ISSN 0511-5728
The West Indian Journal of Engineering
Vol.45, No.2, January 2023, pp.4-13

Investigating the Use of Recycled Concrete as Aggregates in the Construction of Structural Beams

Leighton A. Ellis [a,Ψ], Lee P. Leon [b], and Amy V. Charran [c]

[a] Department of Civil Engineering, The University of the West Indies, Mona Campus, Jamaica, West Indies; Email: leighton.ellis@uwimona.ed.jm

[b,c] Department of Civil and Environmental Engineering, The University of the West Indies, St. Augustine Campus, Trinidad and Tobago, West Indies; Email: lee.leon@sta.uwi.edu

[b]Email: lee.leon@sta.uwi.edu
[c] Email: amycharran@hotmail.com

[Ψ] *Corresponding Author*

(Received 09 January 2022; Revised 15 July 2022; Accepted 08 September 2022)

Abstract: *The World Bank in a decade ago reported a global collective of 1.3 billion tons of solid waste every year with building material accounting for half of this volume annually worldwide. Recycled materials from demolition sites have increased over the years to curtail the demand for natural aggregates (NA). This study investigates the use of recycled concrete aggregates (RCA) produced from high strength concrete and its effects on the mechanical properties of concrete and structural members. Further comparison was made to concrete with steel fibers. The results showed that the compressive strength of RCA concrete was 5% greater than NA concrete. The influence of the properties of durability and crushing resistance of the RCA, which exceeded that of NA, contributed to the higher concrete strengths when compared to NA concrete. Additionally, concrete with RCA and steel fibers had an increase of compressive strength by 16% to concrete without steel fibers. However, no significant increase in the deflection and strain of the beams under third point loading suggest that given the right conditions RCA can be used in place of NA.*

Keywords: *Construction waste; engineering sustainability; recycled concrete aggregate; structural members; steel fiber; waste management*

1. Introduction

Construction and demolition waste (CDW) accounts for the largest contribution to solid waste from a single industry globally (Haung et.al, 2018). The negative environmental and economic impacts of this issue have been a major challenge for the construction industry. Based on the consumption demand for infrastructure and housing, this issue is likely to increase significantly in the future (Limbachiya, 2004). To achieve sustainability, each process within the construction cycle must be evaluated. This has given rise to the Circular Economy (CE), an economic system targeted at eliminating waste and the continual use of resources (Ginga, Ongpeng, and Daly, 2020).

The increase in Construction and Demolition Waste (CDW) is of global concern and one such solution is Waste Management. This process is the collection, transportation, disposal, and recycling of waste. Reusing CDW as aggregates helps to minimise the amount of CDW dumped into the landfills (Ginga, Ongpeng, and Daly, 2020). Dumping of the debris into the landfills in the aftermath of the 12th of January 2010 earthquake in the Republic of Haiti, was not a viable or sustainable option due to the high population density and lack of available land. Thus, the debris was utilised as part of the reconstruction process as a sustainable avenue for Solid Waste Management (DesRoches et al., 2011). In the construction industry, concrete is one of the main composite materials, hence the identification of techniques pointed toward decreasing the environmental impact is critical for achieving the green building goals and sustainable development goals (Merli, 2020), more specifically SDG12 – Sustainable Consumption and Production.

The establishment of international standards such as ISO 13315-1:2012 and ISO 13315-2:2014 (ISO, 2012, 2014) regarding environmental management for concrete and concrete structures demonstrates the global thrust towards managing the negative impacts resulting from concrete production in its various stages. One of the vital components of concrete, cement is a main contributor to greenhouse gases with studies suggesting as high as 8% of the total global Carbon Dioxide (CO_2) emissions (Chandler, 2019). This is contrasted with another major component of concrete, aggregate production, which contributes significantly less than cement production, accounting for 13% to 20% of the total CO_2 emissions of concrete (Braunschweig, Kytzia, and Bischof, 2012). The

https://doi.org/10.47412/XRHG1947

use of natural aggregates is not without faults given the negative effects of riverbed and seaside mining on the ecosystems of local flora and fauna. This gives rise to recycled aggregates (RA) as a suitable replacement. Weil, Jeske, and Schebek (2006)'s research suggests a consumption reduction of about 44%. Marinković et al. (2010)'s study concluded the environmental impact of using recycled concrete aggregates (RCA) in construction will depend on the type of transport used and the distance travelled to obtain NA and RCA.

Another global concern is the reduction of the carbon footprint in construction. The reduction procedure encompasses the substitution of recycled concrete as coarse aggregates in the production of cement concrete, whereby reducing quantities of Natural Aggregate (NA) that are manufactured. The extraction and crushing of NA use more energy and CO_2 than RCA (Behera et al., 2014). Faleschini et al. (2016) examined the environmental impacts of recycled concrete aggregate by conducting a life cycle assessment and analysing the environmental emissions due to the RCA and NA. The results showed that about 50% of carbon can be saved by using RCA instead of NA.

One major argument is that RCA is inferior in strength when compared to concrete produced with natural aggregate (Limbachiya et al., 2000; McNeil et al., 2013; Fiol et al., 2018). However, other studies have found the inverse indicating that the crushing value of RCA was higher than that of virgin aggregates. Parthiban and Mohan (2017) study on RCA with 100% replacement of NA presented very good performance. This was achieved by pre-wetting and saturating the RCA, as well as using superplasticizers to avoid negative effects such as reduced workability and poor mechanical performance. Although RCA has been classified as low quality material research, such as Arulrajah et al. (2012) and Jayakody et al. (2014) have undertaken laboratory bearing capacity testing research, with the results indicating that RCA satisfied the criteria for use in pavement sub-base applications. Typically, the quality of recycled concrete aggregates is usually lower than the quality of virgin aggregate which is a significant consideration for the application of structural concrete (Marinković, 2010).

The old, adhered mortar in RCA reduces its concrete composite strength and during the crushing process micro-cracks are formed (Behera et al., 2014; Kosior-Kazberuk and Grzywa, 2014). The old mortar on the RCA breaks off easily in the weak area in concrete found in the Interfacial Transition Zone (ITZ). NA do not have this coating; thus, they attach to the cement better, creating stronger bonds and increasing the overall strength of concrete (McNeil and Kang, 2013). Monrose et al. (2020) further examined the micro-structure and bonding ITZ of cementitious NA using a scanning electron microscope (SEM). Results indicated that the cementitious paste appeared to be homogenous and dense with solid bonding between the two phases. Though micro-cracking (<2 μm) was observed it was reportedly limited to the bonding zone.

