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EXPERIMENTAL INVESTIGATION OF MECHANICAL PROPERTIES OF RUBBERIZED CONCRETE CONTAINING RECYCLED COARSE AGGREGATE

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ABSTRACT

Mechanical properties, particularly compressive and flexural strength of concrete containing modified crumb rubber (CR) and recycled coarse aggregate (RCA) were investigated in this study. Surface treatment of CR was conducted using 20% solution of sodium hydroxide (NaOH) to improve the adhesion and bonding between CR and cement matrix in the concrete mix. In total 9 concrete mixes were prepared with three varying levels of volumetric replacement for both fine aggregate (FA) and natural coarse aggregates (NCA) by CR and RCA respectively. To specify, the replacement levels for FA by CR were 0%, 10% and 20% and that for NCA by RCA were 0%, 50% and 100%. Compression tests on cylindrical specimens and third-point loading flexural test on beam specimens were conducted to determine the compressive strength and flexural strength respectively for these concrete mixes. Results show that the compressive strength of the control mix decreases by 44% and 78% for 10% and 20% CR replacement respectively. Whereas, the reduction in compressive strength due to the increase of RCA replacement from 0% to 50% and 100% is 48% and 49% respectively from the control mix. Additionally, the reduction of flexural strength in the concrete mixes was found to be much lower than the reduction in compressive strength. To specify, the flexural strength of the mixes with 10% and 20% CR replacement was 28% and 57% lower respectively than that of the control mix. Whereas, for RCA replacement levels of 50% and 100% showed 28% and 33% reduction respectively in flexural strength of the control mix. However, the combination of 50% RCA and 10% CR in concrete exhibited satisfactory compressive strength and flexural strength of 33 MPa and 4 MPa with a reduction of strength 45% and 22% respectively from the control mix. In essence, 10% volumetric replacement of FA by CR in concrete mix was the optimum rubber content and a combination of 50% volumetric replacement of NCA by RCA and 10% FA by CR was the optimal sustainable solution from this study.

1. INTRODUCTION

Concrete is the most widely used construction material in the world with over six billion tons produced each year (Cement Association of Canada, 2003). The abundance in its use is due to several factors: durability, safety, cost, material availability, design flexibility, acoustics etc. Such enormous demand of concrete inevitably led to a continuous and increasing demand of natural materials used for their production.

Particularly, Canada's national municipal infrastructure deficit is estimated to be $123 billion and growing by $2 billion annually. Moreover, 79% of life span of the public infrastructure has been spent (Mirza, 2007). To meet the increasing demands on aggregates various alternatives to the natural aggregates can provide a viable solution. About 52% (by weight) of the 11 million tons of annual solid concrete and demolition waste (C&D) is held by concrete in Canada. Recycled concrete aggregate (RCA) can provide a sustainable solution by offsetting the increased demand on natural aggregates and by reducing carbon dioxide emission in the process of manufacturing cement for new concrete production. Other major advantages of using RCA include reduced transportation and environmental costs and reduced load on landfill (Abbas et al., 2006).

The use of crumb rubber as a partial replacement of fine aggregates in concrete is another alternative. Crushed scrap tires otherwise known as crumb rubbers (CR) are granules of rubber with the steel and fibres removed from them. To elaborate, out of 15 billion of tires produced, only 1 billion of tires reach the end of their useful lives, termed as an end-of-life tire (ELT) each year worldwide. Moreover, 4 billions of ELTs are being disposed in landfills or are being stockpiled around the world. (WBCSD, 2010) Importantly, the government of Canada has categorized waste tires as municipal solid waste which needs to be disposed conforming to the provincial and municipal jurisdiction (Neal, 1994) The huge stock of tires disposed in the landfills essentially consume a lot of valuable space and serve as a potential ground for breeding of harmful insects and pests. For instance, the rapid transmission of the lethal virus named the West Nile virus across North America was linked to the tire piles for being highly potential mosquito breeding site as tires could hold up a lot of water (Pehlken & Essadiqi, 2005). Besides, scrap tire disposal in landfills poses a serious threat of massive fire hazard. The fire break out in the tire dump in Hagersville, Ontario burning about 10 million of tires lasting for 17 days in 1990 and the accidental ignition of the shredded tire drainage layer in the landfill of Iowa city burning about 1.3 million of tires for 18 days manifests the gravity of risks (Ministry of the Environment - DPPR / SEI / BARPI, 2007 Singh et al., 2015). Use of CR as a partial replacement of fine aggregate in concrete provides an environment friendly and effective solution for the exigent crises of natural aggregate demand and the environmental hazards. Overall, recycling of these scrap tires into useful value-added products can serve as a great benefit for both environment and economy.

