EVALUATION OF SHEAR STRENGTH OF SLENDER RC BEAMS WITHOUT SHEAR REINFORCEMENT

Chidananda G[1], Raviraj S[2]

[1]*Research Scholar, Department of Civil Engineering, Sri Jayachamarajendra College of Engineering, Mysuru – 570 006, Karnataka, India*

[2]*Professor, Department of Civil Engineering, Sri Jayachamarajendra College of Engineering, Mysuru – 570 006, Karnataka, India*

Abstract

This paper describes a study on evaluation of shear strength of slender RC beams without shear reinforcement by considering three shear evaluation methods viz. a proposed shear strength equation based on the fracture mechanics approach and the two standard codes of practice namely IS 456 (2000) and ACI 318 (2014). Four hundred and fifty eight test beams selected from ACI–DAfStb database (2013) are considered for the study. The statistical analysis and demerit points classification indicate the proposed equation to show better estimate of shear strength of the test beams. Also the proposed equation captures well the influence of parameters affecting the shear strength of RC beams.

Keywords: *Shear strength, Fracture mechanics, ACI–DAfStb database (2013), Demerits points classification.*

--***--

1. INTRODUCTION

Shear strength of RC beams is a debate subject of the century. Understanding shear behaviour of RC beams is quite complicated. Many investigators through experimental observation have proposed numerous theories on shear mechanism of RC beams. The shear in RC beams without shear reinforcement is resisted by 'uncracked concrete' in the compression zone, 'aggregate interlock' across the cracks and 'dowel action' of the longitudinal reinforcement. Percentage of longitudinal reinforcement, compressive strength of concrete, effective depth of beam and grade of reinforcing steel are the important parameters affecting the shear capacity of RC beams. The expressions for shear strength suggested in various standard codes of practice are empirical or semi empirical and predict the shear strength with suitable safety and strength reduction factors.

2. SHEAR STRENGTH PREDICTION BY THE SHEAR EVALUATION METHODS

Three shear evaluation methods viz. a proposed shear strength equation based on the fracture mechanics approach and the shear strength equations suggested by standard codes of practice namely IS 456 (2000) and ACI 318 (2014) are considered in the present study. The expressions for shear strength suggested in these shear evaluation methods are as follows.

2.1 Proposed Shear Strength Equation

Based on fracture mechanics approach, Chidananda and Raviraj (2016) proposed Eq. 1 for shear strength of RC beams without shear reinforcement

$$v_u = \frac{2}{3} f_{ctm} \left[3.09\,(p_t)^{0.31} (f_{ck})^{-0.40} (d)^{-0.34} (f_{syk})^{0.22}\right] + \frac{0.23\,(p_t)^{8/9} (f_{ck}+4)^{1/3}}{(d)^{1/3}} \qquad (1)$$

with

$p_t \leq 3\%$, $f_{ck} \leq 60$ MPa, $f_{syk} \leq 1000$ MPa

$f_{ctm} = 0.3 f_{ck}^{2/3}$ for $f_{ck} \leq 50$ MPa

$f_{ctm} = 2.12 \ln(1 + 0.1 f_{cm})$ for $f_{ck} > 50$ MPa

The first term in Eq. 1 represents the shear carried by concrete over the effective shear depth which includes the shear mechanisms of 'uncracked concrete' and 'aggregate interlock' effect across the smeared crack. The second term represents the shear carried by 'dowel action' of the longitudinal reinforcement as suggested by Reineck (1991). Further, Eq. 1 is modified to obtain the design shear strength equation $v_{ud} = \varnothing_v v_u$, where $\varnothing_v$= 0.75 is the shear strength reduction factor.

