Mechanical and Durability Properties of Concrete Mixes Containing Coarse Recycled Aggregates and Supplementary Cementations Materials for Interlocking Concrete Pavers

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Abstract

The use of coarse recycled concrete aggregates (CRCA) in concrete as a substitute for natural aggregate (NA) has lately sparked a lot of attention. As more study into its performance has been undertaken, the usage of CRCA is gaining acceptability. In the same way, including supplementary cementitious materials (SCMs) in concrete mixes helps to reduce cement usage and carbon dioxide emissions. The substitution of NA for CRCA and conventional cement with SCMs is a potential step toward a more sustainable concrete that conserves natural resources while lowering concrete's environmental effect. As a result, using these materials is an environmentally friendly solution. This paper includes research on the mechanical and durability qualities of concrete mixes including CRCA and SCMs for use in interlocking concrete pavers (ICP). The performance of three concrete mixes with varying percentages of CRCA and SCMs (0%, 20% and 40%) and (0%, 20% and 30%) respectively is compared to the control mix. Ground Glass Pozzolans (GP), Limestone Cement (GUL), and Slag were employed as SCMs in this investigation. After the air voids and slumps are measured, the compressive strength of various mixtures at different curing times (1, 7, and 28 days), water absorption and freeze-thaw resistance are evaluated. The obtained results indicate that the water-cement (w/c) ratio in each concrete mix changed in order to achieve the slump value of 55 ± 5 mm. Furthermore, the outcomes revealed that the w/c ratio of mixes with just the CRCA was higher than that of the control mix and the mixes with combination of CRCA and SCM was almost equal to that of control mix. The findings also demonstrate that adding SCMs to concrete mixtures enhances the water absorption resistance substantially. Compressive strength values of all the mixes were comparable to that of the control mix. However, CRCA-containing mixtures had a lower strength value than others mixes. Interestingly, the freezing-thawing test results demonstrated that the mass loss of the mixes with CRCA and SCMs was lower than the control mix by 57% to 77%. Finally, the findings of this research provide compelling evidence to support the use of CRCA and SCMs to partly replace NA and conventional cement in concrete, serving as a step towards a more sustainable concrete construction.

Keywords: Coarse recycled concrete aggregate (CRCA), Supplementary cementitious materials (SCMs), Slag, Ground Glass Pozzolans (GP), Limestone Cement (GUL), Sustainable concrete

Introduction

In today's construction sector, natural resource depletion is becoming a major concern. As a result of population increase, fast industrialization, and the introduction of new technologies, raw material consumption has become excessive Concrete is used in several infrastructures, including roads, bridges, buildings and tunnels. These concrete constructions are demolished, and the waste is disposed of in landfills when they reach the end of their service life or need to be replaced. Another critical issue due to population growth is rapid urbanization, and due to this, it is essential to design urban roads that can withstand heavy loads while also responding to the public transportation system.

Concrete recycling as aggregate for concrete mixes has recently become a commercially feasible concrete alternative. Recycled Concrete Aggregate (RCA) is a composite material composed of natural aggregate (NA) and an adhering mortar layer formed by breaking large chunks of concrete into smaller pieces (Paranavithana and Mohajerani 2006). The use of RCA has garnered a variety of responses. Many are concerned about the unpredictability and uncertainty of the RCA's origin and what the RCA had previously been exposed to (Gokce et al. 2004). Many researchers have continued to study the effect of RCA on concrete properties due to its sustainability and economic benefits. On the other hand, mineral admixtures have been used as supplementary cementitious materials (SCMs) in portland cement or as a constituent in blended cement. SCMs used to partially replace cement are typically steel industry waste. Fly ash, metakaolin, and ground granulated blast furnace slag are the most generally used SCMs (Kou, Poon, and Agrela 2011). The use of SCM reduces cement production, lowering fossil fuel consumption and greenhouse gas (GHG) emissions, which helps cement-based material construction (Omran et al. 2018); It Also reduces the waste from the steel industry going to the landfills, thus, making its use in concrete a sustainable option.