However, studies indicate that the use of CR in concrete reduces its compressive strength mainly due to weak adhesion between rubber particles and the cement matrix. Other reasons include the hydrophobic nature of rubber particles, large difference between the modulus of elasticity between rubber and other elements in concrete as aggregates and cement paste. Also, crumb rubber concrete (CRC) has less flexural strength. However, higher toughness and impact strength than conventional concrete contributes to its efficacy for different structural and non-structural use. (Liu, Wang, Jiao, & Sha, 2016a Mohammed, Anwar Hossain, Eng Swee, Wong, & Abdullahi, 2012Kaloush, Way, & Zhu, 2005Xue & Shinozuka, 2013). To this point, different measures can contribute towards the improvement of strength of rubberized concrete. These include- rubber pre-treatment, use of silica fume, steel fiber and chemical admixtures, optimal rubber content and a well-graded combined sized rubber particles.(Li et al., 2016). For surface treatment of rubber, Segre & Joekes (2000) used sodium hydroxide (NaOH) solution to treat crumb rubber and they found improved bond strength between the rubber/cement paste and thus increased strength and toughness. Other researchers have also applied the surface treatment of rubber with NaOH solution and found similar results (Li Stubblefield, M. A., Garrick, G., Eggers, J., Abadie, C., & Huang, B., 2004). Whereas, Su, Yang, Ghataora, & Dirar (2015) used both saturated NaOH solution and Silane Coupling Agent (SCA) to modify the surface of rubber particles. A comprehensive study on pre-treatment of rubber by NaOH presented by Youssf, Elgawady, Mills, & Ma (2014) found increments in compressive strength of concrete by 6% and 15% at 7 and 28 days respectively due an increased adhesion between rubber and the surrounding cement paste. Moreover, the application of this pre-treatment method is relatively less expensive than other chemical modifying methods (Vessalas, 2016). Also, reduced compressive and tensile strength loss were reported by Balaha et al. (2007) after pre-treatment of rubber using polyvinyl alcohol (PVA) and NaOH. On the contrary, few studies have observed insignificant strength improvement in CRC after treatment of rubber by NaOH and Silane (Albano, Camacho, Reyes, Feliu, & Hernández, 2005).

Additionally, control of "carbon footprint" is a primary concern for the government of Canada. The province of British Columbia (BC) has earned international recognition for implementing effective measures towards reduction of carbon footprint and thus acting as a leader in green economy. BC mandate set legislated targets to reduce its carbon emissions by 33% by 2020 and 80% by 2050 (Ambus & Hoberg, 2011). Thus, researchers are focusing more on use of recycled materials in the construction industry to achieve this target. Utilizing recycled CR and RCA in concrete can provide an effective solution for material recovery and environmental hazards.

This study focuses on the experimental investigation of compressive and flexural strengths of conrete containing both RCA and CR. Also, pre-treatment of CR using saturated solution of NaOH was used to improve the performance of the concrete as indicated by previous studies.

2. EXPERIMENTAL STUDY

The experimental study constituted of determination of both fresh and hardened mechanical properties of the concrete mixes. Fresh properties include slump and air content whereas, the hardened properties determined were compressive strength and flexural strength of concrete.

