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USE OF FINE RECYCLED AGGREGATE DERIVED FROM BLOCK PLANT WASTE IN PRODUCTION OF CONCRETE MASONRY BLOCKS

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ABSTRACT

Increased demand for natural aggregate exploits natural resources and has adverse environmental impacts. One solution to address the growing construction waste challenge is adopting large-scale recycling of concrete waste into aggregates. The use of coarse recycled aggregates in masonry blocks is a well-studied topic; however, little attention has been directed to study the use of fine recycled aggregates (FRCA) in masonry blocks. Concrete blocks are manufactured in a controlled environment that produces wastes in the form of culled or broken blocks. The controlled nature of this process makes concrete block masonry an ideal industry to adopt FRCA, given that a consistent source of materials can be gathered from block manufacturing plants. Research has been conducted on hollow concrete blocks produced with FRCA from wastes accumulated at block production facilities and culled blocks that are not fit for use. The FRCA obtained from block manufacturers was used to replace natural sand with proportions of 10%, 25%, 50%, 75%, and 100% by volume of aggregates in prototype blocks manufactured to replicate a production facility. The results indicated that there is no adverse impact on compressive strength by using FRCA in blocks. However, a gradual reduction in density and an increase in water absorption were observed with the increase of FRCA amount in the mix. Having the mix done in a factory, with actual infrastructure and machinery of a block manufacturing plant, would likely result in even higher strength blocks.

KEYWORDS: *recycled concrete aggregates, culled blocks, masonry blocks, sustainability*

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INTRODUCTION

The widespread extensive extraction of natural resources required for the construction of structures has resulted in an alarming opposition of ecologists. In the present times, the production and consumption of concrete blocks are rapidly stepping up, and hence the extraction of natural aggregates is multiplying as well. In 2019, Canada together produced 2.42 million metric tons of gravel, while the province of Ontario and Alberta being the largest producers in the country [1], [2]. The predominant ingredient used in the production of blocks is the natural aggregates followed by sand. The increase in modernization and population has led to a drastic increase in the consumption of natural aggregates by the block manufacturers. In order to substitute the natural extraction of aggregates and use them in manufacturing blocks, the use of recycled aggregates (RA) is being adopted in the present times due to its sustainable source as a raw material [3]. In the past few decades, there has been numerous research work done on the use of coarse recycled aggregates in concrete blocks [4], [5], [6], [7], [8], [9], [10] and [11]. However, very little amount of research has been conducted on the mechanical properties of concrete blocks manufactured using recycled fine aggregates (FRCA) as a replacement of natural fine aggregates (NFA).

Yang and Li [12] studied the compressive and flexural properties of the recycled concrete hollow block by substituting fine aggregates with recycled fine concrete aggregates obtained from demolition wastes from various construction sites. Four different FRCA replacement ratios of 0%, 30%, 60% and 100% were employed. The experiment results indicated up to 50% decrease in the compressive and flexural strength with increase of the replacement rate of fine recycled aggregates increase. Soutsos et al. [13] also replaced the fine aggregates with FRCA of particle sizes ranging between 4mm to dust. The manufacturing process was done in a factory with vibro-compaction on dry concrete mixes. It was found that blocks made with recycled aggregates had lower densities than natural aggregate blocks as a result of a volumetric replacement. The replacement of fine aggregate fraction only with recycled aggregates has more of a detrimental effect on strength than the coarse aggregate replacement. The recommendation was, therefore, to limit the fine aggregate replacement to less than 30%. Kou et al. [14] sourced FRCA from ready mix concrete plant and manufactured wall blocks at the proportions of 0%, 25%, 50%, 75% and 100% by weight. It was found that the density decreased and water absorption increased with an increase of fine aggregates. This was attributed to the lower specific gravity and porosity of FRCA compared to natural sand. The compressive strength was also acceptable and above the minimum set by the British standard (BS 6073-1). The strength was higher than the control mixes, where 50% aggregate replacement showed the highest compressive strength [14]. Bai et al. [15] replaced both fine and coarse aggregates equally in the percentage of 40%, 70% and 100% to manufacture concrete blocks. It was observed that the FRCA has the most influence on the mechanical properties of recycled blocks; very low fineness of the fine recycled aggregates adversely affects the bond between the cement paste and sand and results in low strength recycled concrete blocks. The ideal replacement percentage of FRCA with sand was 50%, after which the strength decreased.

