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Technical Paper

Analysis of stress block parameters for high strength concrete

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Abstract: In Indian Standard code IS: 456-2000 for concrete of grades higher than M55, the design parameters given may not be applicable as structural behaviour of concrete changes as strength of concrete increases. Different international standards give different stress block parameters which can be reduced to these two basic factors. In this paper, stress block parameters K (strength reduction factor) and k2 (factor for the depth of resultant compressive force) were calculated from experimental strain values considering the stress-strain curve as parabolic for lower grades and as linear for higher grades. Also, the method and approach for the calculation of stress block parameters have been worked out. The method so proposed is compared with the model proposed in European design standard EC: 02-2004 by transforming the European stress block parameters to the basic parameters used. Also, the effect of the shape of the stress-strain curve and value of ultimate strain in concrete on stress block parameters and moment capacity of the members was analyzed by working on the representative section. The method or approach so proposed will be useful to understand and compare flexural design philosophies used in different international standards by reducing the stress block parameters to two basic factors.

Keywords: high strength concrete; stress block; strength reduction factor; Eurocode; stress-strain

1. Introduction

The availability and advancement of material technology and the acceptance has led to the production of higher grades of concrete. High strength concrete offers superior engineering properties i.e. compressive strength, tensile strength, durability, modulus of elasticity and overall better performance when compared to the conventional concrete [1,2]. However, high-strength concrete is more brittle in nature because cracks in this material do not always follow the aggregate-hardened cement paste interfaces due to the improved interfacial bond strength of high-strength concrete but may cut right through the hardened cement paste and even the aggregate particles leading to rapid propagation of the cracks and sudden or sometimes explosive failure of the concrete. Because of this problem, many structural engineers hesitate in using high-strength concrete, despite its obvious advantages. Research on the behavior of HSC beams with concrete strength higher than 55 MPa has been carried out in the past and is still continuing, to understand the behavior of HSC beams in flexure. Whilst there are many publications proposing stress block models for HSC beams, a universally accepted stress block model is yet to be developed. In most design standards, the conventional rectangular stress block developed for Normal Strength Concrete is still being used for design of HSC beams. Rectangular stress block is generally used to calculate the ultimate moment capacity of reinforced concrete beams. The stress-strain curves for high strength concrete are more linear than parabolic and hence it was reasonable to infer that the rectangular stress block parameters could be different.

The idea of using the equivalent rectangular stress distribution was first proposed by Emperger [3] and then modified by Whitney [4] for application to ultimate strength design and later experimentally verified by Hognestad et al. [5] and Mattock et al. [6]. To obtain accurate as well as well-controlled data on flexure compression-loaded members, a test procedure for a series of experiments on C-shaped

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concrete specimens subjected to axial load and bending moment was proposed by Hognestad et al. and later was used by several researchers. The position of neutral axis depth was kept fixed by continuously monitoring strains on one surface of the C-shaped specimen and adjusting the eccentricity of the applied force so that the strains on the neutral surface remain zero.

The rectangular stress block model was first introduced by Hognestad et al. (1955) from experimental work involving normal strength concrete. Ashour [7] has shown that the flexural rigidity increases as concrete compressive strength increases. From the experimental study by Oztekin et al. [8], it was observed that the rectangular stress block parameters used in ordinary concrete members cannot be used safely for high strength concrete members. Attard and Stewart (1998) [9] examined the applicability of ACI 318-95 rectangular stress block parameters to high-strength concretes. They have shown that for a ductile singly-reinforced rectangular section, the ultimate moment capacity is relatively insensitive to the stress block model. An experimental study on the evolution of depth of neutral axis at failure with the ductility at bending on HSC beams was carried out by Bernardo & Lopes (2004) [10].

