Incorporating Recycled Concrete Aggregate in Pervious Concrete Pavements

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Abstract

Pervious concrete is a green alternative to conventional pavements with minimal fine aggregate and high void content. Pervious concrete allows water to infiltrate through the pavement thereby reducing the runoff and the requirement for stormwater management systems. The effectiveness of pervious concrete for use in the Canadian climate is currently being evaluated. Virgin aggregate sources within Canada are limited and other sources need to be evaluated for use, such as Recycled Concrete Aggregate (RCA). Recycling concrete from curbs and gutters, sidewalks and parking lots reduces the amount of concrete being put into landfills. Using RCA in new concrete has multiple advantages to the environment namely, reducing dumping at landfill sites, reducing gravel mining and reducing hauling of virgin aggregate and therefore reducing emissions.

The purpose of this research was to incorporate RCA into pervious concrete to create a very sustainable concrete product for paving. The research methodology involved substituting the coarse aggregate in the pervious concrete mix design with 15%, 30%, 50% and 100% RCA. Cylinders were cast in the laboratory for each percentage of RCA and also a control pervious concrete mix design containing only virgin aggregate. Each of the concrete batches that were mixed was tested for slump, temperature, entrained air, and unit weight. The testing was done to determine whether the batches were consistent and within the recommended limits specified. A single sized RCA was used and it was saturated prior to the batching process. Once the cylinders were cast they were tested at 7, 14 and 28 days for compressive strength. Some of the cylinders were cut and tested for permeability and void content. The testing showed that pervious concrete with an optimum RCA content has strengths, voids and permeability comparable to that of pervious concrete containing only virgin aggregate. In short, the paper shows that RCA provides an environmentally friendly material choice for pavements.

Introduction

Fresh water is a natural resource that many people across the world are not fortunate enough to have on a regular basis. While fresh water is available to most people throughout North America, the stormwater management systems that are required to provide this fresh water are not environmentally sustainable. These stormwater management systems are also very costly to build and maintain. Pervious concrete technology has been used throughout the southern United States and Europe as a replacement for stormwater management systems. This concrete is designed for low volume, low speed pavement applications such as sub-division roads, parking lots and driveways. The concrete has a structure with numerous interconnected voids that allows for immediate drainage through the pavement which substantially if not entirely reduces the runoff from the surface of the pavement. The open void structure of this type of pavement would suggest that pervious concrete may not be able to withstand winter freeze-thaw cycles. However, studies have shown that with proper mix proportioning and placement techniques pervious concrete can be successfully used in cold climates. The open void structure of pervious concrete is achieved by creating a concrete mixture with limited to no fine aggregate content and by carefully monitoring the water to cement ratio.

With the increased environmental consciousness every industry is attempting to make their products more environmentally friendly. One of the leading efforts that are being made to achieve this goal is increased recycling of old products. In the asphalt industry various methods of recycling are routinely used and 100% of the old asphalt pavements can be recycled. Recycling of concrete is also well established and similar to asphalt, old concrete products are also 100% recyclable. The recycled concrete product can be used as base and granular material, and between 45% and 80% of the old concrete can be used as coarse material in new concrete mixtures (1). Concrete from old pavements, curbs and gutters, and concrete structures are broken, removed and then pulverized. Care needs to be taken to prevent any contamination of the Recycled Concrete Aggregate (RCA) from material such as soil and rebar. The Portland Cement Concrete Association (PCA) reports that 11 states have used RCA in new concrete mixtures and they report that the concrete is very similar to concrete containing only virgin material (2). Virgin aggregate resources in Canada though far more abundant than that of other countries, is still limited and rapidly being used up. By using RCA as an aggregate source this limited resource can be used in a more sustainable fashion.

This research looked at combining these two sustainable concrete technologies to produce an even more environmentally friendly product. The aim of the research was to determine the optimum RCA content that can be added to pervious concrete pavements while maintaining the structural performance and drainage capabilities of the pervious concrete.

Research Methodology

This research looked at substituting the virgin aggregate with the RCA in different percentages in order to determine the optimum percentage of RCA that can be added. The RCA was directly substituted for the coarse aggregate at 15% (15RCA), 30% (30RCA), 50% (50RCA) and 100% (100RCA) of the virgin material. The RCA that was used for this research was comprised of old concrete curb and gutter, sidewalks and sewers that were successively crushed and sieved. One batch of concrete was mixed for each percentage substitution and a control was also batched. A total of 18 cylinders were cast for each of the 5 batches. During batching various fresh concrete tests were done in order to evaluate the affects of the addition of the RCA in to the pervious concrete mix. The cast cylinders were demoulded 24 hours after casting, at which point they were set to cure in moist conditions for a maximum of 48 days. The samples were tested for compressive strength, void content, and permeability. The coarse aggregate abrasion test was also done on the RCA in order to determine the amount of mortar content of the RCA and to evaluate its durability. Figure 1 displays the research methodology that used during this research.