In summary, against the above literature, it can be said that the FRCA blocks present a suitable alternative in construction because they possess significantly the same mechanical-physical properties as well as other qualities found in natural coarse aggregates (NAC) blocks. However, very little research has been previously done with regards to the replacement of natural sand with FRCA in hollow masonry blocks. With the existing research, it was found that the addition of fine aggregates generally reduces the compressive strength and has a more detrimental effect as compared to recycled coarse aggregates. However, the FRCA blocks promote environmental preservation and the protection of natural resources; besides, they also help in the reduction of expenses and taxes incurred in relation to the management of large construction and demolition waste. With more control over the quality of the recycled aggregates, better results are expected.

EXPERIMENTAL PROGRAM

The aim of this experimental project is to assess the effect of using fine recycled concrete aggregates (FRCA) from culled blocks on the physical and mechanical properties of concrete masonry blocks. A total of six mixes were undertaken; one mix consisted of all-natural fine aggregates, which served as a reference mix (0% FRCA) or (100% NAC). The other five mixes were made of FRCA consisting of different replacement ratios in the percentage of (10%, 25%, 50%, 75% and 100%) by volume of the natural fine aggregates. A total of twenty-four specimens were cast, four per mix. In total, four specimens with no replacement of aggregates and twenty specimens having different proportions of FRCA. Each of these specimens was tested for density, percentage absorption and compressive strength at 28 days.

Materials

Portland Cement (Type GU) was used as a binder for all mixes. The natural coarse aggregates (NAC) used were quarried crushed limestones and acquired from a local supplier. The natural fine aggregates (NFA) were river sand having fineness modulus of 2.65. The recycled fine aggregates (FRCA) was acquired from culled blocks of the Brampton Brick Limited plant in Brockville. The obtained material was a mix of spillage waste that was collected from the production line of the plant and broken concrete blocks. It was cleaned of the existing debris and crushed to the required size of 4.75 and below (up to 150-micron). The specific gravity and absorption rate were found to be 2.25 and 9%. The physical properties of the coarse and fine aggregates that were used in mixes are shown in Table 1. Figure 1 shows photographs of samples of the two types of fine aggregates (sand and FRCA).

Figure 2 shows the particle size distribution of natural fine aggregate (sand), recycled fine aggregates, and natural coarse aggregates. It can be seen that the size distribution of recycled fine aggregates was not similar to the natural sand; therefore, it was corrected to minimize the difference in the particle size distribution. FRCA ranging greater than 150 microns to 2.36mm and less than 2.36mm to 4.75mm were proportioned in a way to bring the particle size closer to that of natural sand.

Table 1: The physical properties of the coarse and fine aggregates

Aggregate type	Maximum size, mm	Relative density (OD)*	Relative density (SSD)**	Water absorption (%)	Unit weight, kg/m^3**
Natural Limestone Coarse Aggregate (NAC)	9.5	2.64	2.69	1.3	1640
Natural Fine aggregate (Sand)	4.75	2.61	2.66	1.0	1700
Recycled Fine Aggregate (FRCA)	4.75	2.15	2.25	9.0	1350
*OD- oven dry, **SSD- saturated surface dry					

Figure 1: Samples of the two types of fine aggregates employed in the investigation: Natural Sand (left), and Recycled fine aggregate (right) (images by authors)