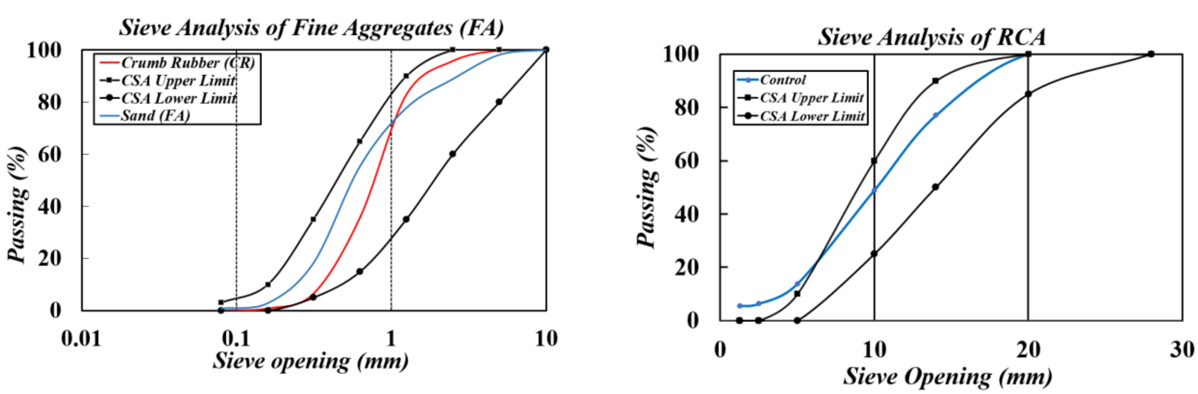
2.1 Materials

Materials for the concrete mixes include GU (General Use) Portland cement conforming to CSA A23.1-14 standards (Canadian Standards Association, 2011), fine aggregate (FA), natural coarse aggregate (NCA), NaOH treated crumb rubber (CR), recycled coarse aggregate (RCA), water reducing admixture – glenium 3030 and air entraining admixture – micro air. Sea sand conforming to the CSA A23.2 standards (Canadian Standards Association, 2011) was used as the natural FA. CR and RCA used in the mixes were obtained from the Liberty tire recycling company and the OK builders company respectively whereas other materials were provided by the Kon Kast products (2005) ltd. Moreover, properties of the aggregates used in the mixes are summarized in Table 1.

Table 1: Properties of Aggregates

Aggregates	Bulk Density (kg/m^{3})	Bulk dry specific gravity	Bulk SSD specific gravity	Apparent specific gravity	Absorption capacity, AC (%)
NCA	1657	2.62	2.65	2.61	1.34
RCA	1389	2.36	2.48	2.63	4.76
Sand	-	-	2.6	-	1.52
CR	-	-	1.15	-	1.20

A combined mix of rubber particles was prepared using different sizes of CR obtained from the company. The gradation of rubber particles thus prepared and used is included in Figure 1(a), which shows that it conforms to the CSA A23.2-2A standards. Also, the RCA gradation shown in Figure1(b) meets the CSA limits as specified by the CSA A23.2-2A standards satisfactorily.



(a) (b)

Figure 1: Sieve Analysis results for (a) fine aggregates (FA) and (b) recycled coarse aggregates (RCA).

2.2 Mix proportions

In total 9 concrete mixes were prepared including the control mix (0% CR, 0% RCA). Notably, three levels of volumetric replacement of FA by CR – 0%, 10% and 20% and three levels of volumetric replacement of NCA by RCA – 0%, 50% and 100% were integrated in the mixes. The target design strength of mixes was 35 MPa. The design water to cement (w/c) ratio was 0.30. However, volume of water was varied in the mixes to attain the required slump and flowability as the water absorbed by the RCA and the CR varied with their proportion in the mixes (Table 1). The control mix in this study was designated as RCA0-CR0 without any RCA or CR. Other mixes were designated accordingly based on volumetric percentage replacement of NCA by RCA and FA by CR respectively. For instance, mix RCA0-CR10 represents the mix with 0% RCA and 10% FA replaced by CR and mix RCA50-CR10 represents the concrete mix with 50% NCA replaced by RCA and 10% FA replaced by CR. The constituents for all mixes used in this study are included in Table 2.

