EFFECT OF VARIABLES ON SHEAR STRENGTH OF RECYCLED AGGREGATE CONCRETE BEAMS (EVSSRACB)

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ABSTRACT

Fifty-four reinforced concrete beams using recycled coarse aggregates (RA) were tested to determine diagonal cracking (v_{cr}) and ultimate (v_u) shear capacities. All the beams were singly reinforced and without any shear reinforcement. The concrete compressive strength fc’ varied from 20 to 40 MPa and RA replacement percentage was kept 25 and 50 %. The beams were tested for three shear spans to depth ratio a/d and three percentages of longitudinal reinforcement ratios ρ. Test results indicated that up to 50 % natural coarse aggregates can be replaced by recycled coarse aggregates for structural members in the range of normal grade applications for sustainable construction without any adverse effect on shear strength. The impact of a/d ratio is more on ultimate strength than cracking shear strength. Value of 2.5 for *a/d* signals the difference in behavior between short beams and long beams. The effect of fc’ on shear strength of recycled aggregate concrete (RAC) beams is not negligible and should be accounted for strength analysis. Effect of fc’ on the shear strength of RAC has produced some contradictory conclusions. For short beams fc’ correlates better with v_u than with v_{cr}, whereas for long beams, fc’ correlates better with v_{cr} than with v_u. This is due to unpredictable path of crack movement in the recycled aggregates with adhered mortar. Both the cracking and ultimate shear strengths of RAC members illustrate increasing trend with the increase in tensile reinforcement ratio ρ.

Keywords: *Cracking shear strength; Compressive strength; Recycled aggregate; Shear span to depth Ratio (a/d); Sustainable construction; Tensile reinforcement ratio (ρ); Ultimate shear strength*

1. INTRODUCTION

Currently, concrete with construction and demolition waste as recycled aggregates has been increasingly used by contractors and designers for sustainable construction, but mostly for low utility applications and nonstructural purpose. In fact, large amount of experimental work (Exteberria et al., 2007; RILEM, 1994; Singh and Sharma, 2007) has been done towards the processing of demolished concrete, the mixture design, the physical and the mechanical properties as well as the durability aspects. Previous investigations have been extensively reviewed (ACI, 2002; Brito and Richardo, 2010; Hansen, 1986, 1992; Nixon, 1978) and it was revealed that the relevant material properties of RAC are generally lower than those of conventional concrete, but they are still sufficient for practical application in civil engineering (Abukersh, 2009; Gull., 2011; Xiao et al., 2005). To popularize the RAC in civil engineering, additional information on the behavior of structural elements of this type of environment friendly concrete will be a positive step.

One of the most important structural requirements and complex phenomenon involving many variables of reinforced concrete constructions is the shear strength of beams. It is well-known that studies on the shear behavior of natural aggregate concrete has arisen wide attention in the engineering world for a long time, and it is now widely accepted that the three main variables affecting the shear strength of concrete members without web reinforcement are the concrete compressive strength (fc'), the shear span-to-depth ratio (*a*/*d*), and the tensile reinforcement ratio (ρ) (Kani, 1966; Rajagopalan and Ferguson, 1968; Zsutty, 1968). However, to the best of the author's knowledge, only a few investigations have been carried out in the field of the shear behavior of RAC (Fathifazl, 2011; González and Martínez, 2007; Han et al.,2001).

The intent of this study is to shed some light on the effects of the main variables on the shear strength of reinforced recycled aggregate concrete beams. Shear strength of concrete depends significantly on the ability of the coarse aggregate to resist shearing stresses. RA used is relatively weaker than NA in most cases and yielded reduced shear strength (Khaldoun, 2007). This paper summarizes the results of an experimental program that examined the effect of concrete made with 25 and 50 % recycled aggregates and with varying amount of shear span to depth ratio and tensile reinforcement ratio on the cracking as well as ultimate shear strength of 54 singly reinforced recycled aggregate concrete beams without shear reinforcement. The scope of this study does not involve the development of design guidelines for reinforced recycled aggregate concrete.

