ASIAN JOURNAL OF CIVIL ENGINEERING (BUILDING AND HOUSING) VOL. 12, NO. 2 (2011)
PAGES 179-195

DEVELOPMENT OF STRESS BLOCK AND DESIGN PARAMETERS FOR RECYCLED AGGREGATE CONCRETE MEMBERS

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ABSTRACT

The objective of present investigation is to develop stress – block parameters for the design of reinforced recycled aggregate concrete members. To arrive at the objectives, a comprehensive experimental programme was undertaken. The influence of replacement ratio, (R_r) the ratio of recycled coarse aggregate to total coarse aggregate (Rr = RCA/TCA) on properties of recycled aggregate concrete was studied. The scope of the investigation programme is defined to generate stress strain test data of concrete, viz; M15, M20, M25, M30, and M35 and five replacement ratios, viz; 0, 0.5, 0.75, 0.85, and 1.0 were considered. A total of 150 cylinder specimens' and 48 RC beam specimens were cast for the stress-strain characteristics and flexural design of hardened concrete and design parameters are developed for recycled aggregate concrete.

Keywords: Stress block parameters; recycled aggregate; stress strain characteristics; design parameters

1. INTRODUCTION

The old structures are frequently demolished for the reconstruction of the buildings. Due to natural hazards like earthquakes also, the existing buildings are demolished. If the buildings demolished for new construction or if the buildings are demolished due to natural calamities then the huge quantity of the demolished rubble comes out as waste disposal. This disposal is causing lots of problems in terms of transportation cost and dumping sights. This is also further leading to environmental related problems. Because of the waste materials anti-pollution and other environmental related issues, the countries like United States of America, European economic communities, United Kingdom, Japan, and the Netherlands have started to use of recycled aggregate in the concrete.

The research by various countries indicated the positive sign to use the recycled aggregate in concrete. This not only solves the waste disposal problem but also solves the

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use of natural resources in affective manner to maintain the ecological balance. The researches on this area of recycled aggregate concrete are in progress in various parts of the world. The behavior of the recycled aggregate concrete strength characteristics with full replacement of the recycled coarse aggregate in place of natural coarse aggregate are the significant findings of the earlier researchers.The partial to full replacement of the recycled coarse aggregate to the natural coarse aggregate are also essential to understand the mechanical behaviour of the concrete in general.

1.1 Aim and objective

To develop stress-block parameters and design parameters for design of reinforced recycled aggregate concrete members.

1.2 Scope of the work

Keeping in view the objective, evaluation of stress block and design parameters of recycled aggregate concrete for, M15, M20, M25, M30 and M35 grade concrete with replacement ratio of 0, 0.5, 0.75, 0.85 and 1.0 were obtained.

1.3 Literature review

Ravindrarajah R.S and Tam (1) reported that the particle shape of recycled aggregate is angular with rough and porous surface texture. The results of the investigations made by BCSJ(2) indicate that, approximately 20% of cement mortar was attached to 20mm to 30mm size aggregate particles, while up to 0.3mm size filler fractions of recycled fine aggregate contain 45 to 65% of old cement mortar. Hansen and Narud (3) in their investigation, found 4.5% to 7.6% decrease in specific gravity value, when compared with specific gravity (ssd) of natural aggregate. The existing literature available except for the investigation carried out by Ravande Kishore (4) revealed that conventional mix design methods were employable for proportioning the constituents of recycled aggregate concretes. Malhothra (5), Kumar Roy et.al (6) have indicated that workability of recycled aggregate concrete can be maintained on par with the conventional concrete if the additional water demand of 5% to 8% required by a recycled aggregate concrete is appropriately met with. A review of earlier research on performance of recycled aggregate concrete by Nixon.P.J.(7) revealed that compressive strength of recycled aggregate concrete was lower when compared with corresponding conventional concretes.

2. EXPERIMENTAL PROGRAMME

Five grades of concrete, four replacement ratios viz, 0.5, 0.75, 0.85 and 1.00 were selected for study. For comparison purpose, conventional concrete of all five grades were considered as reference concrete. The compressive strengths of all replacement ratios are presented in Table 1.

2.1 Modulus of elasticity

The modulus of elasticity values for all grades of concretes with different replacement ratios were obtained based on average test data of three cylinders. These average values for all 25 mix cases are presented in Table 2. The guide lines on test procedure are explained in detail in IS 516(8).

