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Effect of Replacement Ratio on Torsional Behaviour of Recycled Aggregate Concrete Beams

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ABSTRACT

In the past two decade, researchers have studied the flexural, shear and bond behaviour of recycled aggregate concrete (RAC) beams. This work intends to analyze the behaviour of RAC beams under pure torsion, despite the lack of information on its behaviour under pure torsion. The coarse recycled concrete aggregates (RCA) extracted from construction and demolition (C & D) waste was used to replace natural coarse aggregates (NCA) in 0 %, 50 %, and 100 % ratio. Their recycling could help preserve the environment and promote sustainability through solid waste management. Six beams, each of size 150 x 250 x 1800 mm were prepared and tested. To detects minor deformation and to achieve the same strength through the out-of-plane direction, 250 mm inbuilt cantilever projections were provided on opposite faces of the beams at a span of 1000 mm along the longitudinal axis. The ultimate torsional capacity of tested beams was lower by 7.41 %, 8.60 % and 13.58 % than ATENA-3D (FEM) for 0 %, 50 % and 100 % RCA. The change in the replacement ratio of aggregate has a low impact on the ultimate torque and angle of twist. Based on the experimental and analytical results, it was established that the torque resistance capacity of the RAC beam was reduced as the % of RCA increased. Similar crack patterns and failure behaviour were observed in RAC and NAC beams in both studies. Therefore, it is practically possible to apply RAC in structural applications under pure torsional loading.

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1. INTRODUCTION

Torsion progresses in structural elements as an effect of asymmetrical loading, member shape, or structural framing. Stairway lateral beams, bridge decks, and spiral stairs are examples of RC components exposed to strongly eccentric stresses and torsional loading. Several structural components in bridges and buildings are exposed to considerable torsional moments that influence the design. Torsion design has become important in reinforced concrete beams in construction. Recognizing the significance of the issue, a research has been done on the torsional performance of steel fibre concrete [1]. The behaviour of RC members in pure torsion has been subject of extensive investigation. The pure torsional performance of RAC beams has not yet been thoroughly addressed, and limited research on the torsional performances of RAC beams is available in the literature. In seismic torsion, RAC beams fail similar to regular concrete beams [2, 3]. According to Sarsam et al. [4], the application of RCA in RAC is nearly conceivable in torsionally loaded structural elements. The analytical (ATENA-3D) and experimental study showed that altering RCA does not degrade pure torsional behaviour of RAC solid beams and the utilization of RAC in structural applications has become an essential aspect [5, 6]. These studies demonstrated the significance of RAC beams in pure torsional design; as a result, this investigation explored the structural behaviour of RAC beams subjected to pure torsion. On the other hand, NCA are an essential component of NAC, but their availability is decreasing day by day. To overcome this, RCA can be a substitute for NCA in concrete. According to the Central Pollution Control Board of India [7], India had 1.8 million tonnes of RCA each year. The Indian Standard IS: 383 [8] for coarse and fine aggregates allows

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the use of RCA up to 20% in reinforced concrete elements. The C&D waste will be the one source of RCA. The reusing of C&D waste on a large scale has the potential to significantly reduce natural aggregate consumption and contribute to environmental preservation [9] and solid waste management. Different types of waste materials are used to manufacture of concrete for pavement and structural application [10-14]. RAC is becoming an appealing structural material in the building sector. The idea of utilizing RCA in structural concrete is gradually obtaining scalability at present, and investigation in this scope is improving. The tensile strength [15], compressive strength [16], toughness and ductility index [17], and constitutive relationship [18] of RAC have been found in the literature, which showed worthy agreement with the NAC. Many structural engineers and researchers also studied the flexural [19], shear [20], and bond [21] performance of RAC elements, but slight work has been found on the torsion. The research work related to reducing carbon emissions mention that, the globe moves toward sustainable sources and the research toward innovation with new technologies should be transparent and acceptable at large scale [22, 23]. Except the investigation by Sarsam et al. [4], and Masne et al. [6] no test data on the torsional behaviour of RAC beams is available in literature. The current study was conducted to bridge this gap. This study will help to facilitate the safe structural application of RAC beam in pure torsion.