2. RESEARCH SIGNIFICANCE

The recycling of concrete wastes as RA is important because it can minimize the environmental pollution and reduce the huge consumption of natural aggregates in construction. The use of RA will also reduce the environmental impact due to the harvesting and processing of virgin aggregates from natural resources and dumping of construction demolition waste on landfills. Overall, the practical benefits resulting from the current work are not only on environmental and economical fronts, but they could also provide the construction industry with technical information on a marketable product, which is presently under-utilized.

3. EXPERIMENTAL PROGRAMME

3.1 Test Materials

The materials, in general, conformed to the specification laid down in the relevant Indian Standard Codes (IS: 383, 1997; IS: 3812, 2003; IS: 8112, 1989). Two types of coarse aggregates named Natural Aggregate (NA) and recycled aggregates (RA) were used in the RAC mixes. Locally available crushed granite was used as NA and RA was derived from the tested concrete cubes in the laboratory that contained well-graded crushed granite stone. The concrete cubes were crushed to the specified size and gradation using a hammer, washing and sieving. Physical properties (Ravindrarajah and Tam, 1985; Sami and Akmal, 2009) of the natural and recycled aggregates are given in **Table 1**. Deformed steel bars of 12 mm, 16 mm and 20 mm nominal diameters and with nominal yield strength of 423 MPa were used as tension reinforcement (IS: 1786, 1985) in the beams.

Table 1: Physical properties of coarse aggregates

Characteristics	Coarse aggregates	
	NA	RA
Fineness modulus	6.68	6.54
Specific gravity	2.70	2.48
Loose bulk density kN/ m^3	14.30	11.70
Water absorption (%)	1.1	5.3
Moisture content (%)	0.7	1.9
Los Angeles abrasion value (%)	9.3	23.2

3.2 Concrete Mix Design

The mix design was done according to the (IS: 10262, 2009) for normal grade of concrete without admixture. The mix proportions were designed by assuming the aggregates in saturated surface dry condition and appropriate moisture adjustments were made to cater for the different water absorption properties of the aggregates. Fly ash was used as 25% by weight replacement of cement to achieve proper workability of the mix in the range of 50 – 100 mm by avoiding segregation and bleeding. Details of concrete mix are given in **Table 2**. Once the optimum mix was determined for each grade, it was used to produce concrete with 25% and 50% recycled coarse aggregate by weight replacement of natural coarse aggregate.

Table 2: Mix proportions for optimum mixes

Mix	Mix proportion by weight	Fly Ash %	Constituents (kg/m^3)				W/C ratio
			Cement	Fly Ash	Sand	Aggregates	
M20	1:1.5:3.4	25	289	96	578	1310	0.5
M30	1:1.25:2.75	25	337	113	562.5	1238	0.5
M40	1:1:2.5	25	375	125	500	1250	0.5

3.3 Test Procedure

Three series (18 specimens each) of reinforced recycled aggregate concrete beams with concrete grade 20, 30 and 40 N/mm^2 and 0.25 and 0.50 as RA replacement ratio were tested. In each series, the concrete compressive strength was approximately kept constant while the shear span to depth ratio a/d and the percentage of longitudinal steel was varied. All the beams were cast only for adequate flexural strength without any shear reinforcement (ACI 318-02, 2002; IS: 456, 2000). The section of all the beams was kept constant at 150 × 300 mm. For the entire test programme, the distance between two-point loads was kept constant at 600 mm. Beams with three different shear spans to depth ratios a/d 1.5, 2.5 and 3.5 with tensile reinforcement ratio ρ 1, 2 and 3 % was studied.

The beam specimens were tested as simply supported beam by using a manually operated hydraulic Jack that applied load gradually on the mid-span of the beam specimens until shear failure which pre-empted flexural failure (Angelakos et al., 2001). Diagonal cracking along with the formation of a dominant inclined crack is indicative of shear failure. The test setup configuration for the shear tests is shown in **Fig. 1**.

