

Bond Strength of HYSD Bars and SCC with and without Recycled Aggregate-An Experimental Study

K. JaganadhaRao¹, S. Vasam² and M. V. SeshagiriRao³

¹ Department of Civil Engineering, Chaitanya Bharathi Institute of Technology, Gandipet, Hyderabad -75, India

² Research scholar, Department of Civil Engineering, J N T University, Hyderabad – 85, India

³ Department of Civil Engineering, CVR College of Engineering, Hyderabad, India
Email: kjagannadharao@yahoo.com

Abstract. Self Compacting Concrete (SCC) has become inevitable in the current scenario of construction of large and complex structures with heavy reinforcement and complicated shapes. Using normal concrete in such situation may often result in inadequate compaction, affecting performance and long-term durability of structures. In addition, the use of Recycled Concrete Aggregate (RCA) is gaining importance throughout the globe due to the depleting sources of natural aggregate and disposal problem of demolished waste. There is a little work done on the behaviour of SCC with RCA. Therefore, a comprehensive experimental investigation on bond strength and modes of failure of Self Compacting Concrete (SCC) with and without Recycled Concrete Aggregate (RCA) was carried out and the results are presented. The variables studied include grade of concrete (M20, M40 and M60), Percentage of RCA (0% to 100%), diameter of bar (10, 12 and 16) and percentage embedment length. All specimens were tested by conducting pull out test on UTM after 28 days of curing. The bond strength was found to vary with the increase in diameter and the failure mode was observed to change from rod pull out to splitting or rod fracture with increase in percentage of embedment length. The experimental results were compared with the theoretical bond strengths using the authors' formula and the formulae suggested by earlier researchers.

1. Introduction

The concept of sustainability is widely used in the construction industry due to the concern about the future of the planet as this industry consumes huge quantities of natural resources. There has been considerable research carried out on the use of recycled aggregates in concrete over the past 20 years, and this has grown extensively over the past five years as industry and Government have recognised the need for greater sustainability in construction. Research has shown that coarse recycled aggregates can be used in concrete up to a compressive strength of 80 MPa although there is a loss in strength when recycled aggregates are used as a direct replacement of natural aggregate. However, most researchers report that a certain proportion of coarse recycled aggregates (usually in the range 20-30% by mass of coarse aggregate) can be added as partial replacement to natural aggregate without affecting performance. The reason for the loss in strength is usually associated with the weaker interfacial transition zone between aggregate and mortar, due to recycled aggregates having a coat of weak mortar already attached which raises the porosity of the concrete. In general, the flexural strength and modulus of elasticity of recycled aggregate concrete have been reported to be proportional to the loss of compressive strength.



One of the greatest technological challenges of the present time is to utilise large amount of building and industrial wastes, which are generated as result of the development of the modern society. Whether the waste originates from clearing areas after natural disasters or from human-controlled activities, the utilisation of the waste by recycling will provide opportunities for saving energy, time & natural resources. At present, a very limited amount of building wastes is recycled, and the major portion is being deposited or used as landfill material. With the increase in construction activities and shortage of suitable deposit sites, the building wastes are becoming a serious problem, which has forced the civil engineering professionals and researchers to seriously think and develop methods of reuse of building waste in new construction. From the economic point of view, recycling of building waste is only attractive when the recycled product is competitive with the natural resources with respect to cost and quality.