Table 1: Experimental and theoretical stress-strain values for various concrete mix cases

Sl. No.	**Mix Designation**	**Stress (MPa)**		**Strain (ε x 10^{4})**	
		Experimental	**Theoretical**	**Experimental**	**Theoretical**
	RMA-0	19.20	19.12	21.65	22.32
	RMA-50	18.43	17.77	23.56	23.86
	RMA-75	17.48	17.10	24.47	24.63
	RMA-85	16.36	16.83	25.38	24.94
	RMA-100	15.81	16.43	25.86	25.40
	RMB-0	22.99	22.54	19.35	19.29
	RMB-50	20.68	20.91	19.40	19.77
	RMB-75	20.49	20.78	20.05	21.01
	RMB-85	20.20	20.32	20.49	22.11
	RMB-100	19.50	20.19	20.68	23.78
	RMC-0	24.44	24.28	15.80	16.10
	RMC-50	21.84	22.23	21.42	20.56
	RMC-75	21.44	21.21	22.55	22.80
	RMC-85	20.68	20.80	23.65	23.68
	RMC-100	20.32	20.35	25.30	25.02
	RMD-0	25.60	26.15	16.30	16.90
	RMD-50	25.20	24.12	21.75	20.81
	RMD-75	23.12	23.10	22.54	22.77
	RMD-85	22.74	22.70	23.35	23.55
	RMD-100	21.50	22.09	24.84	24.73
	RME-0	28.97	29.40	20.60	20.90
	RME-50	27.24	26.40	23.40	23.20
	RME-75	25.76	24.90	24.60	24.30
	RME-85	23.69	24.30	24.85	24.80
	RME-100	22.95	23.40	25.80	25.50

RMA=M15, RMA=M20, RMA=M25, RMA=M30, RMA=M35
0,50,75,85,100 = Percentage of replacement ratio (Rr)

Table 2: Non dimensional zed experimental and theoretical average stress ratios and strain ratios for m20 grade concrete having different replacement ratios of recycled coarse aggregate (RCA)

	RMB – 0		RMB – 50		RMB – 75		RMB – 85		RMB – 100	
	R_r = 0.0		R_r = 0.50		R_r = 0.75		R_r = 0.85		R_r = 1.00	
($\varepsilon / \varepsilon_u$)	(f / f_u)		(f / f_u)		(f / f_u)		(f / f_u)		(f / f_u)	
	Exp.	Theo.	Exp.	Theo.	Exp.	Theo.	Exp.	Theo.	Exp.	Theo.
0.1	0.0929	0.1200	0.1339	0.1197	0.0914	0.1492	0.0981	0.1394	0.1533	0.1394
0.2	0.2588	0.2330	0.2535	0.2380	0.2178	0.2941	0.2268	0.2755	0.2879	0.2755
0.3	0.4235	0.3467	0.3977	0.3536	0.3555	0.4306	0.3910	0.4054	0.4341	0.4054
0.4	0.5763	0.4568	0.5137	0.4651	0.5145	0.5556	0.5308	0.5263	0.5785	0.5263
0.5	0.6813	0.5625	0.6166	0.5714	0.6366	0.6667	0.6589	0.6363	0.6886	0.6363
0.6	0.7634	0.6629	0.7121	0.6714	0.7434	0.7627	0.7837	0.7342	0.7729	0.7342
0.7	0.8322	0.7572	0.7985	0.7650	0.8378	0.4337	0.8715	0.8193	0.8625	0.8193
0.8	0.8850	0.8451	0.8689	0.8510	0.8933	0.9090	0.9201	0.8917	0.9012	0.8917
0.9	0.9431	0.9261	0.9404	0.9294	0.9485	0.9608	0.9645	0.9516	0.9426	0.9516
1.0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

2.2 Stress - strain curve

Keeping in view the specifications of IS 456 -2000 (9), M15 grade concrete mix case was not taken in to account for further investigations and only four grades of concrete viz.; M20, M25, M30 and M35 were considered. However, same five replacement ratios for each grade of concrete were considered. Thus in all, twenty mix cases were investigated for development of stress block parameters and design parameter.

During the testing of cylinder specimen for stress-strain characteristics, load vs deformation data was recorded for all the specimens of various mix cases of recycled aggregate concrete.The load vs deformation data was then converted to stress vs strain data. Stress-strain data consisting of about 60 pair of observations were plotted. A curve was drawn passing through the origin, which represented the mean relationship between the stress and strain. Twenty such stress-strain curves were drawn corresponding to each type of mix case of recycled aggregate concrete. From these stress-strain relationships, the maximum, minimum, and mean stress values corresponding to ten strain values from10% to 100% were found. The values of stress and strain were then non dimensionalized by dividing each of the stress and strain values by corresponding ultimate stress, ultimate strain values and a typical values of such data presented in Table 3. The non-dimensionalized stress–strain curves can be represented by a second degree polynomial. From the literature, it appears that second degree parabola as suggested by L.P. Saenz (10) seems to better fit, with appropriate constants suitable for the present curves.

