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# DEVELOPMENT OF STRESS – STRAIN CURVES FOR RECYCLED AGGREGATE CONCRETE

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## ABSTRACT

Conservation of natural resources and rapid urbanization has prompted growing demand for natural aggregate by construction industry. This demand is compounded by considerable decline in the availability of good quality natural aggregate and enormous increase in the quantities of demolished concrete. The alternative materials to cement in terms of fly ash and other pozzolanic materials were evolved, popular alternative material to coarse aggregate are being explored. Recycled aggregate is one such alternative and the present research work is a step forward in developing the design parameters using stress block parameters.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 defined above, 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 mechanical 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' were cast for the stress-strain characteristics of hardened concrete.

**Keywords:** Recycled aggregate; stress strain characteristics; design parameters; replacement ratio.

## 1. INTRODUCTION

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 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

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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. To understand the behavior of the recycled aggregate concrete for the different grades of the concrete and different partial to full replacement ratios, the workability is the very important aspect. The important observations in recycled aggregate concrete include the attached cement mortar on the surface of the recycled aggregate.

The objective of this work is to develop the stress- strain curves for design of reinforced recycled aggregate concrete members in flexure.

Keeping in view the objective, evaluation of the properties 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.

Ravindrarajah and Tam [1] reported that the particle shape of recycled aggregate is angular with rough and porous surface texture. Visual inspection of the particles of recycled aggregate reveals that most of the virgin aggregate particles are coated with old cement mortar. 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 Kishore [4] revealed that conventional mix design methods were employable for proportioning the constituents of recycled aggregate concretes. Malhothra [5), Kumar Roy and Sai [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 [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. Cube Compressive Strength of various Concrete Mix Cases

| Sl. No. | Mix designation | Strength (MPa) | |
|---|---|---|---|
| | | Compressive strength | Modulus of elasticity |
| 1. | RMA-0 | 19.20 | 20.50 |
| 2. | RMA-50 | 18.58 | 20.20 |
| 3. | RMA-75 | 18.24 | 20.00 |
| 4. | RMA-85 | 18.16 | 19.80 |
| 5. | RMA-100 | 18.10 | 19.60 |
| 6. | RMB-0 | 25.06 | 22.50 |
| 7. | RMB-50 | 24.71 | 21.12 |
| 8. | RMB-75 | 24.43 | 21.87 |
| 9. | RMB-85 | 24.17 | 21.70 |
| 10. | RMB-100 | 23.93 | 21.42 |
| 11. | RMC-0 | 35.00 | 26.20 |
| 12. | RMC-50 | 34.50 | 25.63 |
| 13. | RMC-75 | 34.00 | 25.50 |
| 14. | RMC-85 | 33.85 | 24.80 |
| 15. | RMC-100 | 33.30 | 25.00 |
| 16. | RMD-0 | 40.00 | 27.60 |
| 17. | RMD-50 | 38.90 | 26.82 |
| 18. | RMD-75 | 37.80 | 26.60 |
| 19. | RMD-85 | 37.65 | 26.40 |
| 20. | RMD-100 | 37.50 | 26.20 |
| 21. | RME-0 | 45.00 | 29.00 |
| 22. | RME-50 | 44.25 | 28.00 |
| 23. | RME-75 | 43.85 | 27.65 |
| 24. | RME-85 | 43.00 | 27.30 |
| 25. | RME-100 | 42.80 | 27.22 |

**RMA=M15, RMA=M20, RMA=M25, RMA=M30, RMA=M350,50,75,85,100=Percentage of replacement ratio (Rr)**

Table 2. Experimental and theoretical stress-strain values for various concrete mix cases

| Sl. No. | Mix designation | Stress (MPa) | | Strain ($\varepsilon \times 10^{4}$) | |
|---|---|---|---|---|---|
| | | Experimental | Theoretical | Experimental | Theoretical |
| 1. | RMA-0 | 19.20 | 19.12 | 21.65 | 22.32 |
| 2. | RMA-50 | 18.43 | 17.77 | 23.56 | 23.86 |
| 3. | RMA-75 | 17.48 | 17.10 | 24.47 | 24.63 |
| 4. | RMA-85 | 16.36 | 16.83 | 25.38 | 24.94 |
| 5. | RMA-100 | 15.81 | 16.43 | 25.86 | 25.40 |
| 6. | RMB-0 | 22.99 | 22.54 | 19.35 | 19.29 |
| 7. | RMB-50 | 20.68 | 20.91 | 19.40 | 19.77 |
| 8. | RMB-75 | 20.49 | 20.78 | 20.05 | 21.01 |
| 9. | RMB-85 | 20.20 | 20.32 | 20.49 | 22.11 |
| 10. | RMB-100 | 19.50 | 20.19 | 20.68 | 23.78 |
| 11. | RMC-0 | 24.44 | 24.28 | 15.80 | 16.10 |
| 12. | RMC-50 | 21.84 | 22.23 | 21.42 | 20.56 |
| 13. | RMC-75 | 21.44 | 21.21 | 22.55 | 22.80 |
| 14. | RMC-85 | 20.68 | 20.80 | 23.65 | 23.68 |
| 15. | RMC-100 | 20.32 | 20.35 | 25.30 | 25.02 |
| 16. | RMD-0 | 25.60 | 26.15 | 16.30 | 16.90 |
| 17. | RMD-50 | 25.20 | 24.12 | 21.75 | 20.81 |
| 18. | RMD-75 | 23.12 | 23.10 | 22.54 | 22.77 |
| 19. | RMD-85 | 22.74 | 22.70 | 23.35 | 23.55 |
| 20. | RMD-100 | 21.50 | 22.09 | 24.84 | 24.73 |
| 21. | RME-0 | 28.97 | 29.40 | 20.60 | 20.90 |
| 22. | RME-50 | 27.24 | 26.40 | 23.40 | 23.20 |
| 23. | RME-75 | 25.76 | 24.90 | 24.60 | 24.30 |
| 24. | RME-85 | 23.69 | 24.30 | 24.85 | 24.80 |
| 25. | RME-100 | 22.95 | 23.40 | 25.80 | 25.50 |

