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Pull-out behaviour of recycled aggregate based self compacting concrete

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Abstract. The use of recycled aggregate in concrete is gaining much attention due to the growing need for sustainability in construction. In the present study, Self Compacting Concrete (SCC) is made using both natural and recycled aggregate (crushed recycled concrete aggregate from building demolished waste) and performance of recycled aggregate based SCC for the bond behaviour of reinforcement is evaluated. The major factors that influence the bond like concrete compressive strength (Mix-A, B and C), diameter of bar (D_b=10, 12 and 16 mm) and embedment length of bar (L_d=2.5Db, 5D_b and full depth of specimen) are the parameters considered in the present study in addition to type of aggregates (natural and recycled aggregates). The mix proportions of Natural Aggregate SCC (NASCC) are arrived based on the specifications of IS 10262. The mix proportions also satisfy the guidelines of EFNARC. In case of Recycled Aggregate SCC (RASCC), both the natural coarse and fine aggregates are replaced 100% by volume with that of recycled aggregates. These mixes are also evaluated for fresh properties as per EFNARC. The hardened properties like compressive strength, split tensile strength and flexural strength are also determined. The pull-out test is conducted as per the specifications of IS 2770 (Part-1) for determining the bond strength of reinforcement. Bond stress versus slip curves were plotted and a typical comparison of RASCC is made with NASCC. The fracture energy i.e., area under the bond stress slip curve is determined. With the use of recycled aggregates, reduction in maximum bond stress is noticed whereas, the normalised maximum bond stress is higher in case of recycled aggregates. Based on the experimental results, regression analysis is conducted and an equation is proposed to predict the maximum bond stress of RASCC. The equation is in good agreement with the experimental results. The available models in the literature are made use to predict the maximum bond stress and compare the present results.

Keywords: sustainable construction; recycled concrete aggregates; pull-out test; bond stress and slip

1. Introduction

The term "sustainability" is defined as "*the development meeting needs of the present without compromising for the needs of future generations*". Sustainability has gained importance after the United Nations report (1987). This has drawn attention worldwide after the Rio summit (1992) and world summit (2002). Construction industry is one of the major industries contributing to the emission of CO_2 to the atmosphere. Sustainability can be achieved through materials used for construction, concrete production process, improving concrete properties and durability, and innovations in construction techniques. The use of alternate cementitious materials (fly ash, ground granulated blast furnace slag, rice husk ask, etc.) and alternate aggregates (recycled aggregates from building demolished waste, bottom ash, etc.) can be employed to achieve sustainability in concrete making materials (De Brito and Saikia 2012).

The bond between reinforcement and surrounding concrete is the result of chemical adhesion, frictional resistance and mechanical interlock. The bond is responsible for the safe transfer of force between steel and concrete. Bond between steel and surrounding concrete can be evaluated using four different methods as specified in ACI 408 (2003), these are pull-out, beam end, beam anchorage and beam splice. Among the four tests, pull-out test is widely adopted as this can be easily fabricated and the testing procedure is also simple. In the pull-out test, the bar is embedded in concrete which is firmly held and then the bar is pulled out from concrete. The bond stress is the ratio of the load taken to completely pull the bar out of the concrete to the contact area between bar and concrete.

Several works were reported on the bond performance of Self Compacting Concrete (SCC) with natural aggregates in comparison with Vibrated Concrete (VC) (De Almeida Filho *et al.* 2008, Foroughi-Asl *et al*. 2008, Sfikas and Trezos 2013, Pop *et al*. 2013, Helincks *et al*. 2013, Valcuende and Parra 2009). The major findings are that the SCC had performed better in terms of bond compared to VC. This improved performance is attributed to the reason that increased binder content reduced the pores in concrete leading to enhanced microstructure. The quality of concrete encapsulating the bar increased in case of SCC than VC and due to this, the load carrying capacity in pulling out of bar increased.

Liang *et al*. (2015) studied the bond behaviour in high volume fly ash concrete. It was found that the behaviour was similar to that of normal concrete. The use of light weight aggregates in concrete and their effect on the bond strength in comparison with normal aggregates was reported by Tang (2015, 2017).

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Table 1 Models for predicting maximum bond stress

Model	Formula	Units	Type of Test Specimen
ACI-408 (2003)	$\tau_u = 0.083045\sqrt{f_{cc}}\{1.22 + 3.13\left(\frac{c_{min}}{D_b}\right) + 53\left(\frac{D_b}{L_d}\right)\}$	S.I	-
Australian Standard (1994)	$\tau_u = 0.265\sqrt{f_{cc}}\{\left(\frac{c_{min}}{D_b}\right) + 0.5\}$	S.I	-
CEB-FIB MC (2012)	$\tau_u = 2.5\sqrt{f_{cc}}$ (for pull out failure) $\tau_u = 7.0(\frac{f_{cc}}{20})^{0.25}$ (for splitting failure)	S.I	-
Al-Jahdali *et al*. (1994)	$\tau_u = \left[-0.879 + 0.324\left(\frac{c_{min}}{D_b}\right) + 5.79\left(\frac{D_b}{L_d}\right)\right]\sqrt{f_{cc}}$	S.I	Pull-out
Chapman and Shah (1987)	$\tau_u = \left(3.5 + 3.4\left(\frac{c_{min}}{D_b}\right) + 57\left(\frac{D_b}{L_d}\right)\right)\sqrt{f_{cc}}$	Psi	Pull-out
Darwin *et al*. (1992)	$\tau_u = 0.083045\sqrt{f_{cc}}\{\left(1.06 + 2.12\left(\frac{c_{min}}{D_b}\right)\right)\left(0.92 + 0.08\left(\frac{c_{max}}{c_{min}}\right)\right) + 75\left(\frac{D_b}{L_d}\right)\}$	S.I	Beam Splice
Esfahani and Rangan (1998)	$\tau_u = 4.9\left(\frac{\frac{c_{min}}{D_b}+0.5}{\frac{c_{min}}{D_b}+3.6}\right)f_{ct}$ (for f_{cc}<50 MPa) $\tau_u = 8.6\left(\frac{\frac{c_{min}}{D_b}+0.5}{\frac{c_{min}}{D_b}+5.5}\right)f_{ct}$ (for f_{cc}>50 MPa)	S.I	Beam Splice
Harajli (1994)	$\tau_u = \left(1.2 + 3\left(\frac{c_{min}}{D_b}\right) + 50\left(\frac{D_b}{L_d}\right)\right)\sqrt{f_{cc}}$	Psi	Beam Splice
Kemp (1986)	$\tau_u = 232.2 + 2.716\left(\frac{c_{min}}{D_b}\right)\sqrt{f_{cc}}$	Psi	Cantilever Beam
Orangun *et al*. (1977)	$\tau_u = \left(0.101 + 0.268\left(\frac{c_{min}}{D_b}\right) + 4.4\left(\frac{D_b}{L_d}\right)\right)\sqrt{f_{cc}}$	S.I	Beam Splice

Also, works were reported on the bond in recycled aggregate concrete (Xiao and Falkner 2007, Guerra *et al*. 2014, Prince and Singh 2013, 2017, Kim and Yun 2013, 2014, Butler *et al*. 2011, Wang 2016). The use of recycled aggregates reduced the bond stress in concrete compared to that of natural aggregate concrete. The reduction in bond stress increased with increase in the percentage replacement of natural aggregates. The normalised bond stress is however, higher in case of recycled aggregates.

