Influence of Recycled Coarse Aggregate on Punching Behaviour of Recycled Coarse Aggregate Concrete Slabs

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ABSTRACT: *This paper reports on the punching shear behavior of simply supported recycled aggregate concrete two-way slabs. The experimentation was conducted on 15 Recycled Coarse Aggregate Concrete (RCAC) slab specimens and 3 Natural Aggregate Concrete (NCAC) slabs were cast tested as control specimens. All the slabs were simply supported on all four edges and tested under a central patch load. Six replacement percentages (0, 20, 40, 60, 80 and 100%) of Natural Coarse Aggregate (NCA) replacements with Recycled Coarse Aggregate (RCA) were considered in this investigation. The results showed that as the replacement of NCA with RCA increases, the Ultimate load, deflection at ultimate load, Stiffness degradation and Energy absorption decreases and the cracking was premature. A Regression model has been developed to predict the ultimate punching shear of RCA slabs.*

Keywords: *Deflections, Energy absorption, Loads, Natural Coarse Aggregate (NCA), Natural Coarse Aggregate Concrete (NCAC), Recycled Coarse Aggregate (RCA), Recycled Coarse Aggregate Concrete (RCAC), Stiffness degradation, Two-way Slabs.*

NOMALNCLATURE

f_c	Cube compressive strength (N/mm^2)
f'_c	Cylinder compressive strength (N/mm^2)
τ	Shear stress (N/mm^2)
r	replacement ratio of NCA with RCA

I. INTRODUCTION

Recycled coarse aggregate concrete (RCAC) can be recognised as a new kind of concrete, in which broken pieces of waste concrete are used as aggregate. The use of RCA is one such an attempt to solve some of the problems in the field of construction industry. The concept of using RCA is now gaining popularity and research in this field has gained some momentum. Most of the findings have been extensively reviewed and discussed by Nixon [1], Hansen [2] and ACI committee 555 [3]. Due to the low strength, low elastic modulus, bad workability, high water infiltration, high shrinkage and creep of RCAC, it is mostly used for only non structural concrete [4, 5]. However, RCAC is well recognised in view of its low thermal conductivity, low brittleness as well as the low specific gravity that reduces the self weight of the structures. It was revealed that the relevant material properties of RCAC are generally lower than those of conventional concrete, but they are still sufficient for practical applications. Most importantly the use of RCA can save natural resources and protect our living environment [6, 7].

The studies of properties of RCAC have been ongoing over the last few decades, leading a number of countries to establish standards or recommendations supporting their views. With regard to popularised RCAC, the structural behaviour of RCAC ought to be investigated. In fact some studies concerning the performance of beams were conducted by Mukai [8], Yagishita [9], Gonzalez-Fonteboa [10], performance of columns were studied by Yang [11] and studies on seismic performance of frame structure by Xiao [12] made with RCAC. This paper reports studies on punching shear behavior of RCAC slab specimens.

II. RESEARCH SIGNIFICANCE

In this investigation, experiments were designed to provide a comprehensive understanding of the structural behavior of RCAC. The tests were particularly focused on the real punching shear behaviour of simply supported reinforced RCAC slabs under action of central patch load and also studied the influence of NCA replacement with RCA on the failure pattern, ultimate loads, load deflection curves, stiffness, stiffness degradation, energy absorption and comparison with the codes of practice of slabs under punching shear. The results presented in this paper may promote the use of RCA in practical applications.

III. EXPERIMENTAL PROGRAM

3.1 Materials

Ordinary Portland cement of 43 grade, confirming to IS 8112:1989 [13], locally available river sand as fine aggregate (zone-II) confirming to IS-2386 [14], coarse aggregates are natural coarse aggregate (NCA) and recycled coarse aggregate (RCA). RCA is obtained from the waste concrete brought from the runway of an Airport in Kadapa, Andhra Pradesh, India (10 to 12.5mm accounting for 50%, and 12.5 to 20mm accounting for 50% in weight) and is used in this investigation. The physical properties of the NCA and RCA are presented in Table 1. Fe415 HYSD bars confirmed to IS-1786:1985[15] with 6mm diameter have been used as slab reinforcement.