Table 3: Comparison of experimental and theoretical design parameters and curvatures for various types of RRAC beams

S. No	Beam designations	Exp. ultimate moment M_e (kN.m)	Design parameter obtained from M_e $k_e=M_e/f_{ck}bd^2$	Proposed design parameter k_t	Ratio k_t/k_t	Exp. curvature (ϕ_e x 10^4)	Theo. curvature (ϕ_t x 10^4)	Ratio ϕ_e/ϕ_t
1	RMB - 0	28.40	0.2050	0.2246	0.9127	1.000	1.000	1.000
2	RMB - 50	27.60	0.2020	0.2209	0.9144	0.632	0.625	1.011
3	RMB - 75	27.00	0.1999	0.2191	0.9123	0.510	0.650	0.784
4	RMB - 85	26.60	0.1990	0.2183	0.9115	0.650	0.650	1.000
5	RMB - 100	26.20	0.1980	0.2172	0.9116	0.432	0.645	0.670
6	RMC - 0	31.0	0.1870	0.19934	0.9382	0.740	0.890	0.831
7	RMC - 50	29.60	0.1850	0.1916	0.9655	0.690	0.983	0.701
8	RMC - 75	28.80	0.1800	0.1877	0.9589	0.930	0.982	0.946
9	RMC - 85	28.40	0.1780	0.1862	0.9559	0.498	0.585	0.851
10	RMC - 100	28.00	0.1750	0.1838	0.9521	0.832	0.823	1.009
11	RMD - 0	36.00	0.1700	0.1933	0.8794	0.978	0.998	0.982
12	RMD - 50	34.60	0.1688	0.1828	0.9190	0.823	0.810	1.018
13	RMD - 75	33.00	0.1686	0.1776	0.9234	0.980	0.953	1.027
14	RMD - 85	32.60	0.1682	0.1755	0.9230	0.655	0.653	1.003
15	RMD - 100	31.60	0.1678	0.1723	0.9228	0.756	0.863	0.875
16	RME - 0	37.20	0.1675	0.1744	0.8944	1.046	1.028	1.017
17	RME - 50	36.80	0.1673	0.1729	0.9485	0.798	0.781	1.021
18	RME - 75	36.60	0.1668	0.1722	0.9465	0.953	0.963	0.989
19	RME - 85	36.40	0.1665	0.1718	0.9604	1.056	0.993	1.006
20	RME - 100	35.00	0.1661	0.1714	0.9568	0.945	0.984	0.960

3. MATHEMATICAL MODEL

Saenz [10] and Bhikshma [11] proposed the following equation to represent stress-strain relationship (Figure 1) of concrete in compression.

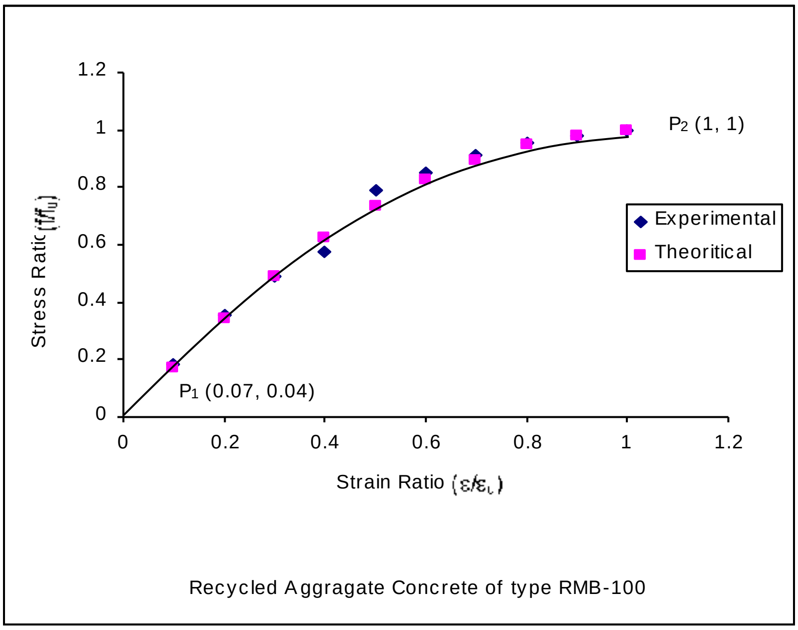

Figure 1. Non - dimensionalised stress-strain curves for recycled aggregate concrete of type RMB-0

$$f = \frac{A\varepsilon}{1 + B\varepsilon^2} \quad .. \quad .. \quad .. \quad .. \quad .. \quad .. \qquad (1)$$

Where, ε = Strain in concrete

f = Stress corresponding to strain in concrete, and

A and B are constants for a stress-strain curve

It is assumed that the equation proposed by Saenz is also valid for recycled aggregate concrete. To express stress-strain behaviour (Figure 1) of recycled aggregate concrete in non-dimensional form as in Saenz model with strain ratio as independent variable and stress ratio as dependent variable, the following equation is proposed

$$\frac{f}{f_u} = \frac{A^{\prime}(\varepsilon/\varepsilon_u)}{1.0 + B^{\prime}(\varepsilon/\varepsilon_u)^2} \quad .... \qquad (2)$$

Where, A′ and B′ are constants of stress-strain curve.

f/f_u = Stress ratio , and $\varepsilon/\varepsilon_u$ = Strain ratio

The constants A′ and B′ are evaluated using boundary conditions pertaining to non-dimensionalized stress – strain curve for each mix type.