Table 2: Mix Constituents

Mix	Batch code	CR (kg)	Cement (kg)	Sand (kg)	NCA (kg)	RCA (kg)	Mixing water (kg)	Water reducer (ml)	Air entraining admixture (ml)
1	RCA0-CR 0	0	30.80	50.64	91.36	0	9.50	251.20	10
2	RCA0-CR10	2.32	30.80	45.60	91.36	0	16.50	62.80	10
3	RCA0-CR20	4.56	30.80	40.56	91.36	0	11.70	62.80	10
4	RCA50-CR0	0	30.80	50.64	45.68	45.68	11.50	62.80	10
5	RCA50-CR10	2.32	30.80	45.60	45.68	45.68	11.90	62.80	10
6	RCA50-CR20	4.56	30.80	40.56	45.68	45.68	13.50	62.80	10
7	RCA100-CR0	0	30.80	50.64	0	91.36	13.50	62.80	10
8	RCA100-CR10	2.32	30.80	45.60	0	91.36	12.50	62.80	10
9	RCA100-CR20	4.56	30.80	40.56	0	91.36	13.50	62.80	10

2.3 Preparation of specimens

The primary reason for reduction in strength of concrete due to addition of rubber particles is poor adhesion between CR and cement paste resulting in week bond strength between them(Mohammed et al., 2012). Henceforth, to improve the strength of rubberized concrete, surface treatment of rubber particles was conducted using NaOH solution. To illustrate, CR particles were first washed with clean water and then immersed in 20% solution of NaOH for a duration of 30 minutes. These threated rubbers were then washed again with water until pH of the solution was about 7.0. Afterwards, these were dried in air to make the particles surface dry for mixing in concrete. Moreover, rubber particles obtained from the industry were bags of particular size which were then mixed in the laboratory in fixed proportions to prepare a combined well graded CR mix conforming to the CSA standards before treatment (Canadian Standards Association, 2011). This also enhanced the strength of concrete mixes, as the use of well-graded CR with distributed combined particle sizes helps to improve the performance of CRC (Li et al., 2016).

Standard Ø100 x 200 mm cylindrical concrete specimens were prepared following the CSA A23.2-9C standard (Canadian Standards Association, 2011) to determine the 7-days and 28-days compressive strength of the concrete mixes. To ascertain the accuracy, three identical specimens were cast for each set of test per mix. Thus, a total of 54 cylinders were cast for the 9 concrete mixes. Additionally, to determine the flexural strength of the concrete mixes standard 150 x 150 x 500 mm concrete beams were cast conforming to CSA A23.2-8C standard (Canadian Standards Association, 2011). Three beam specimens were cast per mix totaling to 27 beams for all 9 concrete mixes to determine their 28- days flexural strength.

2. 4 Test Setup

In order to conduct compression test on the concrete cylinders, an Instron machine was used with a loading rate of 0.15 MPa/sec. to 0.35 MPa/sec. The loading rate was maintained constant until ultimate failure of the specimen. Importantly, to obtain precise stress-strain characteristics, strain gauges were attached to the specimen in both longitudinal and transverse directions. For this purpose, a National Instrument (NI) data acquisition system (DAQ) was operated simultaneously with the Instron machine. However, the stress-strain curves for the mixes are not presented in this paper for the brevity of discussion.