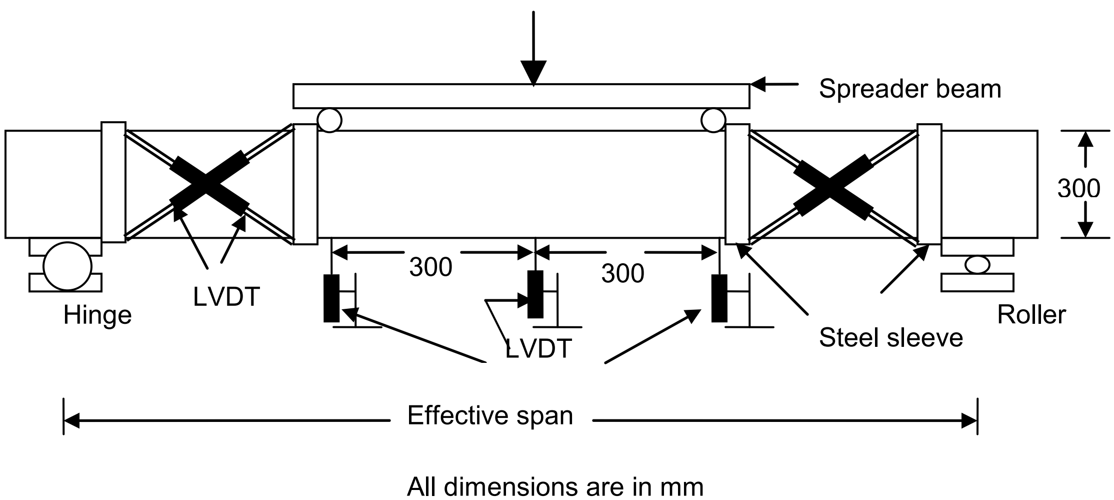
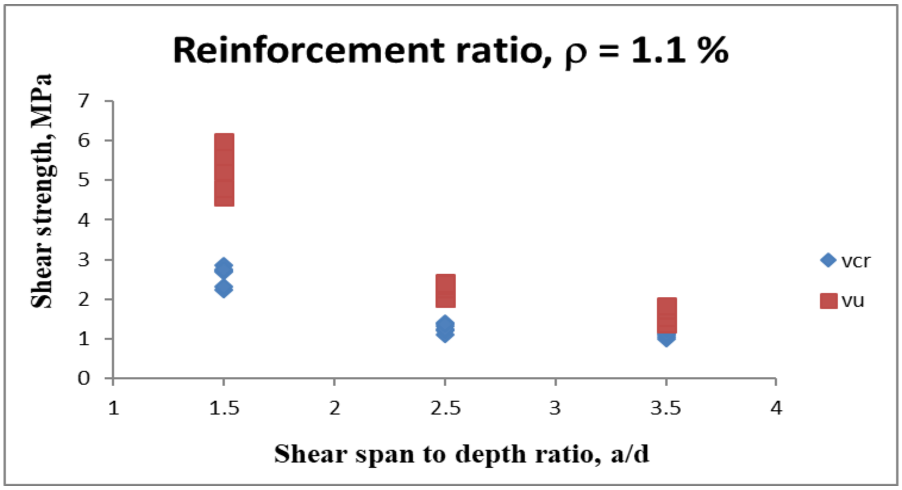


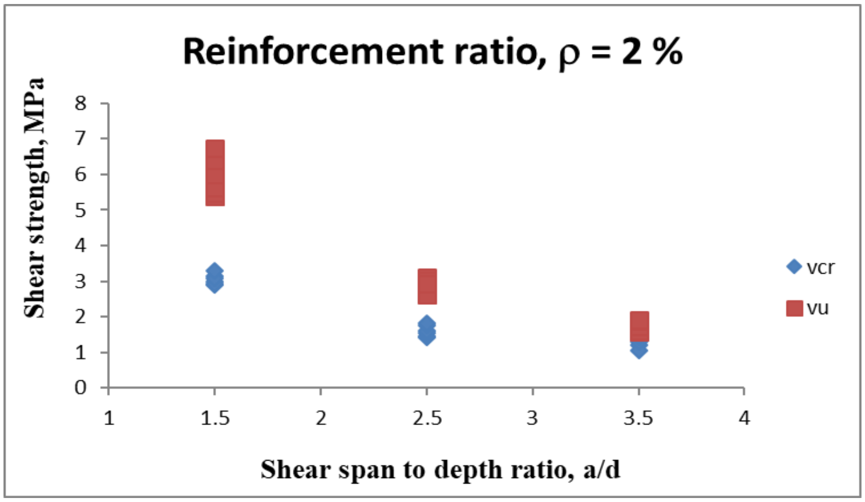
Fig. 1: Test setup configuration for the shear tests

4. ANALYSIS OF TEST RESULTS

Results all the three series of RAC beams are summarized to study the effects of all the three variables.

