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Experimental Assessment over Theoretical Prediction & Analytical Studies on Flexure Behavior of RC Beams with Recycled Coarse Aggregate

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Abstract

The rapid urbanization in Indian cities and the increasing fade of fresh aggregate in different locations generate enormous volumes of demolition and construction waste. Recycling the construction waste will reduce land pollution and economize in natural resources. This paper describes an experimental test program, theoretical and analytical analysis that examines the reinforced beams with recycled coarse aggregate using alccofine. A test result of four-point flexure bending on parameters of flexural capacity and flexural stiffness, theoretical predictions using IS 456:2000, ACI 318-11, ACI 318-14, and EC2; and analytical analysis using ANSYS workbench. The study outcomes and theoretical prediction calculations of IS 456:2000, ACI 318-11, ACI 318-14, and EC2 were compared and the results underestimate the flexural strength whereas analytical results overestimate the flexural strength for the reinforced concrete (RC) beams.

Disciplinary: Civil Engineering & Technology (Construction and Building Material, Structural Engineering).

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1 Introduction

The generation of construction and demolition waste has increased in recent years, owing to razing and replacement of old buildings with new buildings that suit today's space requirements. Landfill yards remain the disposal sites for such huge volumes of building waste (Abbas et al., 2006; Abbas et al., 2008; Robinson et al., 2004; Tabsh & Abdelfatah, 2009; Vyas & Pitroda, 2013; Wagih et al., 2013). The unprocessed building waste materials harm the environment, which led the researchers to develop novel techniques that can not only save the environment but also utilize this waste economically. In this background, Recycled Concrete Aggregate (RCA) is the most popular technique that is prevalently applied to convert construction debris into concrete so that the latter can be used in construction applications. However, certain countries restricted the application of RAC to nonstructural applications up to a certain percentage (Naouaoui & Cherradi, 2021). So, different investigations have been conducted so far by researchers to enhance the characteristics of RAC by strengthening it with cement-based composite materials like GGBS (Ann et al., 2008; Deepa & Anup, 2016; Reddy & Ramadoss, 2020); fly ash (Harrisson, 2019; Reddy & Kavyateja, 2020), alccofine (Ashokkumar et al., 2019), silica fume (Elhakam et al., 2012; Çakır & Sofyanlı, 2015; Naouaoui & Cherradi, 2021; Ashokkumar et al., 2019; Suthar et al., 2013; Tam et al., 2007; Xie et al., 2018), rice husk ash (Bheel et al., 2018), etc.

The crushing of concrete tends to have an impact on the physical as well as mechanical characteristics of the aggregate as there is a consequence in the effectiveness of the process and also the correct grade of the parent concrete, the original source of the recycled aggregate. These consequences can be satisfied by using specified techniques such as two-stage mixing approach (TSMA) (Elhakam et al., 2012), Double Mixing Method (DMM) and Triple Mixing Method (Kong et al., 2010) followed by Surface coated Aggregate (SCA) method (Zhao et al., 2013).

2 Test Setup and Instrumentation

Figure 1 portrays the beam setup on the flexure testing frame. The clear span of the beam is divided into 3 parts of length 933.3mm. The researchers fixed a steel spreader beam between the test beams so as to distribute the point load from hydraulic jacks into two-point loads applied over the mid-span of the beam of length 933.3mm which is the pure or constant bending region of the beam and a shear span region of length 933.3mm on each side. The demountable mechanical strain gauge is placed on the pure bending region of the specimens in the extreme compression and tension zone. A total of three dial gauges was installed at the bottom of the beam between midspan and loading points to determine the deformation of the beam during loading. Then, the researcher placed two electrical strain gauges at the midspan of the beam at the center to note the linear and lateral strain in the concrete surface. A mechanical gauge is placed at the midspan to measure the maximum deformation when the beam falls. The properties of the concrete mix along with the experimental test result of the beam are taken from my previous work (SanthoshKumar, 2022) are tabulated in Table 2, whereas symbols are given in Table 1.

Table 1: Symbols used for this experimental study.