On the other hand, the usage of interlocking concrete pavement (ICP) dates back to the nineteenth century, and ICP has seen tremendous development since then, with significant research still being conducted. ICP is used in a various of applications, such as driveways, crosswalks, sidewalks, parking lots, ports, and airport (Garilli et al. 2020). The use of ICP can address the majority of urban pavement issues, such as accelerated pavement deterioration caused by high traffic volumes in urban areas. Thus, due to the large volume and frequency of traffic on urban roadways, repairing and rehabilitating deteriorated pavement is highly challenging, and keeping these roads closed can have significant economic effects. ICPs are manufactured in industrial and manufacturing facilities, due to which the potential defects caused by on-site conditions are eliminated and results in higher quality and more durable pavement than the conventional one (Vaitkus et al. 2019). ICP's can be built in cold or hot weather, therefore there is no seasonal restriction to when they can be installed. ICPs are precast and can be transported to the site, installed, and opened to traffic immediately. In contrast, the conventional concrete pavement must be cured to gain strength before being opened to traffic (Delatte, 2014). These characteristics of ICPs make them an excellent choice of pavement for urban traffic.

To address the issues of urban traffic, natural resource depletion and disposal of waste concrete in landfill, this paper attempts to utilize CRCA and SCMs in ICPs and evaluate their mechanical and durability performance. The performance of concrete mixtures with varying percentages of CRCA and SCM's has been compared with the control mix. Fresh properties of concrete such as slump and air void and hardened properties like compressive strength, water absorption and resistance to freeze-thaw are studied in this paper.

Experimental program

Materials

General use limestone cement (GUL) with 11.3% limestone powder content that meets the requirements of the CAN/CSA-A3001 standard is used. Ground Granulated Blast Furnace Slag (GGBFS) and ground glass puzzolan (GP) are used as SCMs to replace cement in the concrete mixtures partially. The properties of cement and SCM are given in Table 1. The Micro synthetic fibre used in this study meets the ASTM C 1116 requirements and is used as reinforcement in the concrete mixes. The physical properties of the micro synthetic fibre used in this study is shown below in Table 2.

Natural aggregates (NA) and Coarse recycled aggregates (CRCA) with a maximum size of 20 mm are used in this study. The particle shape of the NA is irregular/rounded and has a smooth/rough surface texture. The CRCA used in this study was obtained from a ready-mix concrete plant by crushing concrete with undesirable properties, performance, and age. The fraction of RCA retained during sieving that ranges between 4.75 mm, and 19 mm was used in the study as the CRCA. The retained materials were thoroughly washed to remove as much adhered mortar as possible before being oven-dried at 110° 5° C and graded using a mechanical shaker. The properties of CRCA and NA used for this study are given in Table 3. BASF Micro-Air was used as an air-entraining admixture (AEA) in all mixes and BASF Pozzolith 100 XR as a water-reducing admixture (WRA).

Three concrete mixtures with CRCA and SCM replacement and a control mix were designed and prepared for this study. To replace the NA and cement content in the concrete mixes, different percentages of CRCA and SCMs (0 percent, 20%, and 40%) and (0 percent, 20%, and 30%) are utilized, respectively. The CRCA and SCM replacement levels were used to differentiate the sample sets. A naming convention for the various concrete types was adopted to keep track of the variables, as shown in Table 4. Each concrete type was given a name based on three distinct elements. The mixtures are labelled RCx/Sy/Gz, with RC standing for CRCA and "x" representing the percentage replacement. The letter S indicates the presence of GGBFS in the concrete mixture, while the letter "y" indicates the percentage of cement replaced by GGBFS. G denotes GP in concrete mixtures, and "z" denotes the percentage of cement replaced with GP. The two-stage mixing approach (TSMA) was used in the batching procedure (Tam, Gao, and Tam 2006).

First, the fine aggregates were added to the concrete mixer's drum, after which all cementitious materials, including SCMs, were manually mixed. After that, the coarse aggregates were added, followed by half of the mixing water, and mixed to begin the aggregate coating. Along with the water, the AE and

WR admixtures were added. The remaining water was then added and mixed into the fresh concrete until it was homogeneous.

