Study of the minimum shear reinforcement in high strength concrete beams

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Concrete with compressive strength approaching 120 MPa is commonly used in practice. Many questions have been raised regarding the applicability of the design provisions stipulated in the codes of practice. The ACI building code and the British standard code of practice recommend a minimum amount of shear reinforcement, equivalent to a 0.34 MPa and a 0.4 MPa shear stress, respectively. These recommendations are based on the results of beam tests using concrete with compressive strengths up to 40 MPa. In this paper, an experimental investigation of the minimum shear reinforcement of high strength concrete beams was conducted. Tests on rectangular beams, with cube strengths in the range of 35 MPa to 90 MPa and with reinforcing indices, which are defined as the shear stress resisted by shear reinforcement of 0.35 MPa to 0.75 MPa were arranged. Results indicated that the minimum quantity of shear reinforcement specified by codes of practice needs to be increased as the concrete strength increases. A relation between the minimum amount of shear reinforcement and the compressive strength was proposed.

ان تطور الخرسانة عالية المقاومة حيث تصل المقاومة فى الضغط الى ١٢٠ نيوتن /مم٢ بدأ استخدامه بشكل كبير فى العالم. ظهر مع هذا التطور ان الحاجة الماسة لإجراء أبحاث فى هذا الموضوع أصبحت ضرورية. إحدى المواضيع الهامة فى هذا المجال هى تحديد الحد الأدنى لتسليح القص فى الكمرات عالية المقاومة. المواصفات العالمية (على سبيل المثال الأميركية "ACI" البريطانية "BS") تقترح قيم للحد الأدنى لتسليح القص بمقدار ٠,٣٤ نيوتن / مم٢ و ٤٠ نيوتن/ مم٢ على التوالى. هذه القيم قد تم الحصول عليها بإجراء اختبارات معملية على كمرات خرسانية ذات مقاومة فى الضغط لا تزيد عن ٤٠ نيوتن / مم٢. ان استعمال هذه القيم للخرسانة عالية المقاومة تحتاج الى اختبارات عملية على خرسانة ذات مقاومة تزيد عن ٤٠ نيوتن / مم٢. فى هذا البحث تم إجراء اختبارات معملية على كمرات خرسانية ذات مقاومة فى الضغط تتراوح بين ٣٥ و ٩٠ نيوتن/مم٢. المتغيرات فى الاختبارات المعملية هى مقاومة الخرسانة فى الضغط وحديد تسليح القص. تحليل النتائج المعملية أشارت أن الحد الأدنى لحديد تسليح القص المقترح بالمواصفات العالمية يجب ان يزيد مع زيادة مقاومة الخرسانة فى الضغط. تم الحصول على علاقة بين الحد الأدنى لتسليح ومقاومة الخرسانة فى الضغط.

Keywords: High strength concrete, Shear strength, Stirrups, Shear reinforcement, Beam tests

1. Research significance

High strength concrete has been used in columns of high – rise buildings in North America for many years [1,2]. High strength concrete is also being utilized more and more in bridge structures. It has been indicated that the specified minimum amount of web reinforcement given by codes of practice [3,4] should be increased as the concrete compressive strength increases. This increase in the minimum amount of web reinforcement is necessary in order to control the extent of shear cracking in beams and to provide a ductile behavior. This study would establish a relationship between the amount of minimum shear reinforcement and the concrete compressive strength.

2. Introduction

In the codes of practice [3,4], the shear strength of a reinforced concrete beam is taken as the sum of the shear force that is carried by the concrete V_c and the web reinforcement V_s. The term V_c in a diagonally cracked beam with web reinforcement represents the sum of three separate components. These components are: (a) dowel action resistance of the longitudinal reinforcement, (b) aggregate interlock resistance along the diagonal crack, and (c) the shear resistance carried by the uncracked concrete compressive zone. The term V_s represents the vertical component of the shear force carried by the vertical (shear) reinforcement. The use of shear reinforcement enhances the ductility of the member. For this reason, all codes of practice recommend a minimum shear reinforcement in reinforced concrete beams to provide enough ductility and adequate reserve strength in the member before failure.

The ability of the minimum amount of shear reinforcement given by the current codes of practice to provide adequate reserve strength with higher strength concrete is questionable. As the compressive strength of the concrete increases, the load causing diagonal tension-cracking also increases. Furthermore, in contrast with rough crack surfaces typical of lower strength concrete, the crack surfaces in high strength concrete tend to be smooth [5]. This difference in crack surfaces may result in a reduction in the shear carried by aggregate interlock after the onset of diagonal cracking, and thus in the shear force carried by (V_c). Therefore, it is expected that the reserve shear strength of beams with the current minimum amount of shear reinforcement decreases as the concrete strength increases and that more shear reinforcement may be needed to provide a comparable reserve shear strength.

In this study, the reserve shear strength provided by the minimum shear reinforcement given by current codes provision in reinforced concrete beams with concrete compressive strength greater than 35 MPa is evaluated. The purpose of this evaluation is to study the adequacy of the minimum amount of shear reinforcement in beams with high strength concrete and to determine a relation between the required minimum shear reinforcement and the concrete compressive strength.