Evaluation of constants A′ and B′, typically for M20 grade concrete having replacement ratio of 1.0 is shown below.

With reference to Figure 1, pertaining to non–dimensionalized stress-strain curve, the boundary conditions are:

(i) at $\varepsilon / \varepsilon_u = 0.04$; $f / f_u = 0.07$ .. The point, where curve departs from its straight-line portion.

(i) at $\varepsilon / \varepsilon_u = 1.0$; $f / f_u = 1.0$ .. .. The point of peak stress corresponding to peak strain.

Substituting the above boundary conditions in Eq. (2), we get

$$A' = 1.75$$
$$B' = 0.175$$

It may be noted here that, boundary condition (ii) remains same for any non-dimensional stress-strain curve. This is due to the fact that non-dimensional stress-strain curve will have the same point (1,1) at peak stress.

As regards to boundary condition (i), care is taken to choose the exact point, from where the stress-strain curve departs from its straight-line portion.

The values of constants A′ and B′ are computed for all 25-mix cases by following the procedure, stated above.

Corresponding values of A and B are then evaluated using equations stated below:

$$A = A' (f_u / \varepsilon_u) \;..\;..\;..\;.. \quad (3)$$

$$B = B' (1.0 / \varepsilon_u)^2 \;..\;..\;..\;.. \quad (4)$$

For example under consideration, substituting A′ and B′ values in Eqs. (3) and (4), we get,

$$A = 1.75(20.192/0.0023788) = 14854.548$$

$$B = 0.175\,(1.0/0.0023788)^2 = 30925.888$$

Thus, using Eq. 2 (with the values of A′ and B′ for each mix case) the data for plotting non-dimensionalized theoretical stress–strain curves are obtained. These non-dimensionalized stress-strain curves are then plotted and superimposed on the non-dimensionalized experimental stress strain curves shown in Figure 1. From the Figure s it may be noted that the non – dimensionalized theoretical stress – strain curve almost matches with experimental curve, thus proving the assumption of Saenz model’s (Figure 2) validity for recycled aggregate concrete (RAC).

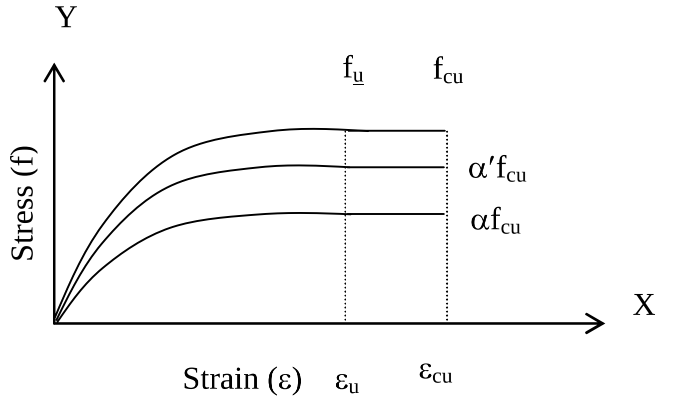

Figure 2. Assumed idealized stress-strain curves for recycled aggregate concrete

3.1 Expressions for compressive force and tensile force

Assuming idealization of stress-strain curve as shown in Figure 3 and superimposing the same on the cross section of the flexural member shown in Figure 4, the expression for compressive force(C) is written as:

$$C = \alpha'.f_{cu}.b.X_n. \quad .. \quad .. \quad .. \quad .. \qquad (5)$$

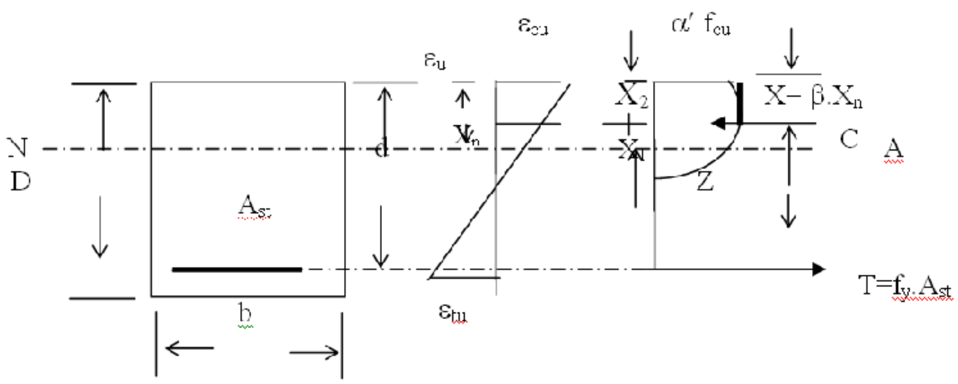

Figure 3. Strain diagram and stress-block diagram for Recycled Aggregate concrete