2. MATERIALS AND METHODS

2. 1. Materials This experiment employed grade 53 OPC with a fineness of 3080 cm^2/g and a specific gravity of 3.14 accordance with IS-12269 [24]. As fine aggregate (FA), zone II river sand that conforms to IS-383 [8] was utilized (fineness modulus = 2.80). The NCA with a size of 20 mm was utilized, according to IS-383 [8]. Deformed TMT steel bars were used as reinforcement of Grade Fe500. The steel bars were tested in a 1200 kN capacity UTM to obtain their mechanical properties as per the procedure recommended in IS-1608 part-I. To achieve the requisite quality of new concrete in the experiment, a polycarboxylic ether-based high-range water-reducing additive (HRWRA) according to IS-9103 was utilized. The admixture dosage was kept at 0.77 % by the weight of cement. Concretes were mixed and cured with tap water, ensuring with IS-456. The coarse RCA were obtained from tested concrete specimens at the concrete laboratory by using mechanical breaker and jaw crusher to prepare concrete. The waste concrete specimens were composed of a variety of beam-column junctions with varying compressive strengths of 20-30 MPa. It was unable to assess the original concrete's quality from such specimens. Because of this, there was no accurate information about the quality of the concrete specimens that were used to make the RCA in this study. The size fractions of RCA after sieving 35 % on 4.75 - 10 mm, 22.5 % on 10 - 12.5 mm, 22.5 % on 12.5 - 16 mm, and 20 % on 16 mm-20 mm respectively, are shown in Figure 1. The obtained RCA was sieved and stored in separate bags so that these fractions could be blended manually.

The mechanical and physical characteristics of both aggregates are shown in Table 1. The aggregate characteristics like water absorption, specific gravity, and residual adhering mortar of RCA are very important when preparing the correct concrete mix. The RCA was porous, less dense, and absorbs extra water than NCA. These RCA particles were spherical and extra fines were broken off during crushing and impact testing was observed from Table 1. The impact and crushing tests are used to determine the aggregate durability. Residual mortar in the interfacial transition zone (ITZ) of RAC can readily be broken off, which is common in concrete. Under the load, the remaining mortar on RCA would break off, but NCA has no such coat to fail.

2. 2. Concrete Mixtures In accordance with IS-10262, the absolute volume method was utilized to create concrete mix grade of the M30 using NCA and RCA. The IS-456 was used to cast concrete. Table 2 presents the NAC and RAC mix proportions of concrete.

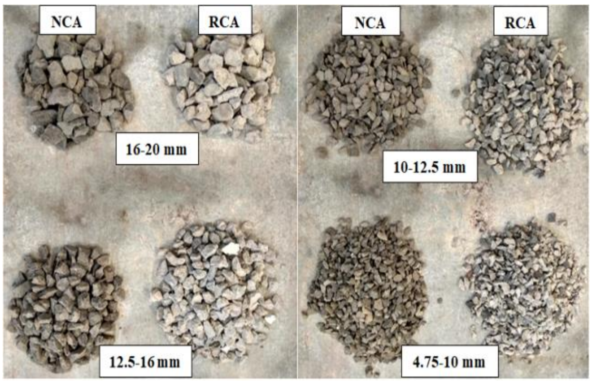

Figure 1. Comparison of different size fraction of NCA and RCA

TABLE 1. Characteristics of the coarse aggregates

Aggregate Type	NCA	RCA
Size (mm)	4.75-20	4.75-20
Water Absorption (%)	1.05	3.85
Specific gravity	2.64	2.45
Aggregate Crushing Value (%)	21.10	25.40
Aggregate Impact Value (%)	15.30	20.80

TABLE 2. Concrete mix proportions

Mix	M-R00	M-R50	M-R100
% of RCA	0.00	50.00	100.00
Cement	1.00	1.00	1.00
W/C ratio	0.40	0.40	0.40
FA	1.67	1.67	1.67
NCA	2.82	1.41	0.00
RCA	0.00	1.30	2.60
HRWRA	0.77	0.77	0.77

In the absolute volume technique, the volume of compacted concrete equals the total volume of all ingredients. The approach described in earlier study [19] was followed while using the RCA particles in the saturated surface dry (SSD) state. In laboratory, the concrete was mixed using a tilting-drum mixer. Before mixing began, measured quantities in terms of weights of concrete materials such as cement, fine aggregate, NCA, and RCA were kept ready in bags. To wet the coarse aggregates, one-third of total water was introduced to the mixer along with coarse aggregates before mixing. Following that, one-third quantity of the cement was added and the constituents were mixed for approximately one minute. Then the fine aggregates were added, followed by the remaining cement and water. The entire mixing time was limited to 30 minutes. A coat of oil was applied to the interior surface of the moulds used to cast the test specimens. Following completion of mixing, concrete was poured into the moulds for a period of 24 hours and then de-moulded. In this study, changed ratios of RCA were considered for the same grade of concrete, so that water content was constant for all the mixt to achieve workability and strength.

2. 3. Test Specimens Concrete's compressive strength IS-516 [25] and its tensile strength IS-5816 [26] were measured using 150 x 300 mm cylinders. Prisms measuring 100 x 100 x 500 mm were made to test the concrete's flexural strength IS-516 [25]. All the samples were cured in water for 28 days before testing. Meantime, six beams were casted into three groups based on % of RCA. The first group was considered a reference group, which consisted of two beams cast from NCA-concrete denoted by B-R00. The second and third groups consisted of two beams each, cast from 50 % and 100 % RCA-concrete, denoted by B-R50 and B-R100, respectively, and the average or best of two from each group is reported. All the beams were reinforced with the same transverse and longitudinal steel shown in Figure 2. All the stirrups were anchored with 135° hooks to resist the torsion specified in CSA-14 [27]. To avoid local failure, the spacing of stirrups in the end zone and lever arms was curtailed to 50 mm c/c.