Codes such as ACI 408 (2003), Australian Standard (1994) and CEB-FIB MC (2012) proposed models to predict the maximum bond stress in vibrated concrete using natural aggregates. Of the models proposed by various codes, ACI 408 (2003) uses all the factors influencing bond stress like concrete strength, bar diameter, embedment length and cover to bar. Australian Standard (1994) considers concrete strength, bar diameter and cover to bar in its equation and this equation is independent of the embedment length of bar and hence it predicts same values of bond stress for different bar embedment lengths. CEB-FIB MC (2012), considers only the concrete strength and so the values of bond stress predicted by this model are independent of bar properties like diameter and embedment length. The CEB-FIB MC (2012) model is based on the type of failure whether a pull-out or splitting of concrete. Many models are proposed by several researchers viz., Al-Jahdali *et al*. (1994), Chapman and Shah (1987), Darwin *et al*. (1992), Esfahani and Rangan (1998), Harajli (1994), Kemp (1986), Orangun *et al*. (1977) in the literature to predict the maximum bond stress for natural aggregate based vibrated concrete. Of these models, Al-Jahdali *et al*. (1994), Chapman and Shah (1987) are based on experiments conducted on pull-out specimen. Darwin *et al*. (1992), Esfahani and Rangan (1998), Harajli (1994), Orangun *et al*. (1977) are based on beam splice specimen whereas, Kemp (1986) was based on cantilever beam specimen. The equations proposed by Al-Jahdali *et al*. (1994), Chapman and Shah (1987), Darwin *et al*. (1992), Harajli (1994), Orangun *et al*. (1977) considers all the factors affecting the bond stress like concrete strength, bar diameter, embedment length and cover to bar, whereas, the models proposed by Esfahani and Rangan (1998), Kemp (1986) does not consider embedment length and cover to bar and hence these models gives same values of bond stress for varying embedment lengths. The models for predicting maximum stress are given in Table 1.

2. Research significance

Many researchers emphasised on testing the bond in vibrated concrete and self compacting concrete with natural aggregates. Some works also reported on the use of recycled aggregates in vibrated concrete. The present work mainly focusses on the effect of use of recycled aggregates in self compacting concrete on the bond stress through pull-out testing. Analytical models to predict the maximum bond stress are available in the literature and are developed based on concrete made of natural aggregate. In the present work, model to predict the bond stress is proposed for self compacting concrete with both natural and recycled aggregates. A typical comparison with the available models is also done. To study the pull-out behaviour in self compacting concrete, the parameters considered included type of aggregate (natural and recycled), concrete compressive strength (Mix-A, B and C), diameter of bar (10, 12 and 16 mm) and embedment length of bar (2.5 and 5 times bar diameter and full depth of the specimen).

3. Experimental program

3.1 Materials

In the present work, Ordinary Portland Cement (OPC) of 53 grade conforming to IS 12269 (2013) is used. Fly ash and Ground Granulated Blast Furnace Slag (GGBS) are the mineral admixtures used in the present work as ternary additions in the mixture. Siliceous type fly ash conforming

Table 2 Properties of cementitious materials

Property	Material		
	Cement	Fly ash	GGBS
Fineness	339 m^2/kg	328 m^2/kg	426 m^2/kg
Specific gravity	3.1	2.2	2.9
Loss on Ignition	1.13%	0.88%	-
Standard Consistency	30%		
Initial setting time	48 minutes		
Final setting time	430 minutes		

Table 3 Properties of aggregates

Property	Material			
	Natural Fine Aggregate	Natural Coarse Aggregate	Recycled Fine Aggregate	Recycled Coarse Aggregate
Specific gravity	2.6	2.72	2.16	2.53
Bulk Density	1595 g/cm^3	1405 g/cm^3	1189 g/cm^3	1280 g/cm^3
Water Absorption	1%	0.5%	5.1%	3%
Fineness modulus	2.61	-	2.66	-

to IS 3812 (Part-1) (2003) is used. GGBS, a rich source of calcium is used conforming to IS 12089 (2004). The properties of cement, fly ash and GGBS are reported in Table 2. The fine aggregate used is of river origin and the coarse aggregate is of granite origin. The fine and coarse aggregates are conforming to IS 383 (1970) specifications. Recycled concrete aggregates from building demolished waste are used as both fine and coarse aggregates in the present work. The properties of natural and recycled coarse and fine aggregates are shown in Table 3. Sieve analysis of natural and recycled fine aggregates is done as per IS 383 (1970) and the corresponding graph of cumulative percent passing versus sieve size is given in Fig. 1. Reinforcing steel used is of Thermo Mechanical Treatment (TMT) type. This steel is conforming to IS 1786 (2008). The physical and mechanical properties are given in Table 4.

3.2 Mix proportions

IS 10262 (2009), gives the procedure for designing mix

Table 4 Properties of reinforcing steel

Property	Diameter of bar (mm)		
	10	12	16
Ultimate Stress, N/mm^2	553	569	571
Yield Stress, N/mm^2	512	512	515
Rib Spacing, mm	5.02	5.06	6.12
Rib Width, mm	2.02	2.04	3.06
Rib Height, mm	2.12	2.18	3.24

Table 5 Mix proportions

Mix	water/ powder ratio	Cement (kg/m^3)	Fly ash (kg/m^3)	GGBS (kg/m^3)	Water (kg/m^3)	FA (kg/m^3)	CA (kg/m^3)	Superplasticizer (lit/m^3)
NASCC								
NA-A	0.35	200	300	100	210	720	755	3
NA-B	0.325	300	200	100	195	794	755	3
NA-C	0.30	400	100	100	180	869	753	5.4
RASCC								
RA-A	0.35	200	300	100	210	598	702	2
RA-B	0.325	300	200	100	195	659	702	2
RA-C	0.30	400	100	100	180	722	701	3.2

proportions of Vibrated Concrete (VC). In the present work, Self Compacting Concrete (SCC) mix proportions are designed using guidelines given in IS 10262 (2009). Three concrete mixes Mix-A, Mix-B and Mix-C having water cement ratios of 0.35, 0.325 and 0.3 respectively were developed. The recycled aggregate SCC is developed with the same guidelines as that of natural aggregate SCC, except that, natural aggregates are replaced 100% by volume with recycled aggregates. The mix proportions are given in Table 5. A comparison of mixes with typical range of mix constituents as given in EFNARC (2005) is given in Table 6. These mix proportions are satisfying the EFNARC (2005) specifications and the fresh properties of the same are given in Table 7.