Okamura and Masahiro [1,2] (2003) carried out investigation for establishing a rational mix design method for SCC. Several authors [3, 4, 5, 6 and 7] investigated on the development of SCC with various materials and different approaches. Jorge and Ricardo Robles [8] (2010) introduced a methodology for predicting long-term properties of recycled aggregate concrete and validated the same based on graphical analysis of the most important properties of hardened concrete. Muhammad Hadi [9] (2008) investigated the bond strength of high strength concrete (M70) with high strength steel (Fe500) with varying diameters of 12 to 36 mm. He proposed a new equation representing the bond based on the test results. How-Ji Chen, et al. [10] (2010) studied the bonding behaviour of Lightweight Aggregate Concrete (LWAC) and normal weight concrete by carrying out experimental investigations. They showed that the difference of the bond failure pattern between the LWAC and normal weight concrete is significant as the compressive strength of concrete is less than 40 MPa. Harajli [11] (2004) undertook a comparative analytical study of the average bond strength at the failure of reinforcing bars embedded in unconfined Normal Strength Concrete (NSC) and High Strength Concrete (HSC). The analysis predicted a highly non-uniform bond stress distribution at bond failure along the development/splice length, particularly for HSC. Below certain limit of the development/splice length (about $15-20d_b$), the average bond strength at failure, normalized to $f_c'^{1/2}$, is larger for HSC as compared to NSC. Ismaeel and James [12] (2013) studied the effect on bond strength when the reinforced steel bars are polluted (oiling the bars). The study was carried out for two embedment lengths and for two modes of polluting the bars. They found that no slip failure occurred in testing all the polluted and non-polluted bars and small bar sizes have greater bond strength than large bar sizes when the embedded length is small. They also observed that the embedment length of the bar greatly affects the bond strength especially for bars of small diameter. Liam, et al. [13] (2015) concluded that as the bonded length increases, the surface area over which the reinforcing bar is bonded to the concrete increases. Thus larger bar forces can be sustained before the tensile hoop stresses developed in the concrete exceed the tensile strength of the concrete causing splitting, slip and bond failure.

1.1. Significance

In the recent years, demand for the natural aggregate has increased enormously due to rapid urbanisation and extensive construction activity. There is a need to find a solution to protect or to conserve the natural aggregate for the coming generations. Therefore, search for the alternative material to natural aggregate started in the recent decades. Nowadays, Self-Compacting Concrete (SCC) is being used in almost all major projects due to its many advantages. But It is very important that we need to understand the behaviour thoroughly of any new material before putting it into use. Therefore, in this project, the bond characteristics of the HYSD reinforced bar with SCC made with and without recycled aggregate are investigated.

2. Experimental Program

2.1. Materials used

2.1.1. Cement: Ordinary Portland Cement conforming to IS 12269:1987 with specific gravity 3.15 was used in this investigation. The physical properties and chemical composition of cement are given in Tables 1 and 2 respectively.

2.1.2. Mineral Admixtures: Fly ash conforming to IS 3812(Part-1):2003 was used. The chemical composition of fly ash is given in Table 3.

2.1.3. Coarse Aggregates: Natural aggregates with a maximum size of aggregates 12.5 mm conforming to IS 383:1970 & Recycled Concrete Aggregate (RCA) of maximum size 12.5 mm, obtained from demolished building, were used.

2.1.4. Fine Aggregates: Locally available sand conforming to Zone-II was used. The properties of fine and coarse aggregates are given in Table 4.

2.1.5. Chemical Admixtures: Superplasticizer (Polycarboxylate Ether based) with specific gravity 1.01 and pH:8, and Viscosity Modifying Admixture (GleniumB233 stream 2) with specific gravity 1.1 and pH:6 were used in this work.

2.1.6. Water: Locally available potable water was used.

Table 1. Physical properties of cement

Property	Value
Specific gravity of cement	2.92
Initial setting time	32 min
Final setting time	185 min
Normal consistency	30 %
Compressive strength	54.7 N/mm ²

Table 2. Chemical composition of cement (as per Manufacturers test report)

S.No.	Chemical Property	Limits (as per IS)	Results
1	Lime Saturation Factor (%)	0.66 to 1.02 (max)	0.82
2	Alumina Iron Ratio	Min 0.665%	1.2%
3	Insoluble Residue	Max 2%	0.95%
4	Magnesia (%)	Max 6	2.4
5	Sulphuric Anhydride	2.5 to 35%	1.1%
6	Loss on Ignition	Max 5%	2.2 %