Sample Preparation

The RCA that was used for the research was first obtained pulverized from the Steed and Evans Limited gravel pit and then was successively sieved in order to obtain the aggregate that was retained on the 9.5 mm sieve. Aggregate that was retained on the 12.5mm sieve and higher was then crushed using an impact crusher and sieved again to obtain the material retained on the 9.5mm sieve. The single sized 9.5mm RCA was then saturated with water for 24 hours to ensure that the mortar in the RCA does not absorb a large amount of water and interfere with the water-cement ratio. The virgin aggregate that was used was 10mm gravel and various additives (i.e. super plasticizer, retarder, air entrainment) and Polypropylene-co-Ethylene (PPE) fibres were also added to the mix. The moisture content of both the RCA and the virgin aggregate were measured prior mixing and the results were taken in to consideration when adding water to the mixes. The moisture content of the virgin aggregate was 1.96% and that of the RCA 3.52%. The high moisture content of the RCA can be attributed to the mortar in the RCA that readily absorbs water and was saturated for 24 hours.

The nominal aggregate size in the mix was 10 mm and therefore cylinders measuring 100mm in diameter and 200mm in height were cast according to the specification CSA A23.2 – 3C (3). A standard proctor hammer was used to consolidate the samples. The cylinders were cast in 2 lifts with 5 blows of the proctor hammer per lift. Prior testing at the University of Waterloo (UW) showed that 150mm pervious concrete samples cast in two lifts with 10 blows of the proctor hammer per lift, best compared to pervious concrete placed in the field (4). Since smaller cylinders were cast the consolidation technique was appropriately adapted. The concrete for each of the 5 batches was mixed until the proper consistency was achieved. Figure 2 shows the manner in which the consistency was tested and the way the pervious concrete should hold once

adequately mixed. Fresh concrete testing was also done during the batching to evaluate the variability between the batches.

Fresh Concrete Testing

During batching the fresh concrete tests that were done included slump, temperature, air content and unit weight. Table 1 displays the results of the fresh concrete tests that were done on the 5 batches. As can be seen in table 1 the slump for all of the batches was zero which is what was expected for pervious concrete as this type of concrete is also referred to as zero slump concrete. The low slump is due to the lower water-cement ratio which enables the voids in the concrete to remain open. The American Concrete Institute (ACI) specifies that the unit weight of Concrete should be within 80 kg/m^3 of a specified density (5). The specified density was that of the control mix which was 2009.71 kg/m3 as can be seen from table 1. Table 1 also shows that the mix containing 15% RCA was within the 80kg/m3 of the specified density. However, the mixes containing 30%, 50% and 100% RCA had densities that were significantly lower than 80 kg/m3 of the specified density and therefore did not meet ACI specification. The temperature of all the batches was very consistent with the average temperature of the batches being 17.8°C. This is above the minimum allowable temperature of 13°C which is specified in the ACI specification 306R – 88 (6). As the percentage of RCA increased the entrained air content of the fresh concrete decreased from 4.29% for the control mix and 2.50% for the 100% RCA mix. One of the main concerns associated with pervious concrete is its freeze-thaw durability, therefore, it is essential that every measure be taken to achieve this end. As the entrained air content decreases the freeze thaw susceptibility of concrete increases, and therefore it is essential that the air content be kept as close to that of the control mix.

Hardened Concrete Testing

The 18 cylinders that were cast were cured in moist conditions, and they were then tested for the following 3 hardened concrete tests.

- Compressive Strength

- Void Content

- Permeability

Compressive Strength Testing

Samples were tested for compressive strength at 7, 14, 28 and 48 days. The samples were cured until they were tested. Prior to testing the sample ends were ground using a diamond blade until

the ends of the samples were level. Figure 3 shows the cylinders in the end grinding apparatus. End grinding was found to be the preferred method of end preparation for pervious concrete rather than sulphur capping, in previous research conducted at UW (4). 3 samples were tested for each mix at 7, 14 and 28 days and finally 4 samples were tested for each mix at 48 days.

Figure 4 shows the results of the compressive strength testing for all the 5 mixes. As the RCA content increased the compressive strength of the samples decreased. The 28 day strengths of the samples were adversely affected by malfunctioning equipment and therefore the 48 day strengths are more representative of the final cured strengths of the samples. The 28 strengths were decided to be disregarded due to the fact that all the 28 day strengths were significantly lower than the 14 days strengths for the same mixes. On the other hand the 48 day strengths either were similar to or higher than the 14 day strengths. At 48 days average strength of the 15RCA samples was 9.2 MPa, which was very similar to the strength of the control mix at 9.76 MPa. There was a significant drop in strengths from the control mix for the 30RCA, 50RCA and 100RCA samples. The 100RCA samples had the lowest average strength of 5.53 MPa at 48 days. It should also be noted that the strengths of the 100RCA samples increased the least over the 48 day curing period. This can be attributed to the already cured mortar within the RCA and the failure of the aggregate in the cylinders rather than the paste. Figure 5 shows the manner in which the 100RCA samples failed.

Table 2 shows the average strengths for each of the mixes at 7, 14, 28 and 48 days. It also shows the standard deviation for each of the compressive strengths for each mix. As can be seen from table 2, the highest standard deviation for the compressive strengths was achieved at 28 days. This was further reason why the results of the 28 day testing were disregarded during the analysis of the results. The standard deviation of compressive strength at 7, 14 and 48 days, for all of the mixes was fairly low. The low standard deviation displays the consistency of all the mixes. Through out the compressive strength testing it can be seen that the 15RCA samples did not lose a significant amount of strength when compared to the control mix.