The equivalent rectangular concrete stress block adopted by various current RC design codes [11,12] (European Committee for Standardization 2004; Standards New Zealand 2006; ACI Committee 318-2008) are depending only on the concrete strength. However, from the comparison conducted by the Ho et al. [13,19] using previous experimental test results done by other researchers, the theoretical flexural strengths predicted by RC design codes are significantly smaller than the actually tested flexural strengths. And from the results obtained by previous researchers [14-17], it was found that the stress block parameters were fairly scattered even though the concrete strength is the same. Therefore, the assumption of stress block parameters should depend on other factors apart from concrete strength only.

It was found that the theoretical formulations based on the use of the rectangular block diagram for the concrete to compute the depth of neutral axis at failure gave substantially smaller values as compared to the experimental values. As such, it was concluded that the rectangular stress block diagram proposed by ACI 318-1989 was not adequate for HSC beams. Cetin and Carrasquillo (1998) [18] reported that no single equation of various codes and research done in past seems to represent the flexural strength of HSC with sufficient accuracy and, therefore, measured values should be used instead of predicated ones.

Ultimate concrete compressive strength is another important variable in the ultimate strength design. Although the ultimate flexural strength of reinforced concrete sections does not depend on this variable, it can noticeably affect the ultimate curvature of reinforced cross sections. Mattock et al. [6] concluded that the value of 0.003 is a reasonably conservative value for ultimate strain of concrete. This value has been accepted by many design codes (NZS 3101 2006; ACI 318-08 2008; AS 3600 2009). Kahn et al. [20] reported that the ultimate value of 0.003 is valid for concrete up to 102MPa and provided the best prediction of the ultimate moment. According to Mansur et al. study (1997), the maximum of 0.003 for concrete in compression may be extended to high strength concrete. Ibrahim and MacGregor (1996) results for ultimate concrete strain were considerably higher than the limiting value of 0.003. However, they concluded that based on the reported values in previous tests of C-shaped specimens, the value of 0.003 used by the ACI code, seems appropriate as a conservative lower bound of experimental data.

The paper focuses on calculation of stress block parameters K (strength reduction factor) and k2 (factor for depth of resultant compressive force) from experimental strain values. In this study, the model proposed in European design standard EC: 02-2004 have been analyzed and stress block parameters are transformed to the parameters used in IS code design procedure. Thereafter, comparison with the design parameters are done with experimental results.

2. Concrete Ingredients

Crushed aggregate with a maximum nominal size of 20 mm was used as coarse aggregate and natural riverbed sand confirming to Zone II as per IS: 383 was used as fine aggregate. Their physical properties are given in Table 1. The petrographic studies conducted on coarse aggregate indicated that the aggregate sample is medium grained with a crystalline texture and partially weathered sample of granite. The major mineral constituents were quartz, biotite, plagioclase-feldspar and orthoclase-feldspar. Accessory minerals are calcite, muscovite, tourmaline and iron oxide. The petrographic studies of fine aggregate indicated that the minerals present in order of abundance are quartz, orthoclase-feldspar, hornblende, biotite, muscovite, microcline-feldspar, garnet, plagioclase-feldspar, tourmaline, calcite and iron oxide. For both the coarse aggregate and fine aggregate sample the strained quartz percentage and their Undulatory Extinction Angle (UEA) are within permissible limits. Feldspar grains are partially fractured and shattered. The quality of both coarse and fine aggregate is fair. The silt content in fine aggregate as per wet sieving method is 0.70 percent.

Table 1 Properties of aggregates

Property		Granite		Fine Aggregate
		20 mm	10 mm	
Specific gravity		2.83	2.83	2.64
Water absorption (%)		0.3	0.3	0.8
Sieve Analysis Cumulative percentage passing (%)	20 mm	98	100	100
	10 mm	1	68	100
	4.75 mm	0	2	95
	2.36 mm	0	0	87
	1.18 mm	0	0	68
	600 µ	0	0	38
	300 µ	0	0	10
	150 µ	0	0	2
	Pan	0	0	0
Abrasion, Impact & Crushing Value		19, 13, 19	-	-
Flakiness % & Elongation %		29, 25	-	-