Also, from the Figure 3 area under stress – strain curve (A_b) is given by

$$A_b = \alpha'.f_{cu}.\varepsilon_{cu}$$

Thus,

$$\alpha = \frac{A_b}{f_{cu}\varepsilon_{cu}} \quad .. \quad .. \quad .. \quad .. \qquad (6)$$

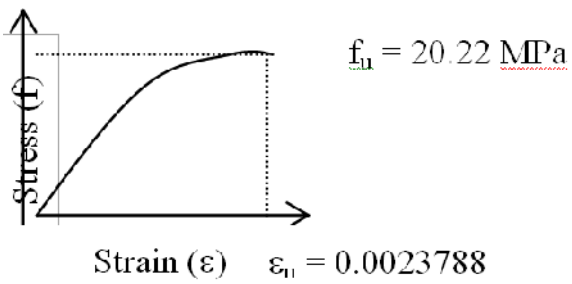

Figure 4. Typical stress-strain curve for recycled aggregate concrete of type rmb-100

Where, α' is a stress block parameter without partial safety factor. Substituting Eq. (6) in Eq. (5), we get

$$C = \frac{b.X_n}{\varepsilon_{Cu}} . A_b \;\; .. \;\; .. \;\; .. \;\; .. \qquad (7)$$

Further, with reference to Figure 3 the tensile force (T) is expressed as

$$T = f_y .Ast \;\; .. \;\; .. \;\; .. \qquad (8)$$

we know,

$$\varepsilon_s = \frac{0.87 f_y}{E_s} + 0.002 \;\; .. \;\; .. \;\; .. \qquad (8a)$$

{ as per clause of 38.1 of IS 456-2000 (8)}

$$\text{thus,} \quad f_y = \frac{E_s(\varepsilon_s - 0.002)}{0.87} \;\; .. \;\; .. \;\; .. \qquad (8b)$$

Substituting for f_y, i.e Eq. (8b) in Eq. (8)

$$T = E_s (\varepsilon_s\text{-}0.002)/(0.87 \, Ast) \;\; .. \;\; .. \;\; .. \qquad (9)$$

3.2 Idealization of stress -strain curve

In earlier presentation under section 2, to derive the expression for compressive force, idealization of stress-strain curve is assumed. However, the assumption of idealization is being proved in the following section with respect to a particular mix case.

The idealization process is demonstrated using the typical concrete mix case of M20 grade concrete with hundred percent replacement (RMB-100). The non-dimensional stress-strain curve obtained for cylinder specimen for RMB-100 is shown in Figure 2.

For idealization, the stress-strain curve obtained from experimental data is to be extrapolated beyond the experimental ultimate stress point. The extrapolation of the curve is done by obtaining further theoretical ultimate values of stress and strain. For this, the condition of equilibrium of forces, (i.e compressive force = Tensile force) is considered.

We know from Eq. (7),

$$C = \frac{b.X_n}{\varepsilon_{cu}}.A_b$$

Further, area under stress – strain curve (A_b) is given by

$$A_b = \frac{A}{2B}\log(\frac{1+B\varepsilon_{cu}^2}{1+B\varepsilon_1^2}) \quad .. \quad .. \quad .. \quad .. \qquad (10)$$

(Details of derivation of expression for 'A_b' is presented in Appendix - D)

Substituting Eq. (9) in Eq. (7), we get

$$C = \frac{bX_n}{\varepsilon_{cu}}\frac{A}{2B}\log(\frac{1+B\varepsilon_{cu}^2}{1+B\varepsilon_1^2}) \quad .. \quad .. \quad .. \qquad (11)$$

where, C = Compressive force
b = Breadth of the section
X_n = Depth of the neutral axis
ε_1 = Initial strain in concrete
ε_{cu} = Ultimate strain in concrete
A_b = Area of stress-block
A and B = Constants obtained from Eq. (3) and (4)

To generate different values of compressive forces, following values are assigned for various parameters. It may be noted that, while values for some parameter are constant, the parameters X_n and ε_{cu} are considered variable for M20 grade concrete with replacement ratio of 1.0 (RMB-100).

A = 14854.548
B = 30925.888
b = 150mm
d = 192 mm
Xn = 0.1d to 0.5d with an incremental value /interval of 0.1d
ε_{cu} = $1\text{x}10^{-4}$ to $1\text{x}10^{-3}$ with an interval of $1\text{x}10^{-4}$,
$2\text{x}10^{-3}$ to $1\text{x}10^{-2}$ with an interval of $1\text{x}10^{-3}$, and
$2\text{x}10^{-2}$ to $1\text{x}10^{-1}$ with an interval of $1\text{x}10^{-2}$

Similarly, to generate different values of tensile forces, following values are assigned for various parameters. It may be noted that, while values for some parameters were constant, the parameter ε_s was considered as variable.

