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EXPERIMENTAL INVESTIGATION OF THE FLEXURAL BEHAVIOUR OF RUBBERIZED CONCRETE CONTAINING RECYCLED CONCRETE AGGREGATE

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Abstract: This study focusses on the use of crumb rubber (CR) (0, 10, and 20%) and recycled concrete aggregates (RCA) (0, 50, and 100%) as partial replacements of natural fine aggregates (NFA) and natural coarse aggregates (NCA), respectively in concrete. The compressive and flexural strengths of this new concrete were experimentally investigated. The load-deflection behavior of the concrete mixtures under flexure was thoroughly analyzed as well. Results show that the inclusion of CR resulted in compressive and flexural strength reduction by up to 38 and 19%, respectively. Whereas, RCA showed a marginal influence on the flexural strength of concrete but had a reduction of up to 10% in the compressive strength. Importantly, rubberized recycled aggregate concrete (RRAC) mixtures met the design compressive strength requirement of 35 MPa for structural concrete. Moreover, RRAC showed enhanced flexural behavior with satisfactory flexural strength and much lower flexural stiffness than NAC.

INTRODUCTION

Owing to the enormous consumption of natural aggregates in concrete production and its further proliferating demand due to the rapid growth of population and urbanization, a significant crisis of virgin aggregates are forecasted in the near future (Behera et al. 2014; Oikonomou 2005). Additionally, extensive amounts of car tires reach the end of their useful service life and are being dumped in landfills all over the world. About one billion end-of-life tires are generated each year with another four billion already being stockpiled worldwide (WBCSD 2008; Goldstein Research 2018; WBCSD Tire Industry Project 2010). Furthermore, the accelerated rate of modernization and industrialization in addition to the increased number of no longer serviceable structures has led to the generation of a tremendous amount of construction and demolition (C&D) waste worldwide. about 900 million tonnes of construction and demolition (C&D) waste is generated every year solely in Europe, the United States, and Japan with additional waste elsewhere around the world (WBCSD 2009). Particularly, in Canada, about 52% of the 11 million tons of annual solid C&D waste is held by concrete. These waste tires and C&D waste can be effectively refined and recycled through further processing for use in concrete as aggregates.

The prospects of using recycled rubber particles as aggregates in concrete mixtures have been explored extensively over the past 20 years by researchers. Rubberized concrete in general possess inferior mechanical properties than normal aggregate concrete (NAC) in terms of compressive strength (Taha et al. 2008; Aslani, Ma, Yim Wan, and Tran Le 2018; Eldin and Senouci 1994; Topçu 1995; Wong and Ting 2009; Zheng, Huo, and Yuan 2008) and flexural strength (Toutanji 1996; Benazzouk et al. 2003; Chou et al. 2007; Assadollahi and Moore 2017; Gupta et al. 2017) . The weaker adhesion between rubber and cement paste is primarily attributed to the strength reduction due to the addition of rubber in concrete

(Pham, Toumi, and Turatsinze 2018; Stallings, Durham, and Chorzepa 2018; Taha et al. 2008). Moreover, coarser rubber particles result in a higher strength reduction under compression than crumb rubber (CR) particles (Taha et al. 2008; Stallings, Durham, and Chorzepa 2018). However, pre-treatment of rubber using different chemical agents have been proved to reduce the strength loss by improving the hydrophilicity of the rubber particles. Among all the chemical treatment methods, pre-treatment using a NaOH solution is the most efficient to improve the strength of rubberized concrete. Also, it is relatively less expensive and more convenient (Mohammadi, Khabbaz, and Vessalas 2016; Su et al. 2015).