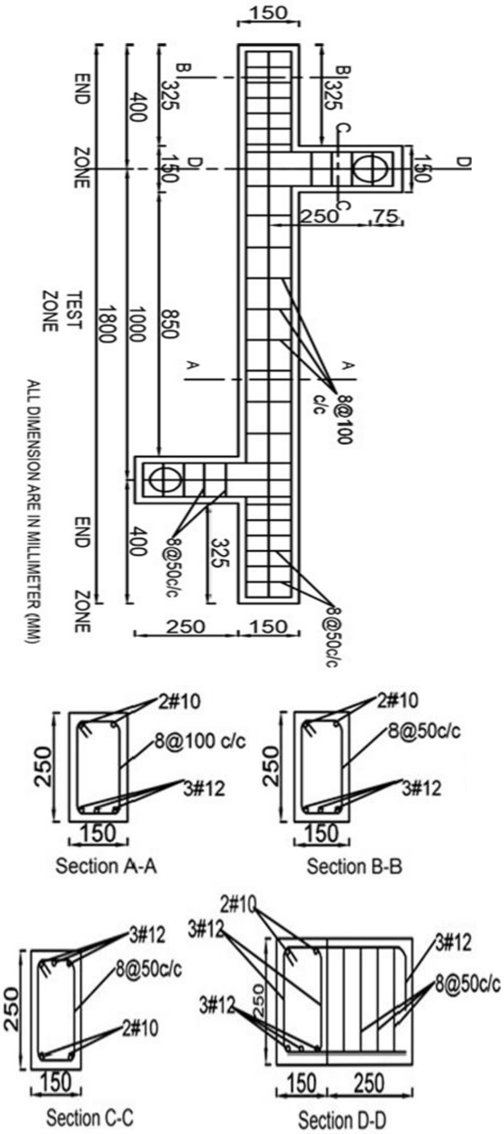

Figure 2. Details of steel reinforcement specimen

The torsion specimens were formed by pouring concrete into the mould and compacting with a needle vibrator on a level and clean surface of lab. The beams were covered with a plastic sheet shortly after casting to prevent evaporation, and demoulded 24 hours. All beams wrapped in gunny bags and cured in the laboratory for 28 days.

2. 4. Test Set-up The test set-up for torsion was planned and manufactured in the structural laboratory. Figure 3 shows the schematic diagram of a typical setup. The specimen was put on roller support at a distance of 1350 mm aligned with the specimen so that the ends of the specimen could freely rotate, extend, and contract shown in Figures 3 and 4. At both ends of the specimen, roller supports were positioned to ensure free rotation and elongation. The load was applied through a steel spreader beam supported by rollers above the lever arms.

Previously, metal mechanisms were used to hold the beam while applying a torsional load. This type of apparatus causes errors in the detection of slight deformation because it permits slippage and gaps between the metal clamping and the beam. To overcome this problem and to achieve the same strength through the out-of-plane direction where the matrix carries the primary load, 250 mm inbuilt cantilever projections were provided on opposite sides of the beams at a span of 1000 mm along the longitudinal axis. The free span of the beam subjected to pure torsion was 850 mm, and the effective range was 1000 mm. To measure the vertical deformations in the RAC beam two linear variable displacement transducers (LVDT) were attached to the bottom of lever arm. The LVDTs and load sensor were connected to the data collecting system. The tested beams were gradually loaded with a hydraulic jack with a 1000 kN capacity till failure at the middle of the spreader beam. The recorded data were load at first crack, the crack pattern, crack angle, crack width, angle of twist, and the overall performance of the specimen when subjected to pure torsion. The spreader beam and hydraulic jack were knotted by a string in the actual test set up, as shown in Figure 4, in such a manner that it should not affect the test setup and readings at any level throughout the test.

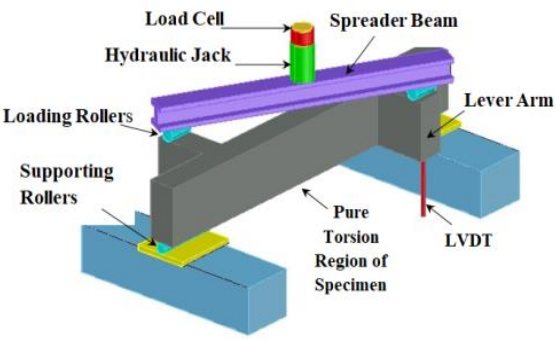

Figure 3. Schematic diagram of test set up

Figure 4. Front and side view of actual test set-up

3. RESULTS AND DISCUSSIONS

This investigation aims to verify the compatibility of RCA in concrete for structural use. The presentation of the outcomes is organized in the same sequence as that in which the experiment was conducted and compared with finite element model by ATENA-3D software.