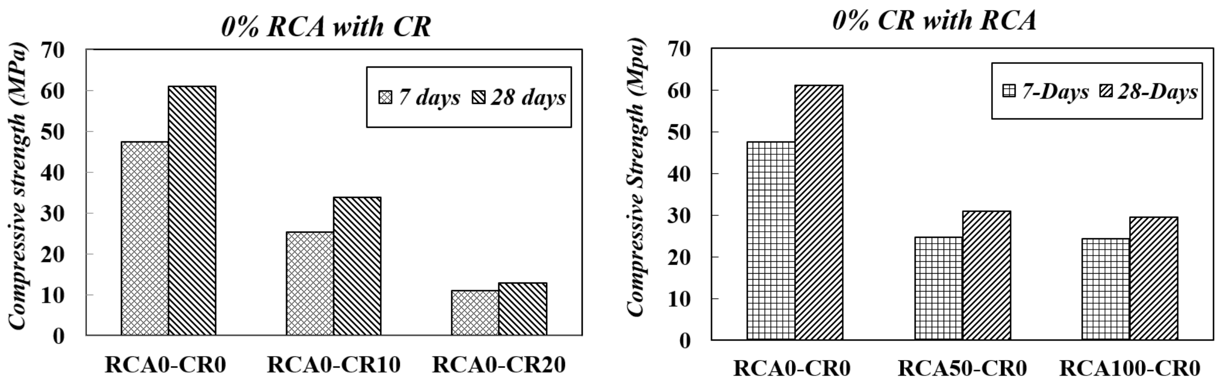
A Humboldt machine was used with a loading rate of 0.85 MPa/min to 1.20 MPa/min to perform the third-point loading flexural test on simple concrete beam specimens. The span length of beams for the tests was 450 mm. As mentioned earlier, the experimental tests were conducted following the CSA standards. (Canadian Standards Association, 2011). The peak load for each test was determined and the flexural strength was calculated from these load values.

3. RESULTS AND DISCUSSIONS

The effects of using either NAOH treated rubber particles or RCA and a combination of both, on the compressive strength and flexural strength of concrete are presented in this section.

3.1 COMPRESSIVE STRENGTH

Concrete loses its compressive strength with the inclusion of either RCA or CR content in it (Ismail & Ramli, 2013Xie, Guo, Liu, & Xie, 2015Liu, Wang, Jiao, & Sha, 2016b). To specify, reduction in the 7-days compressive strength of concrete due to 10% and 20% volumetric replacement of fine aggregate by CR was 47% and 76% respectively from the control mix. Likewise, the 28-days compressive strength was reduced by 44% and 78% for 10% and 20% CR substitution respectively. Figure 2 (a) depicts the 7-days and 28-days cylindrical compressive strengths for RCA0-CR0 (control mix), RCA0-CR10 and RCA0-CR20 mixes.

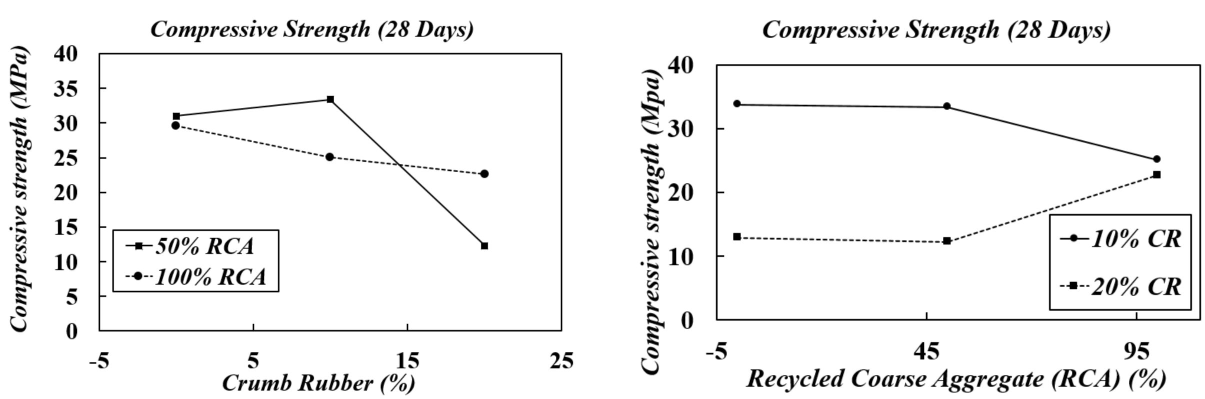


(a) (b)

Figure 2: Compressive strength variation due to the presence of (a) different percentage of crumb rubber (CR), and (b) different percentage of RCA.