Notwithstanding, RCA has aggregate property deficiencies comparative to NA, it can still meet its proposed purpose as replacement coarse aggregate in the production of cement concrete on the grounds that the quality characteristics are kept within the specified design limits (Lee 2013). Furthermore, research such as Limbachiya et al., 2000; Malešev et al., 2010; Marinković, 2010; McNeil et al., 2013; Fiol et al., 2018, all focused on RCA that were weaker than NA. A few researchers (such as Smith (2018)) have investigated the behaviour of concrete with high-strength RCA. Limbachiya et al. (2000) study indicated that coarse RCA can be used in a range of high-strength concrete mixes with satisfactory engineering properties, namely compressive strength, flexural strength, and modulus of elasticity. However, shrinkage and creep strains were found to increase with RCA content in the concrete. Due to the lack of empirical evidence in this area, this study sought to investigate the behaviour of structural concrete produced with 100% replacement of coarse RCA that are equal or exceeded the mechanical properties (hardness and strength) of NA.

Kosior-Kazberuk and Grzywa (2014) suggested that RCA can be used in making non-structural members such as foundations and sub-base layers in pavements. Malešev et al. (2010) suggested that beams made of RCA performed similarly to NA concrete. A successful example of RCA for structural applications is the construction of the Samwoh Eco-Green Building in Singapore which utilised a 100% recycled concrete aggregate (Ho et al., 2015).

Concrete is known for its low tensile strength and ductility. To resist the stress and strains in structural members, reinforcement is added. Various international institutions, such as American Concrete Institute (ACI) and the American Society of Civil Engineers (ASCE), and numerous scholars have recommended the use of steel fibers as an effective way to increase tensile strength of concrete and the ability of resistance to cracking and crack propagation (Chanh, 2005; Biolzi, and Cattaneo, 2017; Lee et al., 2018; Aslani et al. 2019; Chalioris et al., 2019). Steel fiber RCA concrete was suggested by Gao (2019) to have good durability and can be successfully applied to structural members with proper mixture design. Steel fiber reinforced concrete (SFRC) is a composite material made with cement, aggregate, additive, and incorporating discrete discontinuous steel fibers (Zhang et al., 2017). The results of studies conducted by Zhang et al. (2017) show that steel fibers can improve splitting tensile strength of concrete. Other scholars such as Zheng et.al (2018) also show that in SFRC with more than 1% (e.g., 1.5% and 2.0%), the splitting tensile strength increases rapidly.

With the increase in steel fiber content, all these mechanical properties (such as compression strength, flexural strength, and splitting tensile strength) improve gradually, especially for flexural strength and splitting tensile strength, the steel fiber reinforcement effect is obvious. At the same fiber content, reinforcement effect of mechanical properties of high-strength concrete is better (Zheng et al., 2018).

FRC offers several advantages over rebar or wire mesh reinforced concrete which include energy absorption, impact resistance and residual strength. Chanh (2005) added fibers to concrete beams, thereby increasing the compressive strength by 25%. Further to that, assuming that the fibers are randomly distributed, steel fibers can increase the tensile strength by 60%. Research by Smith et al. (2014) also highlights that strategically laying out steel fibers in a preferred direction increases the carrying capacity up to 4 times. The use of fibers in concrete also proved to be very effective in reducing the carbon footprint and cost of reinforcement structural concrete, as well as being eco-friendly and economical than conventional concrete for the same load-carrying capacity (Ali et al., 2020).

In Trinidad and Tobago (T&T), there are three major waste disposal sites, collectively receiving approximately 2,000 tons/day of Municipal solid waste, however, none of which operates as a sanitary landfill (Riquelme, Mendez, and Smith, 2016). Therefore, the use of RCA will contribute to recycling of this disposal material in landfills. The use of RCA in T&T is minimal due to the impurities and defects associated with the aggregates (Lalla and Mwasha, 2014), limiting its application to road filling in the country. However, waste from construction sites, such as RCA, can be recycled and reintroduced into the building life cycle. In a controlled study by Lalla and Mwasha (2014), using RCA from a concrete laboratory, the results indicated the compressive strength (CS) of RAC was comparative to that of its source material with a batch of 25% replacement.

While numerous recent studies (Bui et al., 2018; Wijayasundara et al., 2018; Chen, 2019; Rashid et al., 2020; Munir et al., 2020) examined incorporating RCA concrete in construction, there is a scarcity of information on the utilisation of coarse RCA as 100% replacement of NA. Further, the inclusion of steel fibers in concrete has provided promising results in improving its structural capabilities such as ductility, crack resistance, and flexural strength (Johnston 2001; Kosior-Kazberuk and Grzywa, 2014). Therefore, this study aimed to investigate the effects of RCA concrete on the mechanical properties (compressive strength, flexural behaviour, failure modes, strain and deflection) of structural members with and without the addition of steel fibers.

2. Experimental Programme

Various eco-productive NA and RCA concrete mixtures with and without steel wire fibers were manufactured. The properties of the ingredients utilised, mixture proportions, specimen preparation, and mechanical testing procedures are described below.

2.1 Materials

2.1.1 Portland Cement and Water

As was the case in Lalla and Mwasha (2014), a sample of Portland-Pozzolan Cement manufactured at Trinidad Cement Limited (TCL) was used. Table 1 shows the component and physical properties of the TCL Type 1 cement used. This type of cement, contains 15-40% by weight of pozzolan (fly ash). Natural (i.e., ordinary tap water) pipe borne water was used. Local tap borne water in Trinidad is slightly acidic. The content of humic and organic acids was at minimum. Portland cement of Grade 42.5N conforming to BS EN 197-112 (BSI, 1990) was used throughout the study for concrete production.