3. Previous work

Extensive experimentation resulted in a better understanding of the fundamental behavior and basic engineering properties of high strength concrete. While most properties of the concrete improve with increased compressive strength, some properties such as minimum shear reinforcement require further investigations. To ensure the safety of structural concrete members, certain design equations given by the codes of practice [3,4], which are based on low concrete strength, must be re-examined.

The minimum shear reinforcement of high strength concrete beams is an important issue. Limited research has been carried out in this area. Johnson et al. [6] has indicated the importance of providing a particular value of minimum shear reinforcement to prevent brittle failure and provide enough ductility in the members before failure. It was concluded that the overall reserve shear strength after diagonal cracking diminished with the increase in f_{cu} for beams designed according to the current codes of practice. No attention was given for an adequate minimum amount of shear reinforcement for high strength concrete.

Mphonde [5] in his investigation of aggregate interlock in high strength concrete beams indicated that while aggregate interlock plays a very significant role as a shear carrying capacity at low concrete compressive strengths, it does not have much influence on the shear strength of reinforced concrete beams made of high concrete strengths. They indicated that the shear resisted by aggregate interlock decreased with an increase in the compressive strength. However, dowel action showed some increase at very high strength and the shear resisted by concrete compressive zone remained fairly constant with increasing concrete compressive strength. Further tests [7-9] showed similar results and it was recommended that further investigation is required in this area. Study by Daou [10] showed that shear reinforcement should be increased with the concrete compressive strength.

4. Test program

4.1. Beam test specimens

Twenty five rectangular beams were tested with compressive strengths in the range of 35 MPa to 90 MPa and with web reinforcement index in the range of 0.35 MPa to 0.75 MPa with shear span / effective depth ratio (a/d) = 2.3 designed to fail in shear.

Each specimen is 1700 mm in length, simply supported at 1500 mm span and has a rectangular 120 mm by 200 mm cross section. The test program is divided into five series A to E. Details of the test beams are given in fig. 1. The test program is given in table 1.

The amount and distribution of shear reinforcement are arranged to study their effect on the reserve shear strength. The stirrups are closed hoops with a 135-degree standard hooks. The spacing ranges between 75 mm and 161 mm.

4.2. Steel specimens

Three different reinforcing steel bar sizes were used for all the beam specimens. 10 mm diameter plain bars were used for the longitudinal reinforcement in the tension zone while plain bars 6 mm in diameter were used for the compressive zone. Shear reinforcement (stirrups) of 4mm diameter bars were used in all beam specimens. Tension tests were conducted on the bar samples to determine the yield and ultimate strengths of steel reinforcement. The yield strengths of the 4mm, 6mm and 10mm bars are 275 MPa, 277 MPa and 410 MPa, respectively.

4.3. Cube specimens

The test program consists of five series A, B, C, D and E. Within each series, a number of cubes were cast to determine the compressive strength of the concrete at 28 days. After 24 hours of casting, concrete cubes were put into a rectangular tank for curing. The concrete compressive strengths at 28 days of age ranged between 35 MPa and 90 MPa. For concrete with compressive strength greater than 60 MPa, the brittleness of the concrete increases which, was noticeable at failure.

4.4. Instrumentation and test setup

Beam specimens were simply supported and tested using two concentrated point loads. The shear span / effective depth ratio (a/d) for all beams was 2.30. One end of the beam was hinged and the other end was roller.

A testing machine of 100 tons capacity was used to apply the load. Dial gauges were fixed within the shear span at both ends of the beam to measure the movement in the concrete perpendicular to the expected shear crack, which is perpendicular to the line joining the load position and the support. Details of the beam instrumentation, the testing machine and the two supports are shown in fig. 2.

4.5. Test procedure

All the beams were loaded symmetrically with two equal concentrated loads. The load was applied in increments of about 10 kN up to approximately 70 percent of the expected failure load; thereafter the increments were reduced to 5 kN. At each load increment, all displacement readings were measured, the beam was carefully inspected, and all cracks were noticed. With each beam test, cubes taken from the same concrete mix as the beam specimen were tested to determine the compressive strength of the concrete.

5- Materials

The cement used in the beam specimens is the ordinary Portland cement type 1 which is usually used in normal practice. The maximum size of the coarse aggregate used in the test specimens is 9.5 mm. The fine aggregate used in the beam specimens has a sand equivalent of 78.4 % with 21.6% clay.

In order to obtain high strength concrete, low water cement-ratio, 0.5 to 0.25, was used which led to concrete with low workability. To improve the workability of the concrete mix, a superplasticizer has been used known as Duracem 205. Duracem 205 is a liquid concrete superplasticizer that has been developed to allow concrete to attain particularly high performance in both the plastic and hardened states and which has no effect on the behavior of beam specimens as per specification [11]. It is particularly useful for imparting extreme workability to concrete mixes so that large or difficult pours can be made.