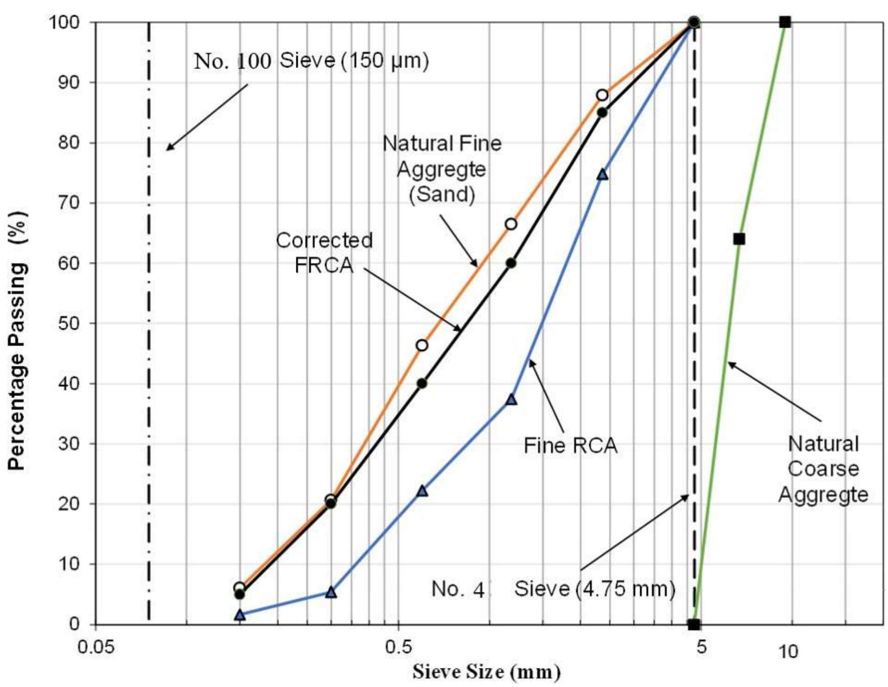

Figure 2: The particle size distributions of different aggregate types used in the project

Mix Design

The mix design implemented in the experimental work was modified from the mix design employed by The Canadian Concrete Masonry Producers Association members (CCMPA 2016). The CCMPA mix design uses a combination of Portland cement along with small amounts of other cementitious materials, such as slag cement, fly ash and silica flour as a binder material. The fine aggregate in the CCMPA mix is a combination of natural sand and crushed fine aggregates. The use of water-reducing and air-entrained admixtures is also suggested by CCMPA mix design. In the current mix design, all cementitious materials were replaced by Portland cement. The natural and crushed fine aggregates were replaced by natural sand and fine aggregate. Only one superplasticizer (specific for zero slump) was used instead of various admixtures with density of 1.2 kg/litre. The water-cement ratio was increased to 0.4 from the 0.3 used in the CCMPA design mix to accommodate the limited vibro-compaction in a laboratory environment. The mix design for this project followed the absolute volume method to determine the concrete mix proportions, as shown in Table 2. The CCMPA mix design guarantees a unit specified compressive strength of 15 MPa. However, the current mix was designed to target a minimum of 10 MPa unit specified compressive strength. The lower targeted strength expectation can be ascribed to the higher water-cement ratio as well as the limited capacity of vibro-compaction in the laboratory setting compared to block manufacturing plants.

Table 2: Mixing proportion (kg/m^3)

Mix	Cement	Water	NAC	FRCA	Sand	SuperPlasticizer
0% RCA (100% NAC)	190	76	880	0	1250	0.60
10% RCA	190	76	880	105	1124	0.80
25% RCA	190	76	880	266	938	1.20
50% RCA	190	76	880	535	625	1.46
75% RCA	190	76	880	800	315	1.80
100% RCA	190	76	880	1064	0	2.10

Manufacturing Process

The moulds used to manufacture hollow blocks were made of stainless steel. The middle part of the hollow block was made with Styrofoam so that it could be removed easily after the curing period. All the sides of the mould were removable, and the middle portion of the mould was hollow where the Styrofoam was placed. After the curing period, the Styrofoam was removed from the blocks making the middle portion hollow. The nominal block dimension was 190 x 190 x 190 mm with a 114 x 114 mm cross-section for hollow part in the middle and a face shell thickness of 38 mm all around the cross-section. The moulds were placed on a vibrating table for casting to replicates the vibro-compaction process adopted in block manufacturing factories.