3. 1. Concrete Density Table 3 shows the densities of all hardened concrete combinations. When the densities of the NAC and RAC mixes were compared, it was found that 50 % and 100 % RCA in concrete reduces the density by 1.92 % and 3.75 %, as compared to 0 % RCA. These results showed that RCA does not affect the density of concrete largely. The density of RAC was mostly affected by the residual adhering mortar of RCA.

3. 2. Mechanical Properties of Concrete Table 3 specifies the mechanical properties of concrete for all mixes. The concrete's elastic modulus was determined by using the IS-456. The ratio of the compressive strength to the flexural strength of concrete is known as brittleness. When the brittleness property of concrete increases, its tensile strength decreases. This means that once the concrete has achieved its tensile strength, it loses its ability to resist loads and cracks developed in the concrete. With increased brittleness, the bond between cement paste and RCA breaks, and aggregates burst. Table 3 showed that the 0 % and 50 % RCA produced similar compressive, tensile, flexural and modulus of elasticity of concrete i.e. 0.80 %, 3.16 %, 1.00 %, and 0.39 %. Meanwhile for a similar grade of concrete, RAC with 100 % RCA produced inferior compressive, tensile and flexural strength, i.e. 13.12 %, 23.35 %, and 25.27 %, respectively, which considerably caused in a higher brittleness ratio i.e. 13.93 %, as shown in Table 3. In the majority of circumstances, it was expected that the mechanical qualities of RAC would be inferior to those of conventional concrete as found in the literature [4, 5]. RAC with 100 % RCA had low mechanical properties because the aggregate-cement paste bond broke down. This caused the RAC to be less durable. The NAC specimens, on the other hand, failed due to aggregate and cement matrix fracture. The modulus of elasticity of

TABLE 3. Test beam material and experimental parameters

Mix Id	M-R00	M-R50	M-R100
Density (Kg/m^3)	2400	2354	2310
Compressive strength (MPa)	37.10	36.80	32.23
Tensile Strength (MPa)	4.11	3.98	3.15
Flexural Strength (MPa)	4.55	4.50	3.40
Brittleness	8.15	8.17	9.47
Modulus of Elastic (GPa)	30.45	30.33	28.38

RAC experiences strain when compressed and resulting in an inferior modulus of elasticity i.e. 6.79 % for B-R100 than B-R00, same observations were found in literature [4, 16].

3. 3. Test Analysis under the Influence of Different Load Levels and Angle Table 4 shows the test analysis under different load level and angles of test beams, which were very helpful to understand the detailed test load information. The average of two beams is reported in Table 4. As the load level changes, the cracks angle and crack pattern were also changes on the concrete surface of test beams.

3. 4. Effect of RCA on Torsional Strength From Table 5, it was observed that the cracking torque for B-R50 and B-R100 was lower by 10.56 % and 27.60 % than B-R00 beam and the ultimate torque for B-R50 and B-R100 was reduced by 6.79 % and 23.2 % than B-R00 beam. The torque resistance capacity of B-R100 was less than that of B-R00 beams at every state of loading i.e. 27.60 % at cracking, 20.30 % at yielding, 23.24 % at ultimate and 28.64 % at failure state respectively. It will help to decide the required changes in a modification to the current standards. Because RAC has an inferior elastic modulus than NAC and the twist angle of beams at every loading state increases as the ratio of RCA was increased. Similar torsional behaviour was mentioned `in the experimental work [4, 5]. Table 5 summarized data when RCA grows, the cracking torque to ultimate torque capacity decreases. Because of the poorer ITZ of older RCA, the cracking torque to ultimate torque ratio for B-R50 and B-R100 beams was reduced by 3.22 % and 4.68 %, than the B-R00 beams. The average of two beams is reported in Table 5. This result indicates slightly inferior than NAC, but considerable behaviour of RAC beam in torsion as found in the literature [2-5].

TABLE 4. Test analysis under different load levels and angle

Beam Type	Load Level	Stage of loading	Observations
B-R00	0.65Tu	Crack stage	45° diagonal cracks, can close after unloading
B-R50	0.61Tu		
B-R100	0.60Tu		
B-R00	0.80Tu	Yield stage	Larger and more number of 45° cracks, that did not recover after unloading
B-R50	0.81Tu		
B-R100	0.83Tu		
B-R00	Tu	Ultimate stage	Complete 45° diagonal cracks
B-R50	Tu		Complete diagonal cracks, same as B-R00 beams,crack angle change
B-R100	Tu		Complete diagonal cracks, faster and larger than B-R00 and B-R50 beams crack angle increases from 52°
B-R00	0.85Tu	Failure stage	Concrete lump caving, brittle failure
B-R50	0.85Tu		Concrete lump caving is a brittle failure mode same as B-R00.
B-R100	0.85Tu		Concrete lump caving is a brittle failure mode that is more severe than B-R00 and B-R50 beams and crack angle increases to 62°.