3.3 Mixing procedure

Concrete mixing in green state is done in a 40 litre

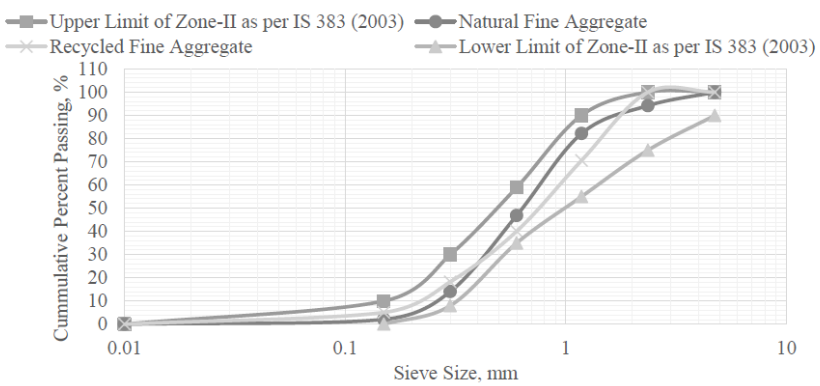


Fig. 1 Sieve analysis of natural and recycled fine aggregate

Table 6 Typical ranges of mix proportion as per EFNARC (2005)

Constituent	EFNARC (2005) Range	Mix Designation					
		NA-A	NA-B	NA-C	RA-A	RA-B	RA-C
Powder	380-600 kg/m^3	600	600	600	600	600	600
Water	150 - 210 kg/m^3	210	195	180	210	195	180
Coarse aggregate	750 - 1000 kg/m^3	755	755	753	702	702	701
Coarse aggregate (by volume)	28 - 35% of total volume	27.76%	27.76%	27.69%	27.76%	27.76%	27.69%
Fine aggregate	48 - 55% of total aggregate weight	49.95%	52.37%	54.68%	49.95%	52.37%	54.68%
water/powder ratio (by volume)	0.85 - 1.10	0.892	0.878	0.861	0.892	0.878	0.861

Table 7 Fresh properties of mixes A, B and C

Property	Test Method	EFNARC (2005) Range	Mix Designation					
			NA-A	NA-B	NA-C	RA-A	RA-B	RA-C
Filling ability	Slump Flow (mm)	550 - 850	660	660	650	620	610	590
Flowability	T_{500mm} (sec)	2 - 5	3	3	4	3.5	3.7	4.2
Flowability	*V*-Funnel (sec)	≤ 25	11	11	8	10	10	9
Segregation resistance	*V*-Funnel T_{5min} (sec)	0 - +3	2	2	1	2	1.8	1.5
Passing ability	*J*-ring (mm)	0 - 10	10	7	6	9	8	6

capacity pan mixer. The specimens for the hardened properties and pull-out tests were cast separately. However, companion standard cubes were cast along with pull-out specimens for the compressive strength value. For natural aggregate SCC, first, the natural coarse aggregates are allowed to mix with natural fine aggregates for about 30 seconds. Then, the binder (cement, fly ash and ggbs) is mixed with mixture of aggregates for 30 seconds. Half of the total water required is added to the dry mix and allowed to mix for 60 seconds. The required amount of superplasticizer is then mixed with remaining water, added to mixture and allowed to mix for another 60 seconds to attain the required flowability. In case of recycled aggregates, first the aggregates (coarse and fine aggregates) are allowed to soak in water for 24 hours. At the time of making concrete, the aggregates are brought to saturated surface dry condition. The same mixing procedure as that employed for natural aggregates is then followed.

3.4 Hardened properties

Hardened properties like compressive strength, split

Table 8 Hardened properties

Mix	Compressive Strength (MPa)				Split Tensile Strength (MPa)		Flexural Strength (MPa)	
	7 days	28 days	56 days	91 days	28 days	56 days	28 days	56 days
Natural Aggregate SCC								
NA-A	28.67	40.05	48.13	55.14	3.77	4.43	3.89	4.51
NA-B	36.34	49.39	61.51	71.79	4.09	4.98	4.18	5.12
NA-C	61.32	70.85	78.68	85.14	5.04	5.49	5.16	5.61
Recycled Aggregate SCC								
RA-A	22.96	32.16	38.74	44.52	3.05	3.50	3.19	3.65
RA-B	28.19	38.35	47.86	55.93	3.19	3.91	3.35	4.04
RA-C	46.68	53.94	60.00	64.97	3.85	4.20	4.02	4.28

tensile strength and flexural strength are evaluated for the mixes developed. Cubes of size 150×150×150 mm are used for determining compressive strength at the end of 7, 28, 56 and 91 days of curing period. Cylinders of diameter 150 by 300 mm height are used for determining split tensile strength at the end of 28 and 56 days of curing period. Beam specimens of size 100×100×500 mm are used for evaluating the flexural strength at the end of 28 and 56 days of curing period. These specimen sizes and testing was done as per IS 516 (2004) specifications. The hardened properties are detailed in Table 8. A total of 72 cubes, 36 cylinders and 36 beams were cast and tested for the hardened properties (three specimens for each category).

3.5 Pull-out specimens and testing

IS 2770 (Part-1) (2007), specifies the procedure for pull-out test of steel bar embedded in concrete. As per the specifications, cube specimens of size 100×100×100 mm were used for evaluating the pull-out strength for bar diameter less than 12 mm. For bar diameter between 12 to 25 mm, cube specimens of size 150×150×150 mm should be used. Cubes of size 225×225×225 mm are to be used for bar diameter greater than 25 mm. In the present study, for 10 and 12 mm diameter bar, cubes of size 100 mm and for bar diameter of 16 mm cubes of size 150 mm are employed as per the standards. Three different embedment lengths of 2.5 times bar diameter ($2.5D_b$), 5 times bar diameter ($5D_b$) and full depth of the specimen are considered to study clearly the effect of embedment on the bond stress (three specimens for each parameter of study were considered). The pull-out specimens are tested at the end of 56 days of curing period.