One brand of Ordinary Portland cement (OPC 53 Grade) with fly ash and silica fume are used in this study. The chemical and physical compositions of cement OPC 53 Grade, Properties of fly ash and silica fume are given in Table 2. Polycarboxylic group based superplasticizer for w/c ratio 0.20, 0.27, 0.30 and 0.36 and Naphthalene based for w/c ratio 0.47 complying with requirements of Indian Standard: 9103 is used throughout the investigation. Water complying with requirements of IS: 456-2000 for construction purpose was used. The 3 days, 7 days and 28 days compressive strength of cement OPC 53 Grade were 36.00 N/mm^2, 45.50 N/mm^2 and 57.50 N/mm^2 respectively. The 28 days compressive strength of controlled sample and sample cast with flyash was 38.53 N/mm2 and 31.64 N/mm^2 respectively, when testing was done in accordance with IS: 1727. The 07 days compressive strength of controlled sample and sample cast with silica fume was 12.76N/mm2 and 14.46 N/mm^2 respectively, when testing was done in accordance with IS: 1727.

3. Mix Design Details

In this study, the four different mixes ranging from w/c ratio 0.47 to 0.20 using granite aggregate were studied for determining short term mechanical properties of High Strength Concrete. For each type of aggregate, three separate batches were prepared.

Table 2 Physical, chemical and strength characteristics of cement

Characteristics	OPC -53 Grade	Silica Fume	Fly Ash
Physical Tests:			
Fineness (m^2/kg)	320.00	22000	403
Soundness Autoclave (%)	00.05	-	-
Soundness Le Chatelier (mm)	1.00	-	-
Setting Time Initial (min.) & (max.)	170.00 & 220.00	-	-
Specific gravity	3.16	2.24	2.2
Chemical Tests:			
Loss of Ignition (LOI) (%)	1.50	1.16	-
Silica (SiO2) (%)	20.38	95.02	-
Iron Oxide (Fe2O3) (%)	3.96	0.80	-
Aluminium Oxide (Al2O3) (%)	4.95	-	-
Calcium Oxide (CaO) (%)	60.73	-	-
Magnesium Oxide (MgO) (%)	4.78	-	-
Sulphate (SO3) (%)	2.07	-	-
Alkalies (%) Na2O & K2O	0.57 & 0.59	-	
Chloride (Cl) (%)	0.04	-	-
IR (%)	1.20	-	-
Moisture (%)	-	0.43	-

The slump of the fresh concrete was kept in the range of 75 - 100 mm. A pre-study was carried out to determine the optimum superplasticizer dosage for achieving the desired workability based on the slump cone test as per Indian Standard. The mix design details of specimens are given in Table 3. Adjustment was made in mixing water as a correction for aggregate water absorption. For conducting studies, the concrete mixes were prepared in pan type concrete mixer. Before use, the moulds were properly painted with mineral oil, casting was done in three different layers and each layer was compacted on vibration table to minimize air bubbles and voids. After 24 hours, the specimens were demoulded from their respective moulds. The laboratory conditions of temperature and relative humidity were monitored during the different ages at 27±2°C and relative humidity 65% or more. The specimens were taken out from the tank and allowed for surface drying and then tested in saturated surface dried condition.

4. Stress Strain Study on High Strength Concrete and Normal Strength Concrete

For stress strain characteristics of the high strength concrete, concrete specimens were tested in a closed-loop servo hydraulic compression testing machine of 3000 kN capacity. Two extensometers at the middle half of the height were used to get strain and two strains were averaged. To obtain a full stress-strain curve, a slow rate of loading in the range of 1300 to 1500 N/sec was adopted for a whole compression test. In general, the normal strength concrete gradually fails after reaching its peak load, but the high strength concrete suddenly explodes at peak load. Strain at peak stress and ultimate strain were recorded for further analysis (Table 4).

