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BOND EFFICIENCY AND EFFECT OF COVER ON BOND STRENGTH BETWEEN STEEL AND STRUCTURAL CONCRETE USING COMMERCIALLY PRODUCED RECYCLED COARSE AND FINE AGGREGATES

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Abstract: Quality recycled concrete aggregates (RCA) for structural concrete has not yet gained prominence in the construction industry due to the lack of proper standards and guidelines. In the production of quality structural concrete, an important parameter is the bond efficiency of rebar in concrete. While using recycled aggregates in concrete, the bond with deformed rebar is expected to be different compared to regular concrete and requires in depth investigation.

In this study, 12 beam-end specimens were tested to understand the bond efficiency of commercially produced structural concrete made of RCA. The study used two rebar covers as parameters (25mm and 40mm) with a M15 test bar and a constant bond length of 200mm was evaluated. The results were compared with the CSA A23 development length bond equation.

The present study showed that the CSA design equation is conservative while designing structures using quality recycled concretes.

1.0 Introduction

In addition, global consumption of cement and concrete continues to soar and it is predicted that emerging economies will consume nearly 90% of the world's total cement production (Statistics n.d.). By the year 2020, the total world production of cement is estimated to reach 4.4 Billion Tons and by the same year it is expected to see an increase of 9% compounded annual rate in industrial growth globally (Statistics n.d.). These upward trends could lead to further greenhouse gas emissions by industries if current practices and regulations, especially within the construction industry, are not changed towards sustainable alternatives.

Many of our civil infrastructure state has passed their service life where many of them require replacement or substantial repair/retrofit and or renovation (CIRC 2016). Such operations are often coupled with the ever rising cost of delivery of these projects. Demands for infrastructure will continue to encourage the current practice of harvesting natural aggregates for structural concrete unless recycled aggregates are well accepted into standards and codes of practices. The CSA A23 states the use of both recycled coarse and fine aggregates for concrete but in practice are not used for structural purposes although research shows that, structural concrete can be produced using quality controlled recycled aggregates (Lotfy & Al-fayez 2015) (Rahal 2007). Recently Pedro et al, (Pedro et al. 2017) demonstrated that using both recycled fines and coarse aggregates (RFA and RCA) can be used for producing structural concrete provided an industrial source of recycled aggregates is used with proper quality control.

Though the bond in reality is imperfect, there are governing empirical relationships (used in design and research) to predict its behaviour and performance, which has been used for decades (ACI Committee 408 2003).

Four test methods (pull-out, beam-end, splice beam and beam anchorage) have been discussed in the ACI408 for determining the bond behaviour, however, the pull-out test method is not recommended. The reason is due to the compressive stress state of concrete around the rebar in the pullout test specimens when used, and could lead to inaccurate experimental results. Though the test is simple to conduct, it only attempts to qualitatively describe the bond behaviour (Xiao & Falkner 2007) rather than quantitative. Besides these four test methods by ACI408, the RILEM RC5 hinge test beam method of bond testing is also reported in literature (Pandurangan et al. 2016).

2.0 Literature Review

2.1 Influence of cover on bond strength

Concrete cover e.g., side cover and bottom cover significantly influences the bond strength of rebar in concrete. The minimum concrete cover provides the critical stress path for surface crack propagation. Providing cover and spacing is fundamental in construction practice and helps in protecting the rebars from rusting, and also allows the coarse aggregates in the concrete to freely flow around the rebars. Essentially, a reduced cover increases the probability of bond splitting failure as the stress path is shorter, while increasing the cover reduces the internal moment arm. In various researches where pullout test method has been used, there is limited opportunity to practically vary the rebar cover for a given fixed size of test specimens.