Table 3. Chemical composition of fly ash

S.No.	Chemical Property	Result (% mass)
1	Loss on Ignition	0.43
2	Alumina (as Al ₂ O ₃)	16.31
3	Silica (as SiO ₂)	60.82
4	Iron (as Fe ₂ O ₃)	17.17
5	Calcium (as CaO)	4.64
6	Magnesium(MgO)	Not found
7	Sodium (as Na ₂ O)	0.34
8	Potassium (as K ₂ O)	0.08

Table 4. Properties of Sand, Natural Coarse Aggregate and Recycled Concrete Aggregate

Property	Sand	NCA	RCA
Specific gravity	2.59	2.81	2.35
Total water absorption	1.0%	0.3 %	2.40%
Moisture content	0.15%	0.8%	0.45%
Bulk Density (Loose)	1567kg/m ³	1380 kg/m ³	1355 kg/m ³
Bulk Density (Compacted)	1713kg/m ³	1530 kg/m ³	1590 kg/m ³
Fineness Modulus (Zone III)	2.39	6.36	6.35
Elongation Index	--	7.10%	15.5%
Flakiness Index	--	6.15%	5.8 %

2.2. Mix Proportioning of SCC with Natural Aggregates (NASCC) and Recycled Aggregates (RASCC)

The mix proportioning was done based on the Modified Nan Su approach and the quantities of various ingredients are given in Table 5.

Table 5. Quantities of different ingredients of various grades of RASCC & NASCC per cum

Mix identification	Cement (Kg)	Fly ash (kg)	Coarse Aggregate		Sand (Kg)	Admix-ture (kg)	VMA (kg)	Water (lts)
			CA (Kg)	RCA (Kg)				
NASCC- M20	338.57	219.11	737.66	0.00	784.49	6.69	0.67	218.00
RASCC- M20	338.57	219.11	368.83	368.83	784.49	6.69	0.67	222.00
NASCC-M40	445.71	143.54	737.66	0.00	784.49	7.07	0.71	204.00
RASCC-M40	445.71	143.54	368.83	368.83	784.49	7.07	0.71	208.00
NASCC-M60	570.00	59.92	737.66	0.00	784.49	7.56	0.76	187.00
RASCC-M60	570.00	59.92	368.83	368.83	784.49	7.56	0.76	191.00

2.3. Experimental Methodology

The experimental procedure involves casting and testing of cubes, prisms and cylinders for the compressive, flexural, and split tensile and bond strengths respectively. The variables of the investigation include RCA content, the diameter of bar and embedment length of the bar for bond studies. The RCA content was varied as 0% and 50% by weight of the natural aggregate. For each cylinder cast, steel reinforcement with three different diameter bars of 10 mm, 12 mm and 16 mm was used with four different embedment lengths of 75 mm, 150 mm, 225 mm and 300 mm respectively. To maintain the verticality of the bar, wooden 'c' shaped clamps were prepared to make them exactly fit the cylindrical mould with a hole at the centre of the top strip for inserting the reinforcement bar. The bar was inserted to the required embedment length and fixed (Figure 1). The next day of casting, moulds were removed, and the respective cylinders and cubes were placed in the curing tank for 28 days. For the cylinders pull out the test was carried out on Universal Testing Machine of 1000 kN capacity. An extensometer was fixed to the rod and a dial gauge was also used to measure any possible slip. The arrangement is shown in Figure 2.



Figure 1. Cylindrical moulds with a wooden channel to support steel rod



Figure 2. The test set up for pull out test

3. Test Results and Discussions

3.1. Workability

The fresh state properties of concrete are shown in Table 6. The workability is found to decrease, in all the grades of concrete tested, with the introduction of 50% of recycled aggregate as partial replacement of natural aggregate. However, the values of different workability tests are within the acceptable limits as given by EFNARC. The workability properties improved with the grade of concrete. This improvement is due to the presence of higher cement paste in rich mixes.