[Remarks : in S.I. units]

2.2 IS 456 (2000) (Bureau of Indian Standards)

Clause 40.2 of IS 456 (2000) and Clause 39.2 of SP 24 (S&T) (1983) suggests the design shear strength τ_c of concrete in RC beams without shear reinforcement as

$$\tau_c = \frac{0.85\sqrt{0.8 f_{ck,cu}}\left(\sqrt{1+5\beta} - 1\right)}{6\,\beta} \leq \tau_{c,max} \qquad (2)$$

where,

$$\beta = \frac{0.8 f_{ck,cu}}{6.89 P_t} \nless 1$$

$f_{ck,cu} \ngtr 40$ MPa
$p_t \ngtr 3\%$
$\tau_{c,max} = 0.85\left[0.83\sqrt{0.8 f_{ck,cu}}\right]$

The factor 0.8 in the formulae is for converting cylinder strength to cube strength and 0.85 is a reduction factor similar to partial safety factor γ_m for materials.
[Remarks : in S.I. units]

2.3 ACI 318 (2014) [American Concrete Institute]

Clause 22.5.5 discusses the shear strength V_c of concrete for non–prestressed members as

$$V_c = \left(1.9\lambda\sqrt{f_c'} + 2500\rho_w \frac{V_u d}{M_u}\right) b_w d \leq 3.5\lambda\sqrt{f_c'}\, b_w d \quad (3)$$

For most designs, the second term in the above equation is taken as $0.1\lambda\sqrt{f_c'}$. Therefore, Eq. 3 simplifies to

$$V_c = 2\lambda\sqrt{f_c'} b_w d \quad (4)$$

where,
λ is the modification factor which is equal to 1 for normal–weight concrete, 0.85 for sand–lightweight concrete and 0.75 for all–lightweight concrete.

$$\sqrt{f_c'} \ngtr 100 \text{ psi}$$

A strength reduction factor ϕ = 0.75 is applied to V_c to get the design shear strength.
[Remarks : In F.P.S. units]

3. SELECTION OF TEST BEAMS CONSIDERED FOR THE STUDY

A total of 458 slender simply supported RC test beams without shear reinforcement are selected from ACI–DAfStb database (2013) compiled by Reineck et al. (2013) to study the performance of the considered shear evaluation methods. The selected beams satisfy the following criteria.

1. Rectangular in cross section having reinforcement only at the tension side.
2. Percentage of reinforcement p_t upto 3%.
3. Characteristic cylinder compressive strength of concrete f_{ck} in between 12 and 60 MPa.
4. Characteristic yield strength of reinforcing steel f_{syk} upto 1000 MPa.

Table 1 shows the list of investigators of 458 test beams selected from ACI–DAfStb database (2013). The values given in the first and second parentheses indicate respectively the year of testing and the number of selected test beams of the investigators. Among the selected 458 test beams, 432 beams are subjected to either mid point or two point loadings and the remaining 26 beams, tested by the last four investigators (Sl. No. 53 to 56), are subjected to uniformly distributed loading. Table 2 shows the consolidated limits for various parameters of the selected 458 test beams.

Table 1: List of Investigators of the selected 458 test beams

Sl. No.	Investigators	Sl. No.	Investigators
1	Ahmad et al. (1986) (2)	29	Leonhardt and Walther (1962) (27)
2	Angelakos et al. (2001) (5)	30	Marti et al. (1977) (2)
3	Aster and Koch (1974) (5)	31	Mathey and Watstein (1963) (9)
4	Lubell et al. (2004) (9)	32	Moody et al. (1954) (21)
5	Bernander (1957) (6)	33	Morrow and Viest (1957) (9)
6	Bhal (1968) (8)	34	Mphonde and Frantz (1984) (1)
7	Bresler and Scordelis (1963) (3)	35	Niwa et al. (1987) (3)
8	Cladera and Mari (2002), Cladera (2002) (3)	36	Podgorniak-Stanik (1998) (3)
9	Chana (1981) (23)	37	Rajagopalan and Ferguson (1968) (5)
10	Chang and Kesler (1958) (15)	38	Regan (1971) (4)
11	Collins and Kuchma (1999) (5)	39	Rehm et al. (1978) (1)
12	Diaz de Cossio and Siess (1960) (2)	40	Rosenbusch and Teutsch (2002) (3)
13	Elzanaty et al. (1986) (6)	41	Rusch et al. (1962) (3)
14	Ferguson (1956) (1)	42	Salandra and Ahmad (1989) (2)
15	Ghannoum (1998) (10)	43	Taylor (1968) (8)
16	Hallgren (1994) (8)	44	Taylor (1972) (5)

