Properties of Pervious Concrete Incorporating Recycled Concrete Aggregate

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ABSTRACT

This work investigated using recycled concrete aggregate (RCA) in pervious concrete, specifically the effects on the density, strength and permeability. Cylindrical specimens of pervious concrete with different percentages of RCA and conventional aggregate were cast. The coarse aggregate was substituted by 0, 10, 20, 30, 50, and 100% RCA. As percent RCA increased both compressive strength and permeability generally decreased. The strength and hydraulic characteristics of mixes examined in this study compared generally well with other studies, on pervious concrete without RCA, found in the literature. The results indicate that up to 50% substitution of course aggregate can be used in pervious concrete without compromising strength and hydraulic conductivity significantly. Further testing evaluating freeze-thaw durability is necessary if pervious concrete with RCA is to be used in cold weather climates.

Key Words: Recycled concrete aggregate, Pervious concrete, Compressive strength, Hydraulic conductivity.

INTRODUCTION

Most traditional paving surfaces prevent water from entering the subsoil underneath them. These impervious surfaces increase runoff, cause flooding, and contribute to siltation and other water pollution. Pervious surfaces allow stormwater to infiltrate into the ground recharging the water table, and thus reduce the amount of runoff. This reduction in stormwater runoff also lessens resulting environmental pollution (1). For these reasons the use of pervious concrete is among the Best Management Practices (BMPs) recommended by the Environmental Protection Agency (2).

Ready-mix concrete for parking lots is normally specified in accordance with the requirements of ASTM C94, *Standard Specifications for Ready-Mixed Concrete* (3). A minimum compressive strength of 24 MPa (3,500 psi) is recommended; however, in areas where freeze-thaw durability is a concern a minimum compressive strength of 28 MPa (4,000 psi) is advised. Typical pervious concrete mixtures can develop compressive strengths in the range of 3 MPa to 28 MPa (500 to 4,000 psi) (4). For this reason pervious concrete is generally limited to low-traffic areas where reduced compressive strength is often acceptable. Applications include parking lots, bike paths, and pedestrian footpaths (5).

Construction materials are increasingly being judged by their sustainable characteristics. The ecological benefits of pervious concrete can be taken a step further by incorporating recycled concrete aggregate (RCA) into the mix design. Concrete recycling has gained importance because it minimizes the need for disposal by reducing dumping at landfills and it protects the natural environment by reducing gravel mining of virgin aggregate (6). The U.S. DOT reported that 38 states use RCA as an aggregate base and 11 states recycle concrete into new portland cement concrete (7). The states that do use recycled concrete as an aggregate source for new concrete report that concrete with RCA has performed as well as concrete with virgin aggregates. Additionally, the quality of concrete with RCA depends on the quality of the recycled material used.

While pervious concrete and incorporating RCA in conventional concrete have been used previously, the use of RCA in pervious concrete is just beginning to be explored. Incorporating RCA in pervious concrete is still a relatively new idea, and the feasibility of RCA in pervious concrete is still under investigation. From an environmental and economic standpoint the optimum RCA content replacement of virgin aggregates will be 100% (8). Though what is known about RCA this does not seem practical. It is likely RCA will not be able to replace virgin aggregate completely unless the minimum compressive strength and hydraulic conductivity criteria are met. Recycled concrete aggregates contain not only the original aggregates, but also low density hydrated cement paste. Resulting in lower density compared to virgin aggregate (8). Typically as density decreases, compressive strength of pervious concrete decreases and hydraulic conductivity increases (9). In this paper, the effects of RCA on density, compressive strength, and hydraulic conductivity of pervious concrete are evaluated.

BACKGROUND

Existing literature on the RCA production process, the properties of RCA, the effects of RCA in regular concrete, and the effects of RCA in pervious concrete are reviewed in this section. A significant amount of literature exists on RCA in conventional concrete but literature on the use of RCA in pervious concrete is sparse.

The RCA Production Process

ACI provides information on concrete removal methods and the reuse of recovered concrete as an aggregate (8). The type of concrete and its location within a structure directly affect how the concrete is removed. Additionally, the selection of proper tools and equipment is critical in determining the cost-effectiveness of concrete removal. The production of RCA starts with the demolition of an existing concrete source. The crushed concrete is either recycled on site or trucked to a plant for further processing. Generally unprocessed material comes in to a plant 30 to 41 cm (12 to 16 inches) in size and is reduced to 6 to 8 cm (2½ to 3 inches) in size. The process of recycling concrete involves breaking the existing concrete, removing the reinforced steel, and then further crushing and sifting the concrete to a specified size. With the exception of removing contaminants the process is similar to the production of virgin aggregate. RCA is typically obtained from curbs, sidewalks, and parking lots and used if it is economical. The primary factors affecting cost-effectiveness is the availability of virgin aggregate and proximity of disposal sites, which is related to the project's location. Pilot studies have indicated that recycling concrete can be as economical as disposing the concrete, but again it is location dependent (8).