Table 6. Workability properties of RASCC & NASCC (M20, M40 & M60 Grades)

Grade of Concrete	Mix Identification	Flow Table	T50	V-Funnel Test (Sec)		U- Box Test	L- Box Test
		(mm)	(Sec)	T0	T5	(mm)	(h2/h1)
		650-800	2-5	6-12	6-15	0-30	0.8-1.0
M20	NASCC-M20-0%	690	2.0	6.5	11.5	28	0.96
	RASCC-M20-50%	674	4.0	7.2	10.2	25	0.86
M40	NASCC-M40-0%	780	3.0	6.3	10.4	28.5	0.94
	RASCC-M40-50%	760	4.5	6.8	8.9	25.8	0.85
M60	NASCC-M60-0%	800	3.0	6.5	10.8	28.5	0.95
	RASCC-M60-50%	762	4.5	7.2	10.2	24.5	0.85

3.2. Hardened state properties

The compressive, split tensile and flexural strengths at the ages of 7 days and 28 days are shown in Table 7. In general, as 50% of the natural aggregates are replaced by recycled coarse aggregates, there is a reduction in strengths of all the grades of concrete tested. However, the reduction is marginal and is within 10 to 15% range. The calculated bond stress values, using authors' formula, Orangun and Darwin formula for M20 grade concrete with different diameters of bars and different lengths of

embedments are shown in Figures 1 and 2. Similarly, the experimental bond stress values and theoretical values for M40 and M60 grades of concrete are shown in Figures 3 to 6.

Table 7. Strength results of NASCC & RASCC with Different proportions of RCA

Mix	Mix identification	Compressive Strength (MPa)		Spilt Tensile Strength (MPa)		Flexural Strength (MPa)	
		7	28	7	28	7	28
		Days	Days	Days	Days	Days	Days
Low Strength	NASCC-M20-0%	22.10	34.25	2.8	3.8	3.2	4.1
	RASCC-M20-50%	20.85	32.93	2.3	3.3	2.7	3.6
Medium Strength	NASCC-M40-0%	32.86	53.6	6.13	9.86	7.54	12.31
	RASCC-M40-50%	30.97	50.3	5.48	8.43	6.39	10.63
High Strength	NASCC-M60-0%	50.85	70.25	5.3	9.27	6.97	8.1
	RASCC-M60-50%	48.2	68.1	4.8	7.15	5.71	7.79

For 150 mm and 225 mm embedment length, the concrete split vertically up to the tip of the rod due to the radial pressures acting around the surface of the rod and normal to it (figures 3 and 5). This splitting failure may be attributed to the fact that the higher tensile strength in the bar, the higher compressive strength of matrix and higher bond strength between the bar and matrix, led to the initiation of crack in the cylinder due to the radial stress exceeding the tensile strength of concrete. This has subsequently led to the vertical splitting of the cylinder from the tip of the bar. For 300 mm embedment length, as the rod tends to pull out of the concrete, radial pressure acts around the surface of the rod and normal to it that leads to splitting of the specimen vertically into two pieces (figure 4). In all the three cases concrete splitting was observed, indicating that the stress in concrete had exceeded its maximum permissible limit before the tensile stress in steel reached the yield strength. However, the failure of specimens with 12 mm bar with 300 mm embedment was by steel rupture (figure 6). The bond strength was observed to improve when recycled aggregate is used in all the grades of concrete tested (figures 2, 4 and 6).

With the increase in the percentage length of embedment, bond stresses are increasing up to 225 mm of embedment, and on further increase in embedment length, a drop in the values of bond stress is observed (figures 1 to 6). The drop in the bond strength is due to the mode of failure changing to splitting. Bond stress curves followed the same pattern with the usage of 50% recycled aggregate.