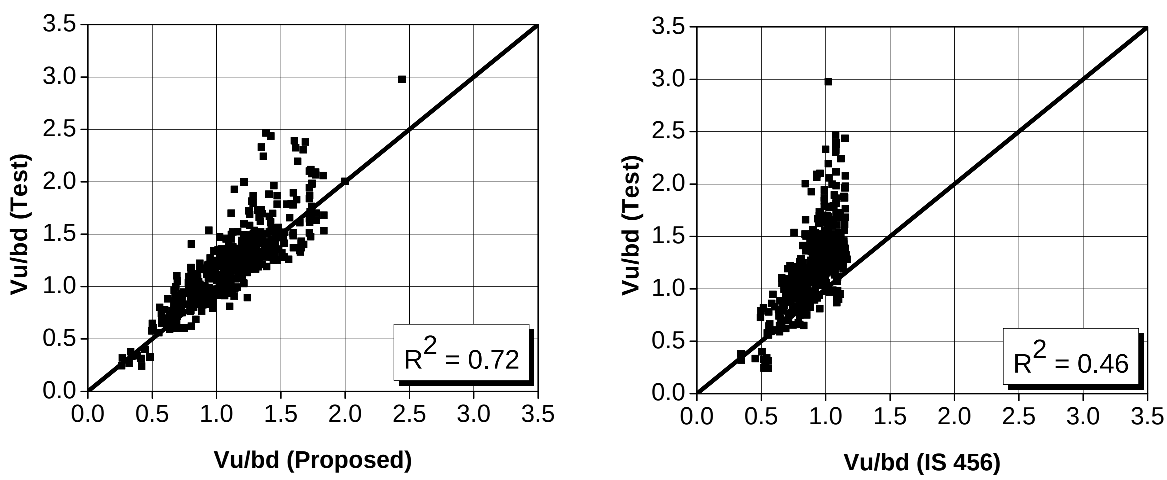
Sl. No.	Investigators	Sl. No.	Investigators
17	Hamadi (1976) (4)	45	Walraven (1978) (3)
18	Hanson (1958) (3)	46	Xie et al. (1994) (1)
19	Hanson (1961) (4)	47	Lubell (2006) (7)
20	Hedmann and Losberg (1978) (4)	48	Sherwood (2008) (8)
21	Kani (1967) (41)	49	Thiele (2010) (5)
22	Kani et al. (1979) (63)	50	Winkler (2011) (5)
23	Kawano and Watanabe (1998) (2)	51	Tureyen (2001), Tureyen and Frosch (2002) (3)
24	Kim and Park (1994) (14)	52	Bentz and Buckley (2005) (9)
25	Krefeld and Thurston (1966) (28)	53	Krefeld and Thurston (1966) (12)
26	Kung (1985) (5)	54	Leonhardt and Walther (1962) (6)
27	Kulkarni and Shah (1998) (4)	55	Iguro et al. (1985) (5)
28	Laupa et al. (1953) (2)	56	Shioya (1989) (3)