100 ton capacity universal testing machine was employed for testing pull-out specimens. The test setup is shown in Fig. 2. The machine consists of a moving upper platen and an adjustable lower platen. The cube specimen with steel bar embedded is inserted through the bottom platen and the free end of the bar is fixed in grips at the upper platen. A steel collar of 25 mm thick is used to transfer

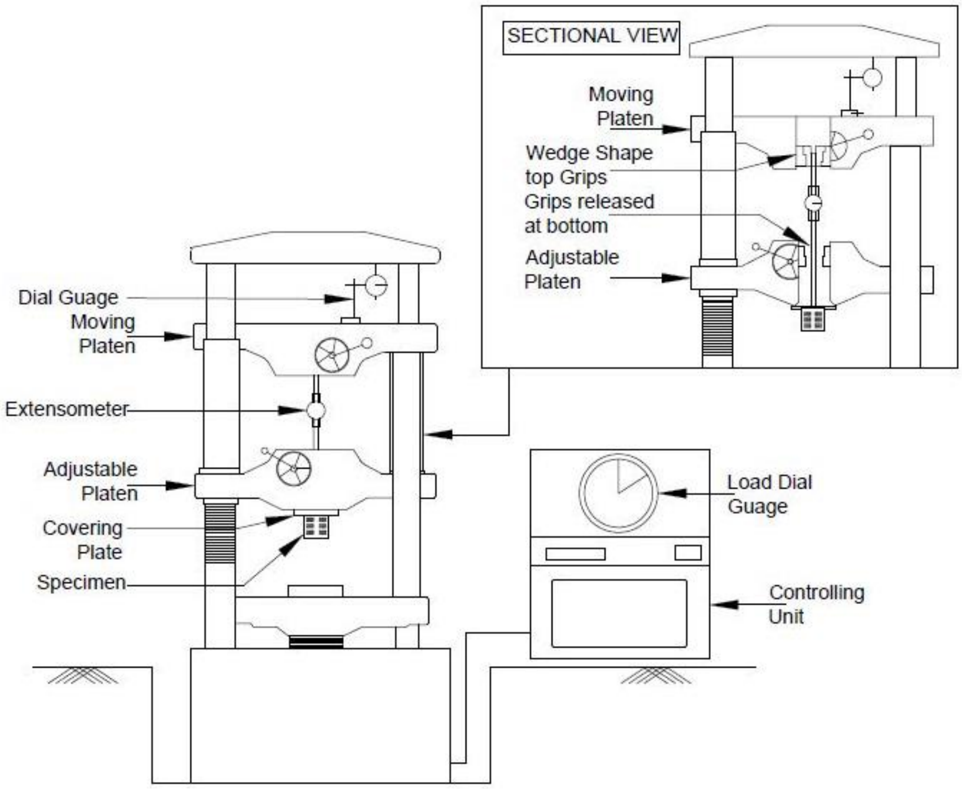


Fig. 2 UTM for conducting pull-out test

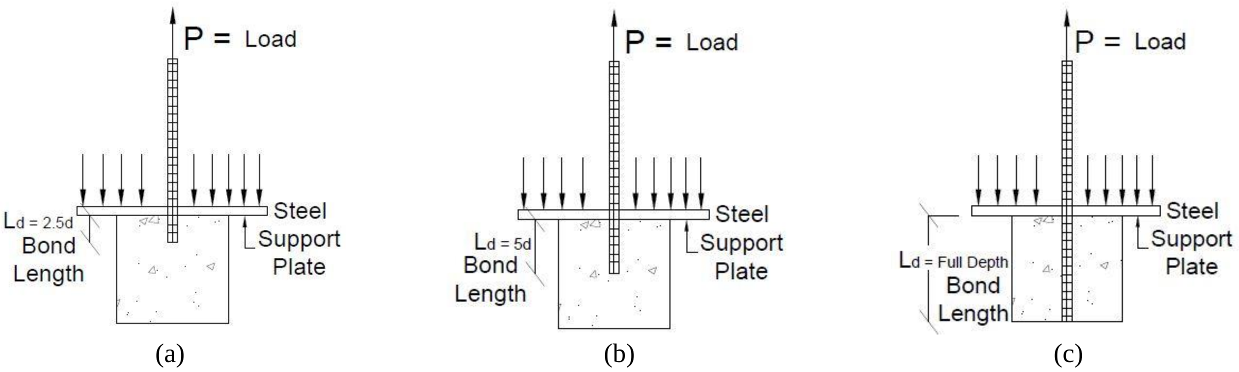


Fig. 3 Development of load transfer mechanism on specimen: (a) L_d=2.5d; (b) L_d=5d; (c) L_d=full depth of specimen

the load onto the cube top surface uniformly (Fig. 3). The lower platen is adjusted in such a way that the cube is in fixed position and ready for pull-out test. An extensometer having least count of 0.002 mm with a gauge length of 50 mm is fixed over the centre portion of the bar to measure the elongation in the bar. A dial gauge with least count of 0.01 mm is attached over the upper platen to measure the elongation in the bar plus slip between steel bar and surrounding concrete. The rate of loading applied is 2250 kg/min which is as per the specifications of IS 2770 (Part-1) (2007). The extensometer (Δ_e) and dial gauge reading (Δ_d) are noted for every 0.1 ton increment in load. The slip (Δ_s) between bar and surrounding concrete is calculated as per the Eq. (1) given below.

$$\Delta_s = \Delta_d - \Delta_e \tag{1}$$

where,

Δ_e =Total elongation of bar measured over a fixed gauge length
=Extensometer constant * Extensometer reading
=0.002 * Extensometer reading

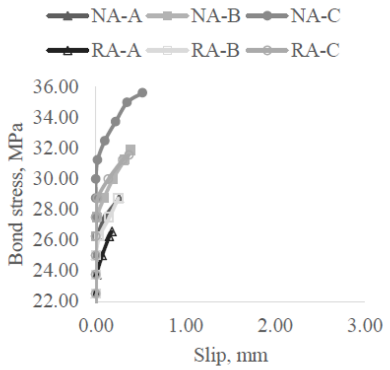
Δ_a =Total movement of the frame
=Dial gauge constant * Dial gauge reading
=0.01 * Dial gauge reading