4.1 Determination of stress block parameters from experimentally obtained strain values

The total compressive force Cu and its location below the top fibre can be expressed in terms of stress block factors k1, k2 and k3.

k1= shape factor = ratio of the area of stress block ABCD to area of rectangle AFCD
k2= ratio of depth of resultant compressive force to depth of neutral axis(X)
$r_1 = \frac{AE}{AD} = \frac{\varepsilon c}{\varepsilon cu}$ and $r_2 = \frac{ED}{AD} = \frac{\varepsilon cu - \varepsilon c}{\varepsilon cu}$,

εc = strain after which concrete yields at constant stress of $(\alpha_{cc} \times S_1)\, f_{ck}$
εcu = ultimate strain in concrete
α_{cc} = factor for consideration of long term effects including the way load is applied = 0.85
S1 = factor for conversion of cube to cylinder strength

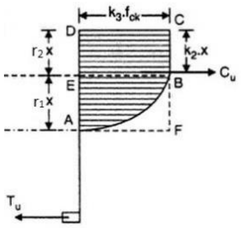
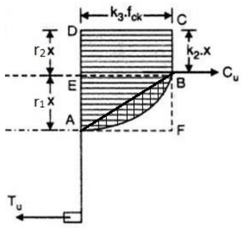
Here, k1 is calculated by calculating the area of the shaded portion and dividing by the area of the rectangle, thus represents the ratio of the area of stress

Table 3 Concrete mix design details for study done

w/c	Total Cementitious Content [Cement C + Fly ash (FA) + Silica Fume (SF)] (Kg/m^3)	Water Content (kg/m^3)	Admixture % by weight of cement	Fine aggregate as % of total aggregate by weight	28-Days strength of concrete (N/mm^2)
0.47	362 (290+72+0)	170	1.00	35	45.72
0.36	417 (334+83+0)	150	0.45	39	68.57
0.27	525 (400+75+50)	140	0.70	39	88.60
0.20	750 (548+112+90)	150	1.75	35	97.76

Table 4 Strain at peak stress and ultimate strain recorded

Cyd str, N/mm^2	Cube/Cyd	Cube Str, N/mm^2	Ec, micro-strain	Ecu, micro-Strain
24.00	1.28	30.72	2284	3711
23.50	1.28	30.08	1972	3789
34.40	1.28	44.03	2175	3063
33.80	1.28	43.26	1877	3220
48.60	1.24	60.26	2151	3324
46.09	1.24	57.15	2341	3323
76.83	1.16	89.12	2702	2931
76.18	1.16	88.37	2539	2729
103.90	1.14	118.45	2774	2774
106.00	1.14	120.84	2799	2799

For Concrete up to M55	For Concrete above M55 to M90
	
For calculation of area ABE parabola is considered	For calculation of area ABE, Triangle is considered as for grade between M55 and M90 in actual stress diagram the shape of area ABE is somewhere between linear and parabola
$k_1 = \frac{2}{3} r_1 + r_2$ $k_2 = [\frac{2}{3} r_1 (r_2 + \frac{3}{8} r_1) + r_2 (\frac{r2}{2})]/k_1$ $k_3 = \alpha_{cc} \times S_1$	$k_1 = \frac{1}{2} r_1 + r_2$ $k_2 = [\frac{1}{2} r_1 (r_2 + \frac{1}{3} r_1) + r_2 (\frac{r2}{2})] /k_1$ $k_3 = \alpha_{cc} \times S_1$

block ABCD to the area of rectangle AFCD. k2 is calculated by taking moment of shaded areas about axis CD and equating it to the moment of resultant force Cu about axis CD. K3 is the stress reduction factor calculated by considering $\alpha_{cc} = 0.85$ and conversion factor S1.

C_u = b × area ABCD = b × k_1 × area AFCD

$C_u = b \times k_1 \times k_3 \times f_{ck} \times X$

Partial factor of safety, $\gamma_{mc} = 1.5$ for concrete & $\gamma_s = 1.15$ for steel

$$C_u = k_1 \times b \times Xu \times \frac{k3 * fck}{\gamma mc}$$

$$C_u = K \times f_{ck} \times b \times Xu \qquad (1)$$

$$\text{where, } K = \frac{k1 * k3}{\gamma mc} \qquad (2)$$

$$\frac{Xu}{d} = \frac{\frac{fy}{\gamma s} * Ast}{K * fck * b * d}$$

$$Mu = C_u \times (d - k_2 \times X) \text{ (Compression)} \qquad (3)$$

$$Mu = T_u \times (d - k_2 \times X) \text{ where } T_u = \frac{fy}{\gamma s} \times Ast \text{ (Tension)} \qquad (4)$$

The two basic factors K and k_2 for flexural design are worked out from the strain values recorded experimentally for different strength of concrete based on the above method (Table 5).