3.3. Model calculations

3.3.1. Experimental Bond stress calculation: For M20 grade of concrete, 12 mm rod with 300 mm as depth of embedment.

$$u = \frac{p}{\pi d l u} = \frac{81000}{(\pi \times 12 \times 300)} = 7.16 \text{ N/mm}^2 \quad (1)$$

3.3.2. Orangun Formula: For M20 grade of concrete, 10 mm rod with 300 mm as the depth of embedment.

$$\text{Bond Stress 'u'} = 0.083045 \left(f_c \left[1.2 + 3 \frac{c}{d} + 50 \frac{d}{l} \right] \right)^{\frac{1}{2}} \quad (2)$$

$$u = 0.083045 \left(20 \left[1.2 + 3 \times \frac{70}{10} + 50 \times \frac{10}{300} \right] \right)^{\frac{1}{2}} = 8.86 \text{ N/mm}^2 \quad (3)$$

3.3.3. Darwin Formula: For M20 grade of concrete, 10 mm rod with 300 mm as the depth of embedment

$$\text{Bond Stress 'u'} = 0.083045 \left(f_c \left(1.06 + 2.12 \times \frac{c}{d} \right) \left(0.92 + 0.08 \frac{c_{max}}{c_{min}} \right) + 75 \times \frac{d}{l} \right)^{\frac{1}{2}} \quad (4)$$

$$u = 0.083045 \left(20 \left[\left(1.06 + 2.12 \times \frac{70}{10} \right) \left(0.092 + 0.08 \frac{70}{70} \right) + 75 \times \frac{10}{300} \right] \right)^{\frac{1}{2}} = 6.83 \text{ N/mm}^2 \quad (5)$$

3.4. Empirical model proposed to estimate the Bond stress of NASCC & RASCC different grades of concrete with different proportions of RCA

Regression analysis was carried out on the experimental data considering the grades of concrete, percentage of recycled aggregates, reinforcing bar diameters and their percentage of embedment as independent variables (x1, x2, x3 and x4 respectively) and bond stress (y) as dependent variable. The following formula is obtained:

$$y = 6.28 + 0.05 \times x1 + 0.007 \times x2 + 0.11 \times x3 - 0.02 \times x4 \quad (6)$$

Where 'y' is the bond stress (concrete and HYSD bars)

x1- the grade of concrete,

x2- The percentage of recycled aggregate mixed in the concrete

x3- reinforcing bar diameter,

x4- The percentage length of embedment of reinforcing bar

The figures 1 to 6 show theoretical bond stress computed as per the authors' formula and earlier authors' formulae and also the experimental bond stress values for the three grades of concrete (with and without RCA) M20, M40 and M60 respectively. It is evident from the curves (figures 1 to 6) that the authors' formula is giving closer values to the experimental values compared to earlier authors' formulae.



Figure 3. Splitting failure for 16 mm dia. bars embedded up to 150 mm in M60 concrete



Figure 4. Steel rupture Mode of failure for 12 mm diameter bars embedded to 300 mm.

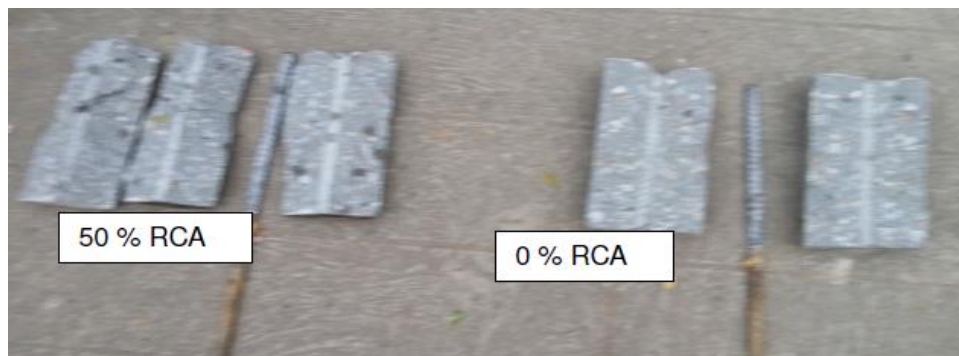


Figure 5. Splitting Mode of failure for 16 mm diameter bars embedded upto 300 mm length in M60 concrete with 0% and 50% RCA.



Figure 6. Splitting Modes of failure for 16 mm diameter bars embedded into various lengths of M60 concrete cylinders with 50% RCA.