RCA Properties

The density of RCA is typically lower compared to virgin aggregate (8). This is a result of RCA also consisting of low density cement paste. RCA is much more absorbent of water than virgin aggregate because the cement paste has a high affinity for water. This absorption capacity of the cement paste is one of the most significant differences in properties and which distinguishes RCA from virgin aggregate. Recycled fine aggregates tend to be more angular than what is preferred for making quality concrete. Acceptable recycled coarse aggregates are relatively easy to produce from concrete; however, fine aggregates remain on coarse aggregates after concrete is crushed. RCA meets requirements specified by ASTM C33, *Standard Specification for Concrete Aggregates* (11) when tested in general accordance with ASTM C131, *Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine* (12). Contaminants found in recycled concrete degrade its strength. Contaminants could include plaster, soil, wood, gypsum, asphalt, plastic, or rubber. (8)

Etxeberria et al. (13) studied concrete made with recycled coarse aggregates obtained from crushed concrete. The study investigated four different mix designs made with 0%, 25%, 50%, and 100% recycled coarse aggregate. It was found that good quality RCA will have properties similar to those that define good quality virgin aggregate. Since recycled aggregates are composed of original aggregates and cement paste, which is typically weak than the original aggregate, it is desired to remove as much hardened cement paste as possible. The amount of cement paste left on an aggregate is influenced by the method used to crush the concrete as well as the dimension the concrete is crushed to. The shape and texture of aggregates are also dependent on which type of crusher is used. When using an impact crusher to crush concrete, a high percentage of recycled coarse aggregate without cement paste can be obtained (13). The amount of cement paste, on a recycled aggregate, increases as the size of the recycled aggregate decreases. Overall, the quality of recycled coarse aggregate plays an important role in determining the quality of the concrete.

Traditional Concrete Made with RCA

ACI reviewed several studies investigating, the effects of RCA on conventional concrete and found that performance of concrete with RCA depends on several factors, including the source of recycled concrete and more specifically the quality of the concrete from that source (8). It is believed that concrete made from recycled aggregates can achieve approximately the same compressive strength as the original concrete from which they were made. Performance of concrete with RCA depends on the water cement (w/c) ratio of the original concrete and the w/c ratio of the newly created concrete. If the w/c ratio of the concrete is less than or equal to that of the concrete used to create the RCA then the compressive strength of the concrete will typically be greater than or equal to that of the concrete used to create the RCA. Performance of concrete with RCA can also depend on the recycled fine aggregates. When maintaining the same w/c ratio of the original concrete, concrete made from recycled coarse aggregates and virgin fine aggregates showed reductions in strengths ranging from approximately 5% to 24%. Concrete made from recycled coarse aggregates and recycled fine aggregates showed reduction in strengths ranging from approximately 15% to 40%

Etxeberria et al. (13) found concrete made with RCA is less workable than conventional concrete. This is a result of the absorption capacity of recycled aggregate. This study found concrete made with recycled coarse aggregates and virgin fine aggregates typically needs 5% more water than conventional concrete to obtain the same workability. Additional cement is needed for concrete made with 100% RCA to achieve similar workability and compressive strength as conventional concrete. The shape and texture of aggregates also plays a role in the workability of concrete. As mentioned earlier, in the case of RCA, the shape and texture are determined by the type of crusher. Tabsh and Abdelfatah (14) found plasticizing, air entraining, retarding, and accelerating admixture in the original concrete had no effect on the performance of concrete made using RCA.

Pervious Concrete Made with RCA

Rizvi et al. (6) studied the effects of different percentages of RCA content on void ratio, compressive strength, and permeability in pervious concrete. Increasing RCA content led to a decrease in compressive strength, an increase in permeability, and an increase in void ratio. Decreases in compressive strength were attributed to RCA being weaker than conventional aggregates. Increases in permeability and void ratio were attributed to RCA being more angular than virgin aggregate. This study showed pervious concrete with 15% RCA had compressive strength, permeability, and void content similar to that of the control mix. The authors recommended further research should be conducted to determine the effects of using different sources of RCA in pervious concrete.

RESEARCH METHODS

This section presents the laboratory methods used to determine the mechanical and hydraulic properties of pervious concrete with RCA.

Mix Designs and Sample Preparation

Pervious concrete is made by mixing water, cement, and uniformly graded coarse aggregate. No fine aggregates are added to these mixes. This design allows the paste to coat and bind the aggregates while maintaining a network of connected voids. All mix designs included 9.5 mm (3/8 inch) crushed stones as coarse aggregate and Type I-II portland cement. Several admixtures were also utilized; they included an air entraining admixture (AEA), a high-range water-reducing admixture (HRWR), and a viscosity modifying admixture (VMA). Proportions for each mix design can be found in Table 1.