4.1 Effects of Shear Span-to-Depth Ratio





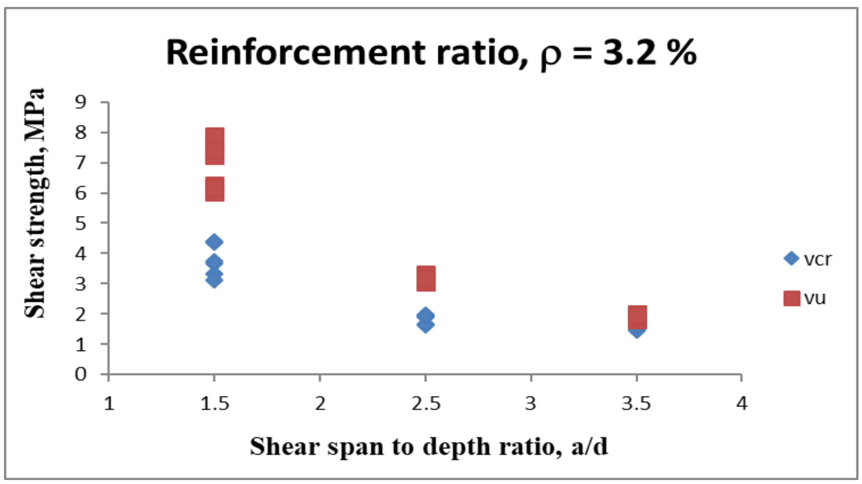


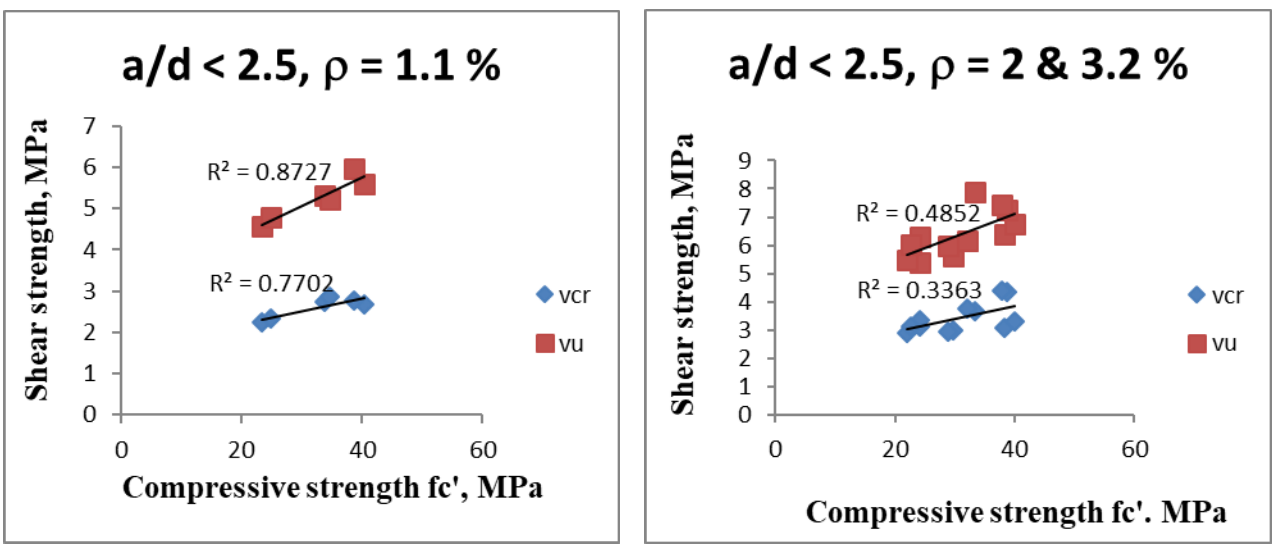
Fig. 2: Effect of shear span to depth ratio on v_{cr} and v_u of RAC beams