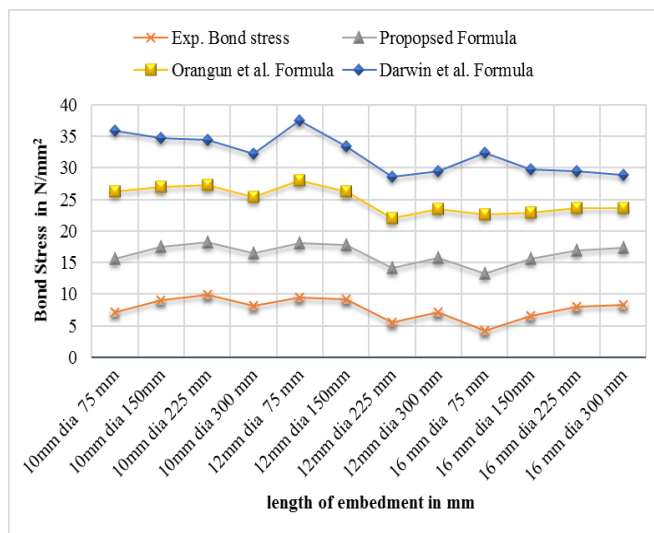


Fig 7. Bond Stress Vs Percentage embedment lengths for different bar diameters (SCC M20-0%RCA)

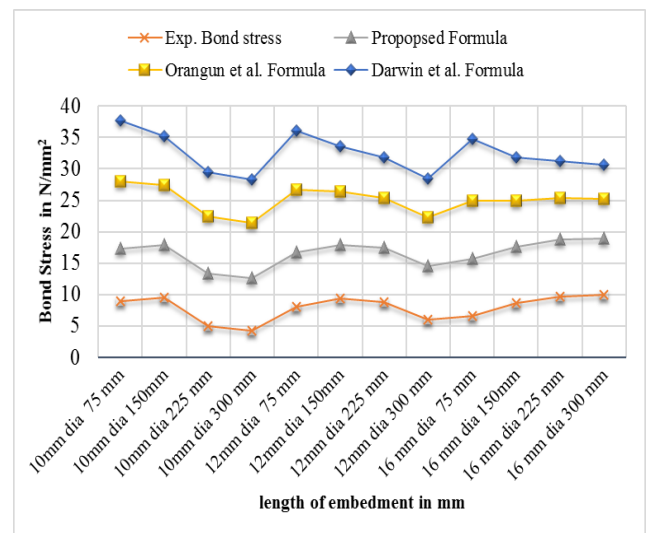


Fig 8. Bond Stress Vs Percentage embedment lengths for different bar diameters (SCC M20-50%RCA)

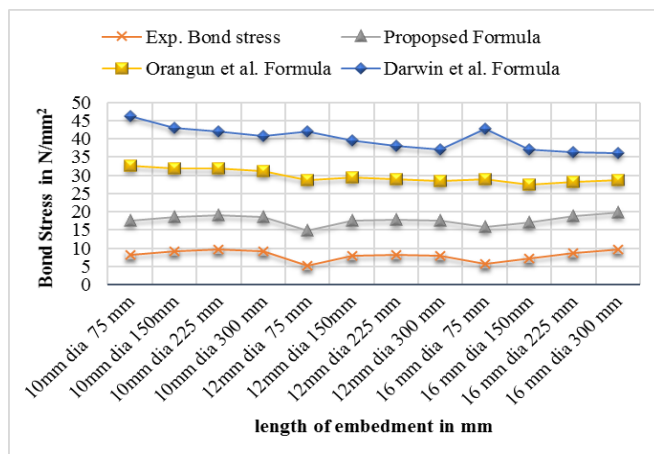


Fig 9. Bond Stress Vs embedment lengths for different bar diameters (SCC M40-0%RCA)