However, compressive strength of concrete was reduced by 48% and 49% for 50% and 100% volume of NCA replaced by RCA respectively from control mix for the 7-days compressive strength. Similar reduction of compressive strength by 49% and 50% for the 28-days test was observed for specified RCA substitution in the concrete mixes. The 7-days and 28-days cylindrical compressive strengths of the RCA50-CR0 and RCA100-CR0 in contrast to the control mix is shown in Figure 2 (b). Therefore, the incorporation of either 10% FA replacement by CR or, 50% NCA replacement by RCA in concrete causes a similar reduction by 45% in compressive strength of concrete.

Importantly, the effects of using combination of both CR and RCA in concrete were experimentally investigated in this study. As only limited number of earlier studies included combination of these two parameters in concrete, it renders a new direction for future research. The change in 28-days compressive strengths of concrete with increase in CR content and a fixed RCA content in the mix and vice-versa is illustrated in Figures 3 (a) and 3 (b) respectively.



(a) (b)

Figure 3: Compressive strength for different percentage of (a) Crumb rubber (CR) and (b) RCA.

Notably, it was found that concrete containing 50% RCA had 8% higher compressive strength with 10% CR substitution than the mix containing no CR. However, the strength reduction for RCA50-CR20 mix containing 20% CR is as high as 60% from the RCA50-CR0 mix without any rubber particles. Additionally, results found for the concrete mixes containing 100% RCA content showed 15% and 23% reduction in strength for increase in CR content from 0% to both 10% and 20% respectively.

Furthermore, the concrete compressive strength decreases with increase of RCA content for a particular amount of CR in the mix as shown in Figure 3 (b). To specify, the reduction of strength obtained for concrete mixes with a CR content of 10% was 1% and 26% with increment of RCA content from 0% to 50% and

100% respectively. And, for concrete mixes with a CR content of 20% the reduction was found to be 5% for increment of RCA content from 0% to 50%. One remarkable observation from the test results was a significant increment of compressive strength by 84% for the increment of RCA content from 50% for RCA50-CR20 mix to 100% for RCA100-CR20 mix. This indicates that for a CR content of 20%, the increase of RCA replacement from 50% to 100% contributed substantially to improvement of compressive strength of the concrete mix combination. However, the compressive strength reduction due to increment of RCA for a particular CR content was negligible compared to that for the increment of CR content for a particular RCA in the concrete mix.

The typical failure patterns of concrete specimens for the control mix (RCA0-CR0) is shown in Figure 4(a). Additionally, the failure of the specimens for the mixes containing CR and 0% RCA, combination of CR and RCA and RCA with 0% CR are shown in Figure 4 (b), 4(c) and 4(d) respectively.

(a) (b) (c) (d)

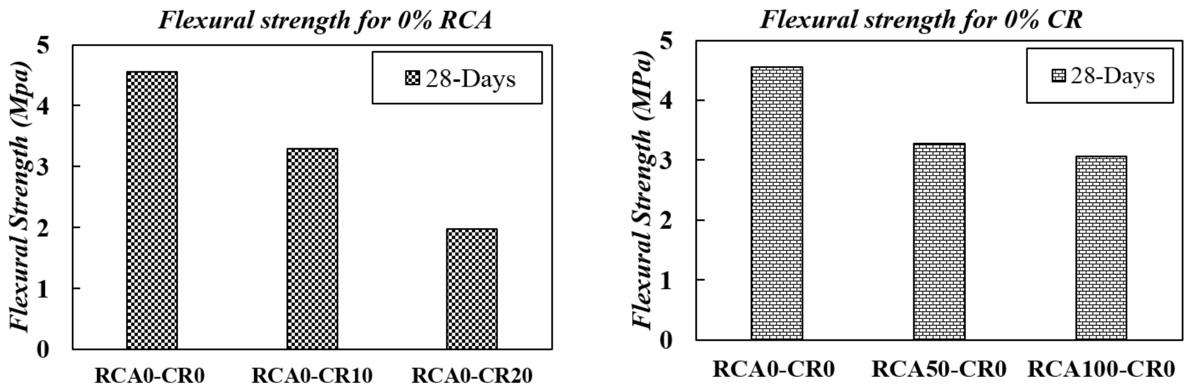
Figure 4: Compression failure of specimens for mixes (a) without RCA and CR, (b) with CR, no RCA, (c) with combination of RCA and CR and, (d) with RCA and no CR.