TABLE 1: Pervious Concrete Mix Designs

% RCA	Virgin Aggregate	RCA	Other Materials
0%	1540 kg/m^3 (2600 lbs/yd^3)	0 kg/m^3 (0 lbs/yd^3)	Cement 356 kg/m^3 (600 lbs/yd^3) Water 98 kg/m^3 (165 lbs/yd^3) AEA 39 mL/m^3 (1 fl.oz/yd^3) HRWR 696 mL/m^3 (18 fl.oz/yd^3) VMA 464 mL/m^3 (12 fl.oz/yd^3)
10%	1390 kg/m^3 (2340 lbs/yd^3)	150 kg/m^3 (260 lbs/yd^3)	
20%	1230 kg/m^3 (2080 lbs/yd^3)	310 kg/m^3 (520 lbs/yd^3)	
30%	1080 kg/m^3 (1820 lbs/yd^3)	460 kg/m^3 (780 lbs/yd^3)	
50%	770 kg/m^3 (1300 lbs/yd^3)	770 kg/m^3 (1300 lbs/yd^3)	
100%	0 kg/m^3 (0 lbs/yd^3)	1540 kg/m^3 (2600 lbs/yd^3)	

The source of the RCA used in this research was a stockpile of crushed concrete from a stone recycling area. The concrete was crushed using an impact crusher and the size of the crushed concrete varied from 25 mm (1 inch) to a size smaller than 4.75 mm (3/16 inch). The sources and properties of the concrete before it was crushed are unknown. To obtain the size aggregate used in this study, crushed concrete from the stockpile was collected and sieved. The aggregate size used was that retained on the No. 4 sieve. The aggregate was then washed to remove excess fine aggregate bound to the coarse aggregate. There is no standard practice for how to process RCA for pervious concrete so the decision to wash the fine aggregate off of the coarse aggregate was based on the literature suggesting recycled fine aggregates result in compressive strength reductions. For this study 9.5 mm (3/8 inch) virgin aggregate was used.

The virgin aggregate consisted of crushed stone containing ore minerals Quartzite, Dolomite, and Limestone.

McCain and Dewoolkar (9) showed that for performing laboratory compressive strength and hydraulic conductivity testing on pervious concrete, a minimum of 10 cm (4 inch) diameter specimens should be used for 9.5 mm (3/8 inch) aggregate. Since a height to diameter ratio of 2:1 is typically adopted for compressive strength testing, specimens were prepared as cylinders with a diameter of 10 cm (4 inches) and a height of 20 cm (8 inches). For permeability testing, specimens were prepared as cylinders with a diameter of 10 cm (4 inches) and a height of 20 cm (8 inches) and then were cut with a concrete saw to a height of 15 cm (6 inches). This specimen height was chosen as a typical pervious concrete pavement thickness found in the field. A total of 16 cylinders per RCA percentage were cast; 8 for compressive strength testing and 8 for hydraulic conductivity testing.

There is no standard practice for making and curing pervious concrete. Therefore, mixing was done in general accordance with the procedure suggested by Schaefer, et al. (15). Cylinders were cast in general accordance with ASTM C192, *Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory* (16). In previous investigations this method has resulted in density values similar for field cores and consistent failure patterns indicating sufficient bonding between the aggregate and paste (9).

Test specimens for compressive strength testing were demolded 7 days after being cast and allowed to air cure in a moist room for a total of 28 days before testing. Test specimens for hydraulic conductivity testing were demolded 7 days after being cast and then cut with a concrete saw and washed to remove debris. The procedure of demolding samples 7 days after casting was chosen to simulate field construction practice (17).

Test Procedures

Compressive Strength

Compressive strength testing was performed in general accordance with ASTM C39, *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens* (18). Samples used 50 durometer unbounded neoprene rubber caps in accordance with ASTM C1231, *Standard Practice for Use of Unbonded Caps in Determination of Compressive Strength of Hardened Concrete Cylinders* (19).

Hydraulic Conductivity

Hydraulic conductivity testing was performed using a falling head permeameter developed by McCain and Dewoolkar (9) shown in Figure 1. Specimens were enclosed in a mold after being lined by a thin rubber sheet. The mold was secured using hose clamps to prevent any flow along the sides of the specimen that would affect the measured results. The specimens were then secured in the apparatus, and water was added to the downstream pipe in order to expel any air that may have been present in the specimen. When the water level had risen above the surface of the pervious concrete specimen water was added to the upstream pipe, and the water level was allowed to reach equilibrium (zero head level). The head was then increased to 38.1 cm (15 inches) and the time it took for the water to fall to a head of 7.6 cm (3 inches) was recorded. Previous research has indicated that under these head values laminar conditions exist in pervious concrete and Darcy’s law is valid (20). Tests were performed a minimum of three times per sample to ensure accuracy of reported results.

FIGURE 1: Falling Head Permeameter.

RESULTS AND DISCUSSION

Results obtained from the laboratory testing are reported and analyzed in this section to assess the effects of RCA on density, compressive strength, and hydraulic conductivity on pervious concrete. Summarized results of all testing can be found in Table 2.