Table 1. Components and Physical Properties of the TCL Type 1 Cement

Component Name	%	Cas No.
Tri-calcium silicate	15-25	12168-85-3
Di-calcium silicate	75-85	10034-77-2
Tetra-calcium-alumino-sulphate	10-15	12068-35-8
Calcium sulphate	1-4	13397-24-5
Tri-calcium Aluminate	7-10	12042-78-3
Calcium Carbonate	0-5	1317-65-3
Magnesium Oxide	0-3	1309-48-4
Calcium Oxide	0-1	1305-78-8
Chromates	0-0.005	
Physical data *pH (in water) – 12 to 13* *Solubility in water – Slight (0.1 to 1.0 %) Specific gravity - ~3.04* *Appearance and Odour – solid, grey powder; no odour.*		

Source: TCL (2020)

2.1.2 Steel Fibers and Superplasticizer

Hooked end steel fibers, commercially known as Dramix-Type ZC, was used in this study. These fibers were 50 mm long and 0.5 mm diameter (aspect ratio, l/d = 100), as shown in Figure 1. Zhao et al. (2009) observed the tensile strength of the SFRC was enhanced more by steel fibers with a higher aspect ratio, since this improves the fiber-matrix bond. A superplasticizer (Conplast SP423) was added to ensure uniformity and fluidity in the recycled concrete mixtures.

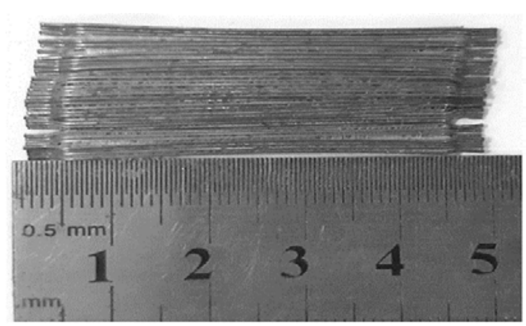

Figure 1. Dramix ZC 50/50 End Hooked Steel Fibers

2.1.3 Natural and Recycled Aggregates

The characteristics of the materials utilised in the investigation are highlighted in Table 2. The virgin aggregates used were 19 mm quartz and natural sand. Given the challenges experienced in procuring concrete demolition, the recycled concrete aggregate used in this research was produced from high strength concrete samples designed at The University of the West Indies having compressive strength greater than 35 MPa (nominal at 28 days) as indicated in Figure 2. The concrete samples were hammered to smaller sizes and then further crushed using a mechanical crusher to produce the required RCA aggregate sizes. The final gradation was selected after a continuous sieving process which was simultaneously done throughout the crushing process. The goal was to achieve a gradation similar to that of the existing available natural aggregate.

Figure 2. Recycled Concrete Cubes and Cylinders Used

Table 2. Fundamental Properties of the Aggregate Materials

Properties	NA	RCA	Test Standard
Water Absorption %	0.9	7.7	ASTM C127*
Particle Density (SSD) (mg/m^3)	2.58	2.33	ASTM C127*
Aggregate Impact Value (AIV) %	40	31	BS 812-112
Aggregate Crushing Value (ACV) %	42	32	BS 812-110
Load required for 10 percent fines (TFV) (kN)	71	77	BS 812-111
Voids Ratio (%)	44.3	46.8	ASTM C29*
Unit Weight of aggregate (kg/m^3)	1420	1173	ASTM C29*
LA Abrasion (%)	35	34	ASTM C131*

* - Sources: ASTM (2015, 2017, 2020)

This research observed RCA with a higher TFV than that of NA. The RCA were able to withstand a greater load to produce 10% of fine values. As indicated in Table 2, RCA is harder than the NA based on these tests and less breaking down of the RCA was observed. Researchers such as Silva et al. (2014) have similarly indicated that low AIV values indicate aggregates that are tougher and able to withstand more impact. Both the coarse NA and RCA aggregate met coarse aggregate particle distribution as highlighted in Figure 3. The gradation of the RCA is similar to that of the natural crushed-rock aggregate; however, it was very porous, angular and coarser than natural aggregate. Moreover, RCA had an average of 9% lower relative density and seven times higher water absorption than NA.

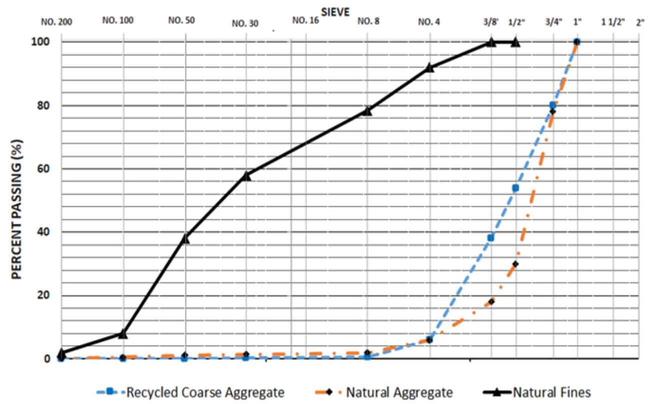

Figure 3. Aggregate Particle Distribution

2.2 Mixtures

As indicated in Table 3, the concrete mixture used in the study was all prepared using the mix ratios of water-to-cement of 0.44, fine-to-coarse of 0.4, total aggregate-to-cement of 3.38 and steel fiber-to-coarse aggregate to 0.016. The coarse aggregates consist of 67% of the total aggregates, thus the RCA replacement was 67% of the total aggregates. This is a 2:1 ratio for coarse-to-fine aggregates. Mix proportions were calculated based on the total mass of the samples. For all mixtures with steel fiber, a 0.4% superplasticizer quantity (by weight of cement) was sufficient to warrant the specified efflux time. The steel fibers were randomly distributed in the mix which aid in reducing the mixing and preparation time for test samples. Table 3 shows the mix types and combinations of materials used in the study.

Table 3. Natural and Recycle Concrete Mixture Proportions

Materials / Mix Type	Concrete with RCA	Concrete with NA	Concrete with RCA + steel fibers	Concrete with NA + steel fibers
water /l	16.6	15.6	15.2	15.9
cement /kg	37.8	36.2	34.7	36.2
fines /kg	51.1	49.0	46.8	49.0
coarse /kg	76.6	73.4	70.2	73.4
superplasticizer/ml	193	-	180	-
Steel Fibers /kg	-	-	2.7	2.7

2.3 Experimental Procedure

A total of sixty 150 mm∅ and twenty 100 mm∅ cylindrical samples were prepared for testing as per the ASTM C192 (ASTM, 2014). As per ASTM C39 (ASTM, 2021), the compressive strength testing was conducted on all cylinders at 7 and 28 days using the Triple Dial Face Hydraulic Compression Testing Machine. At day 7 curing, 2-100 mm∅ and 2-150 mm∅ cylinders were used, and at day 28, 3-100 mm and 3-150 mm cylinders. Cylinders were capped with Sulphur before they were crushed thus providing a smooth, even surface for loading. The compressive strength, density and failure modes were recorded.