4. Discussion of test results

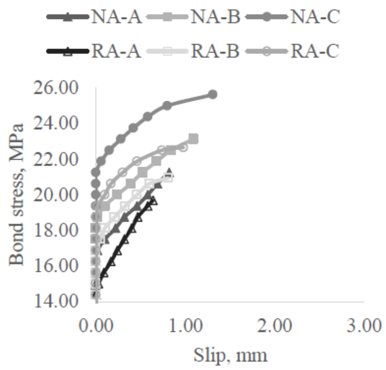
4.1 Bond stress versus slip

4.1.1 Influence of concrete strength

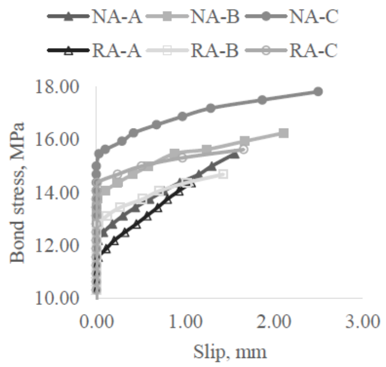
Pull-out test was conducted as per the specifications of IS 2770 (Part-1) (2007). The bond stress versus slip curves were plotted for Natural Aggregate Self Compacting



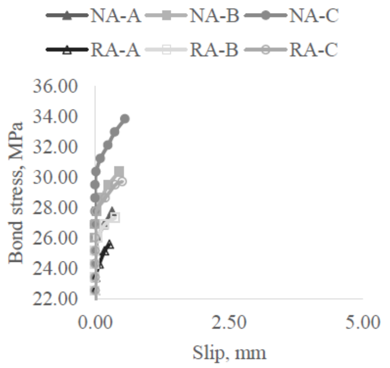
(a) 10 mm (D_b)-25 mm (L_d)



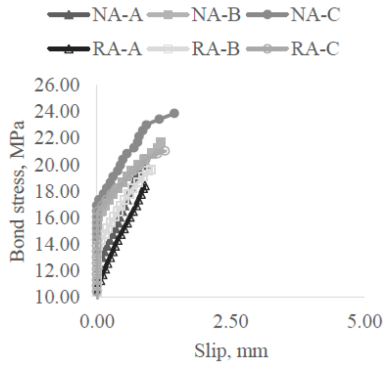
(b) 10 mm (D_b)-50 mm (L_d)



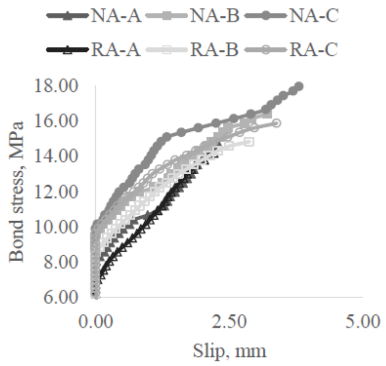
(c) 10 mm (D_b)-100 mm (L_d)



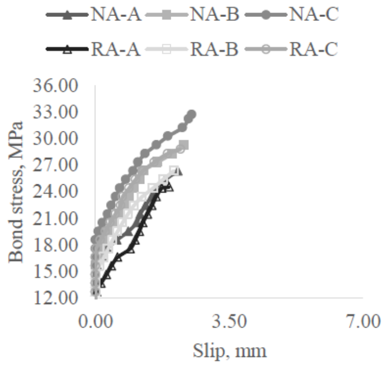
(d) 12 mm (D_b)-30 mm (L_d)



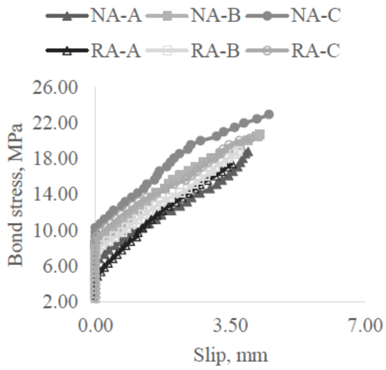
(e) 12 mm (D_b)-60 mm (L_d)



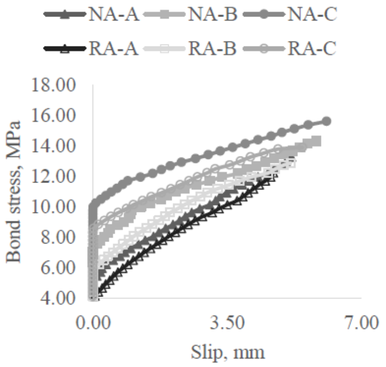
(f) 12 mm (D_b)-100 mm (L_d)



(g) 16 mm (D_b)-40 mm (L_d)



(h) 16 mm (D_b)-80 mm (L_d)



(i) 16 mm (D_b)- 150 mm (L_d)

Fig. 4 Bond stress versus slip curves

Concrete (NASCC) and Recycled Aggregate Self Compacting Concrete (RASCC) and a typical comparison is made (Fig. 4(a)-4(i)). From these figures, it is clear that with the increase in concrete compressive strength, the bond stress versus slip curve moves towards +*y*-axis showing the improved concrete quality surrounding the bar. As the concrete strength increases, the concrete surrounding the bar also improved resulting in higher load carrying capacity thereby increased bond stress. This is true in case of both NASCC and RASCC for 10, 12 and 16 mm diameter bars with different embedment lengths ($2.5D_b$, $5D_b$ and full depth of specimen).

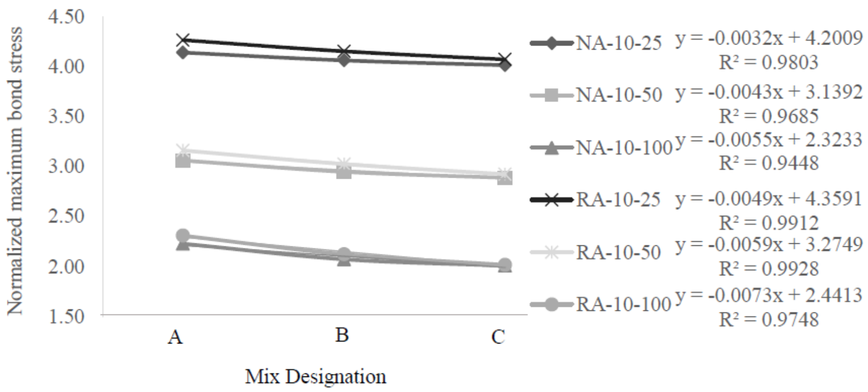
4.1.2 Effect of recycled aggregates

From Fig. 4(a)-4(i), it is clear that the bond stress is reduced in case of specimens where recycled aggregates were used. The maximum bond stress values for NASCC and RASCC for 10, 12 and 16 mm diameter bars for different embedment lengths are given in Table 9. The percentage decrease in bond stress of RASCC compared to NASCC is also given in Table 9. From this table it can be seen that the percentage decrease in bond stress increases with increase in concrete strength. The reason for this is that in high strength concretes, the failure depends on the Interfacial Transition Zone (ITZ) which is weak in case of recycled aggregates due to the presence of old ITZ in recycled coarse aggregates.