TABLE 2: Summarized Results

	Dry Density (kg/m^3)		Compressive Strength (MPa)		Conductivity (cm/s)	
RCA %	Average	Standard Deviation	Average	Standard Deviation	Average Hydraulic	Standard Deviation
0	1860	25	14.90	1.73	0.94	0.07
10	1866	18	15.49	1.56	0.87	0.07
20	1890	24	17.73	1.36	0.75	0.07
30	1838	25	13.96	0.58	0.88	0.06
50	1843	26	14.15	1.30	0.77	0.06
100	1789	20	12.51	1.19	0.86	0.10

Density

Figure 2 displays density testing on pervious concrete samples by percent RCA. Average densities for each mix design are presented along with standard deviation (shaded area) and maximum and minimum values (error bars). Densities for 20 cm (8 inch) and 15 cm (6 inch) samples were found to be similar for a given mix design. Figure 2 contains both the density values from the 20 cm (8 inch) compressive strength samples and the 15 cm (6 inch) hydraulic conductivity samples. Average density values ranged from 1,789 to 1,890 kg/m^3 (111 to 117 lbs/ft^3). This range of values is comparable to density values reported in previous research on RCA in pervious concrete, which ranged from 1,710 to 2,009 kg/m^3 (106 to 125 lbs/ft^3) (6). Standard deviations were similar in all mix designs.

Mix designs with 0 to 50 % RCA replacement were found to have densities within the same general range; however, 100 % RCA replacement resulted in decreased density. Previous studies have seen a general trend of decreasing density as RCA increased (6). In the current study, variability in density values are too great to allow for an accurate comparison to be drawn. The reduction in density for the 100% RCA mix design could be caused by several factors. The manner in which the aggregates are arranged in the samples could affect density results; visual inspection indicated that RCA was more angular, and the angularity of the RCA could result in a less compact sample when compared to traditional aggregate even under similar compaction effort. However this observation was qualitative, and further investigation is needed. Additionally RCA is assumed to be less dense than virgin aggregate due to the presence of hydrated cement pastes as part aggregate particles. Measurement of RCA and virgin aggregate densities are needed to determine how this effect influences density measurements of the pervious concrete specimens and is currently underway.

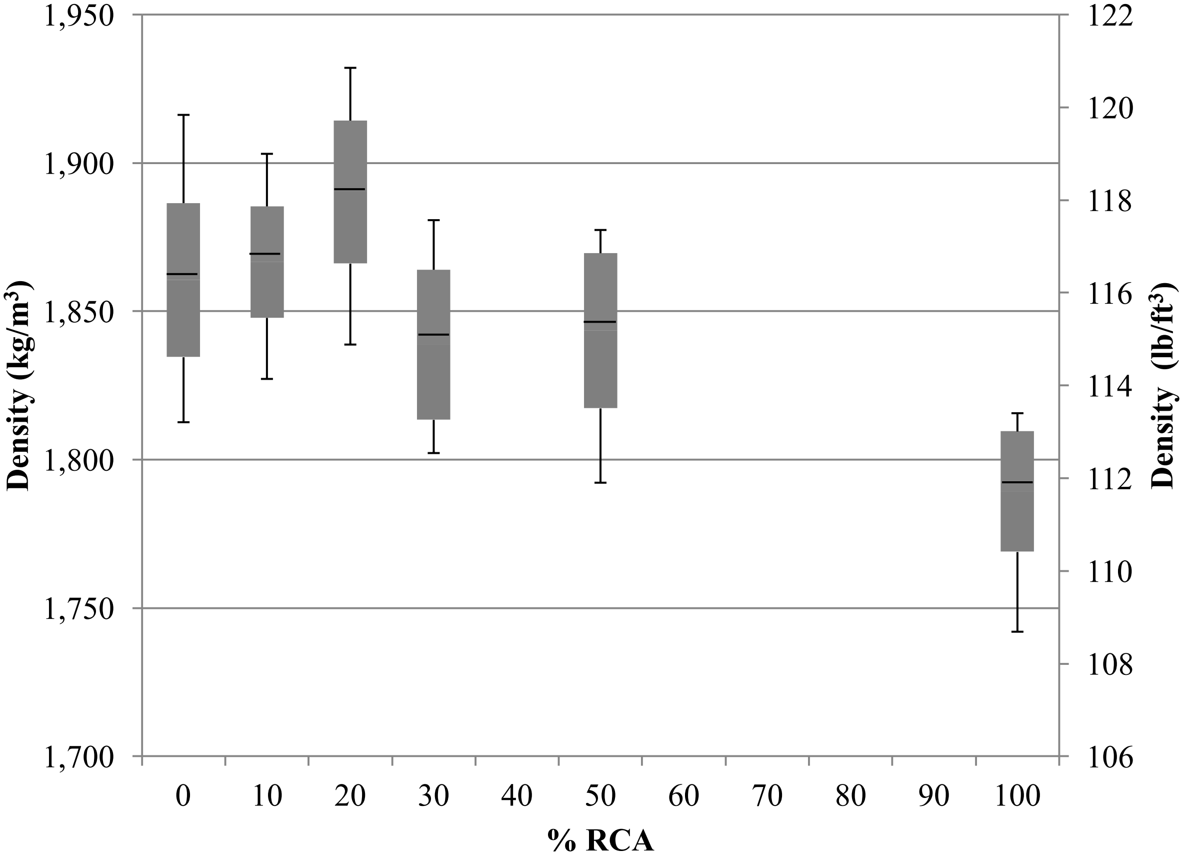

FIGURE 2: Density by Percent RCA

Compressive Strength

Figure 3 compares the compressive strength of the 6 mix designs by density. A trend line has been added to show the general relationship between density and compressive strength. With each data point representing a single specimen.