Table 2: Consolidated limits for the parameters of the selected 458 test beams

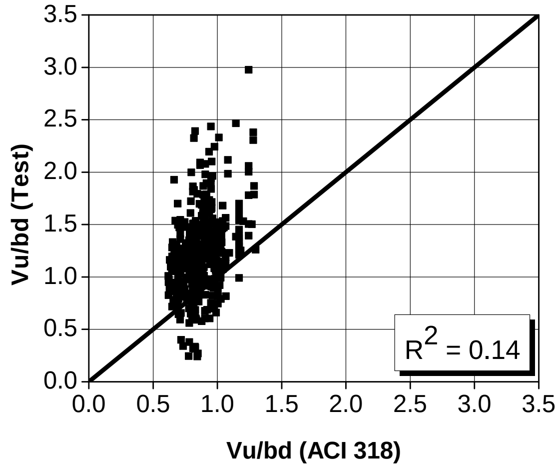
Sl. No.	Parameter	Unit	Minimum	Maximum
1	b	mm	50	3005
2	d	mm	65	3000
3	a/d	–	2.4	8.1
4	p_t	(%)	0.139	2.890
5	f_{ck}	MPa	12.27	59.45
6	f_{syk}	MPa	228.18	908.18

4. STATISTICAL ANALYSIS OF THE SHEAR EVALUATION METHODS

Unit partial safety factors, unit reduction factors and suitable conversion factors for characteristic concrete compressive strength and characteristic yield strength of reinforcing steel given in Appendix A are applied to the expressions suggested in the three considered shear evaluation methods to predict the shear strength (V_{pre}) of the selected 458 test beams. The predicted shear strengths are compared with the corresponding experimental shear strength (V_{test}) results. The statistical results are summarized in Fig. 1 and Table 3.



(a) (b)



(c)

Fig. 1 [(a) to (c)]: Correlation between the prediction from shear evaluation methods and the test results of the selected 458 test beams

Table 3: Statistical results of the shear evaluation methods

Sl. No.	Shear evaluation method	Statistical results		
		$\left(\frac{V_{test}}{V_{pre}}\right)_{Mean}$	Standard deviation	Coefficient of Variation (CV) (%)
1	Proposed	1.10	0.17	15.45
2	IS 456 (2000)	1.34	0.30	22.39
3	ACI 318 (2014)	1.41	0.41	29.08

From Fig. 1 and Table 3, it is inferred that the shear strength predicted by the proposed shear strength equation shows good agreement with the test results having a better correlation coefficient R^2 of 0.72, and a mean (V_{test}/V_{pre}) ratio of 1.10 and a low CV of 15.45% in predicting the shear strength of the selected 458 test beams than IS 456 (2000) and ACI 318 (2014) which predict the shear strength conservatively.

5. DEMERIT POINTS CLASSIFICATION

The demerit points classification suggested by Collins (2001) measures agreement between V_{test} and V_{pre}. In this classification, the ratio $\frac{V_{test}}{V_{pre}}$ is calculated for each of the beam in the database. A demerit point value as given in Table 4 is assigned to each beam which depends on $\frac{V_{test}}{V_{pre}}$ ratio. The summation of the demerit points of all the beams of the database shows the overall performance of the shear evaluation method. A smaller summation indicates the shear evaluation method to be more reliable in predicting the shear strength of RC beams.

Table 4: Collins (2001) demerit points classification

Sl. No.	Classification	$\frac{V_{test}}{V_{pre}}$	Demerit points
1	Extremely dangerous	<0.50	10
2	Dangerous	0.50 – 0.65	5
3	Low safety	0.65 – 0.85	2
4	Appropriate safety	0.85 – 1.30	0
5	Conservative	1.30 – 2.00	1
6	Extremely conservative	>2.00	2