ε_s = $2.2\text{x}10^{-3}$ to $1\text{x}10^{-2}$ with an interval of $1\text{x}10^{-3}$.

On visual inspection of the data on compressive force and tensile force generated, it is noticed that the possibility of C = T appears to be for the value of X_n = 0.5d. This is confirmed and exact value of strain at which C = T, is found from a plot C/T vs strain values as shown in the Figure 5.

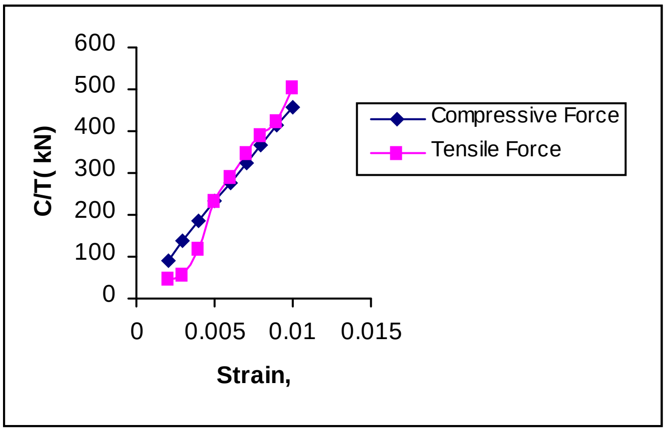

Figure 5. Relationship between strain and compressive force/tensile force (C/T)

For the present example, α and f_{cu} are calculated as illustrated below
From Figure 5, for X_n = 0.5d
we have, ε_{cu} =0.005, and
C = 231.328kN

From Eq. (6) we have, $$\alpha' = \frac{A_b}{f_{cu}\varepsilon_{cu}}$$

Taking $f_{cu} = f_u$ as seen in assumed idealized stress-strain curve (Figure 2)

We have, $$\alpha' = \frac{A_b}{f_u\varepsilon_{cu}}$$

Using partial safety factor of 1.5 for concrete, the modified stress-block parameter (α) is given by

$$\alpha = \frac{\alpha'}{1.5} = \frac{A_b}{f_u\varepsilon_{cu}.1.5},\ \alpha\ =\ 0.54$$

Substituting ε_1 = 0, ε_{cu} = 0.005, A = 14854.548 and B = 30925.888 in Eq. (10), we get A_b = 0.08032244

Substituting for A_b, ε_{cu}, and f_u=20.22 N/mm^2 (from Figure 6)

We have from Eq. (5) C = α′ f_{cu}. b. Xn

Substituting values of α′, b, Xn and C in Eq. (4.5) we get,

231.328 X 10^3 = 0.80 X f_{cu} X 150 X 0.5 X 192

$$f_{cu} = 20.08 N/mm^2$$

Having obtained f_{cu} value corresponding to ε_{cu} value, the stress strain curve (Figure 6) is further drawn with above derived stress - strain values and the extrapolated curve is shown in Figure 6.

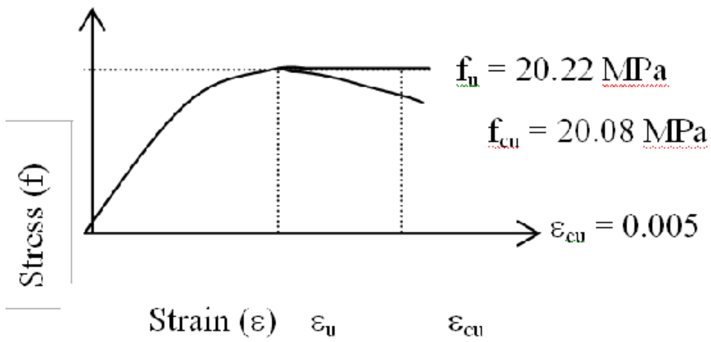

Figure 6. Typical extrapolated stress-strain curve for recycled aggregate concrete of type RMB-100

From Figure 6, it is clear that the values of f_{cu} and f_u differ by just 0.7%, which is quite insignificant. Hence, the curve can be taken straight from the point f_u parallel to abscissa, thus idealizing the stress-strain curve, as shown in Figure 2.

The assumed idealized stress – strain curve is thus validated and all the calculations carried out using the idealized stress-strain curve are appropriate and correct.