Transformation of equation of Euro-code into IS code format (basic flexural design factors)

Euro-code uses different philosophy for determination of compressive force in a section and therefore has different factors. These factors were clubbed together to form the representative equation similar to IS code equation for calculation of compressive force to compare the reduction factor K and factor to calculate lever arm k2.

$$Cu = \lambda \times \eta \times fcd \times b \times Xu$$

Table 5 Calculation of K and k2 as per the IS code approach with experimentally obtained strain values

Cyd str	Cube/Cyd	Cube Str	Ec	Ecu	r1	r2	k1	S1	k3	Ymc	K(IS cur)	k2
24.00	1.28	30.72	2284	3711	0.62	0.38	0.79	0.78	0.66	1.5	0.35	0.41
23.50	1.28	30.08	1972	3789	0.52	0.48	0.83	0.78	0.66	1.5	0.37	0.42
34.40	1.28	44.03	2175	3063	0.71	0.29	0.76	0.78	0.66	1.5	0.34	0.40
33.80	1.28	43.26	1877	3220	0.58	0.42	0.81	0.78	0.66	1.5	0.36	0.41
48.60	1.24	60.26	2151	3324	0.65	0.35	0.68	0.81	0.69	1.5	0.31	0.36
46.09	1.24	57.15	2341	3323	0.70	0.30	0.65	0.81	0.69	1.5	0.30	0.36
76.83	1.16	89.12	2702	2931	0.92	0.08	0.54	0.86	0.73	1.5	0.26	0.34
76.18	1.16	88.37	2539	2729	0.93	0.07	0.53	0.86	0.73	1.5	0.26	0.33
103.90	1.14	118.45	2774	2774	1.00	0.00	0.50	0.88	0.75	1.5	0.25	0.33
106.00	1.14	120.84	2799	2799	1.00	0.00	0.50	0.88	0.75	1.5	0.25	0.33

Euro-code equation for compressive force

$fcd = \{\alpha cc \times S1 / \gamma cc\} \times f_{ck}$

$Cu = \lambda \times \eta \times \{\alpha cc \times S1 / \gamma cc\} \times f_{ck} \times b \times Xu$ (5)

Compare equation (i) and (iii) and assume, $K' = \lambda \times \eta \times \alpha cc \times S1 / \gamma cc$ (6)

$Cu = K' \times f_{ck} \times b \times Xu$
Euro-code equation in IS code format

$k_2 = \lambda/2$

The factor K and k2 are directly related to the bandwidth between strain at peak stress and ultimate strain of the concrete as well as the shape of the stress strain curve of the concrete. The strength reduction factor K reduces as the bandwidth between strain at peak stress and ultimate strain decreases with increase in strength and also the stress strain curve becomes steeper or linear for higher grades of concrete.

4.2 Calculation of moment capacity for balanced section and comparison with that obtained as per Euro-Code

To understand the effect of ultimate strain values on the moment capacities of the flexural members moment capacities were calculated for a balanced section from stress block parameters derived from experimentally obtained strain values and were also compared with the moment capacities calculated as per Euro-code. A representative section with dimension (b=200 mm and D=400 mm with a clear cover of 25 mm) was used for calculation of moment capacity.