The inclusion of recycled concrete aggregate (RCA) in concrete results in a similar reduction in the mechanical properties of recycled aggregate concrete (RAC) (Bhasya & Bharatkumar, 2018; Evangelista & de Brito, 2010; Katz, 2003; McGinnis, Davis, de la Rosa, Weldon, & Kurama, 2017; Oikonomou, 2005). The attached mortar in RCA from the parent concrete results in a weak interfacial transition zone (ITZ) reducing the strength of RAC (Rahal 2007; Behera et al. 2014). However, several studies have obtained a similar or higher performance of RAC compared to NAC in terms of compressive strength and flexural strength (Ho et al. 2013; Otsuki, Miyazato, and Yodsudjai 2003; Choi and Yun 2012; Fathifazl et al. 2009; M.V. and Gómez-Soberón 2002; Y. Li et al. 2011).

An inferior performance of rubberized recycled aggregate concrete (RRAC) in compression and flexure have been reported in the limited studies (Henry et al. 2012; Liu et al. 2015; L.-J. Li et al. 2016; Marie 2017; David, Chandrasegaran, and Karan Nair 2018; Aslani, Ma, Yim Wan, and Muselin 2018) that focussed on the use of a combination of both CR and RCA in concrete. A weak adhesion between rubber and cement paste primarily resulted in the reduction of compressive strength of RRAC (L.-J. Li et al. 2016; Aslani, Ma, Yim Wan, and Muselin 2018; Liu et al. 2015; Henry et al. 2012). The lower flexural strength is attributed to the lower stiffness of rubber particles creating stress concentrations in RRAC on application of load (L.-J. Li et al. 2016; Liu et al. 2015). However, RRAC demonstrated better deformation behaviour with lower flexural stiffness compared to RAC (Liu et al., 2015). Nevertheless, these studies primarily determined the effect of an increase of only CR at a particular replacement level of RCA. Importantly, the behavior of this new concrete at a material level with respect to its compressive/flexural resistance compared to NAC have not been scrutinized in earlier studies.

This study includes a thorough experimental investigation of the mechanical behaviour of concrete containing not only CR or RCA but also, a combination of both at varying replacement levels. For brevity of discussion, only flexural behaviour of the concrete mixtures with a brief summary of the compressive strength is presented in this paper. This will significantly contribute to evaluating the potential of using RRAC in practical engineering applications.

1 EXPERIMENTAL PROGRAM

1.1 Materials

General use (GU) cement, sea sand, and natural stone aggregates conforming to CSA A23.1 (Canadian Standards Association, 2014a) were used as the binding material, NFA, and NCA, respectively. Coarse aggregates (NCA and RCA) with a nominal maximum size of 20 mm was used in this study. Both NFA and CR had a nominal maximum and minimum size of 4.75 mm and 80 μm, respectively. Commercially available CR was used in this study, produced by shredding discarded and recycled waste rubber tires and screening out the steel fibers from it. Material properties of the aggregates are summarized in Table 1. The specific gravity of CR was determined according to FM 5-559 standard (Florida Department of Transportation [FDOT] 2016). Ethyl alcohol was used instead of water to test the properties of CR following this standard, as CR does not fully submerge in water because of its low specific gravity (near unity).

The gradation curves for aggregates obtained following CSA A23.2 2A (Canadian Standards Association 2014) were consistent with the specification of CSA A23.1/A23.2 (Canadian Standards Association 2014) as illustrated in Figure 1. The fineness modulus (FM) of NFA and CR obtained was 2.38 and 1.79, respectively. Overall, a well-graded mixture of aggregates was obtained for both FA and CA.

Table 1 Material properties of aggregates for concrete mixture

Aggregates	Bulk Density (kg/m^3)	Specific gravity			Absorption capacity (%)	Moisture Content (%)
		Bulk dry	Bulk SSD	Apparent		
NCA	1636	2.60	2.65	2.72	1.71	1.64
RCA	1335	2.16	2.33	2.61	8.02	2.82
NFA	-	-	2.60	-	1.52	-
CR	-	-	1.15	-	1.20	-