The mixing process involved a stationary mixer with dedicated arms for rotating and mixing the material. The quantity of each ingredient was weighed beforehand for the mixing. All aggregates were added in a damp condition, i.e., above saturated surface dry (SSD) condition. The FRCA was pre-wetted for 24-hours with water to bring the moisture content to 1% above its SSD condition. This proved to be a significant and effective technique to limit the tendency of FRCA to absorb extra water relative to natural aggregates during the mix and enables RCA concrete to have comparable mechanical properties as concrete with natural aggregates [16]. It is not uncommon in the block manufacturing plants to prewet the aggregates before adding them to the mix in damp conditions. A total of four blocks were cast per mix. The FRCA was mixed well with NAC before being added to the mix. Each material was weighed and then added to the mixer. The sand was added initially, followed by natural and recycled aggregates and was dry-mixed for 2 minutes. The cement was added and mixed thoroughly with the aggregates. The superplasticizer was mixed well with water and this was added gradually to the mix. The mix was aimed to be dry and the industry-implemented technique was used to check the consistency of the mix wherein some amount of mixed material was squeezed in the palm; the consistency was determined to be achieved if the shape retains itself. This is shown in Figure 3a. The mix was manually compacted into the moulds by hitting a flat plate attached to wooden pieces while the moulds were set on the vibrating table for better compaction (see Figure 3b). The compaction was undertaken in three layers, each layer having 25 hits to be consistent between the cast blocks. The top surface of each layer was scratched prior to addition and compaction of the next layer to prevent a weak crack surface between the two layers. The top layer was well-matched with the edges of the mould to limit the variation of block height dimension. After 24-hours, the blocks were taken out of the moulds and wrapped in wet burlaps for three days and then stored at room temperature for a 28-days period (see Figure 3c and 3d). After this period, the blocks' as-built dimensions were noted and their top and bottom surfaces were capped with hydrostone, as per ASTM C1552-16 [17].

Figure 3: Blocks manufacturing process (a) Checking consistency of mix, (b) Compaction of concrete in moulds set on vibrating table, (c) Curing of the blocks, (d) Storing the blocks.

Testing

After 28 days of curing, the blocks were tested under compression in standard testing machine. To apply a uniform load on the blocks, the block was placed between two steel plates and a cylindrical head was used to apply hydraulic force. The tests were conducted as per CSA A165.1-14 for concrete masonry samples [18]. The masonry blocks were tested for compressive strength after 28 days using the standard Forney compression testing machine, with a 2000 kN capacity. The rate of loading was 0.1 MPa/s. Figure 4 shows the compressive strength test setup. To determine the compressive strength, the maximum force of each test samples were divided by the net bearing area of the unit. An average of four test results was taken as the compressive strength per mix. The specified (or characteristic) compressive strength is generally used in masonry design codes rather than average compressive strength, where the specified strength is obtained from a statistical analysis of numerous test results. According to CSA S304 -2014 [19]**,** the specified strength of each mix is determined by subtracting 1.64σ from the average strengths. The standard deviation is taken either as the higher of the reported value or 10%. To measure the block density, block parts were cut and weighted individually. The exact dimensions of these parts were measured by using a digital Vernier calliper to find out the volume. The block density was calculated by dividing the mass over its volume. Similarly, the percentage absorption was determined by submerging the parts under water for 24-hours period and taking their weight in saturated surface dry conditions. The parts were oven-dried at 105ºC for 24-hours period and weighed again. Using this weight, the percentage absorption was calculated for each mix.