The flexural strength of all the concrete mixtures was investigated using the three-point bending test method of ASTM C78 (ASTM, 2022), as highlighted in Figure 4. This test examined in detail the deflection, strain patterns and cracking of beams due to loading. Beams were tested after 28 days and were painted white to allow ease in identifying cracks. On the front face of the beams, demec points were placed to measure the strain in the beam during loading done at 5kN increments. Demec points were placed in a 3x3 grid pattern on the beam as shown in Figure 4, located on the top, middle and bottom of the beam.

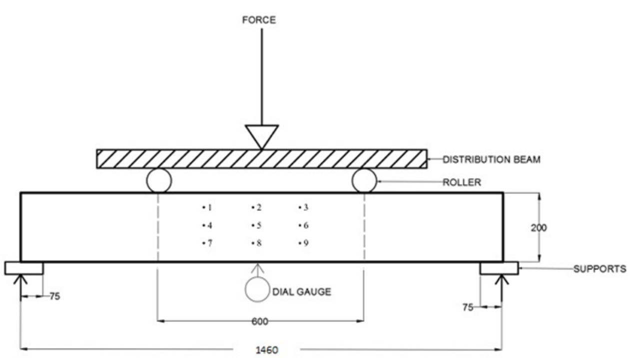

Figure 4. Third-point Loading of Reinforced Beam with 9 Demec Points

The points were spaced 100mm apart along each vertical line on the surface of the beam. The rows were placed 50mm apart, 50mm from the top of the beam. The 2 displacement readings are averaged together to create one displacement reading at the bottom, middle and top of the beam. These values were used to determine the beam compression and tension zones. Assuming the neutral axis is at the center of the beam since the concrete is of a homogenous mixture, a dial gauge was placed at midpoint below the beam to measure the deflection of the beam during loading. The initial deflection of the beam with no loading was set to zero on the dial gauge. Loading was done at a constant rate breaking point, which occurs when the deflection gauge fluctuates.

3. Results and Discussion

3.1 Bulk Properties of Concrete

Figure 5 illustrates the average bulk density of the tested mixtures. Concrete fabricated with RCA has a lower density than NA concrete. The attached mortar on the RCA causes the aggregates to be lighter than NA, which consequently produces densities that are much lower than NA (Behera et al., 2014; Kosior-Kazberuk and Grzywa, 2014). It was also observed that concrete made with NA+sf, and RCA+sf was denser than NA and RCA. This is due to the steel fibers that increase the overall weight of the concrete, thus increasing the density. This general trend was also found by McNeil and Kang (2013) and Ho et al. (2013).

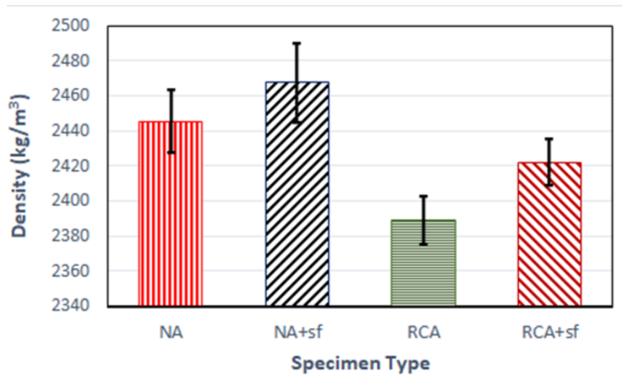

Figure 5. Average Bulk Densities of Mixtures

3.2 Concrete Compressive Strength

Figure 6 illustrates the average 7 and 28 days' compressive strength of both the 100 and 150 mm diameter samples for each of the various mixes. Mindess, Young and Darwin (2003) give a general rule: The ratio of 28-day to seven-day strength lies between 1.3 and 1.7 and generally is less than 1.5, or the seven-day strength is normally between 60% to 75% of the 28-day strength and usually above 65%. In the case of this study, the compressive strength for both NAC and RAC ranged between 1.1 and 13. RCA properties as shown in Figure 6 have a higher compressive strength than NA, which also mirrors the results from the mechanical properties of the aggregates. The range of increase was between 0 – 25%. This finding is not typical as noted by McNeil and Kang (2013); however, this study used a non-traditional source of RCA, that being from a University concrete laboratory as opposed to a demolished structure. The smaller diameter (100 mm) specimens had lower compressive strength than the larger diameter. This can be correlated to the surface area accuracy in determining the compressive strength. A 100 mm diameter cylindrical concrete sample has a lesser surface area thus requiring a lesser amount of load to break the cylinder for the same compressive strength of concrete. However, 150mm concrete cylinders have a greater surface area hence more weight has to be applied to the concrete cylinder to get the required similar compressive strength.

The RCA mixes had a 5% increase in compressive strength compared to NA, while fiber reinforced RCA had a significant increase of 28% to fiber reinforced NA concrete (NA+sf). Fiber reinforced NA concrete (NA+sf) had a 4% increase in compressive strength when compared to NA concrete without steel fibers. Whilst research by Chanh (2005) and Kosior-Kazberuk and Grzywa (2014) found that fibers do not significantly increase compressive strength of concrete, this was not the case in this study. Additionally, as indicated by Smith et al. (2014), further increase in the fiber concrete compressive strength could have been achieved had the steel fibers been strategically laid out by varying the lengths and placing in preferred direction.