The pullout specimens are made of standardized cube (150mmx150mm) or cylinders (150mmx300mm) or other similar, with the test rebars centrally placed. The beam test specimens on the other hand vary widely in length (1.7m to 3.0m) and section (0.18 to 0.3m wide by 0.3m depth), while the spliced test rebars are placed mid-span (Morohashi et al. 2007) (Robert et al. 2017). The rebar cover in a beam test specimen can be adjusted to meet a defined set of test parameters. As can be noted, the beam specimen offers the opportunity to adjust and monitor the effect of rebar cover in an experimental test. Robert, Gaurav and Singh, (Robert et al. 2017) used spliced beam test method with two different covers i.e. 15 and 25mm cover and proposed a descriptive equation considering the effect of increase in cover. The researcher (Robert et al. 2017), concluded that while using 100% laboratory generated RCA, the effect on bond strength is marginal but further suggested that while more experimental data becomes available, a robust descriptive equation can be proposed. The conclusion emphasizes the need for more research while using RCA and RFA for producing structural concrete. Essentially, the use of recycled fines and the effect of cover sizes to unearth the bond behaviour effect cannot be over emphasized.

3.0 Experimental program

3.1 Experimental design

The experimental program was designed with two groups of specimens with the same bond length, but different bottom rebar cover. Besides, each specimen group (size 230mm x 420mm x 600mm) had five different replacement levels of recycled structural concrete and each level had two specimens. Also, these two groups were carefully designed using the CSA A23.3 development length equation with an embedded length of 200mm, and a bottom clear cover of 25mm and 40mm to satisfy splitting criteria which is critical for structural safety, if recycled aggregates are to be used in producing structural concrete. It is proposed to use three different concrete mixes in each group, where the reference concrete is to be made of conventional natural aggregates, and the other four from 100% recycled coarse aggregates and different recycled fines substitution rates (0%, 75% and 100%). The planned specimen design and the schematic details are based on the ASTM A944-15. Same bond length, 200mm was provided, which was 12.5 times bar diameter (12.5*d_b) in each specimen group to ensure that there would be bond failure prior to yielding or fracture of the rebar.

The test matrix for the two groups are presented in table 2 where the specimen denotation has been marked based on the concrete mix design, bar size (d_b), bond length (l_d) cover (c) and other normalized ratios such as c/d_b and l_d/d_b.

Table 1 Proposed experimental test matrix

Group No	Specimen Name-Label	Coarse Aggregates		Fine Aggregates		l_d	Rebar Dia. d_b	l_d/d_b	Cover, c, mm	c/d_b
		RCA	NCA	RFA	NFA	mm	mm			
Group 1	M0/0-M15-L200-C25	0	100	0	100	200	16	12.5	25	1.6
	M75/25-M15-L200-C25	100	0	75	25	200	16	12.5	25	1.6
	M100/100-M15-L200-C25	100	0	100	0	200	16	12.5	25	1.6
Group 2	M0/0-M15-L200-C40	0	100	0	100	200	16	12.5	40	2.5
	M75/25-M15-L200-C40	100	0	75	25	200	16	12.5	40	2.5
	M100/100-M15-L200-C40	100	0	100	0	200	16	12.5	40	2.5

Legend
M0/0=100% NCA and 100% NFA, 75%NFA and 100% RCA, C25, C40=Cover of 25mm, 40mm respectively. *2 Groups of 3specimens each with 2 Repeats=12Specimens*
,

3.2 Experimental materials

3.2.1 Reinforcement

The longitudinal reinforcement was made of grade 400W in accordance CSA G30.18 having yield strength of 432MPa. The reinforcement rib designs were crescent-shaped on opposite sides of the rebars' barrel and merges towards the core. The test bar geometric information, rebar design and mill production engineering data are shown in Fig 2, Table 3 and Table 4 as tested and provided by the manufacturer, Nucor Steel.

3.2.2 Coarse and fine Aggregates Processing

A critical quality assurance aspect of a commercially produced recycled structural concrete is the processing and grading compliance as per CSA A23 during the production process. Grading compliance of coarse and fine aggregates is a major determinant in particle packing density, concrete mix design, target strength optimization, and impacts on the final cost concrete products. The selected recycled concrete aggregate production plant was Lock-Block Ltd in Vancouver, BC. All the materials met the specifications for gradation and and a three stage process was adopted for the aggregate processing. The cleaning process of removing debris, steel and washing plays a critical role in improving the aggregates quality especially the water absorption requirement as pointed out in the literature. Aggregates fractions obtained are in two coarse fractions (19mm and 10mm) and one fine fraction of less than 5mm. The recycled aggregates are separately stock plied per fraction sizes in open-air to avoid cross contamination.