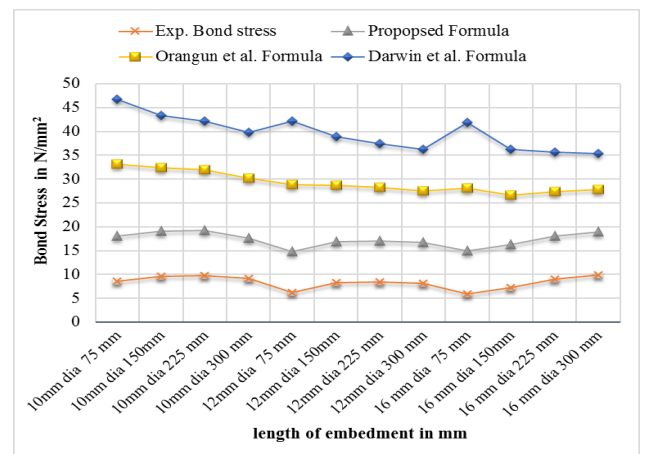


Fig 10. Bond Stress Vs embedment lengths for different bar diameters (SCC M40-50% RCA)

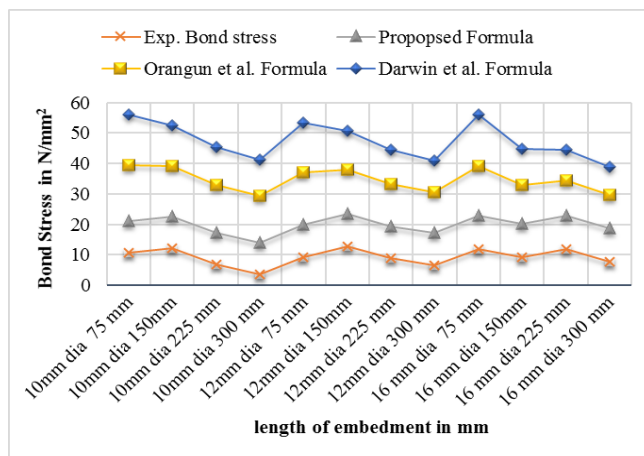


Fig 11. Bond Stress Vs Percentage embedment lengths for different bar diameters (SCC M60-0% RCA)

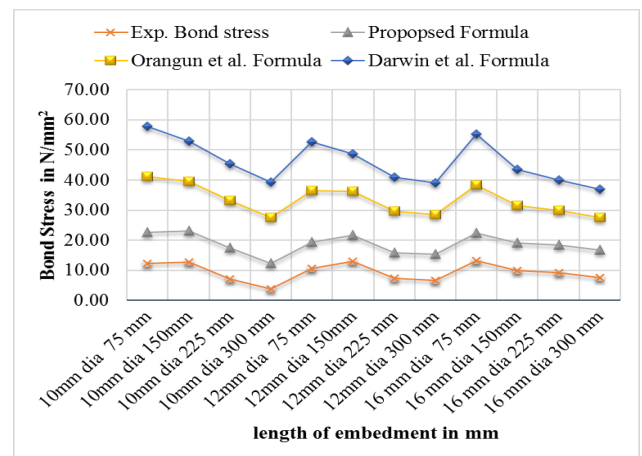


Fig 12. Bond Stress Vs Percentage embedment lengths for different bar diameters (SCC M60-50% RCA)

4. Conclusions:

1. The specimens with 75 mm embedment length failed by pull out for M20 grade concrete with or without recycled aggregate.
2. The bond strength of concrete with steel is found to increase as the diameter of bar increased from 10 mm to 12 mm and again there is a drop in bond strength for 16 mm diameter bar.
3. The failure pattern changed from rod pull out to either bar failure or splitting of concrete as embedment length increased due to the increased bond resistance.
4. Bond stress values are increasing with the increase in depth of embedment up to 225 mm of embedment in M20 and M40 grade concretes while it is increasing up to 150 mm embedment length in M60 concrete.
5. Recycled aggregate concrete showed higher bond stress when compared to natural aggregate concrete.
6. The authors' formula can be used to calculate the bond stress of HYSD bars with concrete of different grades (M20, M40 and M60).

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