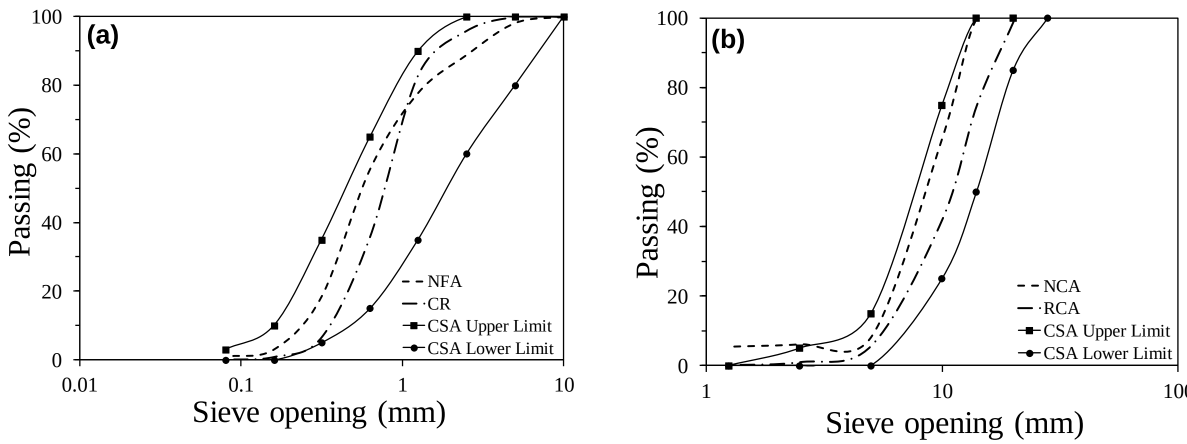

Figure 1: Gradation curve of (a) fine aggregates and (b) coarse aggregates used for concrete mixtures.

1.2 Mixture Design

In total nine concrete mixtures were prepared considering three levels of CR (0, 10, and 20%) and RCA (0, 50, and 100%) replacing NFA and NCA, respectively. The target design strength of mixtures was 35 MPa at 28 days for structural concrete with C-1 class of exposure according to the CSA A23.1/A23.2 (Canadian Standards Association 2014). The design w/c ratio was 0.34.

Table 2 Mixture design proportions of concrete per cubic meter

Designation	NFA (kg)	CR (kg)	NCA (kg)	RCA (kg)	Water (kg)	HRWRA (L)
C_0R_0	633	0	1142	0	141	4.390
C_0R_{10}	570	29	1142	0	140	3.765
C_0R_{20}	507	57	1142	0	140	4.640
$C_{50}R_0$	633	0	571	571	171	4.390
$C_{50}R_{10}$	570	29	571	571	170	5.640
$C_{50}R_{20}$	507	57	571	571	169	3.951
$C_{100}R_0$	633	0	0	1142	200	5.140
$C_{100}R_{10}$	570	29	0	1142	199	3.140
$C_{100}R_{20}$	507	57	0	1142	198	6.390

The aggregates were mixed in their natural state. The absorption capacity of RCA was 8%, which was significantly higher than that of NCA. Based on the moisture content and water absorption of RCA, the mixing water amount was adjusted in the mixtures containing RCA. The resulting total water content considering water absorption of aggregates for all the mixtures are tabulated in the mixture design matrix (Table 2). A constant cement content of 385 kg/m^3 was used in the mixtures. The air-entraining admixture was added at a dosage rate of 125 ml/m^3 to attain uniform distribution of air voids in the concrete mixture. Notably, CR was pre-treated with a 20% concentrated solution of NaOH to prepare the concrete mixtures. Mixture designated as $C_{100}R_{20}$ represents concrete with a combination of 100% RCA and CR at a replacement level of 20%.

1.3 Preparation of Specimens

For each mixture design, six 100Φ×200 mm cylinder specimens were cast to determine the 28 and 56-day compressive strength following CSA A23.2-2C (Canadian Standards Association 2014). Additionally, for each mixture design, three standard 100×100×350 mm beams were cast as per ASTM C192 (ASTM International 2016) to determine the flexural strength. Three beam specimens were cast for nine concrete mixtures totaling to 27 concrete beam specimens. Flexural strength was determined as the average of the modulus of rupture (MOR) values of three beams at a test age of 90 days ± 48 h.