CC- conventional cement	R- river sand	NA- Natural Aggregate
CA- Cement + Alccofine	M- Manufacture sand	RA- Recycled Aggregate
TAMA -Two - Stage Mixing Approach		

Figure 1: Experimental setup of the beam.

Table 2: Summary of the experimental test result of the beam.

Beam	f_{ck} (n/mm^2)	E_{cm} (n/mm^2)	TSR	P_{cr} (kN)	P_s (kN)	P_y (kN)	P_u (kN)	Δ_{cr} (mm)	Δ_s (mm)	Δ_y (mm)	Δ_u (mm)
CCRNA	36.1	30	0.68%	12.16	22.10	39.11	43.96	1.14	3.90	9.27	12.44
			1.03%	19.59	41.68	78.45	82.95	2.67	8.79	16.78	20.04
CARNA	40.4	60	0.68%	17.19	29.42	53.98	58.84	2.96	8.11	13.48	19.27
			1.03%	24.52	49.04	83.21	93.18	3.63	7.93	16.58	20.70
CARRA	49.3	30	0.68%	17.22	29.42	44.05	59.06	1.59	3.62	10.41	18.64
			1.03%	24.45	44.13	83.27	89.75	2.50	8.01	17.51	20.58
CCMNA	33.7	26.67	0.68%	17.09	26.97	48.99	54.04	2.14	5.40	14.23	18.12
			1.03%	19.76	41.68	73.54	83.28	2.13	8.53	15.33	22.18
CAMNA	39.0	40	0.68%	17.36	31.87	53.95	63.80	2.20	6.54	13.38	27.31
			1.03%	14.81	41.68	77.84	82.97	1.18	7.62	16.18	20.20
CAMRA - TSMA	48.8	33.33	0.68%	17.21	29.42	48.92	58.81	1.77	6.84	12.84	21.05
			1.03%	19.54	39.23	68.71	78.18	2.04	7.37	13.16	20.35

3 Theoretical PredictionIS Provisions for the Flexural Design of RC beams

In this study, the Indian Standards (IS)– 456-2000 flexural design provision of reinforced concrete (RC) beams is used.

The Cracking moment and curvature of flexure beam M_{cr} and φ_{cr} is given as

$$M_{cr} = \frac{Ig*fcr}{y} \qquad (1),$$

$$\varphi_{cr} = \frac{Mcr}{Ec*Ig} \quad (2).$$

Here, I_g denotes the beam's gross moment of inertia, f_{cr} corresponds to the modulus of fracture of concrete whereas the modulus of elasticity of concrete is denoted by E_c.

The Stages corresponding to the start of Non-Linearity of flexure beams moment M_{y1} and curvature φ_{y1} is given as

$$M_{y1} = A_{st}*0.8*f_y*jd \quad (3),$$

$$\varphi_{y1} = \frac{\varepsilon c}{kd} \quad (4),$$

where A_{st} is the area of steel in the tension zone, f_y yield strength of steel, jd is the lever arm distance, ε_c strain in concrete and kd is the depth of neutral axis.

The moment and curvature of flexure beam at yielding Stage M_{y2} and φ_{y2} is given as

$$M_{y2} = A_{st}*0.8*f_y*jd \ (5),$$

$$\varphi_{y2} = \frac{\varepsilon c}{kd} \quad (6),$$

where A_{st} is the area of steel in the tension zone, fy yield strength of steel, jd is the lever arm distance at yield stage, ε_c strain in concrete at yield stage and kd corresponds to neutral axis depth at yield stage.

The moment and curvature at ultimate Stage Mu and φ_u is given as

$$M_u = A_{st}*0.8*f_y*jd \quad (7),$$

$$\varphi_u = \frac{\varepsilon c}{X} \quad (8),$$

where A_{st} is the area of steel in the tension zone, f_y yield strength of steel, jd is the lever arm distance at an ultimate stage, ε_c strain in concrete at the ultimate stage and X is the depth of neutral axis at ultimate stage.

3.2 ACI provisions for the Flexural Design of RC Beams

In this study, the researchers made use of the American Concrete Institute (ACI) 318-11 and ACI 318-14 flexural design provision of RC beams.