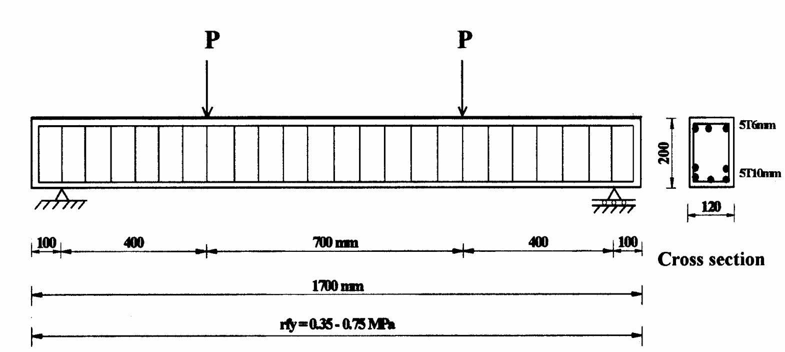

Fig. 1. Test specimen details.

Table 1
Test specimen program

Series	(Cement; W/C)	Specimen No	Spacing (mm)	Reinf. index rf_y (MPa) *	Comp. strength f_{cu} (MPa)
A	(600 x 0.55)	A1	75	0.75	35
		A2	87	0.65	35
		A3	102	0.55	35
		A4	125	0.45	35
		A5	161	0.35	35
B	(500 x 0.5)	B1	75	0.75	45
		B2	87	0.65	45
		B3	102	0.55	45
		B4	125	0.45	45
		B5	160	0.35	45
C	(600 x 0.35)	C1	75	0.75	60
		C2	87	0.65	60
		C3	102	0.55	60
		C4	125	0.45	60
		C5	161	0.35	60
D	(800 x 0.3)	D1	75	0.75	75
		D2	87	0.65	75
		D3	102	0.55	75
		D4	125	0.45	75
		D5	161	0.35	75
E	(800 x 0.25)	E1	75	0.75	90
		E2	87	0.65	90
		E3	102	0.55	90
		E4	125	0.45	90
		E5	161	0.35	90

- $rf_y = (A_{st}.f_y)/(b.S)$

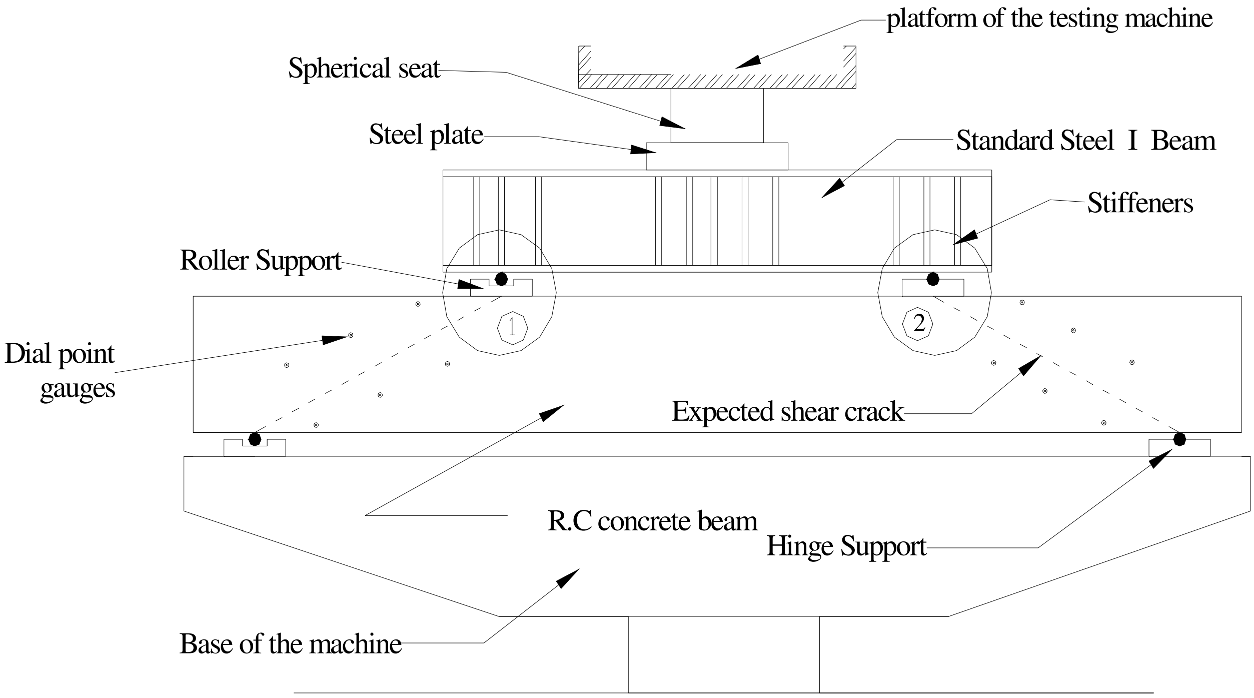

Fig. 2. Details of the beam instrumentations, support and the testing machine.