3.3.3 Concrete Mix Design

The structural concrete mix design was an in-house mix proportion using recycled aggregates from the aggregates and concrete producer, Lock-Block Ltd. The mix design (shown in **Table 2**) using the aggregates (coarse and fines), cement and admixture proportions for the **35MPa** from the concrete plant was used. The recipe slump and air content were measured for compliance as well, shown in **Fig 1.**

Table 2 Mix design for 35 MPa Structural Concrete

Material	NCA100-NFA100 Quantity (Kg/m3)	RCA100-RFA75 Quantity (Kg/m3)	RCA100-RFA100 Quantity (Kg/m3)
Fine Aggregates, RFA	700	575	641
Fine Aggregates, NFA	0	188	0
% (RFA:NFA)	0:100	75:25	100:0
Coarse Aggregates (NCA/RCA)	1018	1023	1023
Cement (General Use)	375	375	375
Cold Water	145 litres	145 litres	145 litres
Admixture AEA 92S	12 ml/100kg	12 ml/100kg	12 ml/100kg
Admixture 341 Mid-Range	350 ml/100kg	350 ml/100kg	350 ml/100kg
Water/Cement= 0.4, Slump= 50-75mm,			

NCA-Natural Coarse Aggregates, RCA-Recycled Coarse Aggregates, RFA-Recycled Fine Aggregates. NCA100=100% Natural Coarse Aggregates, RCA100=100% Recycled Coarse Aggregates, RFA50=50% Recycled Fine Aggregates.


a) b)

Fig 1 Concrete pouring a) slump testing and b) internal concrete vibration

3.3.4 Experimental Set-Up (Beam-End Specimen)

The test procedure was per ASTM A944. The ASTM C42 was chosen to ascertain the true in-situ strength of structural concrete for the test specimens. All specimens were tested after 90 days of pouring

3.3.5 Compressive Strength Test and Specimen Curing

To ascertain the in-situ concrete strength, cylinders cores were drilled from tested beam specimens using the ASTM C42 standard which is an acceptable test method in the ACI318M-11. Cores were collected from the undisturbed portions of the specimens where there were no rebars, and minimal stress exposure. The entire curing of the specimen prior to bond testing was done in the formwork in addition to surface ponding to ensure minimum loss of moisture as proposed by the ASTM A944.

4.0 Experimental test results

4.1 Compressive strength test

. Although the structural concrete target strength was 35MPa the compressive strength obtained from the recycled concrete cores ranged from 30-37MPa, which was not significantly different from each of the group mixes apart from the control.

Table 3 Compressive Strength Test Results

	Control (NCA+NFA)	100RCA+25 NFA+75RFA	100RCA+0NFA +100RFA
Ave	**55.52**	**37.58**	**30.22**
Std. Devn	**2.00**	**2.35**	**1.92**

4.2 Bond testing

The test specimens in each group, (Group 1 and Group 2), and were subjected to monotonic axial loads from an MTS actuator (rate of 2mm/min) which was connected to a CPU controller and monitor. The bar slips were measured via a Linear Variable Differential Transducer (LVDT) installed at the loaded and unloaded end of the test bar. The strain in the steel rebar was similarly measured with a 200Ω Ohm resistance strain gage and connected to a National Instruments DAQ, which was also connected to the CPU. The MTS accurately captured the instantaneous and maximum failure load for all the specimens. While the axial load was gradually increasing, careful observations were made where splitting crack propagations on the concrete surface were marked. The bond splitting failure (cracks) occurred longitudinally on the beam specimen surface starting from the loaded end. The cracks travelled perpendicular from the rebar barrel to the beam surface due to the minimum distance of the clear cover provided in each group of specimen. A total of 12 specimens were tested successfully in the test rig in **Fig 3** with splitting failures as shown in **Fig 4**.