Table1. Physical properties of NCA and RCA

Coarse aggregate	Grading (mm)	Bulk density (kg/m^3)	Apparent density (kg/m^3)	Water absorption (%)
NCA	4.75–20	1520	2680	0.52
RCA	4.75 -20	1360	2560	5.02

3.2 Mix proportions of RCAC

Due to the high water absorption capacity of RCA, they were presoaked by additional water before mixing. The amount of water used to presoak the RCA was calculated according to the saturated surface dry conditions. The target designed strength for 28 days of all the concretes was set as around 25 MPa. The ACI mix design procedure [16] is adopted. The mixtures were divided in to six groups. The main difference among these six groups is the NCA replacement percentage with RCA which is 0, 20, 40, 60, 80 and 100%, respectively. In case of NCA replacement percentage with RCA equating 0, the specimens are termed as NCAC slab specimens, which are served as the control specimens for comparison. The mix proportions of the concrete are shown in Table 2.

3.3 Preparation of test specimens

Steel moulds were used to cast the slab specimens of required size. Two L-shaped frames with a depth of 50mm were connected to a flat plate at the bottom using nut and bolts. Cross stiffeners were provided to the flat plate at the bottom to prevent any possible deflection while casting the specimens. The gaps were effectively sealed by using thin card boards and wax to prevent any leakages.

In the experiment, a total 18 (3 on each group) approximately one-sixth scale square isotropically reinforced concrete slab specimens were made with the NCA replacement with RCA in different percentages and tested under punching shear. The thickness of the slab specimen and the spacing of longitudinal reinforcement was accomplished in accordance with IS 456-2000 [17]. All the slabs are of size 1100 x 1100 x 50mm. All the slab specimens are reinforced with (0.63%) Fe-415 HYSD 6mm diameter bars, with a cover of 10mm and the bars are equally distributed in both the directions.

The test slab specimens were de-moulded after 3 days. Before de-moulding, the slab specimens are cured with wet jute bags. The de-moulded slab specimens were water cured for 28 days in curing pond. After removing the slab specimens from the curing pond, they were allowed to dry under shade for a while and then they were coated with white paint on both sides, to achieve clear visibility of cracks during and after testing. By preserved cubes and cylinders in each group, the measured average mechanical properties of the concrete related to the slab specimens are illustrated in Table 3. From Table 3 it is observed that as the replacement of RCA with NCA increases the compressive strength and split tensile strength decreases.

3.4 Loading arrangement and testing

The slab specimen is placed over the loading platform and steel rods of 16 mm diameter have been kept below the slab along the four edges to simulate the simply supported edge condition. Placing of steel rods allow free rotation along the edges thus simulating the simply supported edge condition. A single concentrated patch load was applied at the geometric center of each slab with a rigid bearing plate of 100x100x20 mm with a 3-mm thick plywood packing between the slab and the bearing plate. Over this rigid plate, solid circular rod of 50 mm diameter was kept to distribute the load from the hydraulic jack to the slab specimen. The load was applied through hydraulic jack was measured in increments of 200N which corresponds to one unit of calibrated proving ring with 500 kN capacity, vertical deflections at the geometrical center of the slab specimens were measured by using dial gauge with a least count of 0.01 mm. The load at the first crack and the corresponding deflection at the bottom centre of the slab were recorded. The ultimate punching shear load and corresponding deflection at the centre were also observed and recorded. The overall view of a specimen in position ready for testing is shown in Figure 1.