Test Methods

Slump and Air Content

The fresh concrete's slump was determined using the procedures outlined in CSA A23.2-5C (Canadian Standards Association 2019). A conventional cone with a top diameter of 100 mm, a bottom diameter of 200 mm, and a height of 300 mm was employed for the testing. In the moist mould, three equal volumes of fresh concrete were placed. A 16 mm diameter steel tamping rod with a rounded end was used in this experiment. Each layer of concrete received 25 blows to the surface. After the third layer of concrete was placed and rodded, the surface of the concrete was levelled. The cone was hoisted vertically for about 5 seconds after the surface layer was levelled. The cone was then flipped over and placed alongside the concrete as a reference for measuring the vertical displacement of the top level of the concrete. To account for the differential settlement of the top layer, the average value of the three measurements was used.

Using the CSA A23.2-4C procedures, the air content of the concrete mixtures was determined. The concrete was consolidated in a pressure vessel. The pressure vessel employed in this investigation was cylindrical, with an interior diameter of 206mm and a height of approximately 212 mm. Three equal layers of concrete were laid and rodded; following rodding; each layer was consolidated with a rubber mallet to ensure that most of entrapped air bubbles in the concrete mixture were released. The vessel was then filled and levelled. The pressure cylinder's lid was air-tightly fastened to the vessel. Any cavities between the lid and the concrete surface were filled with water, and the vessel was filled to a certain pressure with air. The amount of air that could penetrate the concrete indicated the air content of the concrete. Following that, the air content values were recorded.

Compressive strength

The compressive strength tests were carried out in accordance with CSA A.231. Using a compressive strength testing machine, each mixture's compressive strength was measured using 100 x 200 mm concrete cylinders at 1, 7, and 28 days. All of the findings were recorded and presented as a three-test-sample average. The top and bottom surfaces of the specimen were cleaned, and the specimen's axis was aligned with the bearing block's centre in the testing area. A constant load of 0.25 ± 0.05 MPa/s was applied. The maximum load resisted by the sample was recorded once the sample began to fail.

Water Absorption and Freeze-thaw durability

CSA A23.2-11C was used to conduct the water absorption test. The test was conducted using 100 x 200 mm cylinders. Each specimen's oven-dried mass was obtained by placing it in an oven at a temperature of 100 to 110 ° C for 24 hours. After that, the saturated mass of the samples was determined by immersing them in water at 21° C for 48 hours using a 200 x 300 mm container. The samples were immersed until two successive measurements of the surface-dried samples' mass at 24-hour intervals indicated constant mass. The water absorption capability was calculated as shown in the equation:

$$Absorption\ after\ immersion, \% = \left[\frac{B - A}{A}\right] * 100$$

Where:
A = mass of oven-dried sample in g
B = mass of surface- dry sample in air after immersion in g
The freeze-thaw durability test was performed in accordance with CSA A.231.2-7.3. The test specimens were 100 x 200 mm cylinders that had been brushed clean and had all loose burrs and edges removed. Before beginning the freeze-thaw test, the samples were placed in 200 x 300 mm containers and immersed in a solution containing 3 ± 0.1 percent sodium chloride for 24 hours at a minimum temperature of 15 °C. The specimens were subjected to a continuous freeze-thaw cycle, with one cycle completed every 24 hours, and each cycle consisting of 16 ± 1 hour of cooling followed by 8 ± 1 hour of heating. The specimens were exposed to a minimum temperature of -18 °C for 16 ± 1 hour, followed by 8 ± 1 hour at room temperature. Each sample's mass loss was measured at 7 and 28 cycles, respectively. The specimens were washed with distilled water after 7 and 28 cycles to remove any loose particles. The particles and spalled material were collected and filtered through an 80µm sieve before being dried to a constant mass in a drying oven for 24 ± 1 h. This residue is referred to as the mass loss and is measured in grams.

Results and Discussion

Table 5 summarizes the findings of the study. For each test, the averages of three measurements are obtained.