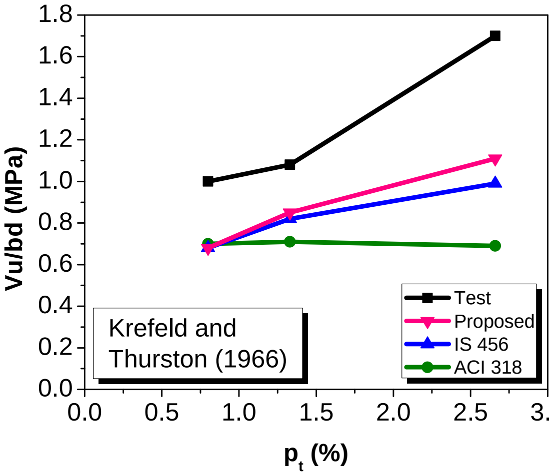
The demerit points classification is applied to evaluate the performance of the three shear evaluation methods in predicting the shear strength of the selected 458 test beams. The demerit points values of the shear evaluation methods for each classification are summarized in Table 5. A low value of 'total demerit points' of the proposed shear strength equation indicates that it performs well in predicting the shear strength of the selected 458 test beams than IS 456 (2000) and ACI 318 (2014).

Table 5: Demerit points value of the shear evaluation methods

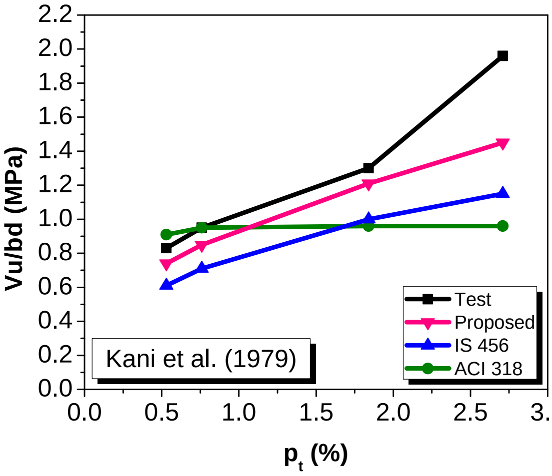
Sl. No.	Shear evaluation method	$\frac{V_{test}}{V_{pre}}$						Total demerit points
		<0.50	0.50 to 0.65	0.65 to 0.85	0.85 to 1.30	1.30 to 2.00	>2.00	
1	Proposed	0	1	24	381	52	0	105
2	IS 456 (2000)	2	4	9	218	210	15	298
3	ACI 318 (2014)	9	2	24	141	248	34	464

6. PARAMETRIC STUDIES

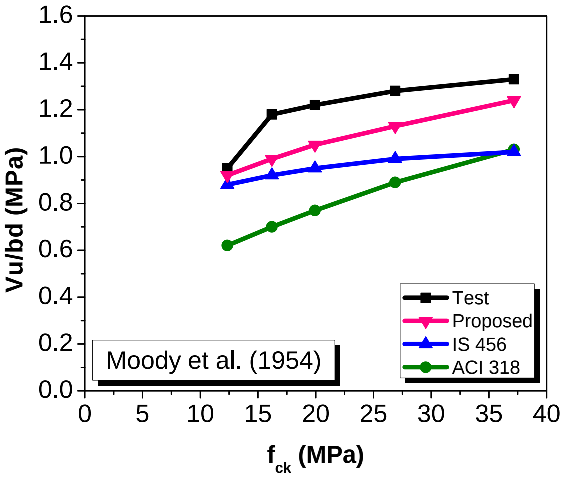
Parametric studies are carried out to study the influence of the parameters viz. p_t, f_{ck} and d on shear strength of RC beams predicted by the shear evaluation methods considering respectively the RC beams tested by Krefeld and Thurston (1966) and Kani et al. (1979); Moody et al. (1954) and Sherwood (2008); and Bhal (1968) and Walraven (1978). Comparison of shear predicted by the shear evaluation methods with the test results, for the three parameters, are shown in Fig. 2. It is inferred that the proposed shear strength equation shows better agreement with the test results and captures well the effect of the aforementioned parameters on shear strength of RC beams than IS 456 (2000) and ACI 318 (2014).