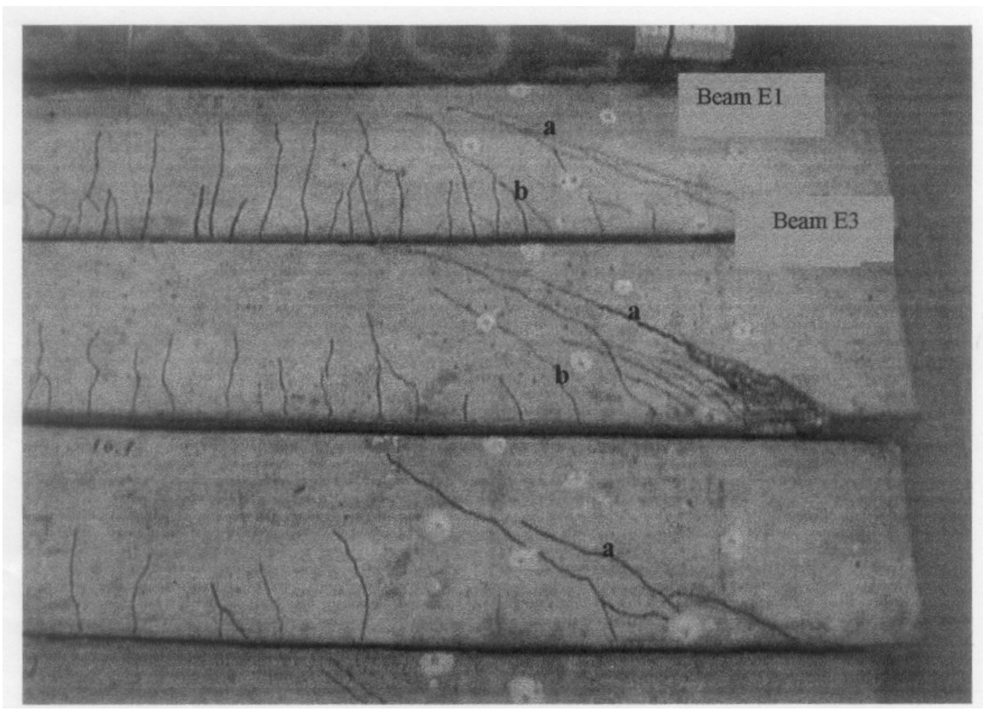

Fig. 3. Crack pattern of beam series E.

6. Test results and discussions

6.1. Crack pattern and general behavior

All tested beams failed in shear. The cracking pattern of all beams was almost similar. Initially, cracks started either vertically or inclined in the shear spans and in some beams as vertical flexural cracks at mid-span. Extension of existing cracks and appearance of new flexural cracks in the shear spans spread from the load application points towards the supports. The flexural cracks in the shear spans tend to become inclined as the load was increased.

With further increase in the applied load, the diagonal shear crack between the loading point and the support (fig. 3- crack a) in one of the shear spans became wider and in some cases a new shear crack was initiated as an extension of an existing flexural crack (fig. 3 – crack b). A small drop in the load accompanied the occurrence of the crack, which was easy to detect from the reading of the testing machine. Inclined cracks in the other shear span occurred within 15 % of load increase above the first load, which caused the inclined cracks in the first shear span. The crack angle varied between 20 ° (the angle formed between the load point and support) and 30° with the axis of the beam. The failure cracks in series E with the highest concrete strength tended to be steeper than those of other series. Generally, the cracks were developed in the shear spans and then propagated upward towards the load bearing plate and downward towards the supports. All beams failed suddenly in shear with large widening and sliding along one of the inclined cracks. This was normally followed by destruction of concrete cover at the surfaces in the vicinity of the cracks and yielding of shear reinforcement. For beams with high strength (series D and E), the failure was preceded by relatively large deflections at midspan and failure occurred due to diagonal cracking followed by crushing of the concrete at the loading point (shear compression failure).

Typical failure crack patterns for the beams of series E are shown in fig. 3. Beam E1 has an amount of shear reinforcement (rf_y = 0.75 MPa) and beam E3 has shear reinforcement rf_y = 0.55 MPa. It can be seen that the number of inclined cracks increased with increasing the amount of web reinforcement, indicating an enhanced redistribution of internal forces in the beam with shear reinforcing index rf_y = 0.75 MPa.

6.2. Ultimate shear capacity adopted by the ACI code of practice

The present ACI code of practice [3] assumes that in beams with web reinforcement, the amount of shear stress resisted by the concrete at ultimate is equal to the amount of shear stress that would cause diagonal tension cracking. The amount of shear strength of the concrete was based and determined from test results on beams without web reinforcement and with concrete compressive strengths up to 41.1 MPa (6000 psi). The shear strength of concrete without shear reinforcement is given by:

$$\upsilon_c = (1.9\sqrt{f_c'} + 2500.\,\rho_w \cdot \frac{V_u.d}{M_u}) \,, \qquad (1)$$

and not greater than $3.5\sqrt{f_c'}$

where:

f_c' = cylindrical compressive strength of concrete (psi),

ρ_w = tensile steel ratio = $\dfrac{A_s}{b_w d}$,

V_u = ultimate shear force at the support, and

M_u = ultimate moment at point of loading

The shear reinforcement contribution to shear resistance is given by $\upsilon_s = \dfrac{Ast.fy}{b.S}$.