Slump and Air void

The slump value of 55 ± 5 mm was observed to be consistent across all mixtures. These slump values indicate that the mixtures are workable to a medium degree. However, the w/c ratio for each mixture varied to achieve the slump value of 55 ± 5 mm. All of the mixes, including CM, had w/c ratios less than 0.5, as seen in Table 5. The RC 20 mixture has the highest w/c ratio value. Higher percentages of CRCA explain the higher w/c ratio values in this mixture. The characteristics of CRCA can be seen to be dependent on the residual mortar adhering to the aggregates, as the mortar content increases, the CRCA has a higher porosity and thus a higher water demand (Cahyani and Rusdianto 2021; Yehia et al. 2015). Despite the presence of CRCA in the mixtures, the w/c ratios of RC 20/S 20 and RC 40/S 20/G 10 are lower or equal to CM. The presence of SCM can be attributed to the lower demand for water in these mixes. SCM particles that are smooth and dense absorb less water than Portland cement particles, making SCM-containing concrete more workable (Cahyani and Rusdianto 2021).
According to the CSA A23.1 specification, the results show that all of the mixtures met the 5-8 percent air content specifications. The results show that all mixtures had comparable air void content to the CM. Air content was measured immediately after mixing to ensure that all mixtures met the standards. To meet the requirements, an air-entraining agent (AEA) was used in all the mixtures.

Compressive Strength

Compressive strength was conducted, the initial compressive strength measurements were taken after one day of curing, and then again after seven and twenty-eight days. The results of compressive strength are shown in Figure 1.
The 28-day strength ranges from 38.5 MPa to 40.5 MPa, as can be seen. Mix RC 40/S 20/G10 has a compressive strength of 40.5 MPa and performs similarly to the CM, which has a compressive strength of 40 MPa. RC 20/S 20 has a comparable strength of 39.9 MPa, while RC 20 has the lowest strength. At 7 and 28 days, a 20% CRCA replacement level reduces the compressive strength of the RC 20 mix compared to

CM. This negative impact was offset by replacing 20% of the cement with SCM (GGBFS) at 28 days, as seen in mix RC 20/S 20. Mix RC 40/S 20/G 10 has the highest compressive strength at 28 days, despite having a CRCA replacement level of 40% and SCM replacement level of 30%, indicating that pozzolanic materials can contribute to strength growth and reduce the weakness caused by a high percentage of CRCA replacement level. The results are very encouraging in terms of increasing the use of CRCA and SCM applications in concrete pavements to reduce natural aggregate consumption and CO2 emissions.

Water Absorption and Freeze-Thaw Durability

The water absorption (WA) test was conducted after 28 days of curing. The absorption results for all mixtures are taken as an average of three samples and are represented in Figure 2.

According to the results, the RC 20 mix has the highest water absorption value, which is approximately 13% higher than that of the CM. It is observed that the absorption values in the RC 20/S 20 and RC 40/S 20/G 10 mixes are about 7% lower than the CM. In general, the results show that the addition of SCM significantly improves WA resistance. The improvement in WA resistance can be attributed to the formation of additional CS-H bonds as a result of the addition of SCM, which also reduces the size and connectivity of pores. In addition to the pozzolanic reaction, SCM's filler effect reduces pore size, disrupting pore connections (Qureshi, Ali, and Ali 2020).

The results of the free-thaw durability test show that mix RC 20 had the greatest loss of mass at both 7 and 28 days as seen in Table 2, which can be attributed to the presence of 20% CRCA in the mixture. Hydrostatic pressure and osmotic pressure are used to explain failure mechanisms in cementitious systems subjected to freeze-thaw cycles (Liu et al. 2020). According to some studies, the strength of old mortar attached to the RCA is lower than that of NA. As a result, its resistance to hydraulic and osmotic pressures caused by freeze-thaw cycles is lower, resulting in more significant mass loss (Hao et al. 2018). RC 20/S 20 and RC 40/S 20/G 10 mixes, on the other hand, have lower than CM by 57% to 77%, respectively. As previously stated, hydrostatic pressure and osmotic pressure are important factors in freeze-thaw cycle resistance (Liu et al. 2020). The pore structure has a strong influence on the hydrostatic pressure in specimens. The specimen pore structure is also related to the wear of cement-based materials, which changes the microstructure during freeze-thaw cycles (Hao et al. 2018). In RC 20/S 20 and RC 40/S 20/G10 mixes, the filler effect of SCM, in addition to the pozzolanic reaction, appears to reduce pore size, thereby improving overall pore structure (Qureshi, Ali, and Ali 2020). The freeze-thaw durability test results encourage the use of CRCA with SCMs and show that CRCA and SCMs can partially replace NA and cement even in cold regions like Canada to produce ICPs.