The cracking moment of flexure beam M_{cr} is given as

$$M_{cr}=\frac{fr*Ig}{yt} \quad (9),$$

where I_g corresponds to the beam's gross moment of inertia, f_r denotes the modulus of fracture of concrete, and y_t denotes the distance from the cross section's centroidal axis.

The yielding moment of flexure beam M_y is given as

$$M_y = As * fy * d * (1 - \frac{k}{3}) \quad (10),$$

where As denotes the area corresponding to non-prestressed tension reinforcement, f_y corresponds to the yield strength of reinforcing bars, d denotes the distance from extreme compression fiber to the centroid of longitudinal tension reinforcement, and k is the depth of neutral axis factor.

The ultimate moment of flexure beam M_n is given as

$$M_n = As * fy(d - \frac{a}{2}) \quad (11),$$

$$a = \frac{As*fy}{0.85fc'b'} \quad (12),$$

where *As* corresponds to tensile rebar's area, *fy* corresponds to rebar's yield strength calculated earlier, *d* denotes the effective depth, *a* corresponds to the depth of equivalent rectangular compressive stress block, fc′ denotes the compressive strength of concrete under measurement, and *b* corresponds to the rectangular beam's width.

3.3 EC Provisions for the Flexural Design of RC Beams

In this study, Euro Code (EC) 2 flexural design provision of RC beams is used. The ultimate moment of flexure beam M_n is given as

$$M_n = T(d - \frac{a}{2}) \quad (13),$$

$$T = A_s{}^* f_{yd} \quad (14),$$

$$a = \frac{As*fyd}{\eta*fcd*b} \quad (15),$$

$$f_{cd}=\frac{\alpha_{cc}*fck}{\gamma c} \quad (16),$$

$$f_{yd} = \frac{fy}{\gamma s} \quad (17).$$

Here, the rebar's tensile force is denoted by T and its design yield strength is denoted by f_{yd}. Further, the rebar's measured yield strength is denoted by f_y whereas the design value of concrete compressive strength is denoted by f_{cd}. In addition to this, the measured concrete compressive strength is denoted by f_{ck} while γ_c corresponds to the partial safety factor of concrete, γ_s denotes rebar's partial safety factor and finally αcc remains a coefficient in current research (=0.85) which takes into account the long-term impact on compressive strength and unfavorable impact as a result of, how the load is applied.

4 Flexural Strength of RCA beams

Table 3 shows the experimental outcomes and calculations performed for nominal flexural strength. The flexural strength values measured for natural coarse aggregate (NCA), as well as recycled coarse aggregate (RCA) beams, were found to be higher compared to normal flexural strength values determined fromIS 456-2000, ACI 318 provision, and EC2 provision.

Table 3: Test results comparison with IS – 456:2000, ACI 318, and EC2

		Comparison with Exp/IS – 456:2000						Exp/ACI 318			Exp/EC2
Beam	TSR	M_{cr}	M_y	M_u	Δ_{cr}	Δ_y	Δ_u	M_{cr}	M_y	M_u	M_u
CCRNA	0.68	0.85	0.82	0.85	1.30	0.62	0.30	0.79	0.88	0.84	0.87
	1.03	1.36	1.10	1.11	3.05	1.06	0.69	1.28	1.29	1.04	1.16
Average		1.10	0.96	0.98	2.18	0.84	0.49	1.03	1.09	0.94	1.02
CARNA	0.68	1.15	1.13	1.13	5.21	0.99	0.44	1.08	1.09	1.12	1.16
	1.03	1.65	1.17	1.24	6.39	1.16	0.68	1.60	1.18	1.16	1.30
Average		1.40	1.15	1.19	5.80	1.07	0.56	1.34	1.13	1.14	1.23
CARRA	0.68	1.11	0.93	1.13	1.34	0.66	0.39	1.03	0.99	1.12	1.16
	1.03	1.57	1.17	1.18	2.11	1.04	0.61	1.60	1.37	1.12	1.25
Average		1.34	1.05	1.16	1.72	0.85	0.50	1.32	1.18	1.12	1.21
CCMNA	0.68	1.26	1.03	1.05	1.83	0.88	0.48	1.17	1.14	1.04	1.09
	1.03	1.45	1.03	1.13	1.82	0.88	0.82	1.29	1.26	1.04	1.16
Average		1.35	1.03	1.09	1.83	0.88	0.65	1.23	1.20	1.04	1.13
CAMNA	0.68	1.27	1.13	1.24	2.80	0.91	0.72	1.18	1.15	1.23	1.28
	1.03	1.08	1.09	1.12	1.50	1.03	0.75	0.97	1.19	1.04	1.16
Average		1.17	1.11	1.18	2.15	0.97	0.74	1.07	1.17	1.13	1.22
CAMRA-TSMA	0.68	1.05	1.03	1.12	1.57	0.84	0.40	0.98	1.08	1.11	1.14
	1.03	1.19	0.96	1.02	1.81	0.80	0.55	1.28	1.10	0.98	1.09
Average		1.12	1.00	1.07	1.69	0.82	0.48	1.13	1.09	1.04	1.12