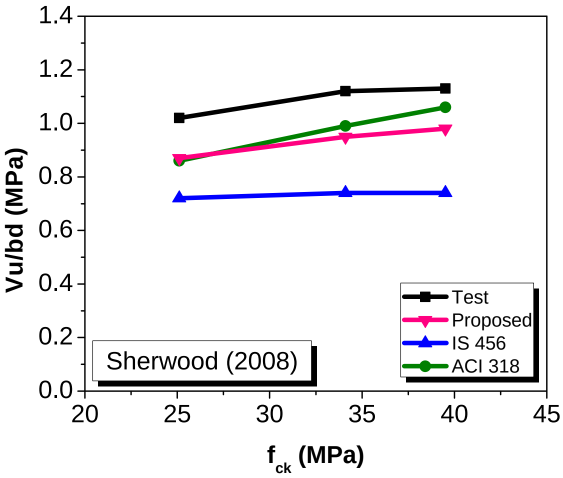
(a)



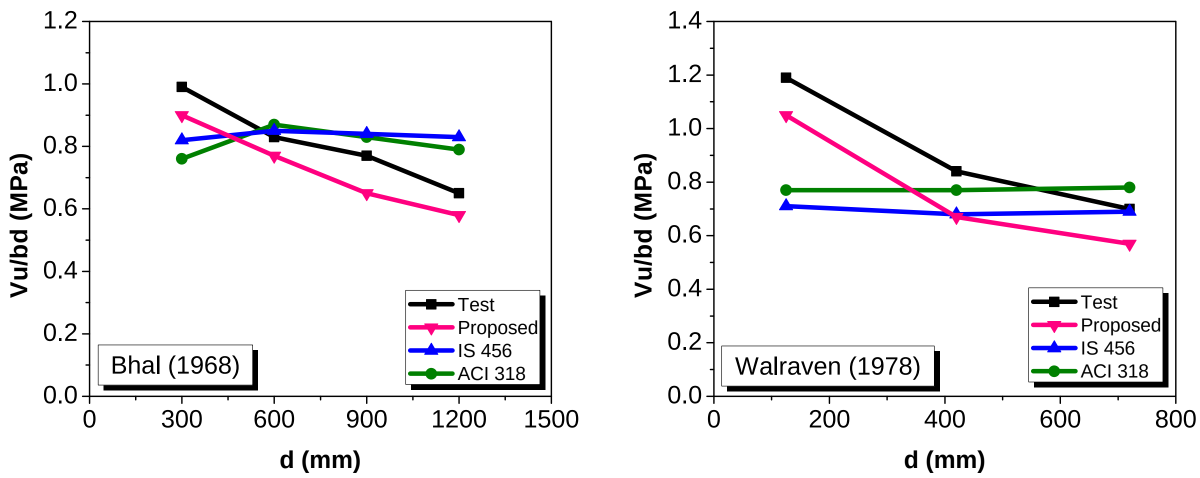
(b)



(c)



(d)



(e) (f)

Fig. 2 [(a) to (f)]: Comparison of the shear predicted by shear evaluation methods with the test results of Krefeld and Thurston (1966), Kani et al. (1979), Moody et al. (1954), Sherwood (2008), Bhal (1968) and Walraven (1978**)**

7. CONCLUSION

The study presents the prediction of shear strength of the selected 458 slender RC test beams without shear reinforcement by the three shear evaluation methods viz. a proposed shear strength equation based on the fracture mechanics approach and two standard codes of practice namely IS 456 (2000) and ACI 318 (2014). The following conclusions are drawn.

1. The statistical analysis and demerit points classification indicate that the shear strength predicted by the proposed equation shows good agreement with the test results, whereas IS 456 (2000) and ACI 318 (2014) predict the shear strength conservatively.
2. The comparison with the test results of Krefeld and Thurston (1966) and Kani et al. (1979); Moody et al. (1954) and Sherwood (2008); and Bhal (1968) and Walraven (1978) shows that the influence of parameters viz. p_t, f_{ck} and d on shear carrying capacity of RC beams is well captured by the proposed equation than IS 456 (2000) and ACI 318 (2014).
3. It is suggested to consider the proposed equation for evaluating the shear strength of RC beams without shear reinforcement for practical design than the two considered standard codes of practice.