6.3. Test results

Table 2 shows the test results of all five-test series. This table also shows the measured diagonal cracking force and the failure shear force for each beam specimen. The fifth column of each sub- table is a measure of the amount of remaining shear force of the beam after the onset of diagonal cracking (P_f – P_{cr}). It can be seen that within each series, as the shear reinforcement was increased, the failure load also increased; i.e. for beam B5 (f_{cu} = 45 MPa and S = 160 mm), the failure load was 100 kN whereas for beam B1 (f_{cu} = 45 MPa and S = 75 mm), the failure load was largely greater and equal to 135 kN, which was expected due to the shear reinforcement contribution to the shear capacity of the beam. Also, another important conclusion can be dedicted from the test results, which is as the compressive strength increases, the failure shear stress increases until the compressive strength f_{cu} reaches a certain limit approximately equal to 75 MPa. These results agree with previous research findings [12] and may require further investigation. This may be caused by the reduction of the aggregate interlock shear resistance in high strength concrete [5].

Table 3 shows the test shear stresses at inclined cracking υ_{cr} and at failure υ_f. Also, included are the shear strength values of the concrete υ_c and of the steel υ_s calculated according to ACI code provision. The ratio between the failure shear stress of the test beams υ_f and the calculated shear stress of the concrete υ_c is expressed as an index in the form υ_f/υ_c. Columns 3 and 4 in table 3 represent the diagonal cracking and the failure shear stresses of the test beams, respectively. Columns 6, 7 and 8 represent the calculated shear stress of concrete υ_c, the calculated shear stress of steel υ_s and the calculated total capacity of the beams υ_n ($\upsilon_n = \upsilon_c + \upsilon_s$).

All beam specimens failed in diagonal tension except beam D1 that failed in shear compression, which indicated that compression reinforcement should be increased in order to increase the capacity of the compression zone. It can be seen that the failure shear stress increased with increasing the compressive strength of concrete until f_{cu} = 75 MPa. Thereafter, it was decreased as the compressive strength increased. For beams A1, B1, C1, D1 and E1, the failure shear stress increased from v_f = 3.137 MPa to υ_f = 3.799 MPa until reaching f_{cu} = 75 MPa and then decreased to υ_f = 3.67 MPa for f_{cu} = 90 MPa. This may be referred to the decrease of one of the components of the concrete contribution to shear resistance "the aggregate interlock" which is ascribed to a smooth surface of the shear crack.

In column 10, the reserve shear capacity was significantly increased as the amount of web reinforcement increased from rf_y = 0.35 MPa to rf_y = 0.75 MPa. For beam C5, υ_f/υ_c was 2.15, and for beam C1, υ_f/υ_c was 2.96.

6.3.1. Effect of compressive strength

Concrete compressive strength plays an important role in determining the shear capacity of reinforced concrete beams. The failure shear stress is plotted versus the compressive strength in fig. 4. It can be seen that as the concrete compressive strength increases, the failure shear stress increases up to f_{cu} = 75 MPa before starting to decrease. For a constant compressive strength, as the shear reinforcement index rf_y increases, the failure shear stress also increases, for beam A2 with f_{cu} = 35 MPa, υ_f = 2.941 MPa and for beam D2 with f_{cu} = 75 MPa, υ_f= 3.554 MPa. Fig. 5 shows the relation between the ratio υ_f/υ_n and the compressive strength of the concrete f_{cu}. The ratio decreased with increasing compressive strength, which indicated that the ACI code equations are more conservative with low concrete strength than for high strength concrete.

6.3.2. Brittle characteristic of high strength concrete

A characteristic of a high strength concrete member loaded to failure is that it fractures suddenly, and in doing so, forms a failure surface, parallel to the inclined shear crack that is typically a smooth plane. This contrasts with the rough surface typical of lower strength concrete, with internal cracking following along the interface between the coarse aggregate and the mortar, and then branching out through the mortar in many

