads to different results. In the present work, the

Table 5. Details of Beams

Beam	f_{ck} (MPa)	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 (%)
M90- 1	96		75	0.18	0.82	0.882	2#25 mm+2#20 mm	2.5
M90- 2	92.5		100	0.14	0.64	0.686	2#25 mm+2#20 mm	2.5
M90- 3	94.63	6	125	0.11	0.50	0.539	2#25 mm+2#20 mm	2.5
M90- 4	94.69		150	0.09	0.414	0.441	2#20 mm+3#16 mm	2
M90- 5	96.43		175	0.07	0.322	0.343	2#20 mm+3#16 mm	2
M90- 6	92.3		200	0.006	0.276	0.294	2#20 mm+3#16 mm	2

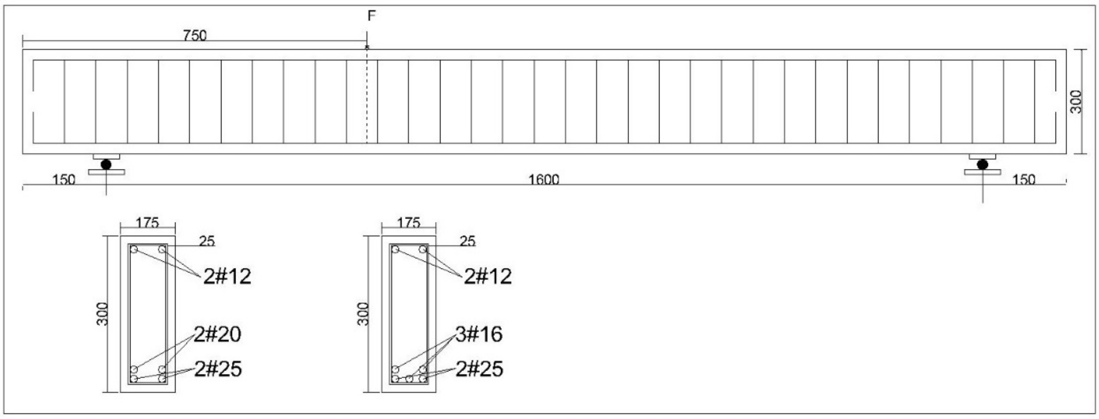

Fig. 2. Details of Reinforcement

Table 6. Critical diagonal cracks and shear forces

Beam	$\rho_w f_y$ (MPa)	ρ (%)	V_{CR} (kN)	V_U (kN)
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

experimental results are compared with 4 international code provisions [13, 28–30]. The Level III approximation of fib Model Code [13], ACI 318:2011 [28] and ABNT NBR 6118:2014 [29] consider the contribution made by concrete as well as transverse steel, while calculating the shear strength (V_R=V_S+V_C), whereas, the Level I approximation of fib Model Code [13] and EN 1992-1-1:2004 [29] consider the contribution of only web steel (VR=VS). $\rho_{w,min} f_y$ values and V_C values were higher using ABNT NBR 6118:2014 [28] as compared to the Level III approximation of fib Model Code 2010 [13] and ACI 318:2011 [31].

The ratio of experimental results to calculated shear capacities using codal provisions (V_U/V_R) is presented in Table 7. In this table, the values in brackets indicate $\rho_{w,min} f_y > \rho_w f_y$.

In order to calculate V_R, the material and shear resistance factor is considered as 1 and average concrete and steel strengths are taken as characteristic strengths. To calculate V_S as per Level I approximation of fib Model Code [13] and EN 1992 -1-1:2004 [29], least permissible angle between the concrete compression strut and beam axis of the truss models is used.

The experimental results and calculated shear strengths are shown in Fig. 6. In Fig. 6, the line connects the V_R values and for $\rho_{w,min} f_y > \rho_w f_y$, the lines are shown dashed. It can be observed that, Level I approximation of fib Model Code [13] and EN 1992-1-1:2004 [29] code formulas provide more conservative results, since they consider the contribution of only web steel, whereas, Level III approximation of fib Model Code 2010 [13] and ACI 318:2011 [28] gives approximately similar values especially for those beams, which are having lower tensile reinforcement although $\rho_{w,min} f_y$ are approximately equal to $\rho_w f_y$. For the beams having $\rho_{w,min} f_y < \rho_w f_y$, none of the codes resulted in V_U/V_R<1.