IS method:

$$\frac{Xu(max)}{d} = \frac{\epsilon c}{\epsilon c + \epsilon su}$$

where, $\mathcal{E}_c$ is ultimate strain in top most compression fiber; $\mathcal{E}_{su}$ is ultimate strain in steel = $0.002 + 0.87f_y/E_s$

$Mu\ (KN\text{-}M) = C_u \times (d - k_2 \times X)$

$M_{u(max)} = K \times f_{ck} \times b \times X_{u(max)} \times (d - k_2 \times X_{u(max)})$ for balanced section

Euro-code method:

$K_4 = 1.25 \times (0.6 + (0.0014 \times 1000000 / \mathcal{E}_{cu}))$

$\frac{Xu(max)}{d} = ((1 - 0.44) / k_4)$ for cylindrical strength less than 50 MPa

$\frac{Xu(max)}{d} = ((1 - 0.54) / k_4)$ for cylindrical strength more than 50 MPa

$Mu = C_u \times (d - (\lambda/2) \times X)$

$M_{u(max)} = K' \times f_{ck} \times b \times Xu \times X_{u(max)} \times (d - (\lambda/2) \times X_{u(max)})$ for balanced section

The ultimate strain of concrete has direct impact on depth of neutral axis for balanced section which is directly related to the maximum capacity of the member. The ultimate strain values decreased as the strength of concrete increases and becomes nearly constant after 90 N/mm2 as seen from experimental values and also as per many international standards. Current IS code gives a constant value of ultimate strain of 0.0035 up to concrete grade M50. This

Table 6 Calculation of K and k2 as per the Euro code transformed in IS code parameters

Cyd str N/mm^2	Cube/Cyd	Cube Str, N/mm^2	Ec, micro-strain	Ecu, micro-strain	λ	η	αcc	S1	Ycc	K'(EC)	k2
24.00	1.28	30.72	2000.00	3500.00	0.80	1.00	0.85	0.78	1.5	0.35	0.40
23.50	1.28	30.08	2000.00	3500.00	0.80	1.00	0.85	0.78	1.5	0.35	0.40
34.40	1.28	44.03	2000.00	3500.00	0.80	1.00	0.85	0.78	1.5	0.35	0.40
33.80	1.28	43.26	2000.00	3500.00	0.80	1.00	0.85	0.78	1.5	0.35	0.40
48.60	1.24	60.26	2000.00	3500.00	0.80	1.01	0.85	0.81	1.5	0.37	0.40
46.09	1.24	57.15	2000.00	3500.00	0.81	1.02	0.85	0.81	1.5	0.38	0.40
76.83	1.16	89.12	2485.95	2610.53	0.73	0.87	0.85	0.86	1.5	0.31	0.37
76.18	1.16	88.37	2479.67	2612.77	0.73	0.87	0.85	0.86	1.5	0.31	0.37
103.90	1.14	118.45	2600.00	2600.00	0.67	0.73	0.85	0.88	1.5	0.24	0.33
106.00	1.14	120.84	2600.00	2600.00	0.66	0.72	0.85	0.88	1.5	0.24	0.33

value of 0.0035 is valid upto M35 grade of concrete only as per the experimental results. Based on trend shown by experimental results the ultimate strain value given in Euro Code EC-02 seems to be more realistic for higher grade concrete whereas constant value of ultimate strain for concrete grade between M25 to M50 (cylindrical strength) does not seems to be realistic. Therefore, the value of ultimate strain in concrete should be restricted to a lower value for higher grades of concrete.

5. Conclusions

The method or approach worked out in the paper will be useful in understanding the basic flexural design philosophy. The stress-strain characteristics or the effect of stress-strain parameters on the flexural design equations are the fundamental of stress block parameters and same needs to be derived from the strain at peak stress and ultimate strain. The factor K (strength reduction factor) and k2 (factor for the depth of resultant compressive force) are directly related to the bandwidth between strain at peak stress and ultimate strain of the concrete as well as the shape of the stress-strain curve of the concrete. The strength reduction factor K reduces as the bandwidth between strain at peak stress and ultimate strain decreases with an increase in strength and also the stress-strain curve becomes steeper or linear for higher grades of concrete. The ultimate strain of concrete has a direct impact on the depth of the neutral axis for a balanced section which is directly related to the maximum capacity of the member.