Figure 3 Splitting failures of tested specimens

The pull load test results of the half-beam specimens for groups 1 and 2 are shown in **Table 7. Fig 5A to D** shows the load vs slip curves of some specimens**.** The load-slip curves depict the ascending and peak branches of the load and slip behaviour occurring at the concrete-rebar interface during the test. **Table 8** shows the summary of the first crack loads, maximum slips and the accompanying strains in the rebar measured during the test.

Table 4 Pull load test results from half-beam specimens (in KN)

f'c	55.52	37.58	30.22
M15-L200-C25, Group 1	M0/0	M75/25	M100/100
	NCA+NFA	100RCA+75RFA	100RCA+100RFA
Sample A	90.38	74.06	67.85
Sample B	86.68	69.85	65.26
Mean	88.53	71.96	66.56
Bond Strength	8.81	7.16	6.62
Normalized Bond Strength, C=25mm	1.18	1.17	1.20
Standard Deviation	2.62	2.98	1.83
Coeff. of Variation (%)	2.96	4.14	2.75
M15-L200-C40, Group 2	M0/0	M75/25	M100/100
	NCA+NFA	100RCA+75RFA	100RCA+100RFA
Sample A	107.33	80.23	73.75
Sample B	101.03	80.59	69.03
Mean	104.18	80.41	71.39
Bond Strength	10.37	8.00	7.10
Normmalized Bond Strength, C=40mm	1.39	1.31	1.29
Standard Deviation	4.45	0.25	3.34
Coeff. of Variation (%)	4.27	0.31	4.68

All units in KN

Table 5: Summary results of initial crack load, maximum slip and strain in test specimens

Specimen Name and Label	First crack load, KN	Load proportion for cracks	Maximum splitting load (KN)	Maximum loaded end slip (mm)	Maximum strain (micro-strain)
Group 1					
M0/0-C25-A	43	48%	90.38	2.63	580
M0/0-C25-B	NV	N/A	86.68	0.20	-
M75/25-C25-A	47	63%	74.06	0.78	2550
M75/25-C25-B	40	57%	69.72	1.30	1300
M100/100-C25-A	44	65%	67.85	1.58	515
M100/100-C25-B	45	72%	62.26	1.34	-
Group 2					
M0/0-C40-A	65	61%	107.30	5.12	750
M0/0-C40-B	87	86%	101.03	5.79	500
M75/25-C40-A	71	88%	80.23	1.31	655
M75/25-C40-B	65	81%	80.59	1.87	2270
M100/100-C40-A	64	87%	73.25	0.60	1900
M100/100-C40-B	60	87%	69.03	0.89	1800

NV-Not visible, N/A-Not applicable,

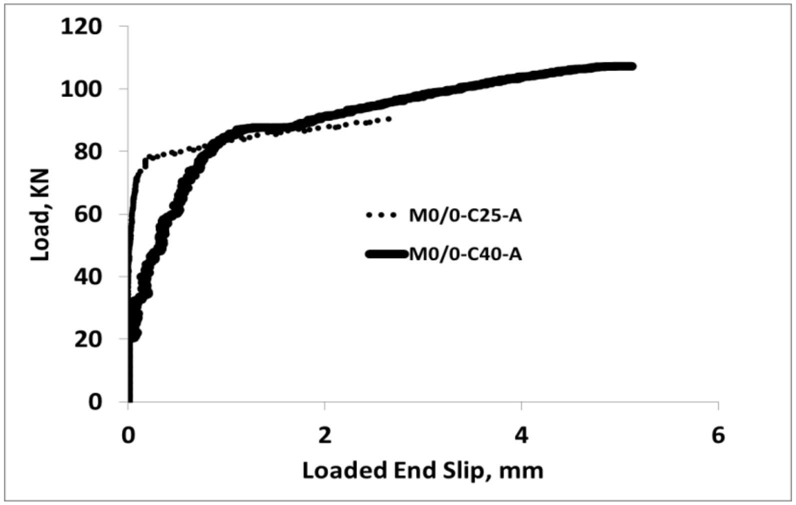


Fig 5A Load-slip curve when cover is increased (25 to 40mm) and using NCA and NFA