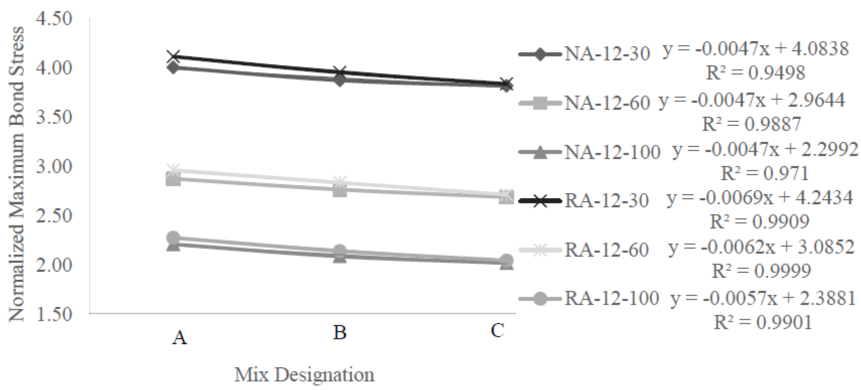
To better understand the effect of recycled aggregates on the bond stress, the effect of concrete strength is eliminated. For this, the bond stress is to be normalized i.e., maximum bond stress is divided by square root of concrete compressive strength. Normalized maximum bond stress values are plotted for NASCC and RASCC for 10, 12 and 16 mm diameter bars with different embedment lengths. From these figures, it is evident that the normalized bond stress values are higher for recycled aggregate than the

Table 9 Maximum bond stress

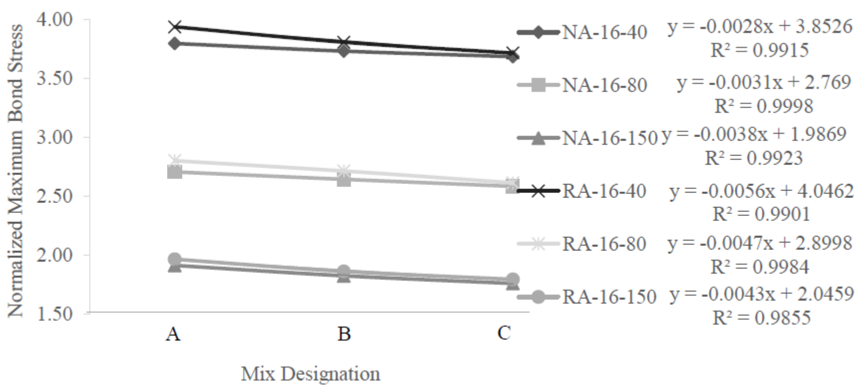
D_b-L_d	L_d/D_b	Maximum bond stress (MPa)								
		NASCC Mix-A	RASCC Mix-A	% Difference	NASCC Mix-B	RASCC Mix-B	% Difference	NASCC Mix-C	RASCC Mix-C	% Difference
10-25	2.5	28.74	26.56	7.59	31.87	28.74	9.82	35.62	31.55	11.43
10-50	5	21.24	19.68	7.34	23.12	20.93	9.47	25.62	22.65	11.59
10-100	10	15.46	14.37	7.05	16.25	14.68	9.66	17.81	15.62	12.30
12-30	2.5	27.77	25.60	7.81	30.37	27.34	9.98	33.85	29.72	12.20
12-60	5	19.96	18.44	7.62	21.70	19.63	9.54	23.87	21.04	11.86
12-100	8.33	15.36	14.19	7.62	16.40	14.84	9.51	17.96	15.88	11.58
16-40	2.5	26.36	24.53	6.94	29.29	26.36	10.00	32.71	28.80	11.95
16-80	5	18.79	17.45	7.13	20.75	18.79	9.45	22.94	20.26	11.68
16-150	9.38	13.28	12.24	7.83	14.32	12.89	9.99	15.62	13.91	10.95
		Average		7.44	Average		9.71	Average		11.73



(a)

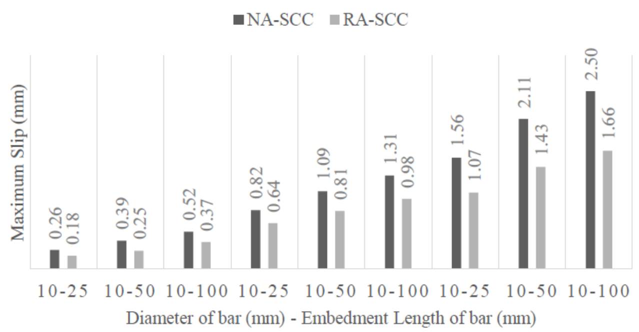


(b)

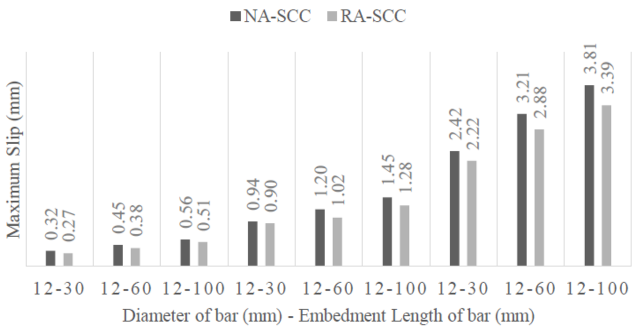


(c)

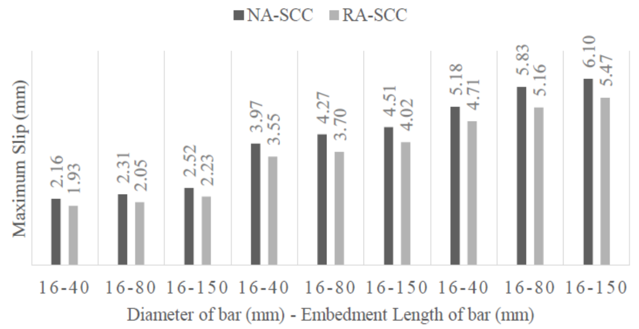
Fig. 5 Plots of normalised maximum bond stress



(a)