Conclusion

The primary goal of this study was to evaluate the mechanical and durability performance of ICPs containing CRCA and SCMs in typical high traffic urban areas. Three concrete mixtures containing varying percentages of CRCA and SCMs as partial replacements for NA and cement and GUL cement instead of conventional cement along with a CM were studied to achieve this goal.

- Concrete mixtures containing CRCA and SCMs produced workable mixtures. The slump value for all of the mixtures was found to be 55 ± 5 mm and the w/c ratio of each mixture varied to achieve these slump values.
- The w/c ratio of mixtures containing CRCA was greater than the CM. The percentage of air voids in all mixtures ranged from 5-5.3 percent.

- After 28 days, the compressive strength varied between 38.5 and 40.5 MPa. The best compressive strength value was found in the RC 40/S 20/G 10 mix.
- CRCA and SCM mixtures performed similarly to the CM in terms of compressive strength. The strength value of the mixture without SCMs and only CRCA was lower. This decrease indicates that the addition of CRCA alone has a negative impact on concrete compressive strength.
- In terms of compressive strength, the addition of CRCA with SCMs ranging from 20-40% to 20-30%, respectively as partial replacement of NA and cement can produce sustainable concrete mixtures for use in ICPs.
- The water absorption results show that the RC 20 mix had the highest value, 13% higher than the CM. The absorption values for all of the mixtures ranged from 3.77 percent to 4.07 percent. The values for RC 20/S20 and RC 40/S20/G 10 were approximately 7% lower than the CM, indicating that the addition of SCMs significantly improves water absorption resistance.
- The RC 20 mix lost the most mass after the freeze-thaw test, which can be attributed to the presence of only CRCA. When compared to CM, RC 20/S 20 and RC 40/S 20/G 10 had a lower loss of mass, which can be attributed to the presence of SCMs as well as CRCA in the mixtures. It can be concluded that the addition of SCMs significantly improves the freeze-thaw durability of concrete with CRCA.

The results obtained in this study provide compelling evidence to support the use of CRCA and SCMs in ICPs and concrete in general to partially replace NA and conventional cement, paving the way for more sustainable concrete construction.

Table 1. Properties of cementing materials

Cementing Material	**CaO (%)**	**SiO2 (%)**	**Al2O3 (%)**	**Fe2O3 (%)**	**MgO (%)**	**SO3 (%)**	**Na2O (%)**	**K2O (%)**
General Use Limestone Cement (GUL)	63.4	18.9	4.4	3.2	0.7	2.7	0.12	_
GGBFS	38.5	40.1	7.8	0.74	9.7	2.21	0.38	0.53
GP	10.9	71	1.82	0.61	0.94	<0.1	13	0.52

Table 2. Properties of micro-synthetic fibres

Aggregate properties	
Specific gravity	0.91
Melting point	160°C
Ignition Point	590 °C
Absorption	_
Alkali Resistance	Excellent
Electrical Conductivity	Low
Thermal Conductivity	Low
Tensile Strength	415 MPa
Modulus of Elasticity	5.52 Gpa
Length	19 mm

Table 3. Properties of NA and CRCA

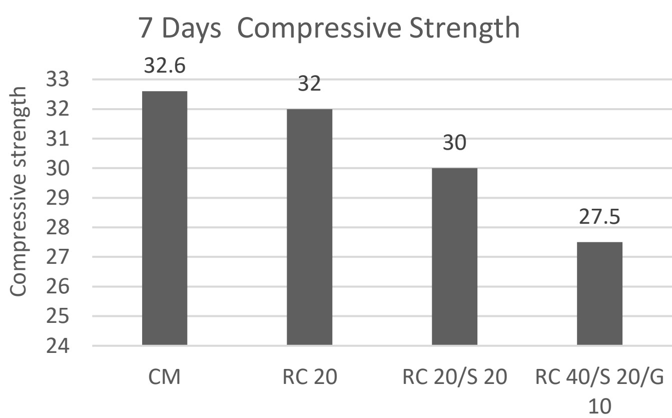
Aggregate Properties	**NA**	**CRCA**
Apparent Specific Gravity	2.7	2.638
Absorption (%)	0.66	5.91
Micro-Deval Abrasion Loss (%)	12.58	23.57
Adhered Mortar (%)	_	3.02