Void Content Testing

The void content of pervious concrete is typically expected to be between 15% and 30%. This parameter is an essential measure of the effectiveness of pervious concrete as it directly affects the draining capacity of the concrete. 5 cylinders were tested for each mix using the vacuum sealing method outlined in the Ontario Ministry of Transportation specification LS-443 (7). The InstroTek Incorporated CoreLok® was the device that was used to vacuum seal the cylinders, as can be seen in figure 6. Prior to testing the 100mm diameter cylinders were first end grinded, to ensure that the ends of the cylinders were smooth to prevent any leaks during the vacuum sealing. The vacuum sealed cylinders were then submerged under water, and subsequently weighed both sealed and opened. Equation 1 and 2 were used to measure the Bulk Specific Gravity (G_{mb}) and the Maximum Specific Gravity (G_{mm}), respectively.

Equation 1

$$G_{mb} = \frac{A}{\left(B - E - \left(\frac{D}{F}\right)\right)}$$

Equation 2

$$G_{mm} = \frac{A}{\left(B - C - \left(\frac{D}{F}\right)\right)}$$

Where,
G_{mb} is bulk specific gravity.
G_{mm} is maximum specific gravity.
A is the initial mass of dry core in air in grams.
B is the mass of dry, sealed core in air in grams.
C is the mass of the saturated specimen in water in grams.
D is the mass of plastic bag in air in grams.
E is the mass of sealed core, submerged in water in grams.
F is the bag volume correction provided by the manufacturer.

The void content for each of the 25 cylinders was then calculated using G_{mb} and G_{mm} form the calculation in equation 3. The G_{mm} and G_{mb} was temperature corrected due to the fact that the water temperature was below 25°C, and the graph displayed in figure 7 and the measured temperature water was used to obtain the correction factor (8).

$$Void\ Content = [1 - (G_{mb} \div G_{mm})] \times 100 \qquad \text{Equation 3}$$

Figure 8 shows the average void content and standard deviation of the void content for each of the 5 mixes. The void content of the samples increased significantly as the percentage of RCA in the mix increased. All the samples had void contents that were higher than the recommended range of 15% to 30%, with the highest void content being 39.3% for the 100RCA samples. The 15RCA samples and the control mix had very similar void content, with the 15RCA samples being only 1.3% higher than the control. However, the 30RCA samples had void contents that were 2.4% higher than the 15RCA mix, and 3.7% higher than the control. Although it could be assumed that a higher void content is preferable, this is in fact not the case. A higher void content usually compromises the compressive strength and load bearing capacity of the concrete. If the void content is close to or within the range suggested, then the compressive strength can be considered to not have been compromised. The increased void content can also be due to the porosity of the RCA. The RCA was significantly more porous than the virgin aggregate which would affect the void content. The mixes containing higher percentages of RCA also had fewer smaller sized aggregates and therefore this could cause the void content to increase.

The standard deviation for the void content of all the mixes was very low, showing that the mixes were consistent and the compaction method used produced consistent samples. The low standard deviation also shows the accuracy of the vacuum sealing method used for measuring the

void content. The standard deviation for the 30RCA samples was the highest. This trend was also observed for the during the compressive strength testing. In table 2 it can be seen that the 30 RCA samples had the highest standard deviations for both the 7 and 48 day compressive strengths.

Permeability

Permeability testing was done on the same 5 samples that were tested for void content. The permeability testing that was done used the falling head principle. The time required for the water to fall from one pressure head to another pressure head, through the pavement was measured. The sides of the 100mm by 200mm cylinders were sealed using a latex membrane. This was done to apply some lateral pressure to the sides of the sample as would be experienced by pervious concrete placed in the field. A Gilson Asphalt Permeameter was used to measure the permeability, however, the permeameter is designed for 150mm diameter samples and therefore some modification needed to be made prior to testing. Figure 9 shows the setup for the permeability testing. As it can be seen the samples were sealed to the second tier of the permeameter rather than the first and the all measurements were taken in this tier. The alterations to the test setup did not alter equation 4 that is used to calculate the coefficient of permeability. Pressure head markings are made on both tiers, however, due to the fact that only the second tier was used, new pressure head markings had to be made using a caliper.

$$K = \left(\frac{aL}{AT}\right) \times ln\left(\frac{h_1}{h_2}\right) \qquad \text{Equation 4}$$

Where,
K is the coefficient of permeability in cm/sec.
a is the area of the stand pipe in cm^2.
L is the length of the sample in cm.
A is the area of the test specimen in cm^2.
T is the elapsed time between h_1 and h_2 in sec.
h_1 is the initial head in cm.
h_2 is the final head in cm.

3 representative lengths of the samples were measure and then averaged. The area of the samples was calculated using a 100mm diameter. For each sample three readings were taken and were then averaged. Figure 10 shows the average permeability of each of the mixes and it also shows the standard deviation of the permeability. As the RCA content in the mixes increased the permeability of the cylinders increased dramatically. Environment Canada defines a severe thunderstorm as rainfall at 50mm in 1 hour or less (0.00139 cm/sec), or 75mm in 3 hours of less (9). The permeability rate for the 15RCA samples of 1.57 cm/sec was very similar to that of the control mix samples at 1.47 cm/sec. As it can be seen these permeability rates are significantly more than that rainfall rate that is categorized as a thunderstorm by Environment Canada. The 30 RCA samples had a significant increase in permeability from both the 15RCA sample and the control samples. Although increased permeability means increased drainage rates, these high drainage rates are unnecessary for the rate of rainfall experienced in Southern Ontario (the area for which this mix design was developed). Increasing the permeability implies a higher void

content which in turn results in decreased load bearing capacity. This decreased compressive strength could mean result in a shorter life of the pavement and could also result in increased frequency and severity of distresses such as raveling and joint failure.