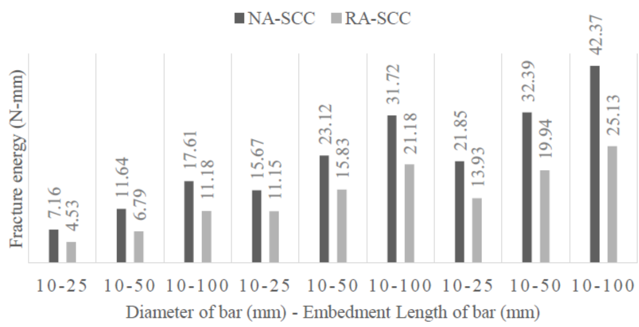


(b)

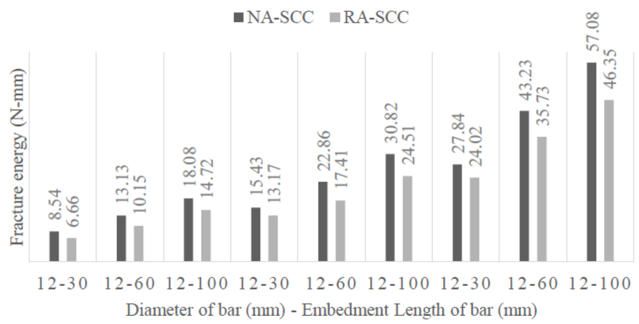


(c)

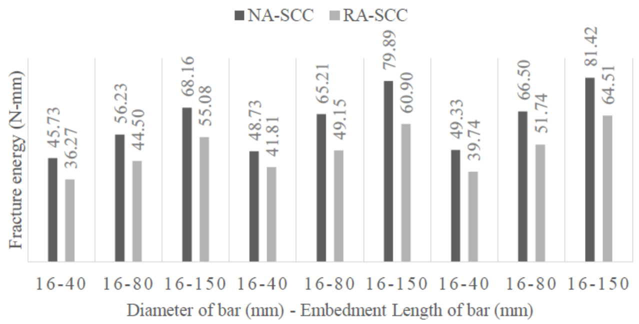
Fig. 6 Plots of maximum slip and diameter of bar-embedment length



(a)



(b)



(c)

Fig. 7 Plots of fracture energy and diameter of bar - embedment length

corresponding natural aggregate specimens. The recycled coarse aggregates contains old mortar attached to it which causes increased friction resulting in enhanced bond properties in RASCC compared to NASCC. This effect has a decreasing trend with increase in compressive strength for all the bar diameters and embedment lengths evident from Fig. 5(a)-5(c). The reason for this decreasing trend is that in case of high strength concretes, the strength of the paste has more influence than the aggregates.

4.1.3 Influence of L_d/D_b ratio

For comparing different bar diameters and embedment lengths, a parameter L_d/D_b ratio is used to understand the variation in the maximum bond stress. The bond stress decreased with increase in L_d/D_b ratio. This is evident from the Fig. 4(a)-4(i) and also from Table 9. With increase in the embedment length, the contact area between the bar and concrete increases causing non uniform stress distribution in the surrounding concrete and leading to decrease in the bond stress.

(a)

(b)

Fig. 8 Typical type of failure of pull-out specimen: (a) pull-out failure; (b) splitting failure

4.2 Slip

The slip is defined as relative movement between bar and adhered concrete. The slip values are plotted against different bar diameter and embedment lengths for both NASCC and RASCC (Fig. 6(a)-6(c)). From these plots, it is