3.2 FLEXURAL STRENGTH

The 28-days flexural strength of the control mix (RCA0-CR0) from third-point loading test on concrete beams was 4.5 MPa. In accordance with previous research (Kaloush et al., 2005 Issa & Salem, 2013 R & Chavan, 2014)(Ismail & Ramli, 2013)(Xie et al., 2015), the flexural strength of specimens showed a lower trend with increment of both CR and RCA content in the concrete mixes.

Figure 5a shows the flexural strengths of the RCA0-CR10 and RCA0-CR20 mixes without RCA and CR contents of 10% and 20% respectively compared to the flexural strength of the control mix. The reduction of the flexural strength was 28% and 57% for 10% and 20% increase in CR content respectively. However, the reduction of compressive strengths for these mixes was much higher than the reduction of the flexural strengths. This indicates that increment of CR contributes more significantly to the reduction of compressive strength than the flexural strength of concrete.

Then again, the flexural strengths of concrete mixes RCA50-CR0 and RCA100-CR0 with 50% and 100% RCA and no rubber particles were reduced by 28% and 33% as compared to the flexural strength of the control mix respectively. One interesting observation was the strength reduction in flexure due to the inclusion of 10% CR content and 50 % RCA content are similar. The flexural strengths for these mixes are shown in Figure 5b.

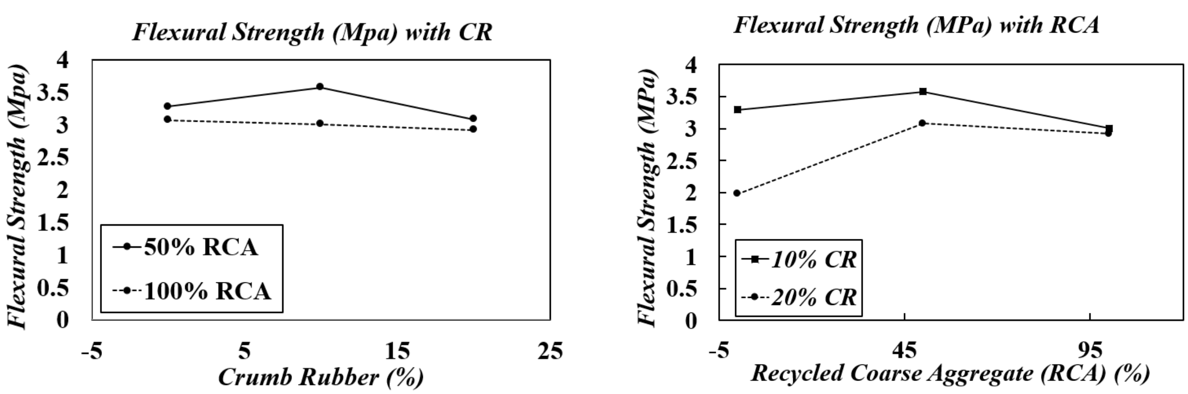


(a) (b)

Figure 5: Flexural strength for (a) 0% RCA and (b) 0% CR.

The mixes containing combination of RCA and CR in varying amounts showed lower flexural strengths than the control mix. The change in flexural strengths with change in CR content for a particular amount of RCA is shown in Figure 6 (a). Results indicate that, for half NCA replacement by RCA, RCA50-CR10 mix and RCA50-CR20 mix with 10% CR and 20% CR had 22% and 32% lower flexural strength respectively than the control mix. Moreover, for a full replacement of NCA by RCA, the reduction in flexural strength for mixes RCA100-CR10 and RCA100-CR 20 was found as 34% and 26% respectively from the control mix.