Figure 4: Compressive test setup

RESULTS AND DISCUSSION

The failure process of the recycled concrete blocks under compression is similar to that of natural concrete blocks. Initially, there is hardly any appearance of crack when the block specimen is loaded. On increasing the load up to 70% of the maximum load, vertical splitting cracks are observed near the corners of the block. Upon further increasing the load, the cracks widen and extend, which leads to the complete failure of the block specimen. A typical failure mode of NAC and FRCA block is shown in Figure 5. The overall results have shown that the failure mode of blocks is not affected by the replacement proportions of fine recycled aggregates. The average compressive strengths of all mixes are presented in Figure 6, with their standard deviation values in the form of error bars. The specified compressive strength values are also presented in Figure 6. It is evident from Figure 6 that the blocks made from all mixes were able to attain the targeted specified compressive strength (10 MPa). The FRCA blocks made with different FRCA replacement ratios, except the 25% FRCA, exhibited higher average compressive strengths than the reference mix (100% NAC). Although the average compressive strengths of 10% FRCA, 75% FRCA, and 100% FRCA blocks were observed to be higher than that of NAC blocks, the variations associated with the average values make these increases statistically insignificant. The specified compressive strength of FRCA made with different FRCA replacement ratios were higher (by 3% to 20%) than that reference mix (100% NAC). These results are in good agreement with those reported by Soutsos et al. [13] and Kou et al. [14]. In contrast to the study undertaken by Yang and Li [12], there was no need for increasing the cement content in the production of the RCA blocks in the current study to attain the required strength. When compared to Yang and Li 's investigation, the current study used a pre-wetting approach instead of increasing the mix's water content to account for the high absorption characteristics of FRCA relative to the virgin aggregate. The comparability in compressive strengths of FRCA and NAC blocks in the current investigation can be attributed to the adoption of RCA pre-wetting and vibro-compaction techniques. Based on these results, it seems reasonable to assume that having the actual infrastructure and machinery of a block manufacturing plant would likely give higher strengths of RCA blocks.

Figure 5: Typical failure mode: NAC Block (left) and 50% FRCA block (right)

The results of density and absorption tests are presented in Figure 7. It can be seen from Figure 7 that as the replacement RCA ratio increased, the densities of RCA blocks decreased, and their water percentage absorption (compliant with CSA A165.1) increased compared to those of NAC blocks. The full replacement of natural aggregate with RCA caused a reduction of 7% in density and a 19% increase in the percentage absorption. However, there is a slight increase in density from 50% RCA to 75% RCA associated with a slight decrease in the percentage absorption. This change in trend is not significant and can be attributed to possible unintended, better compaction for the 75% RCA blocks than the rest of RCA mixes as compaction was performed manually. The increase in density of 75% RCA blocks can also explain the high compressive strength values for these blocks.