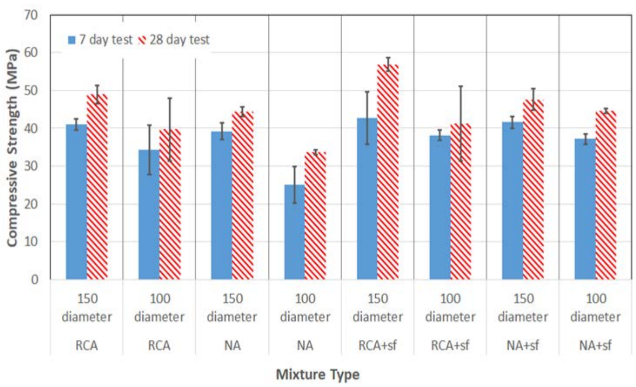

Figure 6: Average Compressive Strength of Mixtures

3.3 Concrete Beams Failure Patterns and Modes

The patterns and mode of specimens' failure were influenced by the steel wire fiber content. Like failure patterns by Kosior-Kazberuk and Grzywa (2014), the shape of the fiber reinforced concrete specimens remained the same under destructive load. Table 4 summarises the failure modes of the samples, as per ASTM C39 (ASTM, 2021).. The NA and RCA concrete made without steel fibers showed similar columnar, shear and splitting failure modes. NA concrete had greater fracture than RCA, which can be the consequence of the mortar coating on the RCA that causes the aggregates to fail at the ITZ (Behera et al., 2014; Kosior-Kazberuk and Grzywa, 2014; McNeil and Kang, 2013).

Table 4. Summary of Failure Types of Concrete Cylinders

Concrete Type	NA	NA+sf	RCA	RCA+sf
100mm	Columnar; Shear;	Column;	Column; Shear;	Column;
150mm	Cone and split; Aggregate failure; Bond failure; Cone and shear; Large cone deformation;	Shear;	Aggregate failure; Shear and cone; Cone and split;	Shear (spiral);

Figure 7 gives a visual depiction of the failure modes and patterns of the 100, 150 mm diameter cylindrical specimens at 28-day strength. RCA had a larger failure region than the NA, although the RCA concrete was more resistant to compression. NA samples mainly experienced bond failure, where the cement paste split from the aggregate. The samples with steel fibers maintained their shape when subjected to axial loading, regardless of the aggregate type. This finding may be attributed to the steel fibers ability to increase splitting tensile strength, especially in SFRC with more than 1% (Zhang et al., 2017; Zheng et al. 2018).

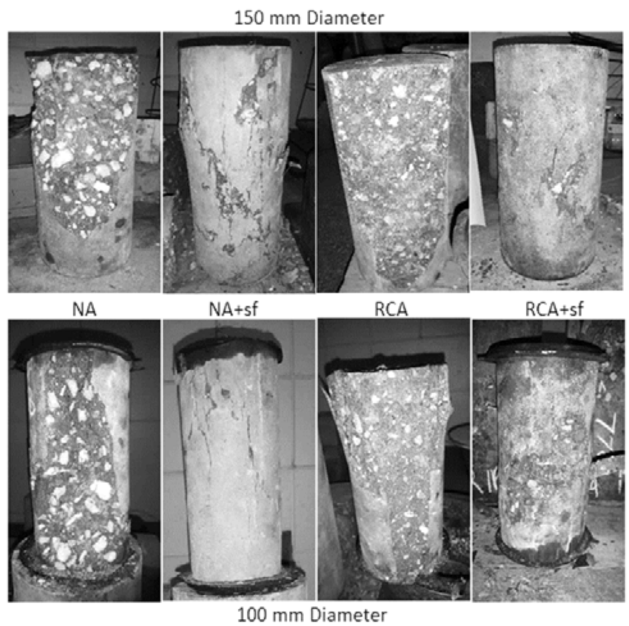

Figure 7. Failure Modes and Patterns of Cylindrical Concrete Specimens

3.4 Flexural Behaviour

To evaluate the tensile behaviour and patterns of the concrete, a total of 12 beams were tested using third-point loading. Evaluation of strain, deflection and cracking pattern were recorded. At the initial cracking at the load of 15kN, similar patterns were observed. This was a subjective analysis, done by observation. The average failure loads of the NA, NA+sf, RCA, and RCA+sf were 55 kN, 67 kN, 60 kN and 67 kN, respectively.

As the loading increased, the width of the cracks also increased. Beams made with NA had less visible cracks when compared to beams with RCA. Therefore, it can be concluded that the steel fibers in RC beams increase the number of cracks and decrease the average crack width due to the higher ductility behaviour of SFARC beams.

As commonly observed in numerous studies (Chanh 2005; Biolzi and Cattaneo, 2017; Zhang et al., 2017; Lee et al., 2018; Aslani et al., 2019; Chalioris et al.,2019), the samples with steel fibers experienced a reduced cracking width regardless of aggregate type as shown in Figure 8.

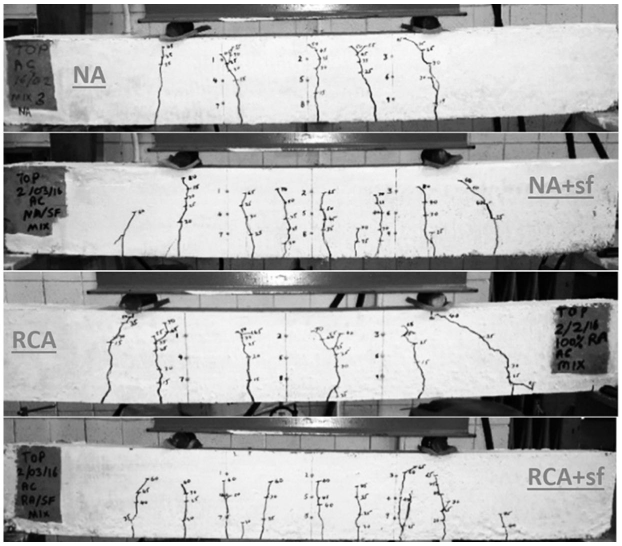

Figure 8. Cracking Patterns for Concrete Beams

3.4.1 Strain

Based on the strain values, all 12 beams experienced compression to the top and tension to the bottom. A reduction in the strain values on the first row of demec points infer compression and an increase in the strain values in the bottom row infer tension. The row in the center (neutral axis) had an increase in strain, hence it experiences tension. It was observed that the concrete beams fabricated with steel fibers measured less strain than beams without steel fibers. Furthermore, tension cracking and strain decreased as the steel absorbed energy and bridged cracks. The strain-load shown in Figure 9, indicates significant changes in strain at the middle and bottom of the beams as load increases.