Fig. 2 shows the effect of *a*/*d* on cracking and ultimate (v_u and v_{cr}) shear strength of recycled aggregate concrete beams of M 20, M 30 and M 40 grades and with 1.1, 2 and 3.2 % of tensile reinforcement ratio. Almost similar trend of normal aggregate concrete members is followed by RAC beams. There is no negative impact on the shear strength of the RAC beams with 25 and 50 % RA. The impact of a/d ratio is more on ultimate strength than cracking shear strength. An examination of the relationship between the shear span-to-depth ratio and the shear strengths reveal that v_u and v_{cr} both decreases very significantly as *a*/*d* increases from 1.5 to 2.5. With further increase in a/d from 2.5 to 3.5, v_u was affected much more as compared to v_{cr}. Average reduction in ultimate and cracking shear strengths from a/d 1.5 to 2.5 was noticed 53.2 and 49.8 % whereas reduction in v_u and v_{cr} from a/d 2.5 to 3.5 was 36.4 and 13.7 % respectively. This trend is very well defined and always occurs, regardless of the values of fc', % of RA and percentage of tensile reinforcement ratioρ. Therefore, a value 2.5 for *a*/*d* signals the difference in behavior between short beams and long beams for RAC beams also.

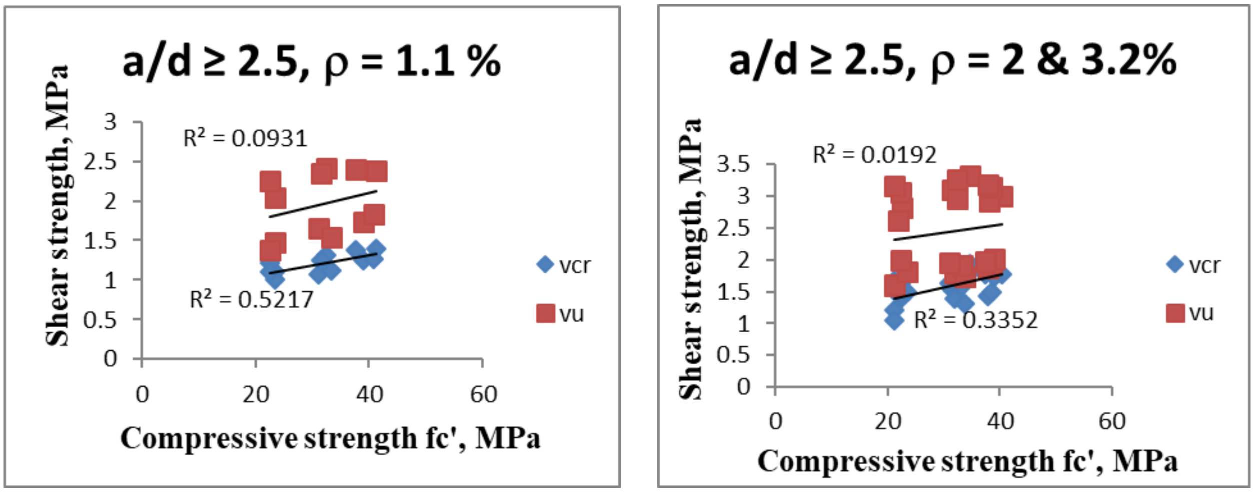
The theory for NAC beams is equally applicable for RAC beams also (González et al.,2009; Zsutty, 1971). In the case of short beams (*a*/*d* < 2.5), a very significant amount of additional loading can be resisted by the reinforced recycled aggregate concrete beams beyond the formation of a first diagonal crack before ultimate failure in shear-compression occurs. The fact is strengthened from the results shown in Fig.2, which show that for a/d 1.5, v_u is almost double than v_{cr}, as ratio of v_u / v_{cr} ranges from 2.15 to 1.66 for all the different combinations of RAC beams. This redistribution of stresses in short beams with a/d 1.5 takes place because of the relatively short distance between the supports and the applied loads and by crushing of the arch rib. Difference between v_u and v_{cr} decreases with increase in a/d ratio. For a/d greater then 2.5, failure was observed always by diagonal tension. As a/d increases from 2.5 to 3.5, this failure mode becomes very sudden as total shear failure occurs almost immediately after the formation of a first major diagonal cracking. The abrupt nature of this failure is evidenced in Fig. 3 by the fact that v_u and v_{cr} are almost equal in magnitude. The failure of long beams was brittle and accompanied with a loud noise.