*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.This procedure was repeated for all the twenty mix cases of recycled aggregate concrete. Using non dimensionalized stress-strain data, non-dimensionalized stress strain curves (experimental and theoretical) were plotted for each of the 20 mix cases of recycled aggregate concrete. The same is depicted in Figure 1. Further, to study the influence of replacement ratio of recycled coarse aggregate, relationships between non-dimensionalized stress ratio and non-dimensionalized strain ratio (experimental) are plotted for four concrete mix cases of each grade of concrete having five different replacement ratios.

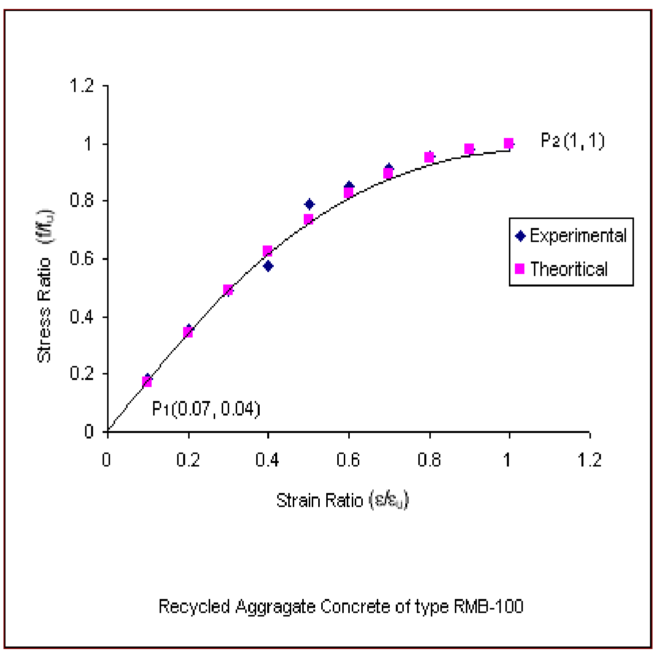


Figure 1. Non-dimensionalised stress-strain curves for recycled aggregate concrete of type RMB-0

Table 3. Non-dimensionalized experimental and theoretical average stress ratios and strain ratios for M20 Grade concrete having different replacement ratios of recycled coarse aggregate (RA)

| ($\varepsilon / \varepsilon_u$) | **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** | |
| | **( $f / f_u$)** | | **( $f / f_u$)** | | **( $f / f_u$)** | | **( $f / f_u$)** | | **( $f / f_u$)** | |
| | **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 |

$(f / f_u)_e$ = Exp. Stress Ratio
$(\varepsilon / \varepsilon_u)_e$ = Exp.Strain Ratio
Avg. = Average Stress Ratio
Max. = Maximum Stress Ratio
Min. = Minimum Stress Ratio
RCA = Recycled Coarse Aggregate
TCA = Total Coarse Aggregate
$R_r$ = Replacement Ratio
$R_r$ = RCA / TCA

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 Saenz [10] seems to better fit, with appropriate constants suitable for the present curves.

## 3. MATHEMATICAL MODEL

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

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

where, $\varepsilon$ = 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:

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

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.

(ii) 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 equation (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:

$$A = A^{\prime} (f_u / \varepsilon_u) \quad (3)$$

$$B = B^{\prime} (1.0 / \varepsilon_u)^2 \quad (4)$$

For example under consideration, substituting A′ and B′ values in equations (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 equation 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 Figures 1. From the figures 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 validity for recycled aggregate concrete (RAC).

## 4. DISCUSSIONS AND CONCLUSIONS

*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. Figures 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 Conclusions*

Saenz mathematical model is successfully evaluated and validated for all recycled aggregate concrete mix cases considered in the investigation programme.

Stress strain values for various grades and percentages of recycled coarse aggregates are developed exclusively for recycled aggregate concrete mixtures, and they are validated for all concrete mixtures considered in the investigation programme.

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