IV. RESULTS AND DISCUSSION

4.1 General

The load versus central deflection curves for the slabs are presented in Figure 2. It may be seen that the typical relationship was linear until flexural cracking, which occurred just below the loading point. This event was characterized by a noticeable reduction in slab stiffness. With increasing load, new cracks were formed and the existing ones kept propagated in the radial direction, predominantly towards the corners of the slab. The slope of the load-deflection curve also kept decreasing until punching failure occurred. A sudden drop in the applied load marked this event. At this stage, punching shear failure was clearly visible on the top face but, on the bottom face, only an outline of the truncated failure cone with a much larger perimeter had formed. Table 3 reveals that the mechanical properties of the recycled concrete slabs decreases with an increase of the NCA replacement percentage with RCA.

The results of the experimental investigation are summarized in Table.4. The values presented here represent the average of punching shear strengths, load and deflection obtained for three specimens in each group. From the Table.4 it is observed that there is a decrease in first crack load as the replacement of NCA with RCA increases. The first crack load of NCAC-S is 14.60kN and for the RCAC-20-S to RCAC-100-S is between 14.20 to 12.20kN. The first crack load of RCAC-20-S to RCAC-100-S decreases by 2.74 to 16.44%, when compared with NCAC-S. The first crack occurs first in RCA than that of natural aggregate, it is due to the presence of adhered mortar over the RCA. Hence, as the percentage replacement increases the first crack load decreases.

The ultimate load of NCAC-S is 48.20kN and for the RCAC-20-S to RCAC-100-S is between 47.20 to 41.40kN. The ultimate load of RCAC-20-S to RCAC-100-S decreases by 2.07 to 14.11%, when compared with NCAC-S. This shows that as the replacement of NCA with RCA increases the ultimate load decreases linearly. It should be noted that the reduction in the ultimate loads are less than at material level, i.e. the mechanical properties as described in Table.3; this may be due to the contribution of steel reinforcement.

The central deflection response of various slab specimens is shown in Figure.4. Central deflection corresponding to first crack load and ultimate load are presented in Table.4. It is observed that the central deflections corresponding to first crack load of RCAC-20-S to RCAC-100-S decrease by 3 to 30%, when compared with NCAC-S. The central deflections corresponding to ultimate load of RCAC-20-S to RCAC-100-S decrease by 3 to 15%, when compared with NCAC-S. Similar trends are observed at first crack stage and ultimate load stage. But, rate of decrease of deflections at first crack stage is more when compared to ultimate stage. At the first cracking stage, rate of decrease of deflections are more due to presence of old mortar over the RCA, but at ultimate stage rate of decrease of deflections are less due to the contribution of steel reinforcement. Typical view of failure slab specimens is shown in Figure 3 and Figure 4.

4.2 Stiffness

From the load-deflection curves, two values of the stiffness of the tested slabs were obtained. The un-cracked stiffness K_i is indicated by the slope of the line of a value less than the first crack load, and the ultimate stiffness K_u is measured by the slope of the line at about 90% of the ultimate load. These values are given in Table 5. From the deflection curves, it can be seen that the slope becomes steeper when the percentage replacement of NCA with RCA increases. This indicates that the un-cracked stiffness increased as the percentage replacement of NCA with RCA increases. Stiffness degradation is defined as the ratio between the ultimate stiffness and the un-cracked stiffness as given in Table 5. As the stiffness degradation increased, the specimen indicated lower ductility. Out of RCAC slab specimens RCAC-100-S shows 9% decrease in stiffness degradation when compared with NCAC-S slab specimens.

4.3 Energy absorption

The energy absorption is defined as the area under the load-deflection curve. The values were determined from test results, and are listed in Table 5. RCAC-20-S to RCAC-100-S show 4.17 to 27.50% decrease in the energy absorption when compared with NCAC-S. Therefore, it can be concluded that as the replacement percentage of NCA with RCA increases energy absorption decreases.

V. REGRESSION MODEL FOR PUNCHING SHEAR STRESS

A simple regression model has been developed from the results of present investigation for predicting the punching shear strength of RCAC slabs. To develop the punching shear strength model, linear regression technique has been adopted. The linear regression is in the form of Y=A+BX where Y is independent variable, X is dependent variable and A and B are called regression coefficients. The A and B are determined from regression analysis in accordance with the principle of least squares method.