4.2 Effects of Compressive Strength

Fig. 3 (a) and (b) shows the effects of fc' on the shear strength (v_{cr} and v_u) of short as well as long RAC beams with 1.1, 2 and 3.2 % of tensile reinforcement ratio. It was observed that for short beams with a/d ratio 1.5 fc' correlates better with v_u than with v_{cr}, whereas for long beams with a/d = 2.5 and 3.5, fc' correlates better with v_{cr} than with v_u for all the three percentage of ρ.



(a) For short beams



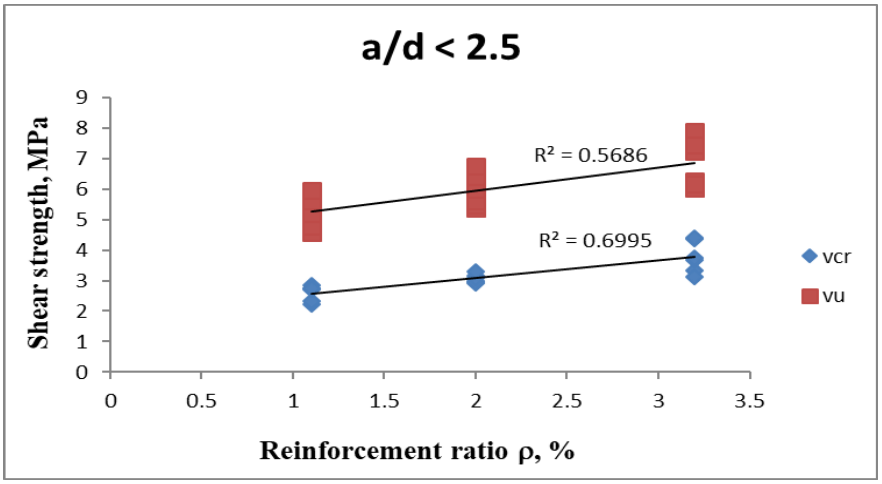
(b) For long beams

Fig. 3: Effect of compressive strength on v_{cr} and v_u of RAC beams

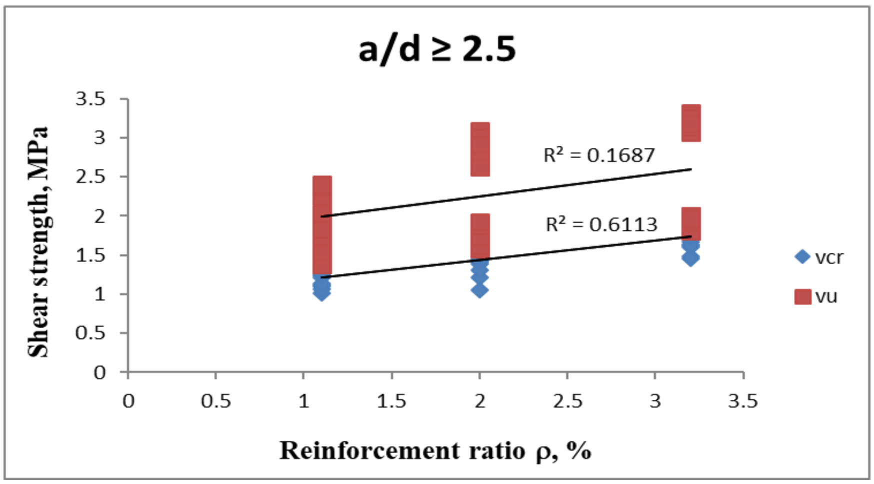
For short beams, the value of coefficient of determination (r^2) for the v_u regression line is 0.87 and 0.49, which is greater than 0.77 and 0.34, the one corresponding to v_{cr}. This confirms that in case of short beams, the applied loads are transferred directly to the supports by arch action, thus allowing additional load to be resisted beyond the formation of a major diagonal crack. Whereas for long beams the value of coefficient of determination (r^2) for the v_{cr} regression line is 0.52 and 0.34, which is greater than 0.09 and 0.02, the one corresponding to v_u. Such influence reaffirms the basic shear transfer mechanisms for long beams are mainly resisted by the shear resistance in the compression zone, the interlocking action of aggregates, and the dowel action. Cracking shear strength of M 30 grade of RAC beams shows increasing trend as compared to M 20 grade of RAC beams. But with further increase in grade, there is no major increase in the v_{cr} of RAC beams. M 40 grade of RAC beams shows very little increase in v_{cr}, as compared to M 30 beams. Ultimate shear strength for M 40 grade is almost equal or sometimes even inferior, as compared to M 30 grade of concrete for RAC beams. As expected, Fig. 3 shows that the magnitude spread between v_{cr} and v_u is much more prominent in the case of short beams than in the long beams. One of the main factors influencing the arch action is the strength of the compression strut, which is related to the compressive strength of concrete. It is worth mentioning that *fc'* does influence v_{cr} and v_u as long as the data are segregated by *a*/*d* (short beams and long beams) and by ρ.