Coarse Aggregate Abrasion Test of RCA

The coarse aggregate abrasion test was done on the RCA to determine both the mortar content of the RCA as well as the strength of the RCA. The Gilson Micro-Deval® was used for the coarse aggregate abrasion test, which was done in accordance with AASHTO TP 58-02 (10). Some modifications were needed to be made to the test method in order to calculate the percent loss. Due to the fact that a single sized 9.5 mm RCA was used in the mix, the sample prepared for the test was comprised of 1500g of RCA retained on the 9.5mm sieve. The sample was soaked in two litres of water for 2 hours and was then run in the Micro-Deval, with a steel ball charge of 5000g, for 105 minutes. The specimen was then washed and sieved over two superimposed sieves of sizes 4.75mm and 1.18mm. The material retained on the 4.75mm and 1.18mm sieves was oven dried and then measured. Equation 5 was then used to calculate the percent loss.

$$Percent\ Loss = \frac{A-B}{A} \times 100\% \hspace{2cm} \text{Equation 5}$$

Where,
A is the initial oven dried mass of the specimen in grams.
B is the final oven dried mass, after testing, of the specimen in grams.

For the case of the RCA the percent loss was calculated to be 13.07% and most if not all the material that was lost appeared to be the mortar in the RCA. Significant amounts of ground up mortar was washed away during the sieving after the Micro-Deval test was run. Figure 11 shows the RCA before and after the abrasion test was done. It can clearly be seen that the aggregate after the test is significantly more rounded and also has significantly less paste than the aggregate prior to the test. Typical premium aggregate in Ontario for an asphalt wearing course should have a percent loss between 5% and 15%, depending on the type of aggregate (11). The 13.07% abrasion of the RCA is within range specified for the premium aggregates, which indicates that it is a good quality aggregate that can be used in pervious concrete. The high quantity of mortar paste in the water after the test was conducted shows the weak point in the RCA. The weak mortar can also explain the weaker strengths that were obtained as the percentage of RCA was increased in the mix.

Analysis

It is absolutely essential with pervious concrete that a very delicate balance be struck between the strength of the concrete and its draining capacity. This research was conducted to establish an

optimum content of RCA that could be added to the pervious concrete, without altering the balance between the strength and the permeability. The compressive strength results showed that up to a 15% replacement of virgin aggregate with RCA did not cause any significant loss in compressive strength. On the other hand, at 30 % replacement and higher there was a significant decrease in compressive strength. Although pervious concrete is expected to not have very high compressive strengths, the concrete still needs to be strong enough to hold static loads in parking lots without raveling.

The void content of the 15RCA and control samples was very similar at 31.7% and 30.4%, respectively, and these were just barely higher than the maximum void content suggested at 30%. The void content for the 30RCA, 50RCA and 100RCA samples was significantly higher than 30% and therefore the samples were also significantly weaker as discussed above. Some of the increased void content can be attributed to the increase in the percentage of the highly porous RCA. However, most of the change in void content was due to the different bonds that were formed between the RCA and the virgin material, and the greater percentage of coarse material in the mix as the RCA content increased. This difference was not evident up to a replacement percentage of 15%. The permeability results also clearly showed the different bonding properties of the RCA. Once again the 15RCA samples had very similar permeability results to the control samples. Further more the measured permeability rates for both the control samples and the 15RCA samples were more than adequate to handle the rainfall in Southern Ontario, without the pavement experiencing any ponding. The 30RCA samples again had significantly higher permeability rates than the control samples. However, such high rates do not further decrease the amount of runoff from the pavement and therefore such high rates are completely unnecessary. Such high rates of permeability also have an adverse affect on the compressive strength of the samples and therefore decreases there load bearing capacity. Therefore, if the permeability rate is increased too much then there is a danger that the life of the pavement will severely be reduced.

In all the testing that was conducted the 15RCA samples performed very similarly to the control samples. A significant change in performance was seen when the percentage of RCA was increased to 30%. The change in performance was such that it would decrease the performance of the pervious concrete pavement. Once the percentage was increased beyond 30% replacement of virgin aggregate, the decrease in pavement performance was aggravated. The results of all the testing showed that it is indeed possible to replace the virgin aggregate in pervious concrete with RCA. The research also clearly shows that the optimum RCA replacement percentage in pervious concrete is 15%. A replacement percentage higher than 15% results in decreased performance of the pervious concrete pavement.

Conclusions

The purpose of this research was to make pervious concrete an even more environmentally sustainable option by introducing RCA in to the mixture. This research evaluated substituting the

virgin aggregate with four different percentages of RCA. Five batches of concrete were mixed and these included the control mix, 15% RCA, 30% RCA, 50% RCA and finally 100% RCA. 18 cylinders were cast for each of the five batches. During the mixing of each of the batches fresh concrete tests, namely slump, temperature, entrained air, and unit weight were done to establish the affect of the addition of the RCA in to the mix. The temperature of all the batches was consistent and the slump for all the batches was zero, which is what was expected. The unit weight and entrained air for the 15RCA samples was very similar to the control mix. However, there was a significant drop in the unit weight and the entrained air for the 30RCA, 50RCA and 100RCA samples. The decrease in entrained air can result in increased susceptibility of the pervious concrete to freeze-thaw cycles. The unit weight of the 30RCA, 50RCA, and 100RCA samples was also not within the 80 kg/m^3 of the specified density (unit weight of control mix), which is the requirement according to ACI specifications.