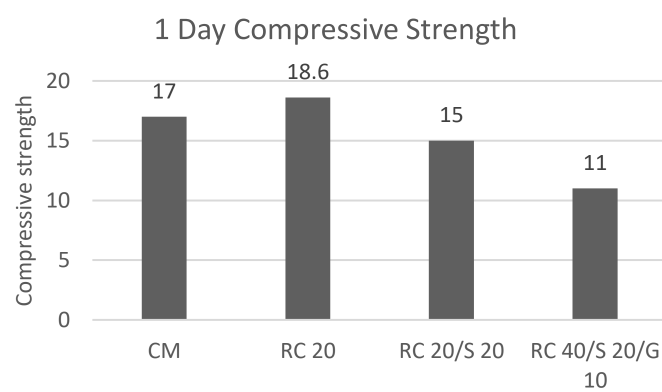
Table 4. Concrete Mix Designation

Sl No.	**CRCA Content (%)**	**GGBFS content (%)**	**GP Content (%)**	**Mix-Designation**
1	0	0	0	CM
2	20	0	0	RC 20
3	20	20	0	RC 20/S 20
4	40	20	10	RC 40/S 20/ G 10

Table 5. Summary of Test Results

Mix	slump		Air Void Content (%)	Compressive strength (MPa)			Water Absorption (%)	Freeze-thaw durability	
	Slump (mm)	w/c ratio		1 D	7 D	28 D		Loss of mass 7 cycles (g/m2)	Loss of mass 28 cycles g/m2)
CM	55	0.461	5.1	17	32.6	40	4.07	55.33	111.26
RC 20	52.9	0.48	5.2	18.6	32	38.5	4.61	92.93	121
RC 20/S 20	55.8	0.46	5	15	30	39.6	3.77	15	55.4
RC 40/s 20/G 10	54.61	0.44	5.3	11	27.5	40.5	3.8	10	27.95





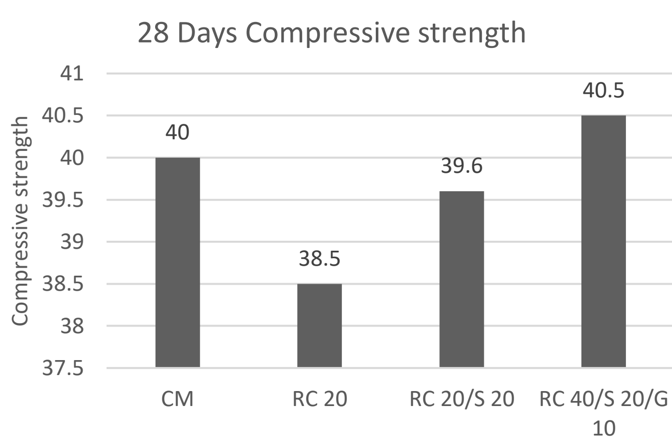


Figure 1. 1, 7, and 28 Days compressive strength

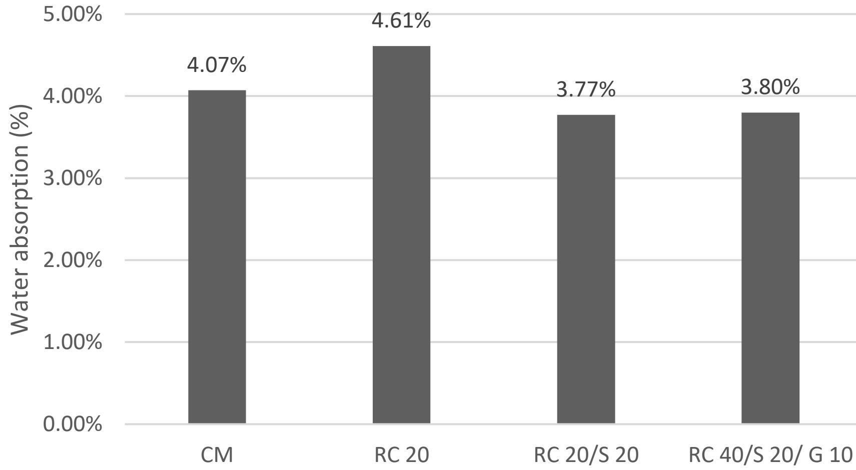


Figure 2. Water Absorption values

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