Compressive strength was found to generally increase linearly with sample density. This relation between compressive strength and density of porous concrete without RCA was also observed in previous research (9, 15). The trend would indicate that mixes with varying amounts of RCA could attain compressive strengths comparable to traditional pervious concrete when prepared at similar densities. Mix designs incorporating low amounts of RCA (0% to 20%) resulted in the highest compressive strength values while 100% RCA replacement resulted in the lowest compressive strength values. Figure 4 shows compressive strength of the pervious concrete mix designs presented in this study compared to those found during the literature review. The data presented from each study vary with material, mixture proportions, and construction techniques, but show a general range of values for pervious concrete. Based on the values found in prior studies, the pervious concrete incorporating RCA exhibited comparable or better compressive strength values. Results were within the typical range of about 3 MPa to 28 MPa (500 to 4,000 psi) for compressive strength (4). The results of Rizvi (6) show lower compressive strength for pervious concrete incorporating RCA than those found in this study.

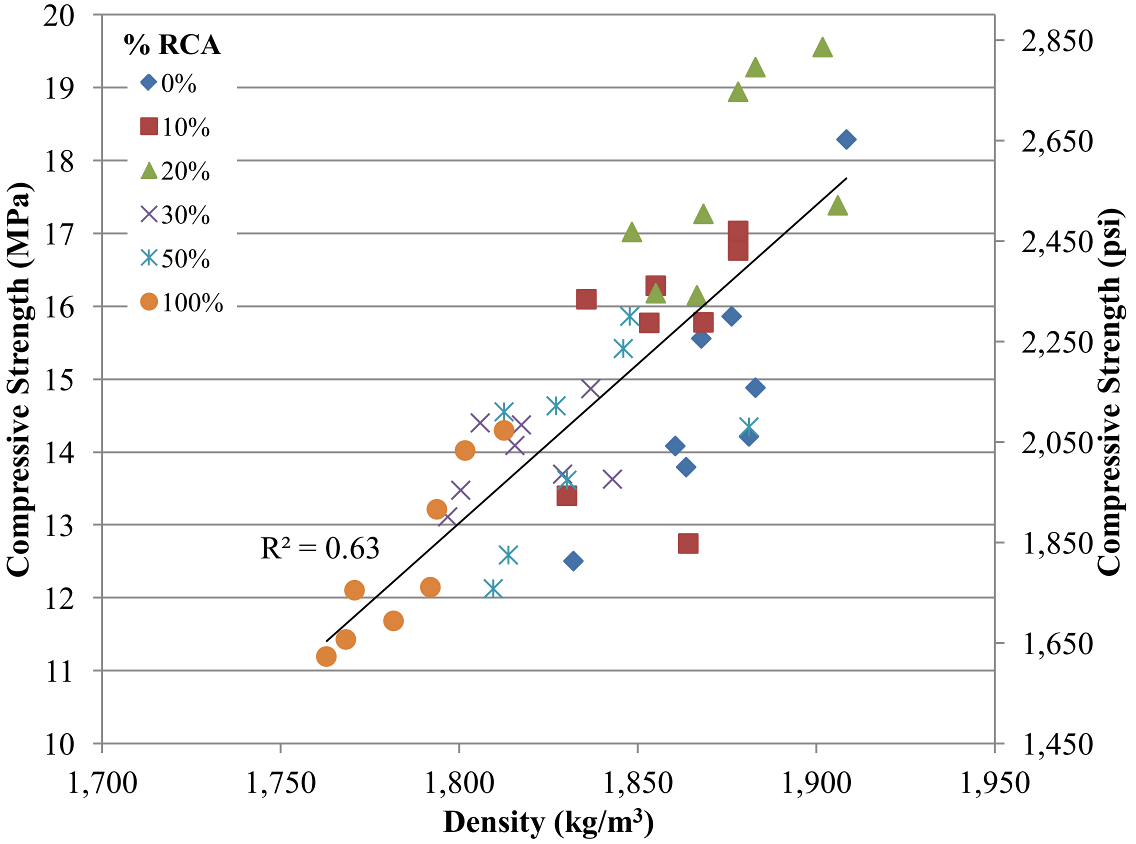

FIGURE 3: Compressive Strength Results

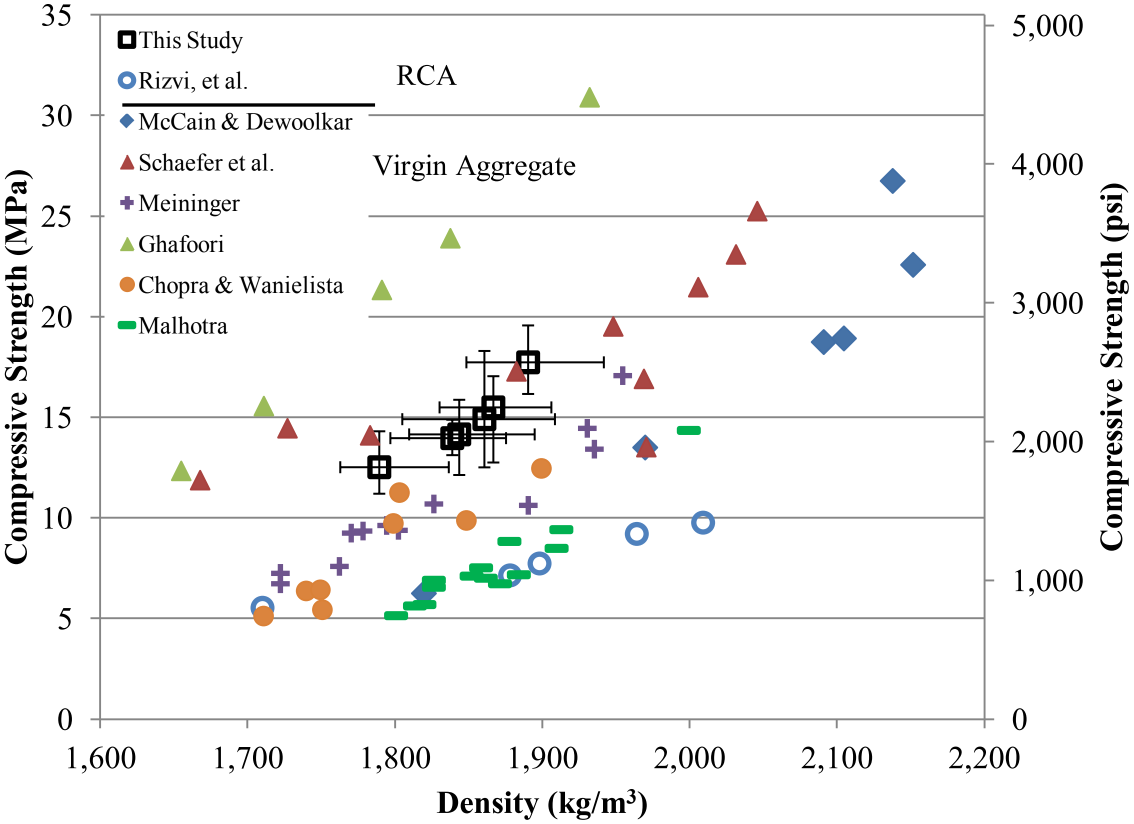

FIGURE 4: Compressive Strength Comparisions

Hydraulic Conductivity

Figure 5 presents the hydraulic conductivity of the six mix designs studied as a function of density, with each data point representing an individual sample. Trend lines have been added to show the general relationship between increasing density and decreasing hydraulic conductivity. Mixes with RCA contents of 0-30% generally grouped in the same range and showed similar density and hydraulic conductivity values. Samples with 100% RCA content were found to have the lower hydraulic conductivity values for a given density than corresponding mixes with 0%-30% replacement. Angularity of the RCA could reduce the connectivity of the pores, resulting in fewer channels to effectively transport water through the pervious concrete.

Figure 6 shows results of this study compared to previous studies investigating the hydraulic properties of pervious concrete. Mix designs including RCA as a replacement aggregate had hydraulic conductivity values that fall within the range of pervious concrete with conventional aggregates studied by other researchers. The trend of decreasing hydraulic conductivity with increasing density matched the trend observed by previous studies as well. The results of Rizvi (6) plotted on Figure 6 show much higher values for hydraulic conductivity of RCA pervious concrete than those found in this study.