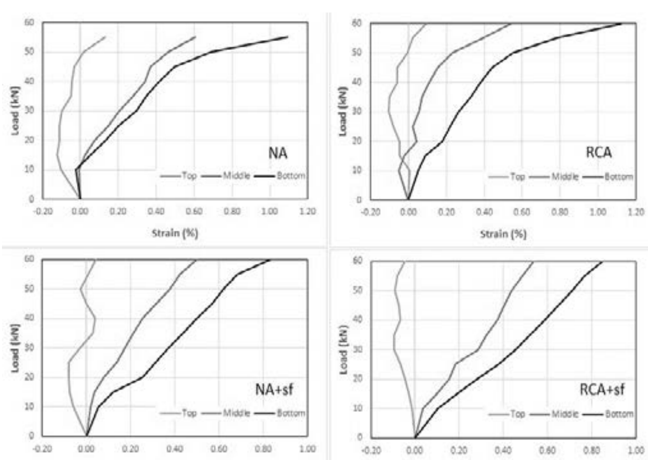

Figure 9. Load vs Strain Curves for Concrete Beams due to Flexural Loading

3.4.2 Deflection

Beam deflection was measured at midpoint and the values for each RCA and NA mix was plotted in Figure 10. The results show the consistently higher resistance to deflection of RAC with steel fibers to loading when compared to RAC without steel fibers. Lok and Pei (1998) and Kosior-Kazberuk and Grzywa (2014) also found that the steel fibers caused the beam to be more ductile given the reduced level of cracking. The beams made with SF had an average failure load of 60kN and above as compared to the beams made without, failing at 55kN. Hence, RCA could be used as a replacement for NCA when SFs were used, with no considerable reduction in the tensile strength.

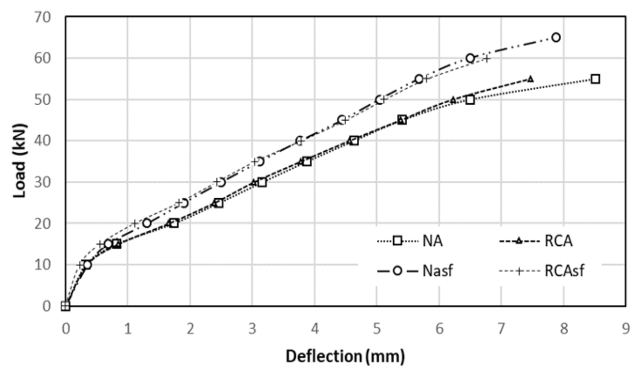

Figure 10. Load vs Average Deflection for Concrete Beams

4. Conclusion

This research was conducted to investigate the effects of RCA use on the mechanical properties of concrete (compressive strength, failure modes, flexural behaviour, strain and deflection) and the impact of RCA on structural members with and without the addition of steel fibers.

Customarily, NA concrete compressive strength exceeds that of RCA concrete, however, this study revealed the inverse. This was true for both RCA concrete with and without SF. This was attributed to the high strength RCA being sourced from a concrete laboratory as opposed to the typical demolished structure. Nonetheless, this finding shows the potential for concrete with 100% RCA and RCA_{sf} to be used in structural members.

Under axial compression, the common failure modes were splitting or columnar failures in 100mm∅ cylinders and shear failure in the 150mm∅ cylinders. However, cylinders with SF revealed less types of failure modes than those without. This was attributed to the SFs capability to increase splitting tensile strength, particularly in SFRC with more than 1%.

The flexural behaviour of twelve reinforced concrete beams being influenced by SF was examined using the third-point loading test method to determine the strain and deflection of the structural members. The average failure loads of NA, $NA_{sf,}$ RCA, and RCA_{sf} were 55kN, 67kN, 60kN, and 67 kN, respectively. Based on the data obtained, structural members fabricated with steel fibers measured a decrease in tension cracking and strain because of the ability of the steel fibers to absorb energy and bridge cracks. The general trends observed indicate that coarse RCA with strengths higher than NA and the combinations of steel fibers can be used to produce high strength concrete mixes. This shows satisfactory improvements in the engineering properties, namely compressive strength, flexural strength, strain and deflections.

The properties of the high-strength coarse RCA, obtained from concrete laboratory waste cylinders and cubes, can be used in high strength concrete and structural members. However, the suitability and effects of varying strengths of RCA should be examined in future studies. Changing the RCA strength from weak to high strength Portland cement concrete can map the effects of RCA strength on mix behaviour. Likewise, it is vital to acknowledge that there should be a move to introduce new standards for recycled aggregates use and illustrate that these materials can be used utilised effectively in practice, under a range of various conditions.

Acknowledgements

The authors would like to acknowledge and thank all the technicians of the Structural and Concrete laboratory in the Department of Civil and Environmental Engineering, UWI, St Augustine Campus, for their assistance.

References:

Ali, B., Qureshi, L.A., and Kurda, R. (2020), "Environmental and economic benefits of steel, glass, and polypropylene fiber reinforced cement composite application in jointed plain concrete pavement", *Composites Communications*, Vol.22, pp.100437.

Arulrajah, A., Piratheepan, J., Ali, M.M.Y., and Bo, M.W. (2012), Geotechnical properties of recycled concrete aggregate in pavement sub-base applications", *Geotechnical Testing Journal*, Vol.35, No.5, pp.743-751.

Aslani, F., Hou, L., Nejadi, S., Sun, J., and Abbasi, S. (2019), "Experimental analysis of fiber-reinforced recycled aggregate self-compacting concrete using waste recycled concrete aggregates, polypropylene, and steel fibers", *Structural Concrete*, Vol.20, No.5, pp.1670-1683.

ASTM (2014), *ASTM C192_C0192M-14: Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory*, ASTM (American Society for Testing and Materials) International, West Conshohocken, PA, USA.

ASTM (2015), *ASTM C 127-15: Standard Test Method for Relative* Density (Specific Gravity) and Absorption of Coarse Aggregate, ASTM (American Society for Testing and Materials) International, West Conshohocken, PA, USA.

ASTM (2017), *ASTM C 29-2017A: Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate*, ASTM (American Society for Testing and Materials) International, West Conshohocken, PA, USA.

ASTM (2020), *ASTM C 131_M131-20: Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine*, ASTM (American Society for Testing and Materials) International, West Conshohocken, PA, USA.

ASTM (2021), *ASTM C 39_C0039-M21: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*, ASTM (American Society for Testing and Materials) International, West Conshohocken, PA, USA.