1.4 Test Setup

In order to conduct compression tests on concrete cylinders, an Instron 3385H testing machine with a capacity of 3000 kN at a loading rate of 0.15 to 0.35 MPa/s was used following CSA A23.3-9C (Canadian Standards Association 2014). Flexural strength test on the concrete beam specimens was conducted following ASTM C78 (ASTM International 2018). The concrete beam specimens were loaded at a displacement rate of 0.25 mm/min using an Instron 3385H testing machine with a capacity of 3000 kN. A special yoke designed and built at UBCO was used to determine the mid-span deflection of the beam specimens devoid of any extraneous deflections that might arise from support settlements. It also eliminates calculation of the vertical elastic component of the fixture. Two linear variable displacement transducers (LVDTs) were used on both sides of the beam at mid-height of the specimen and an average mid-span deflection value was determined for each beam.

2 RESULTS AND DISCUSSION

2.1 Compressive Strength

The compressive strength of the concrete mixtures is presented in Figure 2. There was a general reduction in compressive strength of concrete with an increase in CR content. The reduction in the 28-day compressive strength of mixtures C_0R_{10} and C_0R_{20} was 7 and 38%, respectively, from the control mixture. With a similar reduction in the 56-day compressive strength, mixture C_0R_{20} still had a satisfactory 56-day compressive strength of 35 MPa. The reduction in compressive strength of concrete of crumb rubber concrete (CRC) can be attributed to a poorer adhesion between CR and the surrounding cement paste in general.

Interestingly, an increment in the compressive strength of concrete was observed with an RCA replacement level of 50%, both at 28 and 56 days (Figure 2). However, mixture $C_{100}R_0$ had a reduction by only 10% compared with the control mixture with a compressive strength of 47 MPa at 28 days. The compressive strength of RAC generally decreases with an increase in RCA content. The higher compressive strength of mixture $C_{50}R_0$ can be attributed to the effect of combined well graded CA with the inclusion of 50% RCA.

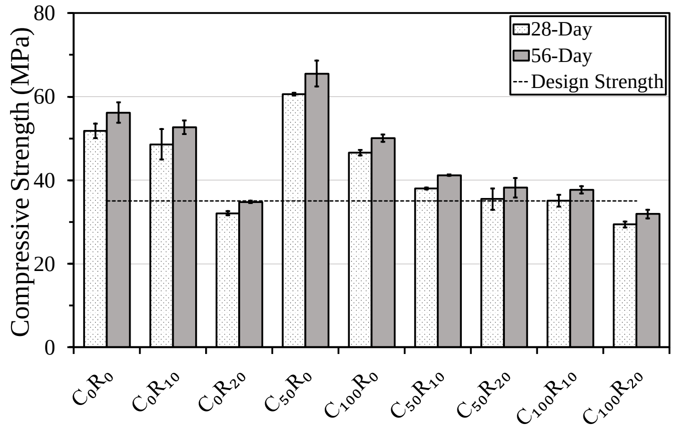

Figure 2: The compressive strength of concrete mixtures. (Note: The error bars represent standard deviation)

For a combination of RCA and CR in concrete, a reduction of 27 and 32% in the 28-day compressive strength was obtained for mixture $C_{50}R_{10}$ and $C_{50}R_{20}$, respectively, from mixture C_0R_0 (Figure 2). Again, mixtures $C_{100}R_{10}$ and $C_{100}R_{20}$ had a reduction of 32 and 43% than the control mixture with the 28-day compressive strength of 35 and 29 MPa, respectively. Regardless, mixture $C_{100}R_{20}$ had the lowest compressive strength among the RRAC mixtures considered in this study, whereas, mixture $C_{50}R_{20}$ still demonstrated a compressive strength of 36 MPa at 28 days satisfying the design strength (35 MPa) requirement.