Among the latter, the experimental flexural strength of NCA, as well as RCA concrete beams, was underestimated by IS 456-2000 provision. In the case of NCA traditional concrete beams, the ratio between the experimental flexural strength and IS 456-2000 provision calculation on cracking moment was in the range of 1.10 to 1.35, while the values for NA + Alccofine beams and RCA concrete beams were in the ranges of 1.17 to 1.40 and 1.12 to 1.34 respectively. Likewise, in the case of NCA traditional concrete beams, the ratio between the experimental flexural strength and IS 456-2000 provision on yield moment was in the range of 0.96 to 1.03, while the values for NA + Alccofine beams and RCA concrete beams were in the ranges of 1.11 to 1.15 and 1.00 to 1.05 respectively. In line with this, for NCA traditional concrete beams, NA + Alccofine beams and RCA concrete beams, the ratio between the experimental flexural strength and IS 456-2000 provision on the ultimate moment was in the range of 0.98 to 1.09, 1.18 to 1.19 and 1.07 to 1.16respectively.

For both NCA as well as RCA concrete beams, ACI 318 provision undervalued the experimental flexural strength. In the case of NCA traditional concrete beams, the ratio between the experimental flexural strength and ACI 318 provision on cracking moment was in the range of 1.03 to 1.23, while the values for NA + Alccofine beams and RCA concrete beams were in the ranges of 1.07 to 1.34 and 1.13 to 1.32 respectively. Likewise, in the case of NCA traditional concrete beams, the ratio between the experimental flexural strength and ACI 318 provision on yield moment was in the range of 1.09 to 1.20, while the values for NA + Alccofine beams and RCA concrete beams were in the ranges of 1.13 to 1.17 and 1.09 to 1.18 respectively. In line with this, for

NCA traditional concrete beams, NA + Alccofine beams and RCA concrete beams, the ratio between the experimental flexural strength and ACI 318 provision on the ultimate moment was in the range of 0.94 to 1.04, 1.13 to 1.14 and 1.04 to 1.12respectively.

For both NCA and RCA concrete beams, the experimental flexural strength was undervalued by EC2 provision. In the case of NCA traditional concrete beams, the ratio between the experimental flexural strength to ACI 318 provision calculation on the ultimate moment was in the range of 1.02 to 1.13, while for NA+ Alccofine beams and RCA concrete beams, the values were in the range of 1.22 to 1.23 and 1.12 and 1.21 respectively. At the time of forecasting the flexural strength with ACI and EC2 provisions, the tension stiffening effect was not taken into account which may result in the underestimation of the flexural strength of RCA beams. From the ratio between experimental values and the calculated results, it can be inferred that the current provisions had a conservative prediction over the flexural strength of RCA concrete beams.

5 FEA

One of the most significant techniques in forecasting the structural response of materials and systems is Finite Element Analysis (FEA) which can be applied in the presence of diverse loading conditions without any need for experimental works. A number of investigations have been conducted earlier to analyze the flexure behaviour possessed by recycled-coarse aggregate-reinforced concrete beams. These study outcomes established that FEA produces more accurate results than other techniques. Various primary element types are used in workbench simulation with default to high order (10 mode quadratic) tetrahedral (H) elements (SOLID 187) for solid model geometrics. In the case of using non-swappable elements, high order (20 modes) brick elements (SOLID 186) are utilized. The input values for the modeling and analysis of the member are taken from the mechanical properties. Figure 3to 7 shows the ANSYS model of the beam, beam after meshing, deflection of beam and reinforcement of beam at the ultimate stage, and maximum deflection of the beam at failure stage.