Table 2
Test results

Series A - f_{cu} = 35 MPa						Series B - f_{cu} = 45 MPa					
Beam No	S	P_{cr}	P_f	P_f - P_{cr}	T.F *	Beam No	S	P_{cr}	P_f	P_f - P_{cr}	T.F *
A1	75	33.5	64.0	30.5	D.S.F	B1	75	37.5	67.5	30.0	D.S.F
A2	87	30.0	60.0	30.0	D.S.F	B2	87	35.0	65.0	30.0	D.S.F
A3	102	27.5	56.0	28.5	D.S.F	B3	102	33.5	61.0	27.5	D.S.F
A4	125	25.0	50.0	25.0	D.S.F	B4	125	32.5	55.0	22.5	D.S.F
A5	161	24.0	45.0	21.0	D.S.F	B5	161	30.0	50.0	20.0	D.S.F
Series C - f_{cu} = 60 MPa						Series D - f_{cu} = 75 MPa					
Beam No	S	P_{cr}	P_f	P_f - P_{cr}	T.F *	Beam No	S	P_{cr}	P_f	P_f - P_{cr}	T.F *
C1	75	35.0	76.5	41.5	D.S.F	D1	75	35.0	77.5	42.5	S.C.F
C2	87	32.5	71.5	39.0	D.S.F	D2	87	35.0	72.5	37.5	F.S.F
C3	102	30.0	65.0	35.0	D.S.F	D3	102	32.5	66.0	33.5	F.S.F
C4	125	30.0	61.0	31.0	D.S.F	D4	125	27.5	62.5	35.0	F.S.F
C5	161	28.0	55.5	27.5	D.S.F	D5	161	27.5	57.5	30.0	F.S.F
Series E - f_{cu} = 90 MPa											
Beam No	S	P_{cr}	P_f	P_f - P_{cr}	T.F *						
E1	75	35.0	75.0	40.0	F.S.F						
E2	87	32.5	71.0	38.5	F.S.F						
E3	102	32.0	65.0	33.0	F.S.F						
E4	125	28.5	61.5	33.0	F.S.F						
E5	161	26.5	55.5	29.0	F.S.F						

P_{cr} = Shear force at the onset of diagonal cracking (test values) (kN)
P_f = Shear force at failure (kN)
S = Spacing between shear reinforcement (mm)
*T.F = Type of failure
F.S.F Shear failure initiated by flexural crack in the shear span
D.S.F Diagonal shear failure
S.C.F Shear compression failure

Table 3
Measured and computed shear stresses using the ACI code

Series No	Beam	v_{cr}	v_f	v_f / v_{cr}	v_c	v_s	v_n	v_{cr} / v_c	v_f / v_c	v_f / v_n
Series A	A1	1.642	3.137	1.91	1.001	0.754	1.755	1.64	3.13	1.79
	A2	1.471	2.941	2.00	1.001	0.650	1.651	1.47	2.94	1.78
	A3	1.348	2.745	2.04	1.001	0.554	1.555	1.35	2.74	1.76
	A4	1.225	2.451	2.00	1.001	0.452	1.453	1.22	2.45	1.69
	A5	1.176	2.206	1.88	1.001	0.351	1.352	1.18	2.20	1.63
Series B	B1	1.838	3.309	1.80	1.116	0.754	1.870	1.65	2.96	1.77
	B2	1.716	3.186	1.86	1.116	0.650	1.766	1.54	2.85	1.80
	B3	1.642	2.990	1.82	1.116	0.554	1.671	1.47	2.68	1.79
	B4	1.593	2.696	1.69	1.116	0.452	1.569	1.43	2.41	1.72
	B5	1.471	2.451	1.67	1.116	0.351	1.467	1.32	2.20	1.67
Series C	C1	1.716	3.750	2.19	1.267	0.754	2.121	1.35	2.96	1.86
	C2	1.593	3.505	2.20	1.267	0.650	1.917	1.26	2.77	1.83
	C3	1.471	3.186	2.17	1.267	0.554	1.821	1.16	2.51	1.75
	C4	1.471	2.990	2.03	1.267	0.452	1.720	1.16	2.36	1.74
	C5	1.373	2.721	1.98	1.267	0.351	1.618	1.08	2.15	1.68
Series D	D1	1.716	3.799	2.21	1.40	0.754	2.154	1.23	2.71	1.76
	D2	1.716	3.554	2.07	1.40	0.650	2.050	1.23	2.54	1.73
	D3	1.593	3.235	2.03	1.40	0.554	1.954	1.14	2.31	1.66
	D4	1.348	3.064	2.27	1.40	0.452	1.852	0.96	2.19	1.65
	D5	1.348	2.819	2.09	1.40	0.351	1.751	0.96	2.01	1.61
Series E	E1	1.716	3.676	2.14	1.521	0.754	22.74	1.13	2.42	1.62
	E2	1.593	3.480	2.18	1.521	0.650	2.170	1.05	2.29	1.60
	E3	1.569	3.186	2.03	1.521	0.554	2.075	1.03	2.10	1.54
	E4	1.397	3.015	2.16	1.521	0.452	1.973	0.92	1.97	1.52
	E5	1.299	2.721	2.09	1.521	0.351	1.872	0.85	1.79	1.45

υ_{cr} = Shear stress at the onset of diagonal cracking (MPa)

υ_f = Shear stress at failure (MPa)

υ_c = Calculated concrete shear strength (MPa)

υ_s = Calculated shear strength of shear reinforcement (MPa)