Hardened concrete tests were also done on the samples and these included compressive strength, void content and permeability. Three samples were tested for each mix at 7, 14 and 28 days and 4 samples were tested for each mix at 48 days. The 28 day testing results were disregarded during analysis due to errors in testing resulting from malfunctioning equipment. The 48 day strengths were considered to be the final cured strength for each of the mixes. The 15RCA samples had very similar strengths to the control samples. On the other hand, there was a significant decrease in strength for the 30RCA, 50RCA and 100RCA samples. The void content and permeability of the 15RCA samples was very similar to the void content and permeability of the control samples. The 30RCA, 50RCA and 100RCA samples had a significant increase in void content and permeability from the control samples. The decrease in strength, and increase in void content and permeability when the RCA percentage is above 30% has adverse affects on the delicate balance between the durability and drainage capacity of the pervious concrete. The 15RCA did not significantly affect any of the parameters when compared to the control mix of pervious concrete. It was determined that the optimum replacement percentage for RCA in to pervious concrete is 15% as it does not significantly affect the pervious concrete.

Future Work

Further research should be completed on using different sources of RCA and introducing it in to pervious concrete. Further more research should be done to develop guidelines for the quality of RCA and processing of RCA so that standard types of RCA can be produced for use in new concrete mixes. Research is currently underway at the University of Waterloo (UW) to establish the optimum RCA content that can be used in conventional concrete. This research was done only in a laboratory setting and to establish its validity in the field it is essential that a field trial be conducted. The field trial should also have different percentages of RCA replacement so that the field results can compared to the laboratory results.

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Tables

Table 1: Fresh Concrete Test Results

Batch No.	Batch Type	Temperature (°C)	Unit Weight (kg/m^3)	Slump (mm)	Air Content (%)

1	0% RCA	19.3	2009.71	0	4.29
2	15% RCA	18.7	1964.57	0	3.60
3	30% RCA	15.6	1878.14	0	3.30
4	50% RCA	17.2	1898.86	0	3.80
5	100% RCA	18.4	1710.00	0	2.50

Table 2: Average Compressive Strengths and Standard Deviation of Strengths

| Sample Type	7 Days		14 Days		28 Days		48 Days	
	Avg Strength (MPa)	Std. Dev	Avg Strength (MPa)	Std. Dev	Avg Strength (MPa)	Std. Dev	Avg Strength (MPa)	Std. Dev
0% RCA	8.69	0.47	9.95	1.22	8.85	2.18	9.76	0.63
15% RCA	7.27	0.72	8.31	1.06	6.81	1.94	9.20	0.44
30% RCA	5.62	1.14	7.78	0.33	6.69	0.14	7.14	0.92
50% RCA	6.06	0.21	6.40	0.67	6.46	0.54	7.73	0.48
100% RCA	5.05	0.27	5.03	0.49	5.02	0.38	5.53	0.15

Figures
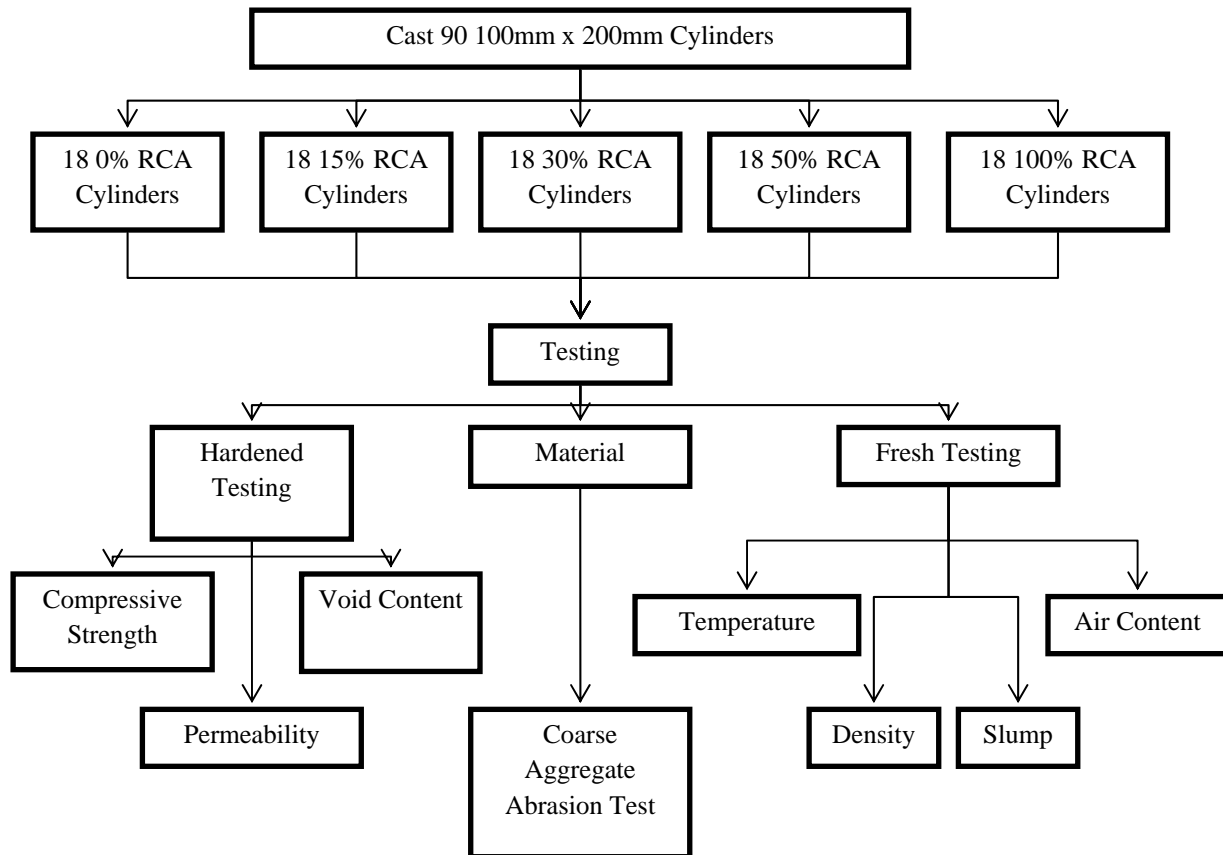
Figure 1: Research Methodology Flowchart