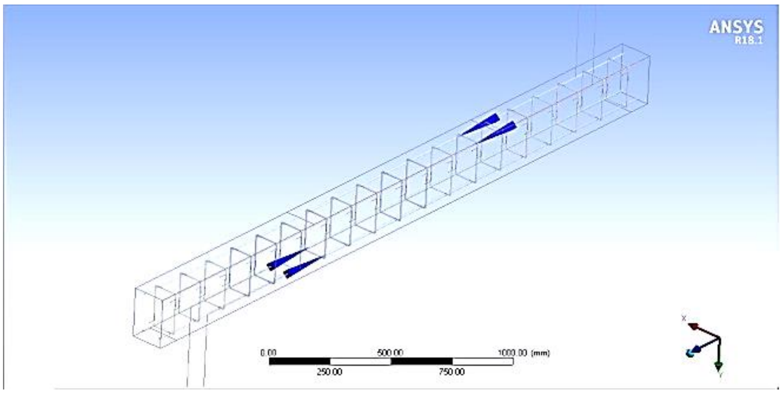

Figure 3: the ANSYS model of the beam.

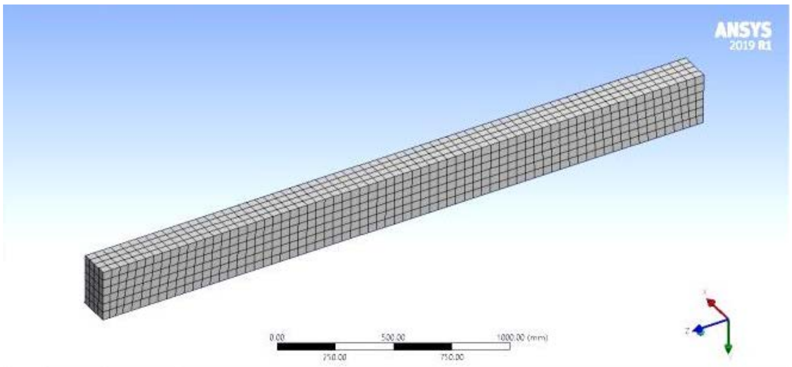

Figure 4: The beams after meshing.

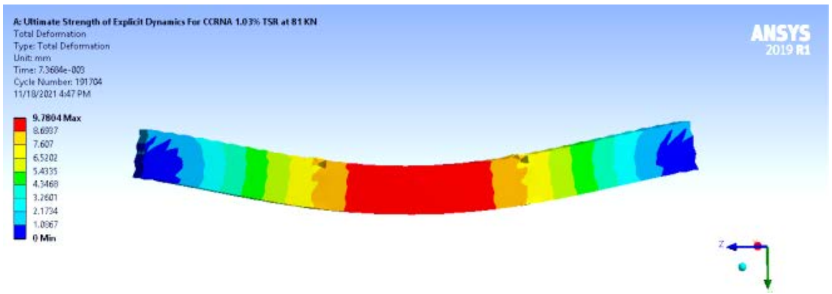

Figure 5: Deflection of the beam at ultimate stage.

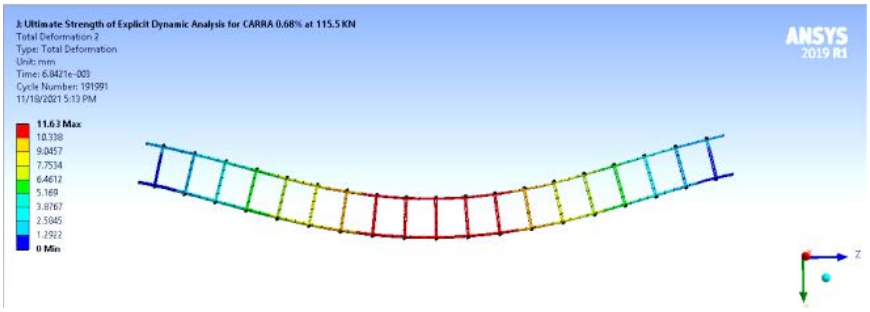

Figure 6: Deflection of the reinforcement in the beam at the ultimate stage.