2.2 Flexural Strength

Figure 3 illustrates the flexural strength variation of the concrete mixtures in contrast to the control mixture (C_0R_0). Flexural strength of concrete demonstrated a general decrease with the increase in CR content in the mixtures. To specify, the increase in CR content from 0% for the control mixture to 10% and 20% resulted in a reduction of the flexural strength by 9% and 19%, respectively at 90 days. The reduction in flexural strength of these mixtures followed a similar trend as the reduction in compressive strength, but with lower reductions for the former. The reduction in flexural strength can be attributed to the weaker bond between the rubber particles and the cement matrix reducing its load carrying capacity under flexure.

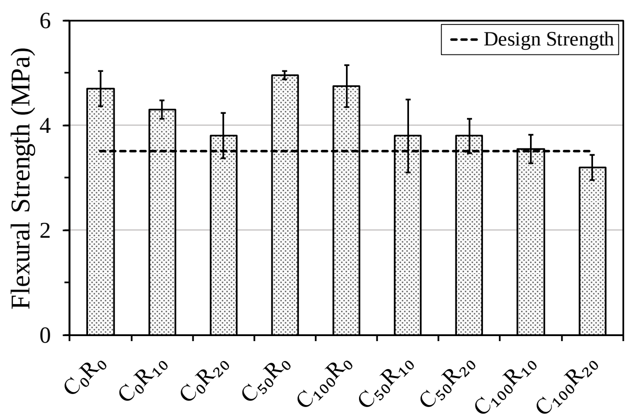

Figure 3: The static flexural strength of concrete mixtures. (Note: The error bars represent standard deviation)

The RAC mixtures exhibited a similar flexural strength compared to the control mixture with a flexural strength of 4.95 MPa at 90 days for mixture $C_{50}R_0$. Notably, the RCA replacement level of 50% resulted in the maximum value of compressive strength as well.

The mixtures containing combinations of RCA and CR in varying amounts showed lower flexural strengths than the control mixture. In particular, mixtures $C_{50}R_{10}$ and $C_{50}R_{20}$ showed 28% and 19% lower flexural strengths than the control mixture, respectively. Similar reductions of 25% and 32% were observed for mixtures $C_{100}R_{10}$ and $C_{100}R_{20}$, respectively when compared to the control mixture. Also, the reductions obtained for the RRAC mixtures are higher than those of CRC mixtures. Thus, the incorporation of RCA and CR together in concrete resulted in an overall decrease in its flexural strength. All the RRAC mixtures except mixture $C_{100}R_{20}$ satisfied the target flexural strength of 3.5 MPa (Canadian Standards Association 2015) at the time of testing.

The effects of increasing CR content in the concrete mixture for a particular RCA content and vice-versa were also studied and are depicted in Figure 4 (a) and (b), respectively.

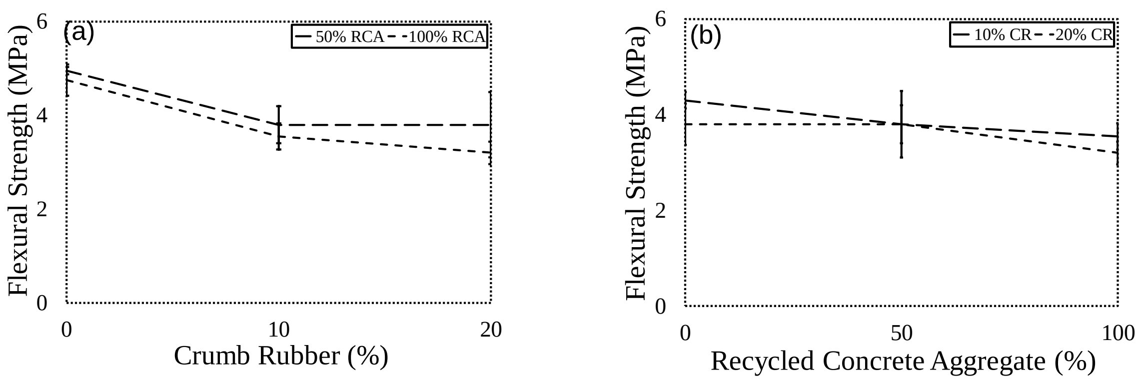

Figure 4: The flexural strength of RRAC mixtures for different percentages of (a) CR, and (b) RCA.