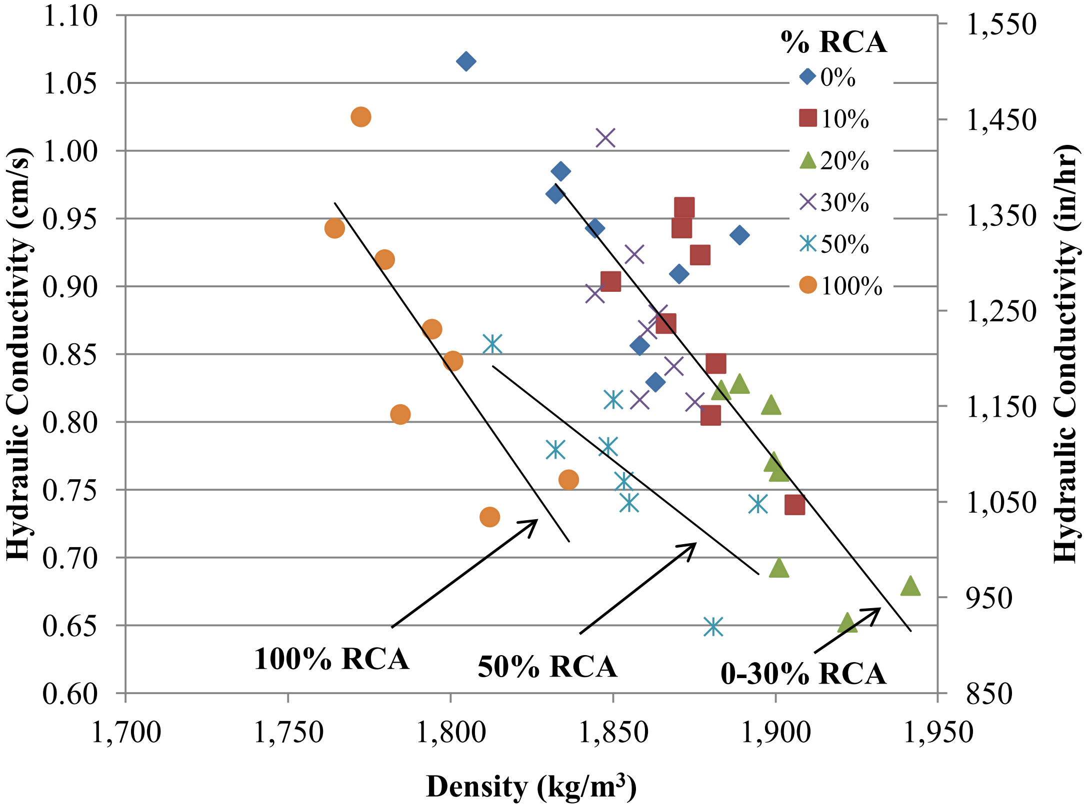

Figure 5: Hydraulic Conductivity

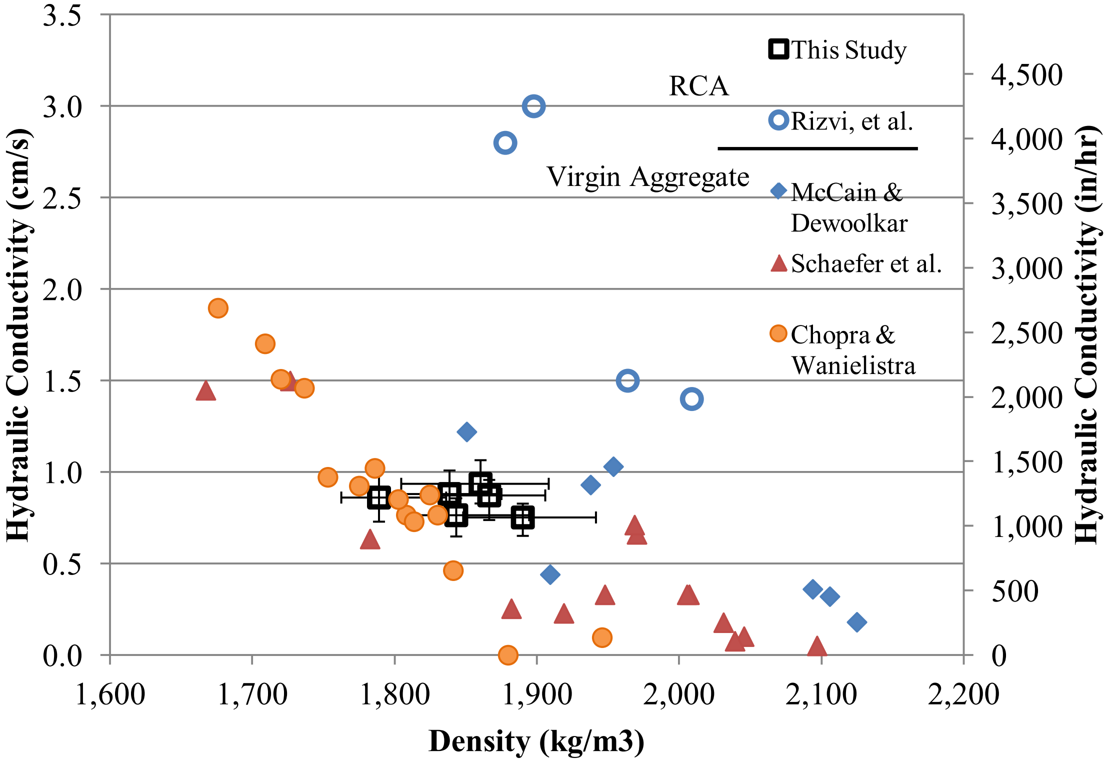

Figure 6: Hydraulic Conductivity Comparison

Hydraulic Conductivity-Compressive Strength Relationship

Figure 7 shows the hydraulic conductivity and compressive strength relationship of the pervious concrete mix designs presented in this study compared to those found in the literature. The overall trend appears to be that as compressive strength increases, hydraulic conductivity decreases. The data presented in this study fit well within the trend of the data collected in prior studies; however the expected decrease to hydraulic conductivity with increasing strength was not observed.