The ultimate strain values decrease as the strength of concrete increases and become nearly constant after 90 N/mm^2 as seen from experimental values and also

Table 7 Calculation of moment capacity as per the IS code approach with experimentally obtained strain values for balanced section

Cyd str. N/mm^2	Cube/Cyd	Cube Str N/mm^2	Ɛc, micro-strain	Ɛcu, micro-strain	Ɛsu, micro-strain	K (IS cur)	k2	Xu(max)/d	Moment (kN-M)
24.00	1.28	30.72	2284.00	3711.00	4175	0.35	0.41	0.471	109.35
23.50	1.28	30.08	1972.00	3789.00	4175	0.37	0.42	0.476	111.49
34.40	1.28	44.03	2175.00	3063.00	4175	0.34	0.40	0.423	139.38
33.80	1.28	43.26	1877.00	3220.00	4175	0.36	0.41	0.435	146.72
48.60	1.24	60.26	2151.00	3324.00	4175	0.31	0.36	0.443	184.52
46.09	1.24	57.15	2341.00	3323.00	4175	0.30	0.36	0.443	168.28
76.83	1.16	89.12	2702.00	2931.00	4175	0.26	0.34	0.412	222.27
76.18	1.16	88.37	2539.00	2729.00	4175	0.26	0.33	0.395	210.97
103.90	1.14	118.45	2774.00	2774.00	4175	0.25	0.33	0.399	271.46
106.00	1.14	120.84	2799.00	2799.00	4175	0.25	0.33	0.401	278.21
103.90	1.14	118.45	2600.00	2600.00	4175	0.25	0.33	0.384	262.51
106.00	1.14	120.84	2600.00	2600.00	4175	0.25	0.33	0.384	267.82

Table 8 Calculation of moment capacity as per the Euro code (transformed in IS code parameters) for balanced section

Cyd str. N/mm^2	Cube/Cyd	Cube Str, N/mm^2	Ɛc, micro-strain	Ɛcu, micro-strain	k4	K'(EC)	λ/2	Xu(max)/d	Moment (kN-M)
24.00	1.28	30.72	2000.00	3500.00	1.25	0.35	0.40	0.448	106.60
23.50	1.28	30.08	2000.00	3500.00	1.25	0.35	0.40	0.448	104.38
34.40	1.28	44.03	2000.00	3500.00	1.25	0.35	0.40	0.448	152.79
33.80	1.28	43.26	2000.00	3500.00	1.25	0.35	0.40	0.448	150.13
48.60	1.24	60.26	2000.00	3500.00	1.25	0.37	0.40	0.368	186.19
46.09	1.24	57.15	2000.00	3500.00	1.25	0.38	0.40	0.368	179.93
76.83	1.16	89.12	2485.95	2610.53	1.42	0.31	0.37	0.324	210.12
76.18	1.16	88.37	2479.67	2612.77	1.42	0.31	0.37	0.324	209.60
103.90	1.14	118.45	2600.00	2600.00	1.42	0.28	0.35	0.323	251.85
106.00	1.14	120.84	2600.00	2600.00	1.42	0.28	0.35	0.323	256.94

as per many international standards.

The study indicates that it is better to give idealized stress strain curve for different concrete grades in Design Standards which will also highlight the decrease in the bandwidth of strain values with increase in the grade of concrete and will take into effect the steepness of curve also. Therefore, it is important to include the influence of stress-strain characteristics i.e., the shape of the stress-strain curve, the strain at peak stress and ultimate strain in the flexural design for safe and efficient design of structural members using high strength concrete.

References

1. V.V. Arora; Brijesh Singh; and Shubham Jain (2017) “Effect of indigenous aggregate type on mechanical properties of High Strength Concrete”, Indian Concrete Journal, 91(1):34-44.