3. 5. Effect of RCA Content on Cracking Behaviour Crack origination and the crack pattern were the important constraints of this experiment. At the commencement of the experiment, no cracks were seen as the load increased linearly. Concrete generally resisted torsion until the beam cracked. In testing, the first crack was detected in the test zone on the longer face of the beams, then it spread diagonally to the other faces, which formed a spiral crack. This is because the main paths of compressiveand tensile and spiral around the beams in directions that are 45 degrees apart from the beam's axis [26]. As the torque reached its ultimate torsional strength, a 45°- 62° diagonal crack was observed as displayed in Figure 5. The angle of the primary diagonal crack depends on the principal stress orientation and the diagonal compressive stress angle. RAC beam diagonal crack angles increased with RCA.

As an example crack behaviour of beam B-R50-01 and B-R50-02 was examined, shown in Figure 6. To undetarstand the cracking behaviour under different load level two beams with same concrete mix are reported from all the beams with average torque in Figure 6. The first crack was observed diagonally at average torque of 5.25 kN.m. As the load increases, more digonal cracks were emerged on the longer side beams at yeild state 6.88 kN.m. As the torque near is peak, a major diagonal crack occurred. After the average peak torque of 8.50 kN.m

TABLE 5. Measured torque and corresponding angle of twist at cracking, yield, ultimate, and failure state

State of Loading		B-R00	B-R50	B-R100
Cracking State	T_{cr} **(kN.m)**	5.87	5.25	4.25
	θ_{cr} **(rad/m)**	0.012	0.012	0.014
Yield State	T_y **(kN.m)**	7.29	6.88	5.81
	θ_y **(rad/m)**	0.022	0.022	0.025
Ultimate state	T_u **(kN.m)**	9.12	8.50	7.00
	θ_u **(rad/m)**	0.043	0.044	0.047
Failure State	T_f **(kN.m)**	8.25	7.37	5.87
	θ_f **(rad/m)**	0.053	0.054	0.058

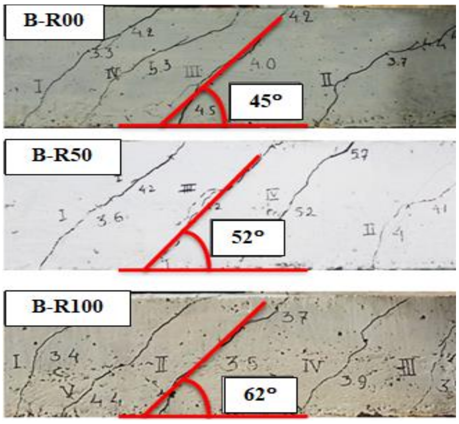

Figure 5. Angle of major diagonal cracks

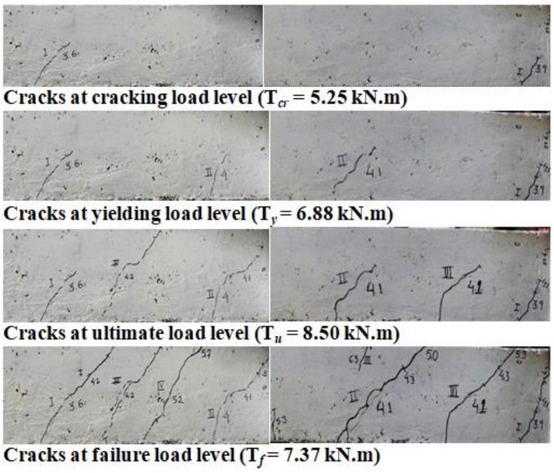

Figure 6. Comparison of cracking under different load levels (B-R50-01 and B-R50-02)

was reached, the torque decreases gradually to 7.37 kN.m. All the emerging cracks were parallel to first digonal crack with increasing load from cracking to failure level. The failure mode indicated a diagonal tensile failure in all the beam.