Figure 2: Testing the Pervious Concrete for Consistency

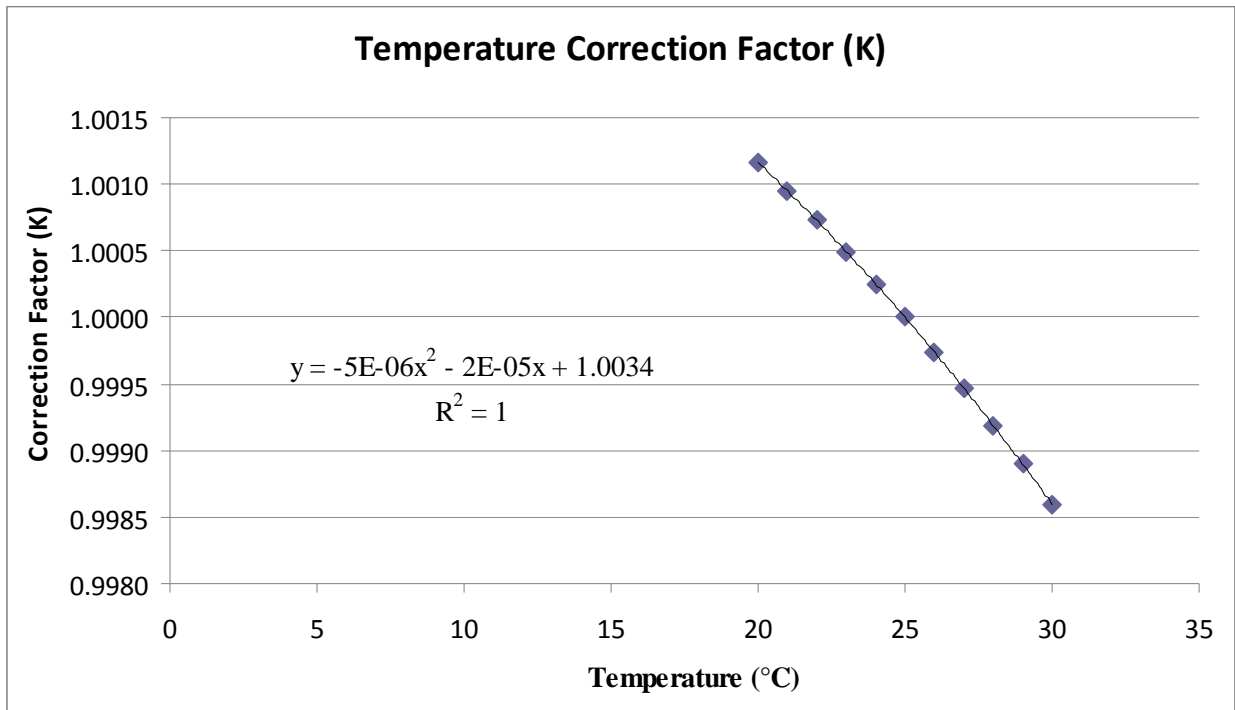**Figure 3: Compressive Strength Samples in the Diamond Blade End Grinder**
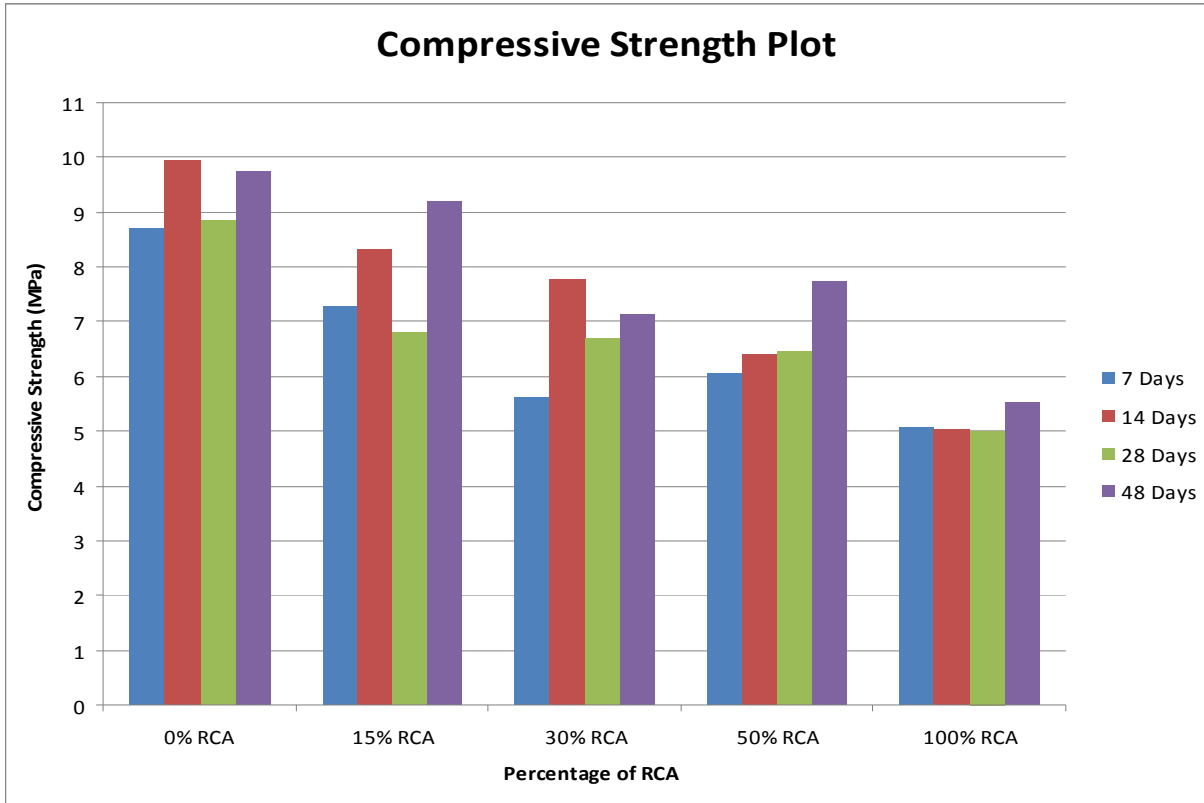
Figure 4: Compressive Strength Results