For predicting the shear stress IS code [17] and ACI [18] code uses cube and cylinder compressive strength, respectively. Hence, the proposed models for punching shear stress with f_c and f'_c are as given below

$$\tau = A + BX \qquad \text{..... (1)}$$

From the results of the present study, a simple regression models has been developed connecting shear stress with cube compressive strength f_c and cylinder compressive strength f'_c and are presented as equation 3 and 4 with a standard deviation of 0.0020 and 0.0025, respectively

$$\tau = (0.359 - 0.0067\, r)\sqrt{fc} \qquad \text{..... (2)}$$

$$\tau = (0.403 - 0.0091\, r)\sqrt{f'c} \qquad \text{..... (3)}$$

A comparison of the ultimate shear stress by regression models (Eq. 3 and 4) and experimental values are presented in Table 6 and Figure 5. From the Table 6 and Figure 5 it can be observed that the proposed model compared well with the experimental shear stress. The experimental and regression model values give more conservative predictions.

VI. CONCLUSIONS

The following observations and conclusions can be made on the basis of the current experimental results.

1- As the percentage replacement of natural coarse aggregate with recycled coarse aggregate increases the compressive strength and split tensile strength increases. Up to 40% replacement of NCA with RCA there is a marginal decrement in compression and split tensile strength when compared with natural coarse aggregate concrete.
2- All the slabs behave similar in the aspect of failure patterns under punching shear regardless of the replacement percentage of natural coarse aggregate with recycled coarse aggregate. The presence of recycled coarse aggregate reduces the first crack and ultimate loads of slab specimen. However, this reduction is less than that of the mechanical properties of the recycled coarse aggregate.
3- Slab specimens up to 40% replacement of NCA with RCA there is a marginal decrement in first crack and ultimate loads when compared with natural coarse aggregate concrete.
4- As the percentage replacement of natural coarse aggregate with recycled coarse aggregate increases the stiffness degradation decreases and energy absorption decreases.
5- A Regression model is developed for predicting the ultimate punching shear and is given as
$\tau = (0.359 - 0.0067\, r)\sqrt{fc}$
$\tau = (0.403 - 0.0091\, r)\sqrt{f'c}$

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Table2. Mix proportions of concrete (kg/m^3)

Nomenclature	Replacement percentage of NCA with RCA	W/C	Cement in kgs	Sand in kgs	NCA in kgs	RCA in kgs	Mixing water in liters
NCAC-S	0	0.53	379	804	942	-	200
RCAC-20-S	20	0.53	379	820	754	168	200
RCAC-40-S	40	0.53	379	823	566	337	200
RCAC-60-S	60	0.53	379	833	377	506	200
RCAC-80-S	80	0.53	379	846	188	675	200
RCAC-100-S	100	0.53	379	863	-	843	200

Table3. Average mechanical properties of concrete (MPa)

Nomenclature	Percentage Replacement of NCA with RCA	Cube compressive strength (f_c)	Cylinder compressive strength ($f^1{}_c$)	Split tensile strength (f_t)
NCAC-S	0	43.33	34.35	3.35
RCAC-20-S	20	42.52	33.50	3.25
RCAC-40-S	40	40.96	32.37	3.16
RCAC-60-S	60	38.37	30.86	3.11
RCAC-80-S	80	35.48	28.40	2.88
RCAC-100-S	100	33.48	26.42	2.78

Table.4. Test results

Nomenclature of slab specimen	First crack Load (kN)	Deflection at first crack load (mm)	Ultimate Load (kN)	Deflection at ultimate load (mm)
NCAC-S	14.6	1.51	48.20	33.23
RCAC-20-S	14.2	1.46	47.20	32.15
RCAC-40-S	14.2	1.42	45.80	30.19
RCAC-60-S	13.4	1.28	44.60	29.22
RCAC-80-S	12.8	1.14	42.80	28.49
RCAC-100-S	12.2	1.06	41.40	28.11