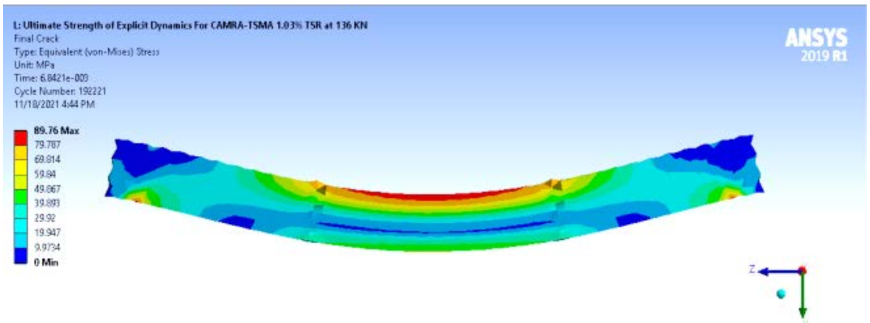

Figure 7: Maximum Deflection of the beam at failure stage.

4 FEA Result

Table 4 shows the comparison of experimental results with analytical results obtained from ANSYS workbench. In case of traditional concrete using NCA beams, the ratio between experimental flexural strength and ANSYS workbench calculation on ultimate load ranged from 0.61 to 1.19 and from 0.8 to 1.11 for alccofine with NCA beams and from 0.51 to 0.64 for RCA beams. Overall, the ANSYS workbench technique outcomes were found to have mildly overestimated the experimental flexural strength which was similar to that of results obtained by

Ibrahim et al. (2021). This might be attributed to the difference that exists between the tension stiffening impact incorporated in the program against the actual RCA concrete beams.

Table 4: Comparison of experimental results with analytical results obtained from ANSYS workbench.

Beam ID	TSR	Ansys Result		Experimental Result		P_{FEA} / P_{EXP}
		Ultimate Load (kN)	Deflection at ultimate load (mm)	Ultimate Load (kN)	Deflection at ultimate load (mm)	
CCRNA	0.68	72	8.28	44.1	12.42	0.61
	1.03	81	9.78	83.36	20.06	1.03
CARNA	0.68	74	9.19	58.84	19.21	0.80
	1.03	84	10.99	93.16	20.59	1.11
CARRA	0.68	115.5	11.67	58.84	18.78	0.51
	1.03	137	14.53	88.26	20.62	0.64
CCMNA	0.68	62	7.34	53.94	18.06	0.87
	1.03	70	8.71	83.36	22.12	1.19
CAMNA	0.68	77.5	8.62	63.74	27.22	0.82
	1.03	87.5	10.21	83.36	20.21	0.95
CAMRA-TSMA	0.68	116.5	11.85	58.84	21.05	0.51
	1.03	136	14.5	78.45	20.21	0.58

5 Conclusion

From the observation and experimental comparison over theoretical and analytical analysis of recycled aggregate beams, it is found that when the experimental flexural outcomes were compared against the flexural results calculated from IS 456-2000, ACI 318 and EC 2 provisions, it was found that the former was undervalued by the latter. This infers the conservative nature of current provisions that are used to predict the flexural strength of RCA beams. The results on flexural strength provided by the FEA are in an acceptable range for natural aggregate concrete (NAC) beams which are not in the case of RCA beams.

The laboratory findings infer that finite element (FE) models are stiffer compared to all the beams examined in the study. The high stiffness observed in FE models for NAC and RAC might be attributed to the full bond implicit between steel and concrete. This scenario arrests any slippage between steel and concrete while the experimental work lacks this condition. Further, small cracks were generated in tested beams owing to dry shrinkage whereas the FE model did not take this into account.

6 Availability of Data and Material

Data can be made available by contacting the corresponding author.

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