4. Comparison of NVC and HSSCC Beams

The experimental results of all the 6 HSSCC beams are compared to the NVC beams tested by Garcia [32]. The NVC beams were cast using silica fume as mineral admixture (10%), w/c ratio around 0.3 and 40% coarse aggregates (maximum size=19 mm). The beams were having rectan-

Table 7. Ratios of experimental results to calculated shear capacities using codal provisions

Code	V_U/V_R					
	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)

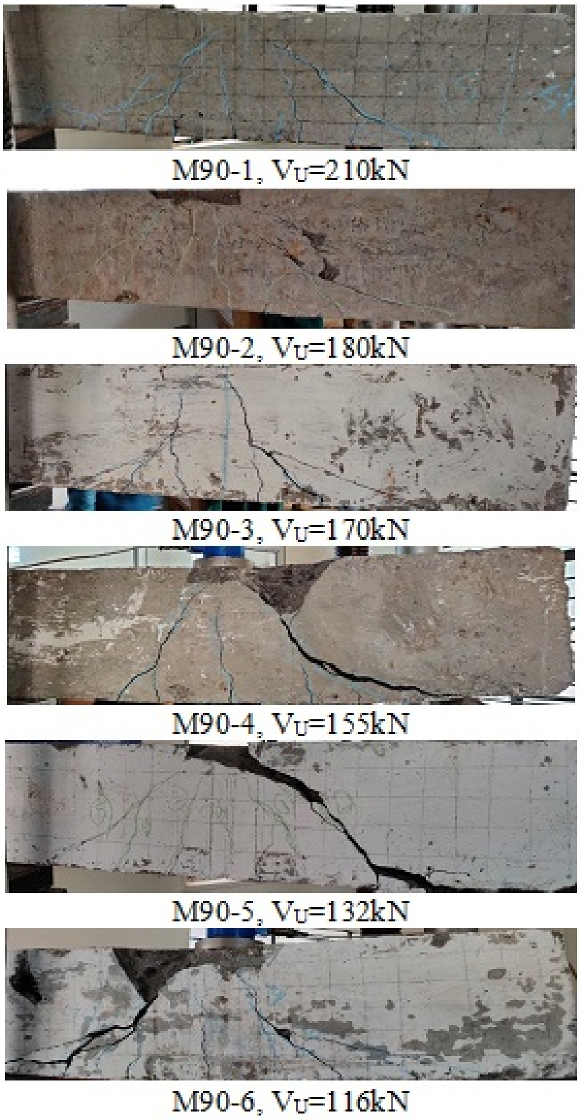

Fig. 3. Crack Patterns

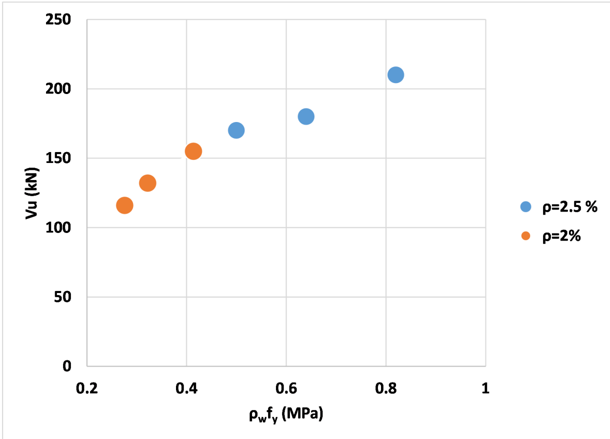

Fig. 4. Experimental V_U as a function of $\rho_w f_y$

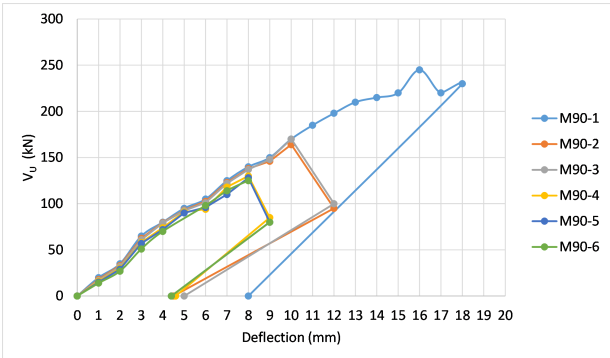

Fig. 5. Deflection Vs shear strength at critical shear span

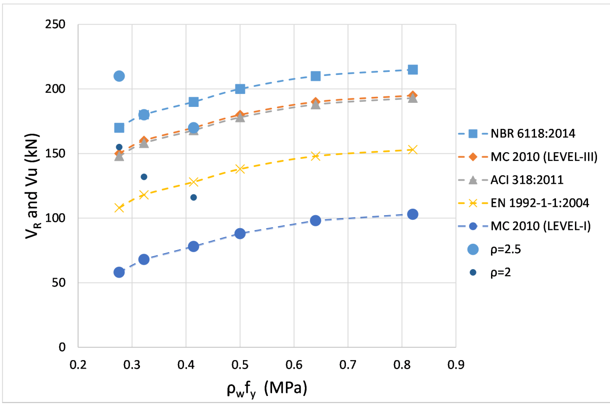

Fig. 6. Experimental results and calculated shear strength

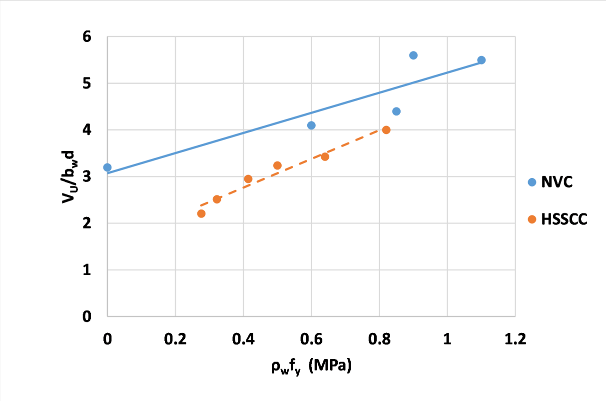

Fig. 7. Ultimate shear stresses of HSSCC and NVC beams

gular section of width-150 mm, overall depth-450 mm and effective depth-405 mm with tension steel reinforcement of about 2.6%. $\rho_w f_y$ was in between 0 to 1.16 MPa with shear span to depth ratio of 3.

Two of the beams failed by yielding of tension steel reinforcement and all the other beams failed by shear failure. Fig. 7 shows the comparison of ultimate shear stresses of HSSCC beams with that of NVC beams. It can be seen from the figure that HSSCC beams have lower ultimate shear stresses compared to NVC beams. It was observed that as the transverse reinforcement index, $\rho_w f_y$ increases, the differences in ultimate shear stress of HSSCC and NVC beams is reduced. Thus, for transverse reinforcement index with more than 1, the shear stress matches with the NVC beams, while for less than 1, the shear stress of HSSCC beams is less than NVC beams.