With reference to the Figure 2, the depth of the parabolic portion of the stress-block can be obtained from strain diagram, that is

$$X_1 = \frac{\varepsilon_u}{\varepsilon_{cu}} . X_n \quad .. \quad .. \quad .. \quad .. \qquad (12)$$

Similarly, depth of the rectangular portion of the stress-block is given by

$$X_2 = \left(\frac{\varepsilon_{cu} - \varepsilon_u}{\varepsilon_{cu}}\right). X_n \quad .. \quad .. \quad .. \quad .. \qquad (13)$$

The compressive force component for parabolic portion (C_1) of stress- block without partial safety factor is given by

$$C_1 = \frac{2}{3} . X_1 (\alpha' f_{cu}). b \quad .. \quad .. \quad .. \quad .. \qquad (14)$$

The compressive force component for rectangular portion (C_2) of stress- block without partial safety factor is given by

$$C_2 = X_2.\,\alpha'\, f_{cu}.b \quad .. \quad .. \quad .. \quad .. \qquad (15)$$

Thus, the total compressive force (C) is given by

$$C = C_1 + C_2 \quad .. \quad .. \quad .. \quad .. \qquad (16)$$

Let X be the distance of the line of the action of compressive force from the extreme top fiber, then

$$X = C_1\,(3/8X_1 + X_2) + C_2\,(X_2/2)/C \quad .. \quad .. \quad .. \quad .. \qquad (17)$$

$$\text{Let, } X = \beta.X_n$$

Where β is another stress-block parameter, which is a function of X_1, X_2, C_1, C_2 and C as given by Eqs. (12), (13), (14), (15), and (16) respectively.

3.3 Computation of moment factor (k_t)

With reference to the Figure 3

Moment of resistance, $M_t = C \times Z$

Substituting for C from Eq. (5), we get

$$M_t = \alpha'.f_{cu}\, b\, X_n\,(\,d - \beta.X_n) \quad .. \quad .. \quad .. \qquad (18)$$

Substituting for α' from Eq. (6) , we get

$$M_t = \frac{b.Xn}{\varepsilon_{cu}}.\,A_b\,(\,d - \beta.X_n) \quad .. \quad .. \qquad (19)$$

Also, moment of resistance (M_t) is given by

$$M_t = k_t\,.\,f_{cu}.b.d^2$$

where, k_t = Moment factor

Therefore, $$k_t = \frac{M_t}{f_{cu}.bd^2} \quad .. \quad .. \quad .. \qquad (20)$$

Substituting Eq. (18) in Eq.. (20), we get

$$k_t = \alpha'.\frac{X_n}{d}\,(1 - \beta.\frac{X_n}{d})$$

Using partial safety factor,

$$k_t = \frac{\alpha'}{1.5} \cdot \frac{X_n}{d}\left(1 - \beta \cdot \frac{X_n}{d}\right) \quad \ldots \ldots \quad (21)$$

From the experimental observations and analysis of test results, the value of stress-block parameter is computed as illustrated earlier, for each of the 20 mix cases. For each mix case, the values of X_1, X_2, C_1, C_2 and C shown in Figure 3 are computed using the Eqs. (12), (13), (14), (15) and (16) respectively, thus enabling the calculation of β. Hence, the value of X in terms of β and X_n is obtained. By following the above procedure, for each of the 20 mix cases the values of β are computed.

By virtue of the principle of equilibrium, where in compressive force is equal to tensile force, the value of X_n/d is calculated for each mix case considered in the present investigation. Thus, the data pertaining to X_n/d is generated for all the 20 mix cases.

The data of $\mathbf{R_r}$ vs. $\boldsymbol{\alpha}$, $\mathbf{R_r}$ vs. $\boldsymbol{\beta}$ and $\mathbf{R_r}$ vs. $\mathbf{X_n/d}$ for each grade of concrete are then subjected to regression analysis and the following best fit equations and corresponding correlation coefficients are obtained.

(i) Regression/best fit equations for α, for four grades of concrete are:

For M20 grade concrete (RMB), $\alpha = 0.6430 - 0.0241R_r$, R = 1.00
For M25 grade concrete (RMC), $\alpha = 0.5760 - 0.0640R_r$, R = 1.00
For M30 grade concrete (RMD), $\alpha = 0.5730 - 0.1005\ R_r$, R = 1.00
For M35 grade concrete (RME), $\alpha = 0.5400 - 0.1088\ R_r$, R = 0.99

(ii) Regression/best fit equations for β, for four grades of concrete are:

For M20 grade concrete (RMB), $\beta = 0.4650 - 0.0051\ R_r$, R = 0.99
For M25 grade concrete (RMC), $\beta = 0.4530 - 0.0093\ R_r$, R = 0.99
For M30 grade concrete (RMD), $\beta = 0.4502 - 0.0069\ R_r$, R = 0.99
For M35 grade concrete (RME), $\beta = 0.4390 - 0.0160\ R_r$, R = 1.00

(iii) Regression/best fit equations for X_n/d , for four grades of concrete are:

For M20 grade concrete (RMB), $\frac{X_n}{d} = 0.4389 + 0.0016\ R_r$, R = 0.99

For M25 grade concrete (RMC), $\frac{X_n}{d} = 0.4300 + 0.0180\ R_r$, R = 1.00

For M30 grade concrete (RMD), $\frac{X_n}{d} = 0.4140 + 0.0420\ R_r$, R = 0.99

For M35 grade concrete (RME), $\frac{X_n}{d} = 0.3900 + 0.0830\ R_r$, R = 1.00

Where, R_r = Replacement ratio, and R = Correlation coefficient

Using the respective best-fitting equation, the values $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$ & $\mathbf{X_n/d}$ are computed for each grade of concrete for different values of $\mathbf{R_r}$.