Figure 7 shows the crack pattern in test region for all the six tested beams at their final state. The crushing of the concrete cover was detected only when the beams were twisted much beyond their ultimate limit for all the beams. Concrete crushing perpendicular to diagonal cracks was found at 0.047 rad/m and increased to 0.058 rad/m. This resulted in crushing of concrete cover because of excessive twisting deformation, as the torque increases. It was an indication toward the end of the experimentation. The width of the crack was measured with a hand microscope that could count to at least 0.02 mm. The width of the cracks measurements were made at the middle of the widest face as the crack width was the maximum at this point and the best of the two is reported. The detected performance of crack width was the same in all beams. When torque approaches its

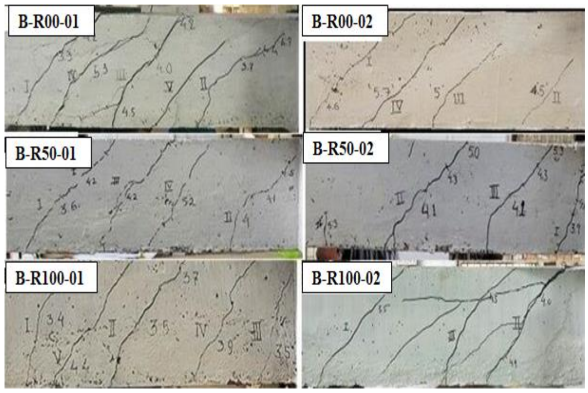

Figure 7. Comparison of crack pattern in test region for all specimens

ultimate torque, it's possible that the beam will break because of the excessive expansion of one large crack relative to the other cracks in the beam. When the types of concrete beams were tested for torsion, similar cracks with excessive expansion were found in the literature [1]. The structures may become unusable as a result of these excessive wide cracks in beams. The recommended limiting value of crack width in IS-456 and in ACI-318 [28] is 0.30 mm and 0.41 mm, respectively, for NAC.The ITZ from the old mortar and new mortar meet the RCA, this ITZ might grow and crack. When it comes to crack width in torsion, the use of RCA was not a concern for structural concrete beams since it has less influence, as found in the test region, as shown in Figure 8 (a, b, c). The crack width was measured for both beams of each mix and best of two results are reported in Figure 8.

3. 6. Finite Element Model Comparison with Test

The diagonal cracking patterns observed in ATENA-3D FEM software and experiment for the test beams were similar, shown in Figure 9. Due to the huge amount of data collected from each test specimen, the average torque–twist curve for each factor was found by averaging the data from the two beam specimens that were tested together. Figure 10 displays the average torque-twist curves for all the beams that were tested in this study. It was also found that, the ATENA-3D FEM software torque-twist curves of test beams was nearly same when compared with the experimental curves.

Figure 10 shows the normalised measured average torque-twist curve in the test and compared with ATENA-3D (FEM) for all the beams. The overall behaviour from cracking to failure state of all curve was similar in both results. Pre-cracking and post-cracking behaviour of each pair (one test and one ATENA-3D) of beam was identical in both methods. The following noteworthy remarks were made in light of this study. (a) Beams B-R00 had similar torque-twist behaviour before and after the maximum torque achieved in both methods.

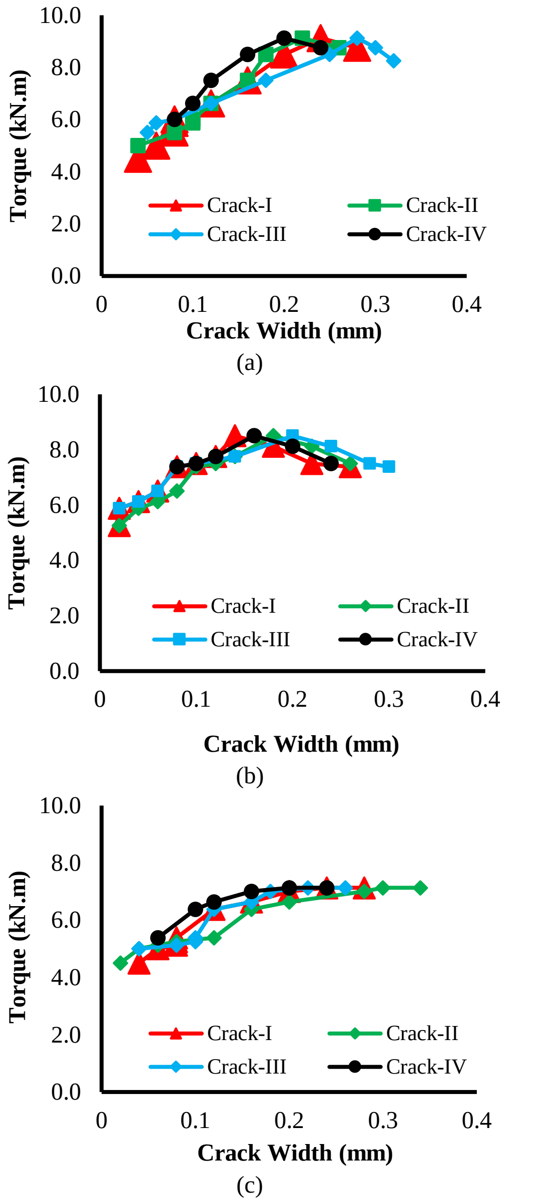

Figure 8. (a) Crack width for B-R00, (b) Crack width for B-R50 and (c) Crack width for B-R100