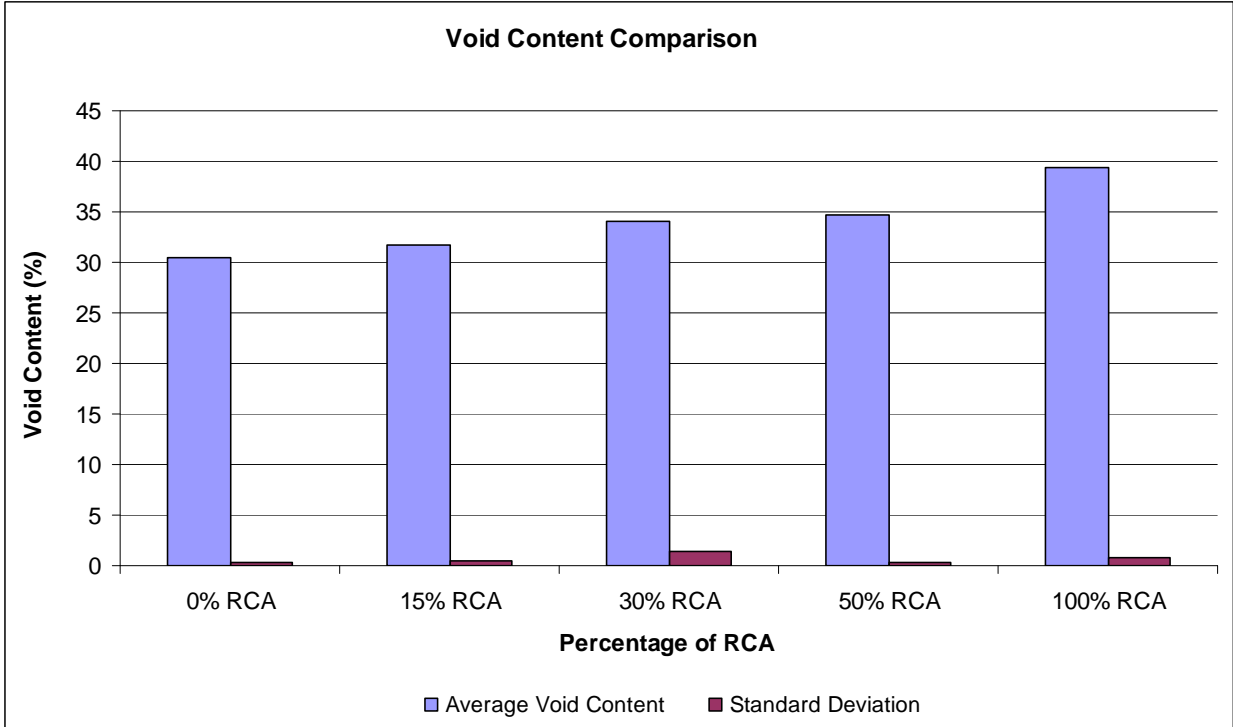
Figure 5: Failure Plane of the 100RCA Samples

Figure 6: Vacuum Sealed Specimen to Test for Void Content

Temperature Correction Factor (K)