2. V.V. Arora; Brijesh Singh; and Shubham Jain (2016) “Experimental studies on short term mechanical properties of High Strength Concrete”, Indian Concrete Journal, 90(10):65-75

3. Emperger, F. (1904) "Ein graphischer Nachweis der Tragfahigkeit und aller in einem Tragwerke aus Eisenbeton auftretenden Spannungen", Beton und Eisen 4(5):306-320

4. Whitney, C. S. (1937) “Design of reinforced concrete members under flexure or combined flexure and direct compression”, ACI Journal Proceedings, ACI

5. Hognestad, E., N. W. Hanson, et al. (1955) “Concrete stress distribution in ultimate strength design”, ACI Journal Proceedings, ACI

6. Mattock, A. H., L. B. Kriz, et al. (1961) “Rectangular concrete stress distribution in ultimate strength design”, ACI Journal Proceedings, ACI

7. Ashour, S. A. (2000) “Effect of compressive strength and tensile reinforcement ratio on flexural behavior of High-Strength Concrete Beams”, Engineering Structures, Vol.22, p.413-423

8. Oztekin E.; Pul S.; Husem, M. (2003) “Determination of rectangular stress block parameters for High Performance Concrete”, Engineering Structures, 25:371-376

9. Attard M.M.; Stewart M.G. (1998) “Two parameter stress block for High-Strength Concrete”, ACI Structural Journal 95(3):305–317

10. Bernardo, L.F.A.; Lopes S.M.R. (2004) “Neutral axis depth versus flexural ductility in High-Strength Concrete Beams”, J. Struct. Eng., 130(3):452-459

11. ACI Committee 318 (2008) “Building Code Requirements for Reinforced Concrete and Commentary ACI 318M-08”, Manual of Concrete Practice. American Concrete Institute. Michigan. pp 465. USA

12. Standards New Zealand, NZS 3101 (2006), “Concrete Structures Standard, Part 1 - The Design of Concrete Structures”, Wellington, New Zealand

13. Ho JCM; Pam HJ; Peng J; Wong YL (2010) “Maximum concrete stress developed in flexural RC members”, Computers and Concrete

14. Swartz SE; Nikaeen A; Narayan BHD; Periyakaruppan N; Refai TME (1985) “Structural bending properties of high strength concrete”, ACI Special Publication, 87(9): p.147-178

15. Tan TH; Nguyen NB (2005) “Flexural behavior of confined high-strength concrete columns”, ACI Structural Journal. 102(2):198-205

16. Mansur MA; Chin MS; Wee TH (1997) “Flexural behavior of high-strength concrete beams”, ACI Structural Journal. 94(6):663-673

17. Kaar PH; Hanson NW; Capell HT (1978) “Stress-strain characteristics of high strength concrete”, ACI Special Publication. Douglas McHenry International Symposium on Concrete and Concrete Structures. ACI. Detroit. pp.161-185

18. Cetin, A.; Carrasquillo, R. L. (1998) “High-Performance Concrete: Influence of Coarse Aggregates on Mechanical Properties”, Journal of ACI Materials, 95:252-261

19. Peng Ho; Pam Wong (2012) “Equivalent stress block for normal-strength concrete incorporating strain gradient effect”, Magazine of Concrete Research Volume 64 Issue

20. Kahn, L. F.; K. F. Meyer (1995) "Rectangular

stress block for nonrectangular compression zone", ACI Structural Journal 92(3)

21. Ibrahim, H. H. H.; J. G. MacGregor (1996) "Flexural behavior of laterally reinforced high-strength concrete sections", ACI Structural Journal 93(6)
22. Eurocode 2-2004: Design of concrete structures, European Committee for Standardization
23. IS: 456-2000, “Code of Practice for Plain and Reinforced Concrete”, Bureau of Indian Standards, New Delhi
24. IS: 383-2016, “Coarse and fine aggregate for Concrete-Specification”, Bureau of Indian Standards, New Delhi
25. CPWD-2009, Central Public Works Department Manual, Government of India
26. IS: 1727-1967, “Methods of Test for Pozzolanic Materials”, Bureau of Indian Standards, New Delhi
27. IS: 516-2018 "Hardened concrete-method of tests", Bureau of Indian Standards, New Delhi