4.3 Effects of Tensile Reinforcement Ratio

According to Bukhari and Ahmed, 2008; Kani, 1966, the tensile reinforcement ratio,ρ, has considerable effect on the shear strength of concrete. For RAC beams also, the impact of ρ on the cracking shear strength is predominantly apparent than on ultimate shear strength since Fig. 4 (a) and (b) shows that coefficient of determination (r^2) for the v_{cr} regression line is greater than the one corresponding to v_u for short and long beams.



(a) For short beams



(b) For long beams

Fig. 4: Effect of Tensile Reinforcement Ratio on v_{cr} and v_u of RAC beams

The nature of the relationship between ρ and v_{cr} is like the one existing between ρ and v_u for the same range of values of *a*/*d,* fc’ and with 25 as well as 50 % of recycled aggregates. Significant increase is noted in the cracking as well as ultimate both the shear strengths of RAC beams for short beams with a/d ratio 1.5, whereas for long beams with a/d ratio 2.5 and 3.5, increase in ultimate shear strength is not as significant as cracking shear strength with the increase in tensile reinforcement ratio.

5. CONCLUSIONS

The following observations can be made regarding the effects of the important variables on the shear strength of reinforced recycled aggregate concrete members without web reinforcement:

1. RAC beams follows almost similar trend as of normal aggregate concrete members. Also, the shear strength of recycled aggregate concrete beams remains largely unaffected by the level of recycled aggregates used. In fact, up

to 50 % natural coarse aggregates can be replaced by recycled coarse aggregates for structural members in the range of normal grade applications for sustainable construction.

2. The shear span-to-depth ratio has a much more significant effect on the ultimate shear strength than on the cracking shear strength of recycled aggregate concrete members. The cracking as well as ultimate shear strength decreases radically as the shear span-to-depth ratio increases from 1.5 to 2.5. In the case of long beams ($a/d \geq 2.5$), both the ultimate shear strength and the cracking shear strength are virtually not much affected by variations in the shear span-to-depth ratios. This trend is very well defined and always occurs, regardless of the values of fc', % of RA and percentage of tensile reinforcement ratioρ.
3. Although, cracking shear strength of RAC beams increases with the increase in compressive strength of the concrete, the ultimate shear strength does not follow any set pattern – sometimes it increases with the grade of concrete whereas at certain other times the trend may change. This is due to unpredictable path of crack movement in the recycled aggregates with adhered mortar. Cracking was slightly premature in RAC beams due to the presence of two interfacial zones (ITZ) between the mortar and recycled coarse aggregates, which is a source of micro-cracks and reduced bond strength. In other words, fc' has an impact on v_{cr} and v_u if the other two variables, a/d and ρ, are kept constant.
4. With the increase in the tensile reinforcement ratio ρ, both the cracking and ultimate shear strengths of recycled aggregate concrete members illustrate increasing trend regardless of the conditions like long or short beams, light or heavy reinforcement ratios, when recycled coarse aggregate replacement percentage are kept relatively constant.

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