Using $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$ and $\mathbf{X_n/d}$ values for each of the 20 mix cases, and substituting them in Eq. (21), the values of design parameter $\mathbf{k_t}$ are computed. The data $\mathbf{k_t}$ vs $\mathbf{R_r}$ is then subjected to regression analysis and the following regression/ best-fit equations are obtained with correlation coefficients for four grades of concrete considered in the investigation.

For M20 grade concrete (RMB), $k_t = 0.2246 - 0.00732R_r$, R = 0.99

For M25 grade concrete (RMC), $k_t = 0.19934 - 0.01551R_r$, R = 1.00
For M30 grade concrete (RMD), $k_t = 0.1933 - 0.0210R_r$, R = 1.00
For M35 grade concrete (RME), $k_t = 0.1744 - 0.0030R_r$, R = 0.99
Where, R_r = Replacement ratio, and R = Correlation coefficient

The best fit equation is then used to generate the values of design parameter k_t for different values of replacement ratios (R_r). Thus, the values of stress block parameters and design parameter generated for different values of replacement ratio (R_r = 0 to 1.0 with an interval of 0.05), provide a ready reckoner data for the design of R.C member in flexure with a choice of replacement ratio of coarse aggregate that can be used.

4. DISCUSSIONS

4.1 Mathematical model

In the formulation of the mathematical model, according to L.P.Saenz (10), no exact theory is available for stress-strain curve of concrete. However, the theoretical stress strain curve can be verified by comparing it with experimental stress strain curve developed from the observed data.

As stated above, both theoretical and experimental non-dimensionalized stress strain curve (Figure 1) almost matched with each other, thus proving the correctness of the assumption of Saenz model being valid for recycled aggregate concrete. This is indeed a significant achievement of the present investigation, paving way for carrying out further analysis to satisfy the objectives of the investigation defined earlier.

While, non-dimensionlized theoretical and experimental stress strain curve is found identical, it is interesting to note the influence of replacement ratio of coarse aggregate on stress-strain behaviour of concrete. Figure s 1 depict the non-dimensionalized experimental stress strain curves for each of the four grades of concrete and five replacement ratios considered in the present investigation. A look at this Figure reveals that, the curve indicated more or less similar profile irrespective of replacement ratio of coarse aggregate in the concrete. A few curves deviating from the normal trend could be due to heterogeneity of constituent materials of concrete, which is sometimes beyond control. However, some influence of replacement ratio of coarse aggregate is visible on stress and strain values. Thus, the stress block parameters and design parameter are evaluated and validated.

4.2 Validation of stress block parameters and design parameter

The validation of stress block parameters and design parameter was carried out in terms of moment carrying capacity and moment curvature relationship.

4.3 Moment carrying capacity

The theoretical moment carrying capacity computed both by conventional limit state method of design and proposed design parameter is compared with the observed experimental moment carrying capacity for all the 20 types (20 mix cases) of beam specimens. Moment carrying capacity, otherwise also understood as moment of resistance or ultimate computed and reveal that the experimental values of moment carrying capacity are higher by about 9% to 14% when compared with the corresponding theoretical values observed by using proposed design parameter (k_t). However, experimental moment carrying capacity are about 35% to 88% higher, when they are compared with the corresponding values calculated by conventional limit state design method. The above comparison reveal the fact that the conventional limit state design method is highly conservative and estimates moment carrying capacity of a structural member lower side. On the other hand, the estimate of moment carrying capacity by using proposed design parameter is reasonably close to the observed experimental values. It is interesting to note that, the above observations are the even in case of conventional concrete mix cases (R_r=0). A margin of 9% to 14% between experimental and theoretical values is certainly an acceptable margin keeping in view several uncertainties associated with constituent material properties. Further, the experimental and theoretical values of design parameters tabulated in the Table 5.8 also indicate a close match with their ratio being in the range of 0.91 to 0.95. This is obvious in the light of discussion on theoretical and experimental moment carrying capacity of various types of beams (types of mix cases).

5. CONCLUSIONS

1. Saenz mathematical model is successfully evaluated and validated for all recycled aggregate concrete mix cases considered in the investigation programme.
2. Stress block parameters (α, β and X_n/d) and design parameter (k_t) are developed exclusively for recycled aggregate concrete mixtures, and they are validated for all concrete mixtures considered in the investigation programme.
3. Experimental moment carrying capacity values (M_e) of all beam specimens (20 mix cases) is found to be in close agreement with the theoretical moment carrying capacity (M_p) computed by using proposed design parameter. A variation of 9 to 14% observed, could be considered as an acceptable range of variation for an experiment oriented work, thus validating the proposed stress block parameters and the design parameter.

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