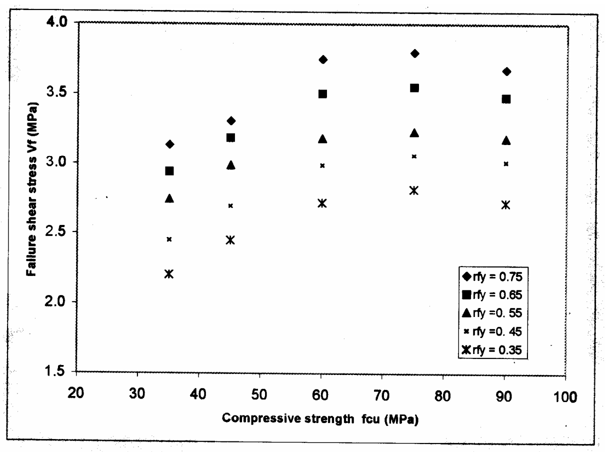

Fig. 4. Effect of compressive strength of concrete.

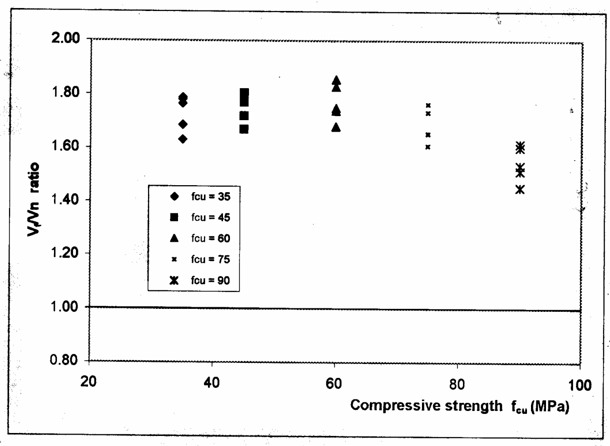

Fig. 5. Effect of compressive strength (v_n is calculated according to ACI code).

directions. This could be explained by the fact that the smooth fracture plane occurs due to the difference in strength and stiffness of the mortar relative to the course aggregate. However, this requires further investigation.

6.3.3. Graphical representations of v_f/v_c, rf_y and compressive strength f_{cu}

Fig. 6 shows graphically the ratio v_f/v_c versus and the concrete compressive strength f_{cu}. All test results suggest that the ratio v_f/v_c decreased with the increase in concrete compressive strength f_{cu}. For beam A1 with f_{cu} = 35 MPa, v_f/v_c was 3.13 and for beam E1 with f_{cu} = 90 MPa, v_f/v_c was 2.42. In order to determine the amount of minimum shear reinforcement, the value of rf_y = 0.35 MPa, which is considered to have enough ductility in the ACI code, has been used, which is also equivalent to v_f/v_c = 2.2 as shown in the graph of the reinforcing index rf_y versus the ratio v_f/v_c as shown in fig. 7.

6.3.4. Proposed relation between f_{cu} and rf_y

Different values of the ratio v_f/v_c may be assumed which depends on how much ductility is required for design purpose. As described in the previous section, the value of rf_y = 0.35 MPa which is equivalent to v_f/v_c = 2.2 has been used as shown in fig. 7. The corresponding values of rf_y at v_f/v_c = 2.2 (that is the intersection of the vertical line at v_f/v_c = 2.2 with the curves in fig. 7) represent the minimum values of shear reinforcement for different compressive strength f_{cu}. These values are used to draw a relation between the reinforcing index rf_y and the concrete compressive strength f_{cu} as shown in fig. 8. This relation represents the minimum shear reinforcement in high strength concrete members, which is based on the limited test results carried out in the project and is given by:

$$rf_y = 10^{-4}(f_{cu})^2 - 0.0089(f_{cu}) + 0.526 . \quad (2)$$

Where:

rf_y = shear reinforcement index in MPa,
f_{cu} = cube compressive strength in MPa.

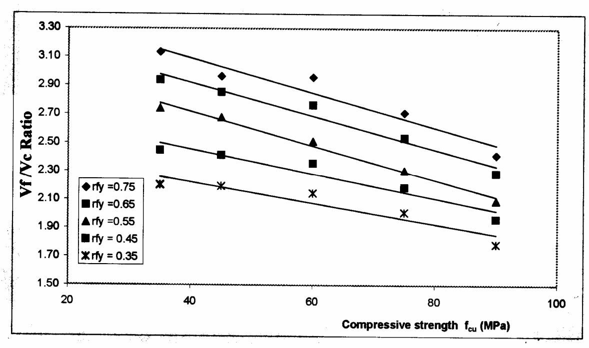

Fig. 6. Effect of compressive strength on the ratio v_f/v_c.