NOTATION

a	Shear span
b	Width of beam
d	Effective depth of beam
a/d	Shear span to effective depth ratio
$f_{c,cu}$	Mean cube (150 mm) compressive strength of concrete
f_{ck}	Characteristic cylinder (150x300 mm) compressive strength of concrete
$f_{ck,cu}$	Characteristic cube (150 mm) compressive strength of concrete
f_{cm}	Mean cylinder (150x300 mm) compressive strength of concrete
f_{ctm}	Mean axial tensile strength of concrete
$f_{lc,cu}$	Uniaxial compressive strength of concrete derived from $f_{c,cu}$
$f_{lc,cyl}$	Uniaxial compressive strength of concrete derived from f_{cm}
f_{sy}	Yield strength of reinforcing steel
f_{syk}	Characteristic yield strength of reinforcing steel (i.e. Grade of steel)
p_t	Percentage of longitudinal reinforcement
v_u	Shear strength
V_{pre}	Predicted shear strength
V_{test}	Experimental shear strength

REFERENCES

[1] Chidananda G., Raviraj S. (2016) Fracture mechanics model for prediction of shear strength of slender RC beams without shear reinforcement. Communicated to International Journal of Advanced Structural Engineering.

[2] Collins MP (2001) Evaluation of shear design procedures for concrete structures. A report prepared for the CSA technical committee on reinforced concrete design, Canada.

[3] Reineck KH (1991) Ultimate shear force of structural concrete members without transverse reinforcement

derived from a mechanical model. ACI Struct J, 88 (5):592–602.
[4] Reineck KH, Kuchma DA, Fitik B et al (2010) Extended databases with shear tests on structural concrete beams without and with stirrups for the assessment of shear design procedures–Research report. Institute for Lightweight Structures Conceptual and Structural Design (ILEK), University of Stuttgart and University of Illinois.
[5] Reineck KH, Bentz EC, Fitik B, Kuchma DA Bayrak O et al (2013) ACI–DAfStb database of shear tests on slender reinforced concrete beams without stirrups. ACI Struct J, 110 (5):867–876.
[6] ACI 318 (2014) Building code requirements for structural concrete (ACI 318–14) and commentary (ACI 318R–14). American Concrete Institute, Michigan, United States of America.
[7] IS 456 (2000) Plain and reinforced concrete–Code of practice. Bureau of Indian Standards, New Delhi, India.
[8] SP 24 (S&T) (1983) Explanatory handbook on Indian standard code of practice for plain and reinforced Concrete (IS : 456–1978). Bureau of Indian Standards, New Delhi, India.

Appendix A

Conversion factors for characteristic compressive strength of concrete and characteristic yield strength of reinforcing steel

1. Concrete :

a. Cylinder compressive strength [Reineck et al. (2010)]

$f_{ck} = f_{cm} - \Delta f$, where $\Delta f = 4$ MPa (for laboratory conditions)

$f_{1c,cyl} = 0.95 f_{cm}$

$f_c' = \frac{f_{1c,cyl}}{0.95} - 2.4$ (in MPa, for ACI cylinder compressive strength)

b. Cube compressive strength [Reineck et al. (2010)]

$f_{1c,cu} = 0.79 f_{c,cu}$ for $f_{cm} \leq 54$ MPa

$f_{1c,cu} = 0.95 f_{c,cu} - 10.5$ for $f_{cm} > 54$ MPa

c. Relation between cylinder and cube compressive strengths are obtained by equating uniaxial compressive strengths.

d. $f_{ck,cu} = f_{c,cu} - 3$ [from Clause 16.1 of IS 456 (2000) for compliance requirement]

2. Reinforcing steel :

$f_{syk} = \frac{f_{sy}}{1.1}$ [Reineck et al. (2010)]