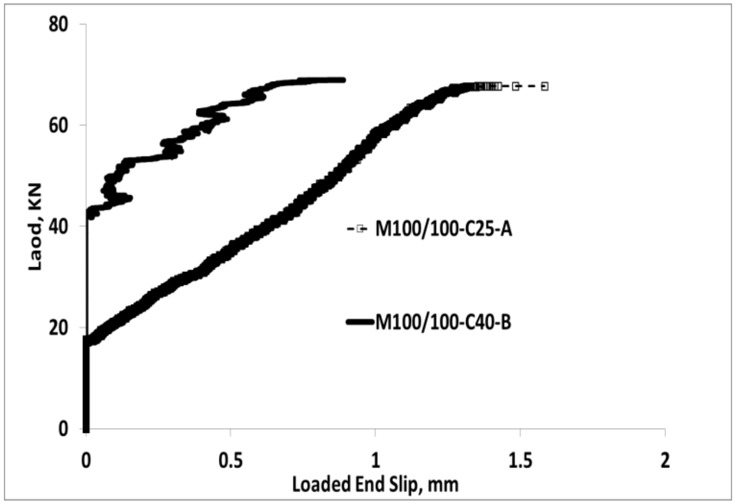


Fig 5B Load-slip curve with increased cover (25 to 40mm) and using only RCA and RFA

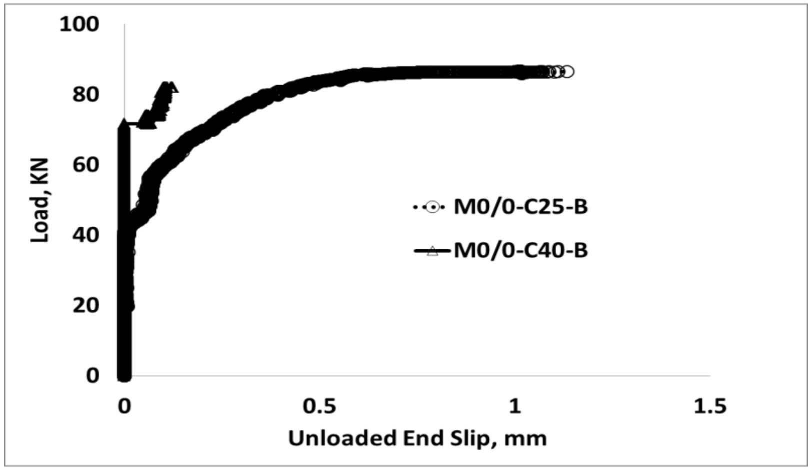
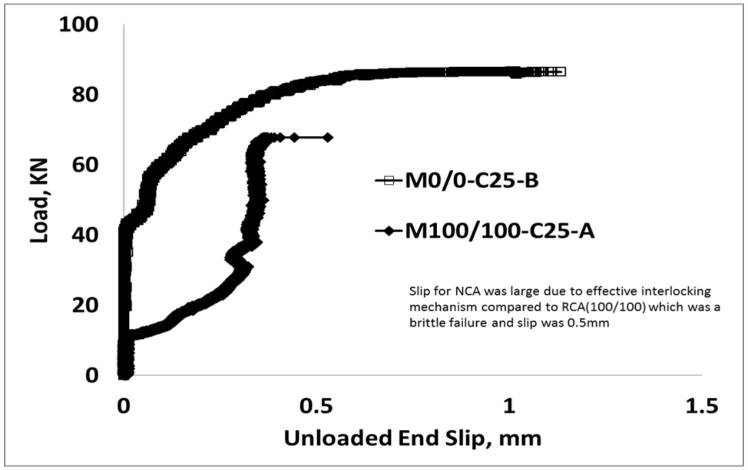


Fig 5CLoad-slip curve when cover is increased (25 to 40mm) and using NCA and NFA only