Table.5. Stiffness and Energy absorption

Nomenclature of slab specimen	Stiffness			Energy absorption (kNm)
	Initial K_i (kN/mm)	Ultimate K_u (kN/mm)	degradation K_u/K_i	
NCAC-S	12.20	1.77	0.145	1.20
RCAC-20-S	12.20	1.74	0.142	1.15
RCAC-40-S	12.20	1.71	0.140	1.04
RCAC-60-S	12.20	1.66	0.136	0.94
RCAC-80-S	12.00	1.62	0.135	0.90
RCAC-100-S	12.00	1.58	0.132	0.87

Table6. Ultimate punching shear strength of slabs

Nomenclature of slab specimen	Experimental Ultimate shear stress (N/mm^2)	Ultimate shear stress by using equation 2 (with f_c) (N/mm^2)	Ultimate shear stress by using equation 3 (with f'_c) (N/mm^2)
NCAC-S	2.38	2.36	2.36
RCAC-20-S	2.33	2.33	2.32
RCAC-40-S	2.26	2.28	2.27
RCAC-60-S	2.20	2.20	2.21
RCAC-80-S	2.11	2.11	2.11
RCAC-100-S	2.04	2.04	2.02

Fig. 1: Overall view of a specimen in position ready for testing

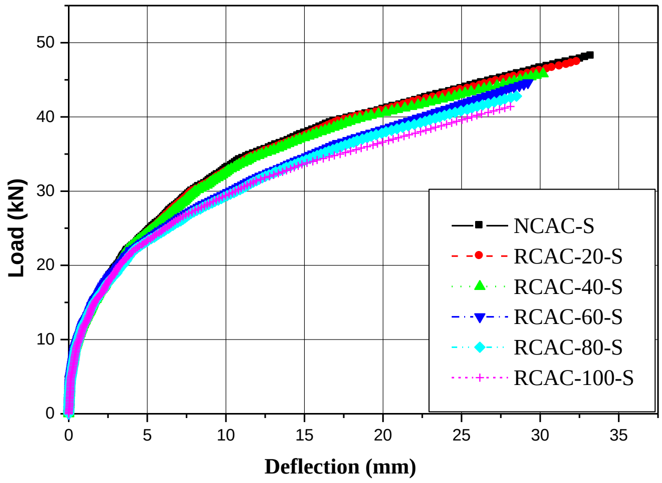

Fig 2: Load deflection curves

Fig 3: Typical top view of failure RCAC slab specimen

Fig 4: Typical bottom view of failure RCAC slab specimen

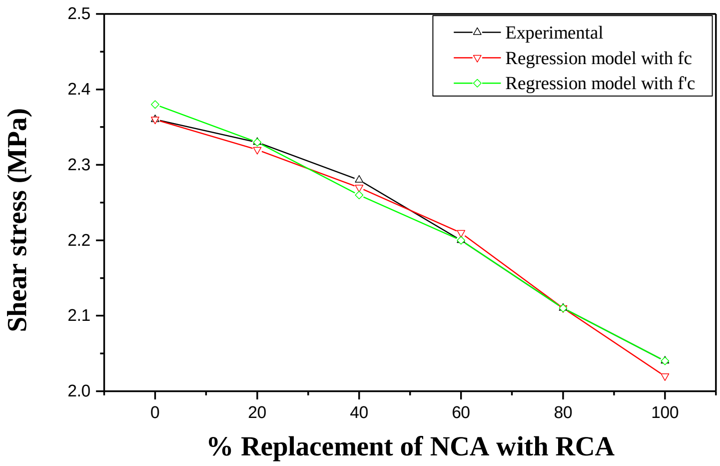

Fig 5: Variation of Shear stress with the replacement of NCA with RCA