A general reduction in flexural strength was observed with the increase in CR content from 0 to 10 and 20% at a particular RCA replacement level. However, mixtures $C_{50}R_{10}$ and $C_{50}R_{20}$ had a similar flexural strength of 3.80 for an increment of CR content from 10 to 20% at an RCA replacement level of 50%. Regardless, mixtures $C_{50}R_{10}$ and $C_{50}R_{20}$ had a reduction of 23% compared to mixture $C_{50}R_0$. Again, mixture $C_{100}R_{10}$ and $C_{100}R_{20}$ had lower flexural strengths than mixture $C_{100}R_0$ by 25% and 33%, respectively.

For a particular CR content, the increase in RCA replacement level from 0 to 50 and 100% resulted in a general decrease in flexural strength of the mixtures as depicted in Figure 4 (b). To specify, mixtures $C_{50}R_{10}$ and $C_{100}R_{10}$ had reductions of 12% and 17%, respectively compared to mixture C_0R_{10}. Notably, mixture $C_{50}R_{20}$ had a similar modulus of rupture of 3.80 MPa as mixture C_0R_{20}, whereas, mixture $C_{100}R_{20}$ had a 16% lower flexural strength than mixture C_0R_{20} at 90 days.

Overall, considering a combination of RCA and CR in concrete, mixtures $C_{50}R_{10}$ and $C_{50}R_{20}$ had the highest flexural strength of 3.80 MPa at 90 days with 19% reduction from the control mixture (4.7 MPa).

2.3 Load-Deflection Behaviour

The flexural load-deflection curves of the CRC and RAC mixtures are presented in Figure 5 (a) and (b), respectively. Deflection corresponding to specific load values increased with the increase in CR content in the mixture. Thus, the addition of CR reduced the flexural stiffness of the concrete mixtures. In contrast, load-deflection curves for the RAC mixtures had a similar trend with slightly lower gradients than the control mixture as shown in Figure 5 (b). To detail, the maximum deflection of the rubberized concrete beams with 10% and 20% CR without RCA, was increased by 55% and 149% with 11% and 19% lower peak load, respectively at flexure compared to the control mixture. Whereas, both peak load and deflection at failure under flexure for mixtures $C_{50}R_0$ and $C_{100}R_0$ increased when compared to the mixture C_0R_0. Mixture $C_{50}R_0$ had the highest peak flexural load of 18.5 kN and a maximum deflection of 0.040 mm with 3% and 29% increment, respectively than the control mixture. Likewise, mixture $C_{100}R_0$ had a 13% higher maximum deflection corresponding to a similar peak load when compared to the control mixture.