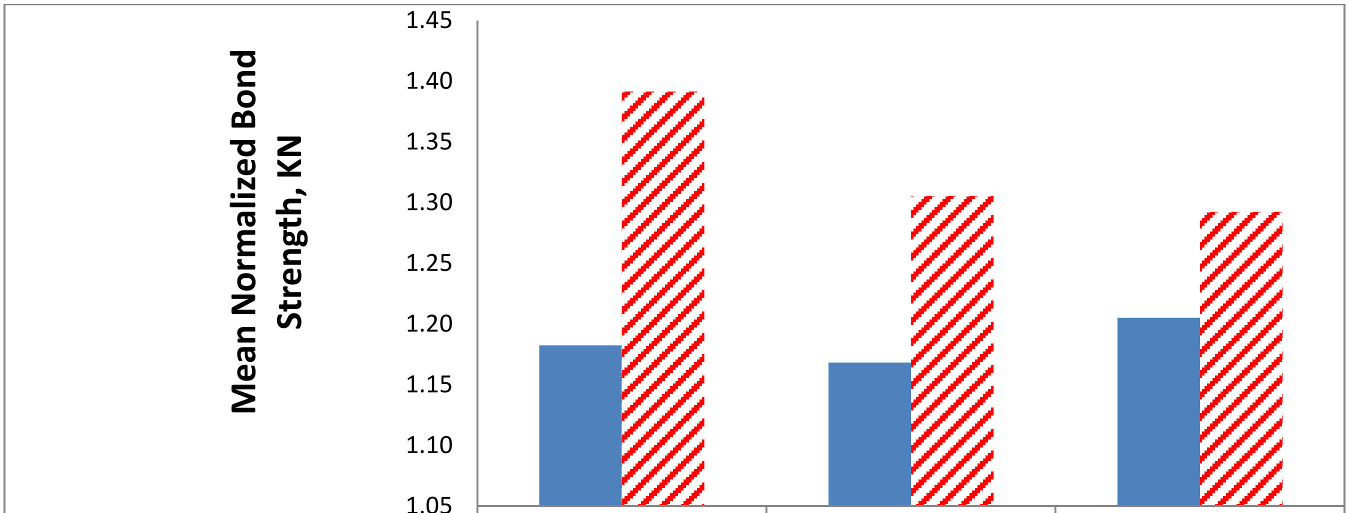


Slip for NCA was large due to effective interlocking mechanism compared to RCA(100/100) which was a brittle failure and slip was 0.5mm

Fig 5D Load-slip curve when cover is same (25mm) and comparing NCA,NFA RCA and RFA

Figure 5A-D: Typical load-slip curves of loaded and unloaded specimens of various mixes.

Figure 6 shows the mean normalized bond strength data of the specimens.



	NCA+NFA	100RCA+75RFA	100RCA+100RFA
🟦 Normalized Bond Strength, C=25mm	1.18	1.17	1.20
▨ Normalized Bond Strength, C=40mm	1.39	1.31	1.29

Figure 6: Normalized Bond Strength with square root function

5.0 DISCUSSION AND ANALYSIS OF RESULTS

Structural elements generally require an adequate cover to protect the reinforcement from corrosion and ensure that the internal moment due to tension and compression is not compromised. In the experiment, the cover of 25mm was chosen to fit for internal members whereas a 40mm cover for external members also usually suffices. In addition to the cover, concrete strength and provision of development lengths are requirements of structural details in many standards and are provided and marked on drawings, and hence making it an important parameter for investigation.

5. 1 Discussion on bond testing and its effect on increasing cover

The **Table 4** shows the mean tensile load variation of the two groups of specimens compared with the control specimen of conventional concrete mix. As observed, the mean bond force when using recycled concrete mixes was increased by 7% for 100% RCA and RFA 17% for NCA and NFA when the cover was inceased 25mm to 40mm respectively. The variation in results shown can be attributed to the differences in concrete strengths between conventional concrete (55MPa) and the recycled concrete in this experiment (37MPa) for 100RCA+75RFA shown in **Table 3.**

5. 2 Discussion on load slip curves and effect on cover increase

Slipping of the rebars from its surrounding concrete is a critical parameter in determining not only failure mode of specimens but also the composite bond which existed between the concrete and steel. In concrete structures however, brittle failures are not preferred since it is important to maintain the structural integrity of the entire elements. Though ductile failure behaviour is most preferred in a brittle concrete material, crack formation and gradual crack propagation at the concrete surface is a good indication towards a ductile behaviour when recycled structural concrete is used.