As per Yu and Bažant [14], the differences in tension steel reinforcement and shear span to depth ratio does not influence the results up to 30% and also, the difference in depth does not affect the results since the presence of transverse reinforcement reduces the size effects.

5. Conclusion

It was observed that HSSCC shows higher deformability as compared to conventional concrete. This high deformability observed was mainly due to the higher amount of paste content present in HSSCC as compared to NVC. The reason behind this is due to the fact that aggregates are less deformable than hardened paste and high deformability can be observed in higher paste content in a hardened composition.

Based on the experimental programme and test results, it is concluded that the ultimate shear stress of HSSCC beams and NVC beams differ based on the constituents of the concrete, compressive strength, depths and transverse reinforcement ratio. The test results of this experimental programme having different stirrup spacing when compared with NVC beams, indicate that the differences in ultimate shear stress is significant and cannot be neglected. For transverse reinforcement index with more than 1, the shear stress matches with the NVC beams, while for less than 1, the shear stress of HSSCC beams is less than NVC beams.

Provisions on shear given by some of the codes do not safely predicts the shear capacities for beams with lower transverse reinforcement index, $\rho_w f_y$ even when $\rho_{w,min} f_y > \rho_w f_y$. It was seen mainly in beams having smaller tension steel reinforcement since the tension steel reinforcement stress at the time of shear failures affect the shear capacities of beams.

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