ASTM (2022), *ASTM C 78_C0078M-22: Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)*. ASTM (American Society for Testing and Materials) International, West Conshohocken, PA, USA.

Behera, M., Bhattacharyya, S.K., Minocha, A.K., Deoliya, R., and Maiti, S. (2014), "Recycled aggregate from C&D waste & its use in concrete–A breakthrough towards sustainability in construction sector: A review", *Construction and Building Materials*, Vol.68, pp.501-516. doi:10.1016/j.conbuildmat.2014.07.003.

Biolzi, L., and Cattaneo, S. (2017), "Response of steel fiber reinforced high strength concrete beams: Experiments and code predictions", *Cement and Concrete Composites*, Vol.77, pp.1-13.

Braunschweig, A., Kytzia, S., and Bischof, S. (2012), "Recycled concrete: Environmentally beneficial over virgin concrete", *Proceedings of the XVI ERMCO Congress*, Berlin, Germany, 21–22 June 2012, p.12.

BSI (1990), *BS 812-112:1990. Testing aggregates. Method for determination of Aggregate Impact Value (AIV)*, British Standards Institution, London, UK.

Bui, N.K., Satomi, T., and Takahashi, H. (2018), "Mechanical properties of concrete containing 100% treated coarse recycled concrete aggregate", *Construction and Building Materials*, Vol.163, pp.496-507.

Chalioris, C.E., Kosmidou, P.M.K., and Karayannis, C.G. (2019), "Cyclic response of steel fiber reinforced concrete slender beams: An experimental study", *Materials*, Vol.12, No.9, pp.1398.

Chandler, D. (2019), "New Approach Suggests Path to Emissions-Free Cement", Available online: http://news.mit.edu/2019/carbondioxide-emissions-free-cement-0916 (accessed on 20 December 2020).

Chanh, N.V. (2005), *Steel Fiber Reinforced Concrete*, Ho Chi Minh City University of Technology, Vietnam.

Chen, Y., Chen, Z., Xu, J., Lui, E. M., and Wu, B. (2019), "Performance evaluation of recycled aggregate concrete under multiaxial compression", *Construction and Building Materials*, Vol.229, pp.116935.

DesRoches, R.R., Kurtis, K.E., and Gresham, J.J. (2011), "Breaking the reconstruction logjam", *American Ceramic Society Bulletin*, Vol.90, No.1, pp.20-28.

Faleschini, F., Zanini, M., and Pellegrino, C. (2016), "Environmental impacts of recycled aggregate concrete. Italian Concrete Days", Proceedings of the Giornate Aicap 2016 Congresso CTE, available at: https://www.researchgate.net/publication/311517943_Environmental_impacts_of_recycled_aggregate_concrete

FHA (2013), "Federal Highway Administration", US Department of Transport, available at: http://www.fhwa.dot.gov/ (Assessed February 2013)

Fiol, F., Thomas, C., Munoz, C., Lopez, V., and Manso, J.M. (2018), "The influence of recycled aggregates from precast elements on the mechanical properties of structural self-compacting concrete", *Construction and Building Materials*, Vol.182, pp.309-323.

Gao, D., Zhang, L., Zhao, J., and You, P. (2020), "Durability of steel fiber-reinforced recycled coarse aggregate concrete", *Construction and Building Materials*, Vol.232, pp.117119. https://doi.org/10.1016/j.conbuildmat.2019.117119.

Ginga, C.P., Ongpeng, J.M.C., and Daly, M.K.M. (2020), "Circular economy on construction and demolition waste: A literature review on material recovery and production", *Materials*, Vol.13, pp.2970. https://doi.org/10.3390/ma13132970

Ho, N.Y., Lee, YPK, Lim, W.F., Ting, S.K., Chew, K.C., and Low, G.L. (2015), "Evaluation of RCA concrete for the construction of Samwoh Eco-Green Building", *Magazine of Concrete Research*, ICE, Vol.67, No.12, pp.633-644.

Huang, B., Wang, X., Kua, H., Geng, Y., and Bleischwitz, R. (2018), "Construction and demolition waste management in China through the 3R principle", *Resources, Conservation and Recycling*, Vol.129, pp.36-44.

Jayakody Arachchige, S.P., Gallage, C., and Kumar, A. (2014), "Assessment of recycled concrete aggregates as a pavement material", *Geomechanics and Engineering*, Vol.6, No.3, pp.235-248.

Johnston, C.D. (2001), *Fiber-reinforced Cements and Concretes*, Gordon and Breach, Amsterdam, the Netherlands

Kosior-Kazberuk, M, and Grzywa, M. (2014), "Recycled aggregate concrete as material for reinforced concrete structures", *Journal of Sustainable Architecture and Civil Engineering*, Vol.2, No.7, pp.60-66.

Lalla, J.R.F. and Mwasha, A. (2014), "Investigating the compressive strengths of Guanapo recycled aggregate concrete as compared to that of its waste material", *The West Indian Journal of Engineering*, Vol.36, No.2, pp.12-19.

Lee, J.Y., Shin, H.O., Yoo, D.Y., and Yoon, Y.S. (2018), "Structural response of steel-fiber-reinforced concrete beams under various loading rates", *Engineering Structures*, Vol.156, pp.271-283.

Lee, Y.P.K., Lim, W.F., Ting, S.K., Chew, K.C., Zayed, T., Ho, N.Y., and Low, G.L. (2013), "Efficient utilisation of recycled concrete aggregate in structural concrete", *Journal of Materials in Civil Engineering* ASCE, Vol.25, No.3, pp.318-327.

Limbachiya, M.C. (2004), "Coarse recycled aggregates for use in new concrete", *Proceedings of the Institution of Civil Engineers-Engineering Sustainability*, Vol.157, No. 2, pp. 99-106.

Limbachiya, M.C., Leelawat, T., and Dhir, R.K. (2000), "Use of recycled concrete aggregate in high-strength concrete", *Materials and Structures*, Vol.33, No.9, pp.574-580.

Lok, T-S. and Pei, J-S. (1998), "Flexural behaviour of steel fiber reinforced concrete", *Journal of Materials in Civil Engineering*, Vol.10, No.2, https://doi.org/10.1061/(ASCE)0899-1561(1998)10:2(86)

Malešev, M., Radonjanin, V., and Marinković, S. (2010), "Recycled concrete as aggregate for structural concrete production", *Sustainability*, Vol.2, No.5, pp.1204-1225. doi: 10.3390/su2051204.