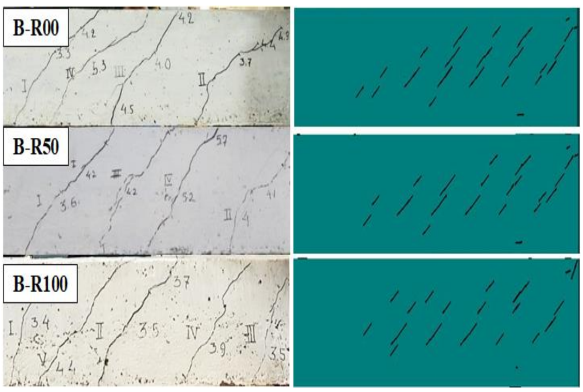

Figure 9. Comparison of Test and ATENA-3D (FEM) cacks

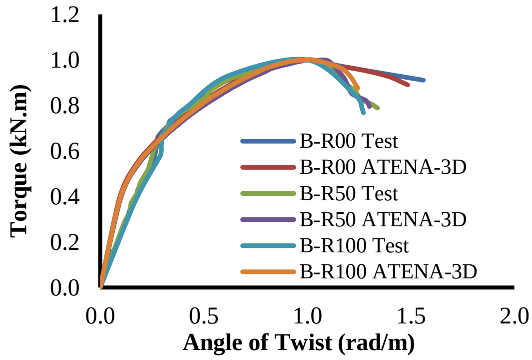

Figure 10. Normalised average test and ATENA-3D (FEM) torque-twist curve

(b) Beams B-R50 had equal torque-twist behaviour upto peak torque, then B-R50 curve turned as the B-R100 curve in both methods. (c) As the level of RCA replacement increases, the area beneath the torque-twist curve decreases in the both methods. (d) Adding RCA to concrete reduces torque-twist curve slopes after the peak, demonstrating RAC brittleness rather than NAC in both methods. The preceding observation suggests that B-R00 and B-R50 beams perform similarly up-to peak torque. The B-R50 and B-R100 behave similar after peak. The change in the replacement ratio of aggregate has a low impact on the ultimate torque and angle of twist; the effect was not enough to discourage the use of RCA in RAC beams in pure torsion in both methods. For the achieved results in the literature [4, 5], also agree that well after the outcome of torsional behaviour, crack pattern and failure mode of RAC beams. So, the use of RAC in structural applications under pure torsional loading is practically possible.

From Table 6, the cracking torque of tested beam was lower by 3.77 %, 4.19 % and 9.18 % than ATENA-3D (FEM) for 0 %, 50 % and 100 % replacement ratio, respectively. The ultimate torque of tested beams was lower by 7.41 %, 8.60 % and 13.58 % than ATENA-3D (FEM) for 0 %, 50% and 100% replacement ratio of NCA by RCA. The cracking and ultimate torque for 0% and 50% RCA was not influed much as compare to 100%

TABLE 6. Measured (Test) and ATENA-3D (FEM) torque at cracking, and ultimate state

Beam ID		B-R00	B-R50	B-R100
Cracking Torque (kN.m)	Test (Ex)	5.87	5.25	4.25
	ATENA-3D (An)	6.10	5.48	4.68
	Ex/An	0.96	0.95	0.91
Ultimate Torque (kN.m)	Test (Ex)	9.12	8.50	7.00
	ATENA-3D (An)	9.85	9.30	8.10
	Ex/An	0.92	0.91	0.87

RCA. Similar finding was reported in the literture [6]. It can be conclude that full replacement of NCA by RCA will be possible in the structural concrete with due care.

3. 7. Coparisons of Measured (Test) and ATENA-3D (FEM) with Skew Bending Theory and Space Truss Anlogy To determine whether the existing approach for designing torsional beam of NAC can be applied to RAC beam in their current state. The usually accepted methods of skew bending theory [29, 30] and space truss analogy [28, 30, 31] have been considered for comparison against the experimentally and analytically ATENA-3D (FEM) obtained values of average ultimate torsional moments. The ACI codes [28] issued between 1971 and 1995 were based on Kamiński and Pawlak's [32] and Hsu's [33] skew bending hypothesis. Indian code's provisions for torsion are also based on the skew bending theory. The space truss analogy has replaced the skew bending theory, which was based on the plane truss analogy for shear recognized by Ritter [34] and Morsch [35]. The space truss theories were initially sensible and have been adopted in several building codes, among them: CSA [27], ACI 318-14/318R [28], GB-50010 [36], AS-3600, and BS EN 1992-1-1 [37]. Figure 11 shows that both methods give same value as compared to measured (test) and ATENA-3D (FEM) with small accuracy differences.