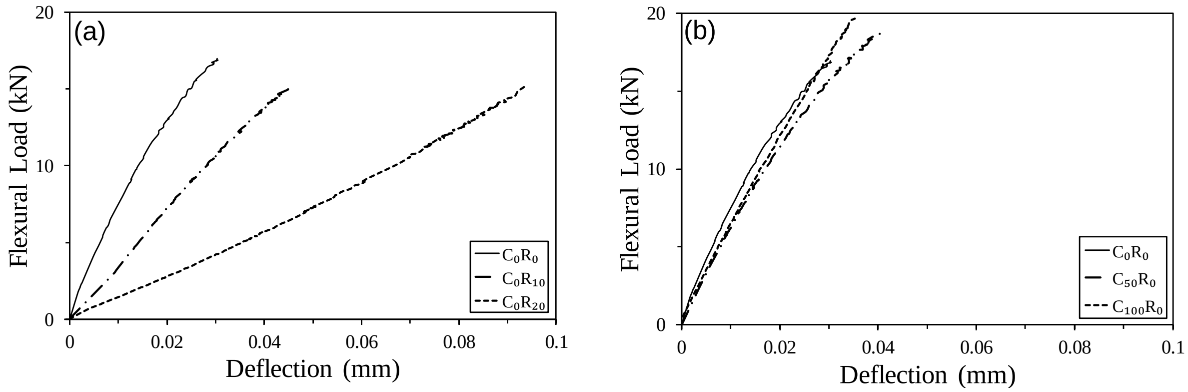

Figure 5: Flexural load-deflection behaviour of concrete mixtures with different percentages of (a) CR and (b) RCA.

The combination of RCA and CR in concrete resulted in a lower flexural stiffness compared to the control mixture. RRAC mixtures had higher deflections than the control mixture under the same flexural load as shown in Figure 6. Also, the maximum deflection values were higher with much lower peak load values in flexure compared to the control mixture. However, the RRAC mixtures had similar gradients in the load-deflection curves up to approximately 40% of the peak load values. Mixture $C_{100}R_{20}$ had the lowest peak flexural load with 30% reduction than the control mixture. The highest average maximum deflection value was obtained for mixture $C_{50}R_{10}$ with a deflection value of 0.046 mm, 48% higher than the control mixture. Additionally, the inclusion of 10% CR to mixture $C_{50}R_0$ resulted in a 15% increment in the maximum deflection value, but, a reduction of 37% in the peak load value for mixture $C_{50}R_{10}$. Also, the addition of CR at 20% replacement level with 100% RCA in mixture $C_{100}R_{20}$ contributed to an increment of the maximum deflection value by 11% with a 37% lower flexural load compared to mixture $C_{100}R_0$.

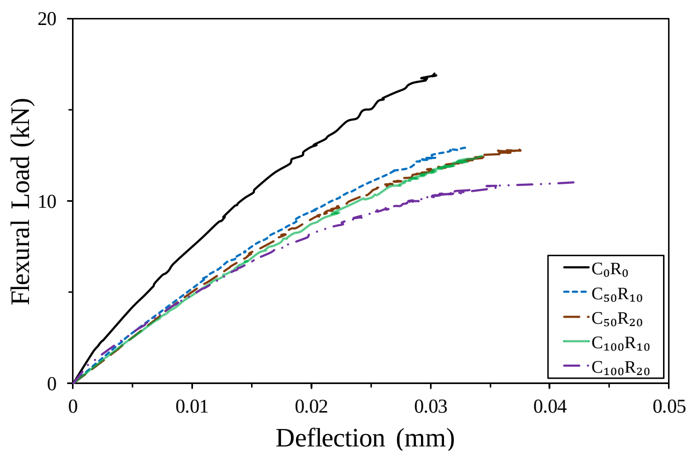

Figure 6: Flexural load-deflection behaviour of RRAC mixtures.

3 CONCLUSION

The inclusion of CR resulted in a general reduction in the compressive and flexural strength of concrete with lower flexural stiffness than NAC. However, RCA had a marginal effect on the flexural strength of concrete but with lower compressive strength than NAC. Also, it exhibited a lower flexural stiffness than NAC. In the case of RRAC, all combinations of CR and RCA achieved the design compressive strength of 35 MPa considered in this study but mixture $C_{100}R_{20}$. Notably, the RRAC mixtures although had lower flexural strength, still exhibited enhanced flexural behaviour compared to NAC, CRC, and RAC in terms of flexural stiffness. Thus, the incorporation of a combination of CR and RCA in concrete will be effective in providing enhanced performance of concrete.

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 NFA and NCA by CR and RCA respectively in concrete yields satisfactory mechanical strength in terms of flexural strength. Other strength criteria of concrete with a 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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