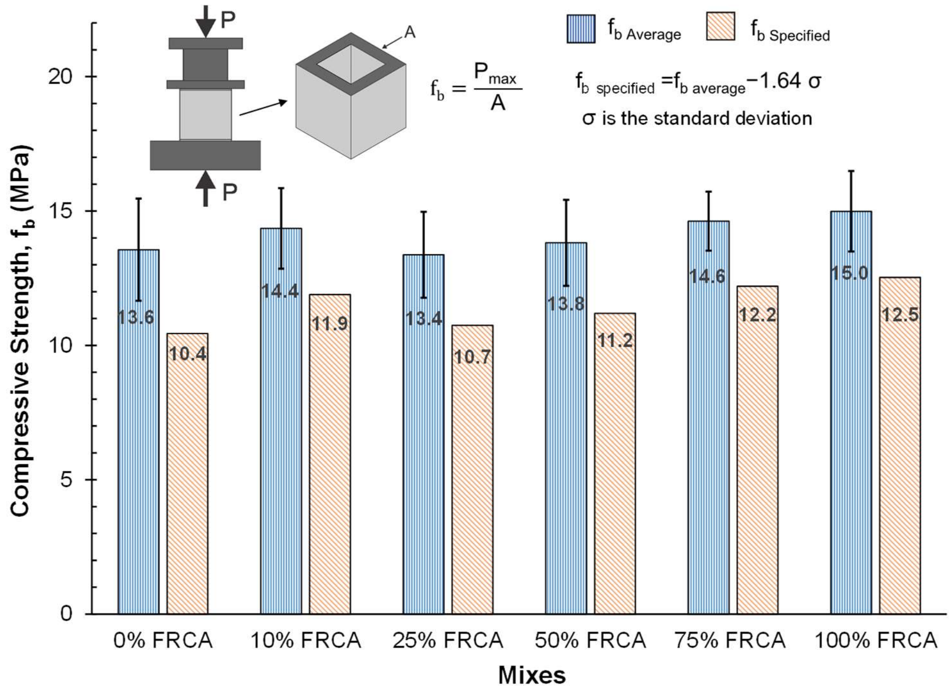

Figure 6: Average compressive and specified strengths of all mixes

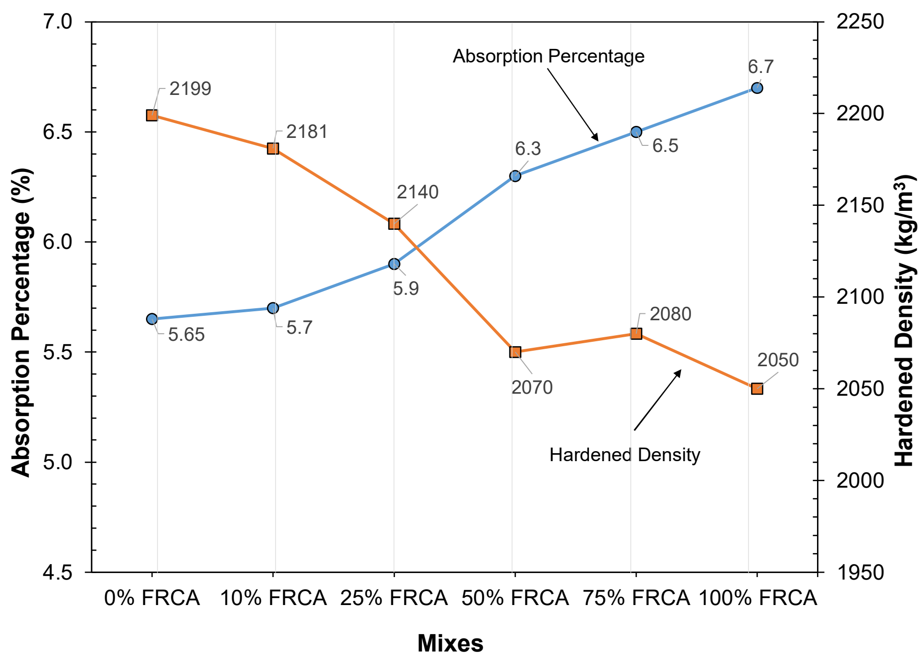

Figure 7: Results of density and water absorption (in %) tests

CONCLUDING REMARKS

The results obtained from the experiment indicate that it is viable to manufacture concrete blocks with fine recycled aggregates obtained from waste materials and culled blocks unfit for use. The results showed a comparable compressive strength of blocks with various proportions of FRCA up to 100% to that of the reference mix. However, with the increase in FRCA, lower densities were observed along with high percentage absorption, which can be attributed to the physical properties of FRCA. The obtained results can be further controlled and improved using the actual infrastructure and machinery used in block plants. This would also reduce the necessity of transporting the waste or raw material to the landfill or recycling facility.

For further research, work is in progress at Queen's university, Kingston, Canada to examine the possibility of using FRCA in higher strength blocks (20 MPa). FRCA blocks will be tested under repeated freeze and thaw cycles to assess their durability. The test will include the stress-strain behaviour of the RCA blocks. The scientific data resulting from this study is intended to be used to encourage block producing plants to adopt the concrete blocks made with FRCA that have similar strength and durability as those made with natural aggregates at larger scale.

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