Importantly, mix RCA50-CR10 showed 8% higher flexural strength than the RCA50-CR0 mix with no CR in it. As mentioned previously, the compressive strength of the mix RCA50-CR10 also has similar increment as compared to strength of the mix RCA50-CR0. However, the flexural strength for RCA50-CR20 mix was reduced by 8% compared to that of RCA50-CR0 mix. Similar downward trend of flexural strengths was found for the mixes with NCA replacement by 100% RCA. To specify, the obtained reduction in flexural strengths for the concrete mixes RCA100-CR10 and RCA100-CR20 is 2% and 5% as compared to that of RCA100-CR0 mix without any rubber particles in it. Thus, it is inferred that the combination of 50% RCA and 10% CR content in concrete helps to maintain an acceptable flexural strength with only 22% reduction in the flexural strength from the control mix.



(a) (b)

Figure 6: Flexural strength for different percentage of (a) CR, and (b) RCA

The effect of increasing RCA content in the concrete mix for a particular CR content was studied and is depicted in Figure 6 (b). The experimental results show that for a CR content of 10%, the flexural strengths for both mixes RCA50-CR10 and RCA100-CR10 increased by 9% and 56% respectively from RCA0-CR10 and RCA0-CR20 mixes without any RCA. This indicates that a combination of RCA and CR in the concrete mixes help to improve the flexural properties. Moreover, the flexural strength of RCA100-CR20 mix showed an increase in the flexural strength of as high as 48% than RCA100-CR0 mix. However, the strength of

RCA100-CR10 mix was 9% lower than RCA0-CR10 mix. Furthermore, flexural strength of mix RCA100-CR20 obtained was only 3% lower than the flexural strength of mix RCA100-CR10.

4. CONCLUSION

Compressive strength and flexural strength of concrete containing 20% NaOH solution treated rubber particles and RCA was studied experimentally in this study. Major conclusions obtained from this study can be summarized as follows-

1. Incorporation of only recycled rubber particles as a partial replacement of fine aggregates in concrete results in reduction of both compressive strength and flexural strength of the mix. However, the optimum CR content was found to be 10% volumetric replacement of FA with 44% and 28% reduction in the 28-days compressive and flexural strengths from the control mix respectively.

2. Likewise, the addition of only RCA as a partial replacement of NCA also shows a negative effect on compressive strength and flexural strength of the concrete. However, the reduction of compressive strengths with increase of RCA from 50% replacement of NCA to a full replacement is not significant with 48% and 49% reduction from the control mix respectively. The optimum RCA content from this study was found as 50% volumetric replacement of NCA by RCA with 48% and 28% reduction in the compressive and flexural strengths respectively of concrete.

3. Importantly, the incorporation of both recycled CR and RCA as partial replacement of fine aggregates and natural coarse aggregates respectively in concrete was found to improve mechanical strength of concrete compared to addition of either of RCA or CR in the mix for particular percentage replacements. To specify, the mix RCA50-CR10 with 50% and 10% volumetric replacement of NCA by RCA and FA by CR was found to have satisfactory compressive strength and flexural strength with 45% and 28% reduction in compressive and flexural strength respectively compared to the control mix.

Integration of recycled rubber particles and recycled coarse aggregates as partial replacement of fine aggregates and natural coarse aggregates respectively in concrete can contribute substantially towards the production of green concrete and can provide a viable solution to address the harmful environmental effects of solid waste disposal. Based on the experimental results in this study, it can be perceived that the partial replacement of FA and NCA by CR and RCA respectively in concrete yields satisfactory mechanical strength in terms of compressive and flexural strengths. Other strength criteria of concrete with combination of both CR and RCA can be further studied to comprehend the overall performance of rubberized concrete with RCA for structural applications of concrete.

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