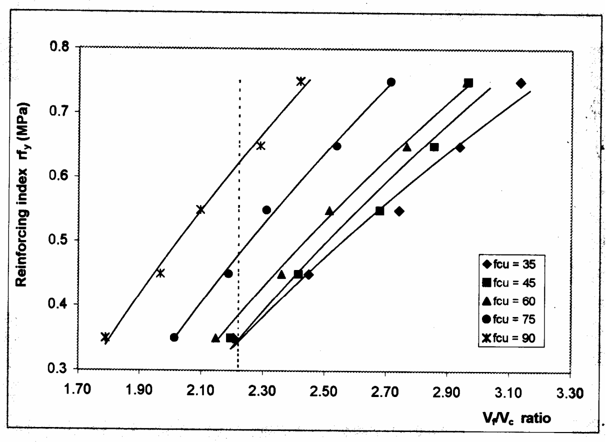

Fig. 7. Effect of shear reinforcement on the ratio v_f/v_c.

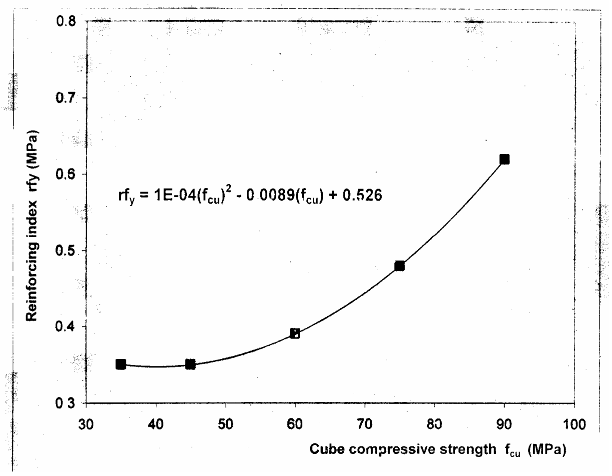

Fig. 8. Minimum shear reinforcement in high strength concrete.

7. Conclusions and recommendations

7.1. General conclusions

On the basis of the test results obtained in this study, the following conclusions have been reached:

(i) The failure shear stress increased with increasing the compressive strength of concrete, f_{cu}, until a certain value equal to 75 MPa. Thereafter, it was decreased as the compressive strength was increased. This may be caused by the reduction of the aggregate interlock shear resistance in high strength concrete.

(ii) One of the characteristics of high strength concrete members loaded to failure is that it fractures suddenly and forms a smooth failure surface. In order to prevent the brittle failure, the minimum shear reinforcement suggested by codes of practice should be increased with the concrete compressive strength. Shear reinforcement resists very little shear prior to inclined cracking. When diagonal cracks forms, shear reinforcement starts to carry a portion of the shear stress. As the amount of shear reinforcement increases, the shear failure becomes more ductile and less sudden. The required minimum shear reinforcement should be increased as the concrete compressive strength increases. The increment increase in the compressive strength is greater than that of the increment increase in the failure shear stress and which tends to decrease when the compressive strength exceeds 75 MPa.

(iii) Depending on how much ductility is required for the design of reinforced concrete members, a relation between the minimum shear reinforcement and the compressive strength, f_{cu}, can be obtained from the test results. Such a relation was obtained based on the minimum shear stress (rf_y = 0.35 MPa) for compressive strength (f_{cu} = 35 MPa) as required the building ACI code. This relation represents the minimum shear reinforcement in high strength concrete members.

7.2. Recommendations for further work

The test results carried out in this project were based on constant cross section dimensions and, the shear span / effective depth ratio is limited to 2.3, and constant percentage steel ratio of 1.7 %. In future research, effort should be made to:

(i) Verify the results obtained in this project, by considering full-scale reinforced concrete members made of high strength concrete.

(ii) Study the scale effect on the shear strength of high strength concrete.

(iii) Consider higher strength concrete, f_{cu} > 90 MPa.

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Notations

- b Beam width (mm),
- d Effective beam depth (mm),
- S Stirrup spacing (mm),
- f_{cu} Concrete cube compressive strength (MPa),
- f'_c Concrete cylinder compressive strength (MPa),
- f_y Specified yield strength of the reinforcement (MPa),
- rf_y Reinforcing index = $\frac{A_{st}}{bS} f_y$ (MPa),
- A_{st} Area of the stirrups (mm^2),
- ρ_w Longitudinal steel ratio = $\frac{A_s}{bd}$,
- A_s Area of tensile steel reinforcement (mm^2),
- P Applied shear force (kN),
- P_{cr} Applied shear force at the onset of diagonal cracking (kN),
- P_f Applied shear force at failure (kN),
- υ_s Shear stress carried by stirrups (MPa),
- υ_c Shear stress carried by concrete (MPa),
- υ_n Total nominal shear strength = v_c+v_s (MPa),
- υ_{cr} Shear stress at the onset of diagonal cracking (MPa),
- υ_f Shear stress at failure (MPa),
- V_c Shear force carried by concrete (kN),
- V_s Shear force carried by stirrups (kN),
- V_u Ultimate shear force at the support (kN),
- M_u Ultimate moment at point of loading (kN.m),
- a Shear span, distance between concentrated load and support centerline (mm), and
- W/C Water cement ratio

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