The load-slip curves shown in **Figure 5** are indicative of the stiffnesses of the bond between concrete and deformed rebars. It can be observed from the graphical plots in **(Fig5A-D)** that NCA specimens were much stiffer with higher bond strength and large slips than those of recycled concrete mixes. The bond slip curves generaly showed no slip initially, followed by a gradual slip of the rebar around the concrete, until it reaches the peak. The reported maximum loads were comparable to those reported by(Pandurangan et al. 2016),(Butler et al. 2015),(Yang et al. 2016) (Lin & Zhao 2016) and (Butler et al. 2011) when using either conventional and recycled concrete using beam test specimens. Though this experiment used commercially processed (quality) RCA and RFA in the concrete mixes, the comparable maximum loads and slips shows no effect when compared to similar experimens of using NFA.

5.3 Discussions on Experimental and Theoretical Bond Strength using CSA Code Design Equation

The use of design standards has been the benchmark of engineering best practices for decades. As shown in equation 3 below from the CSA A23,

CSA A23-14

$$l_d = \left(\frac{1.15k_1k_2k_3k_4}{\sqrt{f'_c}}\right)\left(\frac{f_y}{d_{cs} + K_{tr}}\right)d_b \quad \text{where, } K_{tr} = \frac{A_{tr}f_{yt}}{10.5sn} \tag{1}$$

Table 6 shows the summary of bond strength calculated from equation (1) indicating the bond efficiency which is a comparative bond strength of experimental and theoretical/code-defined bond strengths. These measures of comparisons were chosen to help ascertain the validity of the bond performance and to give an indication of any residual capacity in the experimental and theoretical calculations.

Table 6 Summary of bond strength efficiency using CSA A23.3 code design equation

Group 1, Cover=25mm

M15-L200-C25	Experimental Bond Strength	Bond Strength	Bond Efficiency
M0/0	**8.81**	4.05	**2.18**
M75/25	**7.16**	3.33	**2.15**
M100/100	**6.62**	2.99	**2.22**
Group 2, Cover=40mm			
M15-L200-C40			
M0/0	**10.30**	6.48	**1.59**
M75/25	**8.00**	5.33	**1.50**
M100/100	**7.10**	4.78	**1.49**

Note: conservative yield strength, f_y =420MPa used in calculations

It can be observed that, the CSA design equation was well conservative for the specimen cover provisions of 25mm and 40mm when using either conventional or recycled structural concrete.

Conclusions

The experimental work was successful in determining the bond strength between a deformed rebar and industrial processed recycled coarse and fine aggregates. The test results compared well with various empirical models, and are indicative of a comparable and efficient bond performance when quality recycled aggregates are used to produce recycled structural concrete.

The main factors primarily affecting the bond performance which have been used extensively in research and found in literature bond model are the cover (c_b), bar size (d_b), concrete strength(f'_c) and the embedment or bonded length (l_d). These were used in a beam specimen design based on ASTM A944 and tested with both conventional and recycled structural concrete to determine the bond performance.

Within the experimental limitation of the tested specimens and barring any experimental inconsistencies and errors, it can be concluded that:

a. The experimental data obtained for both the conventional and recycled structural concrete compared with the ACI408 database fitted closely within the scatter plot and thus recycled structural concrete did not show any significant deviations and confirms a good fit.

In conclusion, the detailing requirements in standards e.g. CSA A23 and other such which are aimed at preventing bond failures can be maintained and additional cover is not necessary. Thus using a similar commercially processed and high quality recycled aggregates (coarse an
d fine) for structural concrete can help promote the sustainability initiative in the construction industry and address major waste generation and rapid filling up of landfill sites.

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