Marinković, S., Radonjanin, V., Malešev, M., and Ignjatović, I. (2010), "Comparative environmental assessment of natural and recycled aggregate concrete", *Waste Management*, Vol.30, No.11, pp.2255-2264. doi.org/10.1016/j.wasman.2010.04.012.

McNeil, K., and Kang, T.H.K. (2013), "Recycled concrete aggregates: A review", *International Journal of Concrete Structures and Materials*, Vol.7, No.1, pp.61-69. doi: 10.1007/s40069-013-0032-5

Merli, R., Preziosi, M., Acampora, A., Lucchetti, M.C., and Petrucci, E. (2020), "Recycled fibers in reinforced concrete: A systematic literature review", *Journal of Cleaner Production*, Vol.248, pp.119207. doi.org/10.1016/j.jclepro.2019.119207.

Mindess, S., Francis Young, J., and Darwin, D. (2003), *Concrete*, 2nd Edition, Pearson

Monrose, J., Tota-Maharaj, K., Mwasha, A., and Hills, C. (2020), "Effect of carbon-negative aggregates on the strength properties of concrete for permeable pavements", *International Journal of Pavement Engineering*, Vol.21, No.14, pp.1823-1831. doi.org/10.1080/10298436.2019.1567924.

Munir, M.J., Kazmi, S.M.S., Wu, Y. F., Patnaikuni, I., Zhou, Y., and Xing, F. (2020), "Stress strain performance of steel spiral confined recycled aggregate concrete", *Cement and Concrete Composites*, Vol.108, pp.103535.

Rashid, K., Rehman, M.U., de Brito, J., and Ghafoor, H. (2020), "Multi-criteria optimisation of recycled aggregate concrete mixes", *Journal of Cleaner Production*, Vol.276, pp.124316.

Riquelme, R., Mendez, P., and Smith, L. (2016), "Solid waste management in the Caribbean: Proceedings from the Caribbean Solid Waste Conference", Technical Note No. IDB-TN-935, April 2016,

Silva, R.V., De Brito, J. and Dhir, R.K. (2014), "Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production", *Construction and Building Materials*, Vol.65, pp.201-217.

Smith, J., Cusatic, G., Pelessone, D., Landis, E., O'Daniel, J., and Baylot, J. (2014), "Discrete modelling of ultra-high-performance concrete with application to projectile penetration", *International Journal of Impact Engineering*, Vol.65, pp.13-32. doi: 10.1016/j.ijimpeng.2013.10.008.

Smith, J., Rampit, R., and Parey, R. (2018), "Characterisation of vibration effects on the internal structure and strength of regular and high strength recycled concrete", *Proceedings of the 6th International Conference on Durability and Concrete Structures*, University of Leeds, UK, July 18-20, 2018, pp.703-710.

TCL (2020), "Material Safety Data Sheet", Trinidad Cement Limited, available at: http://www.tclgroup.com/wp-content/uploads/2020/11/TCL-CEMENT-MSDS.pdf. (Accessed 2021)

Weil, M., Jeske, U., and Schebek, L. (2006), "Closed-loop recycling of construction and demolition waste in Germany in view of stricter environmental threshold values", *Waste Management and Research*, Vol.24, pp.197-206.

Wijayasundara, M., Mendis, P., and Crawford, R.H. (2018), "Integrated assessment of the use of recycled concrete aggregate replacing natural aggregate in structural concrete", *Journal of Cleaner Production*, Vol.174, pp.591-604.

Zhang, T., Zheng, G., Song, H., Wei, M., Shao, J., and Zhou, Y. (2017), "Steel fiber volume fraction and splitting tensile strength of steel fiber reinforced concrete", *Proceedings of the International Conference on Advances in Materials, Machinery, Electrical Engineering (AMMEE 2017)/ Advances in Engineering Research*, Vol.114, pp.5-8.

Zhao, J., Gao, D.Y. and Du, X.L. (2009), "Seismic behaviour of steel fiber reinforced concrete low-rise shear wall", *Journal of Earthquake Engineering and Engineering Vibration*, Vol.29, No.4, pp.103-108.

Zheng, Y., Wu, X., He, G., Shang, Q., Xu, J., and Sun, Y. (2018), "Mechanical properties of steel fiber-reinforced concrete by vibratory mixing technology", *Advances in Civil Engineering*, Vol.2018, Article ID.9025715, 11 pages. https://doi.org/10.1155/2018/9025715.

Authors' Biographical Notes:

Leighton A. Ellis *is a Senior Lecturer in Civil Engineering at The University of the West Indies, Mona Campus and has served as the Deputy Dean for 3 years in the Faculty of Engineering. Dr. Ellis holds a Ph.D. and MSc. Degrees in Construction Engineering from the UWI, Trinidad, and a BSc in Construction Engineering from the University of Technology, Jamaica. He also holds an MBA in Leadership, Entrepreneurship and Innovation from Anglia Ruskin University, United Kingdom. Dr. Ellis is a Chartered Civil Engineer (CEng MICE) with Institution of Civil Engineers (ICE) and is registered with the Engineering Council (ECUK). He is also a registered Professional Engineer with the relevant engineering associations bodies in Trinidad and Tobago and Jamaica. He currently serves as the ICE Representative for Jamaica and the Civil Division Chairperson with the Jamaica Institution of Engineers (JIE). His main research interests are in the areas of Sustainable Construction, Circular Economy, Engineering Leadership and Innovation.*

Lee P. Leon *holds a BSc, MSc and PhD in Civil Engineering and is currently a Lecturer in Highway/Pavement Engineering, Department of Civil and Environmental Engineering, The University of the West Indies. He is a young academic who has*

authored or co-authored in peer reviewed journals, conference proceedings, and several technical reports. He has also worked on research on behalf of state and private agencies in the area of pavement materials and performance. His area of research also includes the use of soft computing techniques in civil engineering applications. Dr Leon holds membership in CIHT (member and interim CEng), ASCE (associated member), APETT (member) and ISAP (voting member).

Amy V. Charran *graduated in 2016 with a BSc in Civil Engineering from the Department of Civil and Environmental Engineering, at The University of the West Indies. She has gained professional experience as an Engineering Technician and Engineering Analyst in Florida.*

■