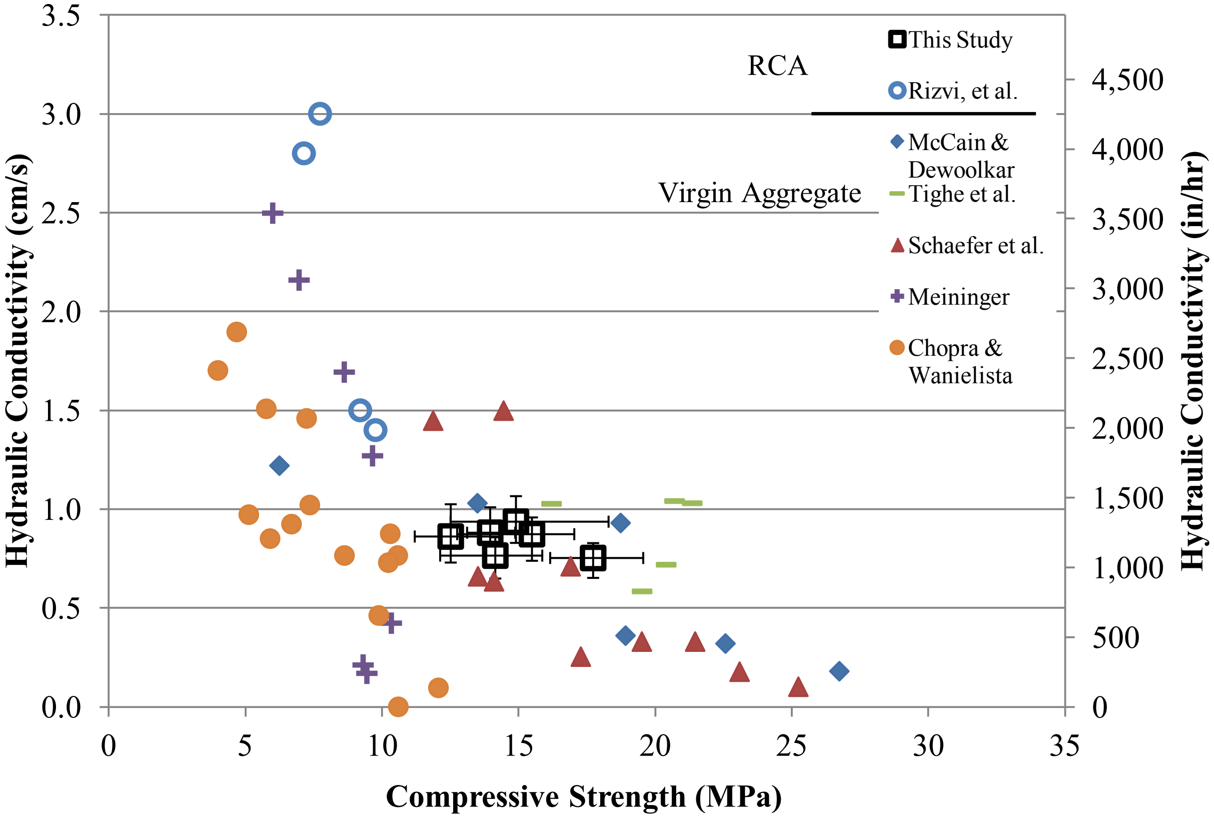

Figure 7: Relationship between Hydraulic Conductivity and Compressive Strength

CONCLUSIONS

This laboratory study examined some of the effects of incorporating varying amounts of RCA on the strength and hydraulic properties of pervious concrete. The experiments included compressive strength and hydraulic conductivity testing on specimens of varying mix designs substituting coarse aggregate with RCA ranging from 0 to 100%. The following conclusions are drawn for the mix designs studied.

Density values were generally similar with increasing RCA content; however, 100% replacement of RCA resulted in lower density values. There are several factors including differing aggregate densities and angularities could be the cause of this difference; however further investigation is needed to determine what role these factors play. Pervious concrete incorporating RCA exhibited similar relations between density and compressive strength found by previous studies using conventional aggregate. Increasing RCA generally decreased compressive strength, with 100% RCA content still providing strength values above 10 MPa (1,400 psi).

Hydraulic conductivity measurements indicated that increasing RCA content decreased hydraulic conductivity. Nonetheless, all mixes yielded acceptable hydraulic conductivity. Angularity of the RCA likely resulted in a more inefficient distribution of pore spaces, resulting in fewer pore spaces for water to flow. The relationship of compressive strength to hydraulic conductivity showed that pervious concrete with RCA display a similar relationship to pervious concrete with conventional aggregates, and falls within an expectable range to be considered an adequate substitute.

Based on the results of this study the particular RCA can be substituted up to 50% and provide strength and hydraulic conductivity values similar to the control mix design. Comparisons to Rizvi et al. (6) indicate that some differences in results exist. These differences indicate that specific RCA source and virgin aggregate as well as particular mix design may yield different results. However, results of this study and of Rizvi et al. (6) suggest use of RCA is feasible.

Further investigation is currently underway. Properties of the RCA including bulk density, water absorption, hardness and angularity are being determined and will be compared to the properties of the virgin aggregate to better understand the results of this study and to allow for comparisons to other studies. Freeze-thaw durability and additional strength testing are also planned to better characterize the performance of pervious concrete incorporating RCA.

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