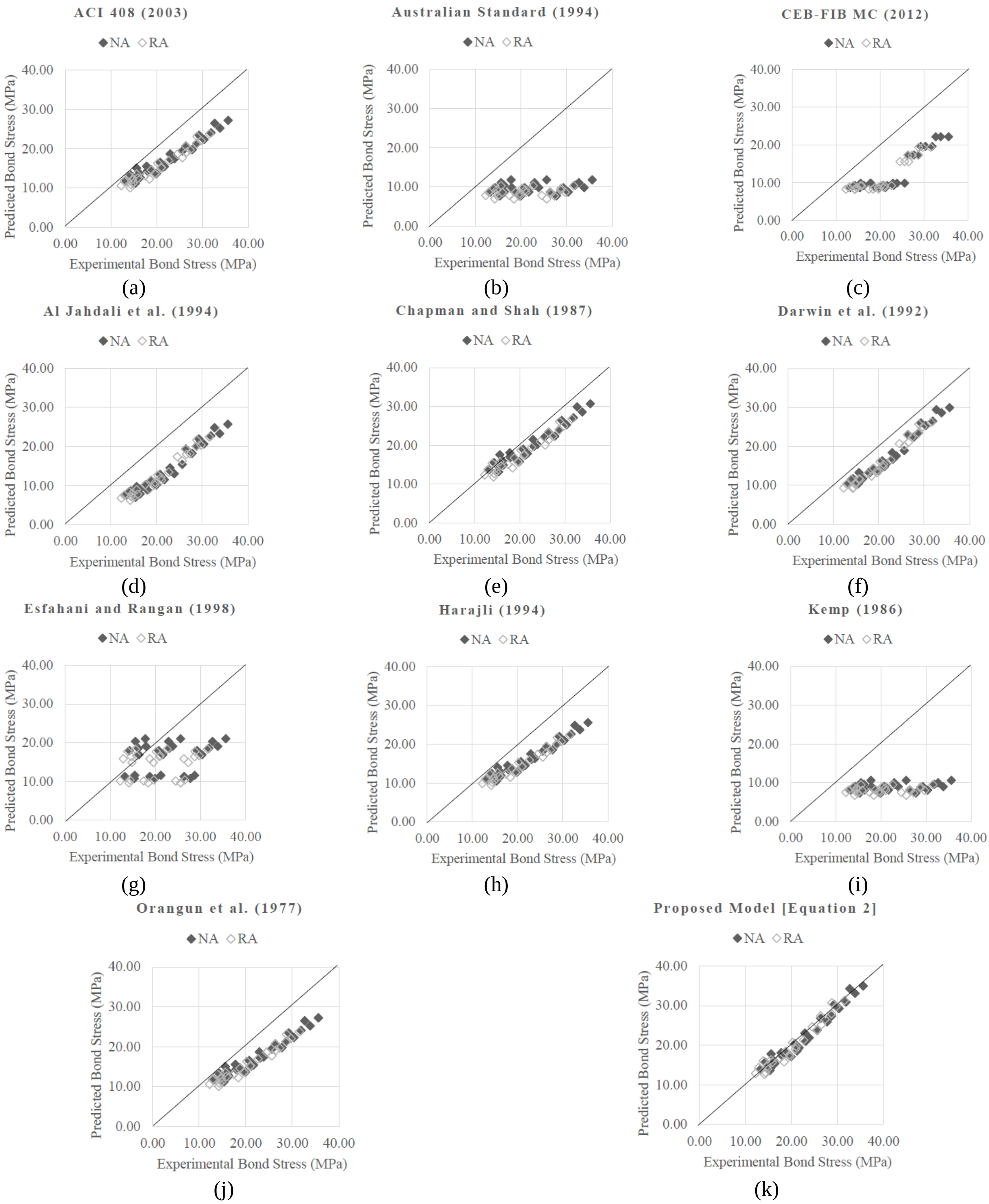


Fig. 9 Comparison of predicted bond stress based on various models

clear that, with the use of recycled aggregates in SCC the slip has decreased. In case of recycled aggregates, the reduced load carrying capacity is the reason for reduction in the slip. As the bar diameter increases, the slip increases because of increased contact area between bar and concrete. Also, with the increase in embedment length the slip increases as number of ribs on the bar in contact with concrete increases with the embedment length. This is true in case of both NASCC and RASCC specimens.

4.3 Fracture energy

Fracture energy is defined as the minimum energy required to cause failure in bond between concrete and steel bar. Fracture energy is calculated as area under the bond stress versus slip curve. From Fig. 4(a)-4(i), the fracture energy is calculated based on the trapezoidal rule. A comparison of fracture energy of NASCC and RASCC for 10, 12 and 16 mm diameter bars are given in Fig. 7(a)-7(c).

From these plots it can be noted that the fracture energy of RASCC is less than that of the corresponding NASCC specimens. The reduced bond stress and slip are the reason for this reduction in fracture energy. With increase in bar diameter and embedment length, the fracture energy increased and this was true for both NASCC and RASCC specimens.

4.4 Failure type

The embedment length of bar has determined the type of failure of pull-out specimens in both NASCC and RASCC. In case of NASCC and RASCC specimens with embedment length of $2.5D_b$, pull-out type of failure i.e., bar embedded in concrete has pulled out without causing significant damage to the surrounding concrete was observed. Whereas, the specimens (both NASCC and RASCC) with embedment length of $5D_b$ and full depth of specimen have exhibited splitting type of failure i.e., concrete specimen has failed by splitting cracks. Typical illustration of pull-out and splitting failure of pull-out specimens is given in Fig. 8(a) and (b) respectively.

4.5 Bond stress equation

By performing regression analysis on the experimental results obtained on bond stress versus slip and taking into account all governing parameters, an equation is proposed to predict the maximum bond stress of NASCC and RASCC. The equation is given below

$$\tau_u = \left(X + Y\left(\frac{c_{min}}{D_b}\right) + Z\left(\frac{D_b}{L_d}\right)\right)\sqrt{f_{cc}} \qquad (2)$$

Where, X=0.28 for NASCC; 0.33 for RASCC; Y=0.25 for NASCC; 0.25 for RASCC; Z=6.33 for NASCC; 6.45 for RASCC; f_{cc}=compressive strength in MPa; D_b=diameter of bar in mm; L_d=embedment length of bar in mm; $c_{\min}$= minimum cover to reinforcement in mm

The comparison plots of experimental bond stress and different models are given in Fig. 9(a)-9(k). A 45° line is drawn through the origin point and the coincidence of points with this line shows good correlation of values proposed by the model with the experimental values. Out of all the models proposed by different codes, the model proposed by ACI 408 (2003) involves parameters like concrete strength, diameter of bar, embedment length and cover to bar, whereas, models proposed by Australian Standard (1994), considers only concrete strength and diameter of bar while the CEB-FIB MC (2012), considers only concrete strength for determining bond stress. The coincidence points of model (Australian Standards 1994, CEB-FIB MC 2012) and experimental bond stress values falls far away from the 45° line showing their inefficiency in predicting the maximum bond stress for various factors affecting bond stress. ACI 408 (2003) model predicts the bond stress values better compared to models proposed by other codes. Among the models proposed by various researchers, in the model proposed by Chapman and Shah (1987), Darwin *et al*. (1992), Orangun *et al*. (1977) the coincidence points of experimental bond stress values and model values are nearer to the 45° line. Other models like Al-Jahdali *et al*. (1994) is based on the experiments conducted on pull-out specimens having higher embedment length and hence this model does not predict the bond stress values correctly for lower embedment length specimens. Esfahani and Rangan (1998), Kemp (1986) considers only concrete strength and bar diameter in their model and so the coincidence points of bond stress values of models with experimental results are far from the 45° line. In these models bond stress values are independent of embedment length and so the bond stress values are same for all embedment lengths.

The proposed model in Eq. (2) is in good agreement with experimental results which is evident from Fig. 9(k).

5. Conclusions

Based on the detailed experimental investigation conducted on natural and recycled aggregate self compacting concretes, the following conclusions are drawn

- The mix proportions are designed as per IS 10262 (2009) specifications and satisfy EFNARC (2005) guidelines also. Hence, SCC mixes satisfying fresh and hardened properties could be produced.
- With increase in the concrete strength there is an increase in bond stress. The average increase is about 8.8% in case of Mix B over Mix A and 10.5% in case of Mix C over Mix B for NASCC for all bar diameters and embedment lengths. In case of recycled aggregates this average percentage increase was 6.1% and 8% respectively. The reason can be attributed to the increase in concrete strength in mixes B and C.
- The bond stress increased with decrease in bar diameter and embedment length. This is true in case of both natural and recycled aggregate concretes.
- With the use of recycled aggregates the average percentage reduction in maximum bond stress was 7.4%, 9.7% and 11.7% in case of mixes A, B and C respectively for all bar diameters and embedment lengths.
- The maximum slip and fracture energy of recycled aggregate concrete reduced when compared to that of natural aggregates concrete specimens. This can be attributed to lesser maximum bond stress in recycled aggregate concrete.
- With the increase in bar diameter and embedment length there is an increase in slip and fracture energy in case of natural and recycled aggregate specimens irrespective of bar diameter and embedment length.
- Based on the experimental results a regression analysis is done and an equation is proposed for predicting the maximum bond stress (Eq. (2)). This equation is in good correlation with the experimental results.

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Notations

f_{cc} = compressive strength in MPa
D_b = diameter of bar in mm
L_d = embedment length of bar in mm
$c_{\min}$ = minimum cover to reinforcement in mm
$c_{\max}$ = maximum cover to reinforcement in mm
f_{ct} = tensile strength of concrete in MPa