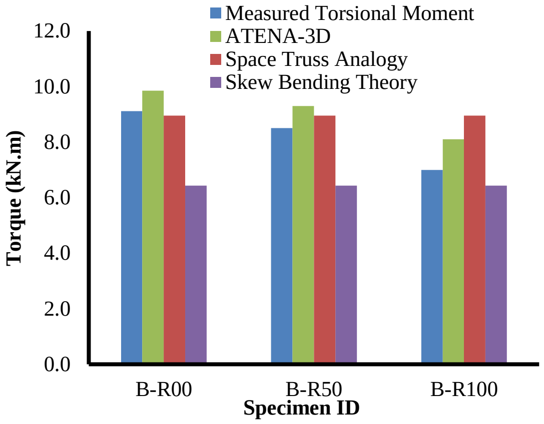

Figure 11. Comparisons of measured (Test) and ATENA-3D (EFM) torsional strength with Skew Bending Theory and Space Truss Analogy

4. CONCLUSIONS

The successful experimental pure torsion study of RAC beams determined that 50 % RCA was closely matched with 0 % RCA and that of 100 % RCA decreases the mechanical properties marginally lower than the 0 % RCA. It is due to weakened ITZ from the residual mortar. However, the torsional capability of the beam was reduced as the RCA content increased in the RAC. The analytical and experimental torque resistance capacity of 50 % RAC beams was reduced by 5.58 % and 6.79 % as compared to NAC beams and for 100 % RAC it was lowered by 17.76 % and 23.24 %. The ultimate torque value of tested beams was lower by 7.41 %, 8.60 % and 13.58 % than ATENA-3D (FEM) value for 0 %, 50 % and 100 % RCA. Also, the torque-twist behaviour and orientation of cracks were also identical in all the beams in both methods. The crack width of 100 % RCA beams was greater, but this variation was not much different from 50 % and 0 % RCA concrete beams. Based on the experiments and analytical results, it was established that the torque resistance capacity of the RAC beam was reduced as the % of RCA increaesed. The replacement of RCA in concrete has no major effect on the overall torsional behaviour RAC beam compared with NAC beams in pure torsion after comparing the experimental and analytical results. It can conclude that full replacement NCA by RCA will be possible in the structural concrete with due care.The results of this investigation will be useful to add value to the state of the art with respect to the application of RAC in structural beams and current code design procedures in pure torsion. The recycling of waste concrete could help to preserve the environment and promote sustainability through solid waste management. The findings specify that additional large-scale studies are required to establish a consensus about its pure torsional performance of RAC beams and to enhance the database for structural concrete.

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Persian Abstract

چکیده

در دو دهه گذشته، محققان رفتار خمشی، برشی و پیوند تیرهای بتن بازیافتی (RAC)را مورد مطالعه قرار داده‌اند. این کار در نظر دارد رفتار پرتوهای RAC را تحت پیچش خالص، علیرغم کمبود اطلاعات در مورد رفتار آن تحت پیچش خالص، تجزیه و تحلیل کند. سنگدانه های درشت بتن بازیافتی (RCA)استخراج شده از ضایعات ساخت و ساز و تخریب (D& C) برای جایگزینی سنگدانه های درشت طبیعی (NCA)در نسبت ۰٪، ۵۰٪ و ۱۰۰٪ استفاده شد. بازیافت آنها می تواند به حفظ محیط زیست و ارتقای پایداری از طریق مدیریت زباله جامد کمک کند. شش تیر با ابعاد ۱۵۰*۲۵۰*۱۸۰۰ میلی متر تهیه و مورد آزمایش قرار گرفت. برای تشخیص تغییر شکل جزئی و دستیابی به استحکام یکسان در جهت خارج از صفحه، برجستگی‌های ۲۵۰ میلی‌متری کنسول داخلی در وجوه مخالف تیرها در دهانه ۱۰۰۰ میلی‌متر در امتداد محور طولی ارائه شد. ظرفیت پیچشی نهایی تیرهای آزمایش شده ۷.۴۱ درصد، ۸.۶۰ درصد و ۱۳.۵۸ درصد کمتر از (FEM) ATENA-3Dبرای ۰٪، ۵۰٪ و ۱۰۰٪ RCA بود. تغییر در نسبت جایگزینی سنگدانه تأثیر کمی بر گشتاور نهایی و زاویه پیچش دارد. بر اساس نتایج تجربی و تحلیلی، مشخص شد که ظرفیت مقاومت گشتاور پرتو RAC با افزایش درصد RCA کاهش می‌یابد. الگوهای ترک مشابه و رفتار شکست در تیرهای RAC و NAC در هر دو مطالعه مشاهده شد. بنابراین، عملاً امکان اعمال RAC در کاربردهای سازه ای تحت بارگذاری پیچشی خالص وجود دارد.