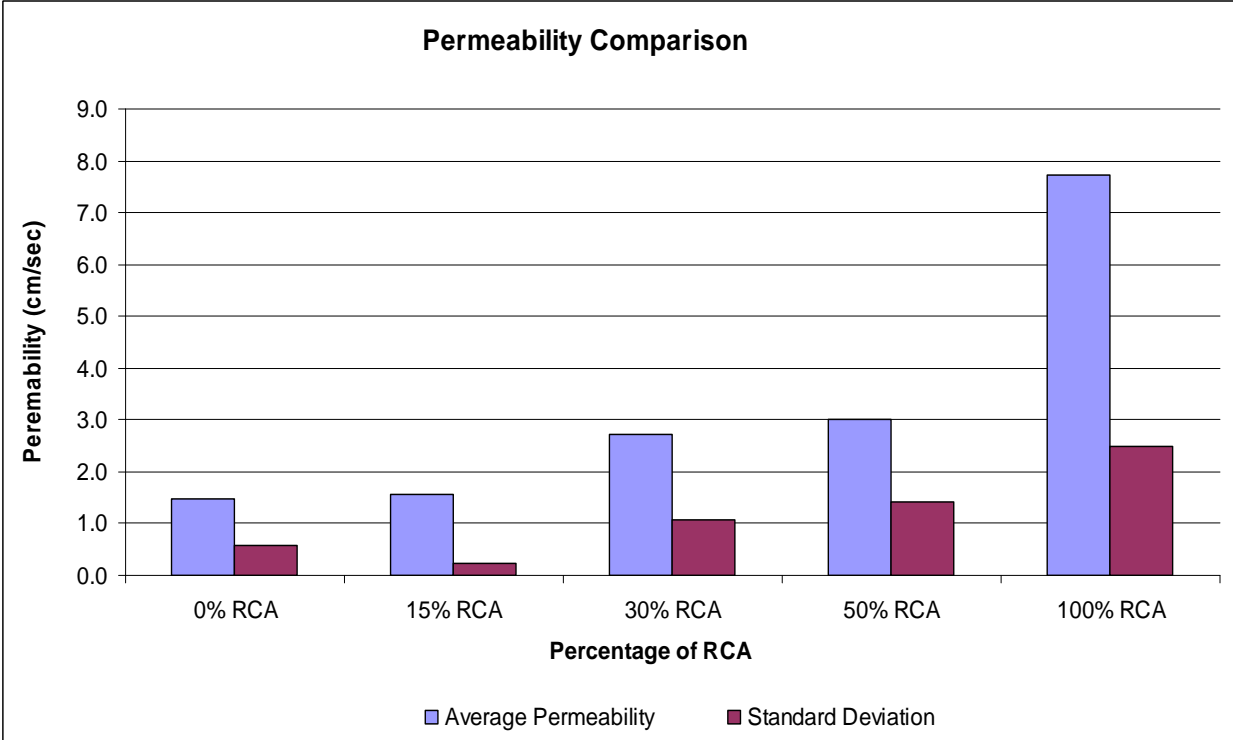$y = -5E\text{-}06x^2 - 2E\text{-}05x + 1.0034$

$R^2 = 1$

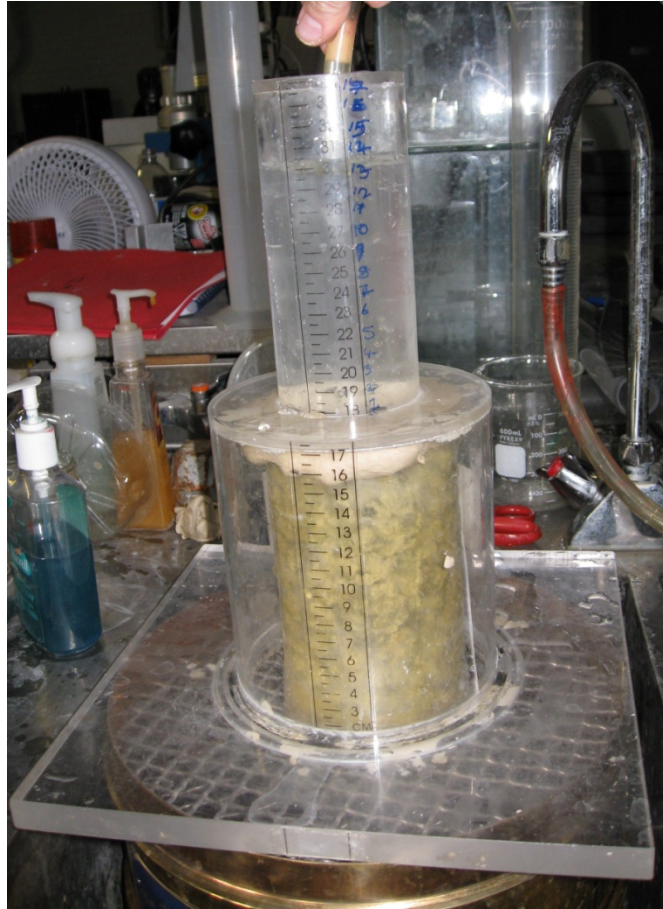**Figure 7: Temperature Correction Factor (K) Plot**

Figure 8: Void Content Results for the 5 Mixes

Figure 9: Coefficient of Permeability Results

Figure 10: Improvised Test Setup for Coefficient of Permeability Testing

Figure 11: RCA before and after the Micro-Deval Abrasion Test