EVALUATION OF SUSTAINABILITY, DURABILITY AND THE EFFECT OF SPECIMEN TYPE IN PERVIOUS CONCRETE MIXTURES

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EVALUATION OF SUSTAINABILITY, DURABILITY AND THE EFFECT OF SPECIMEN TYPE IN PERVIOUS CONCRETE MIXTURES

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To my circumstances

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ABSTRACT

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Pavements are one of the most important components of a city's infrastructure covering significant portions of urban land while simultaneously generating negative impacts such as the increase of urban temperature, lack of clear surface for rainwater percolation and traffic noise. In order to minimize the negative impact of pavements, several agencies have increased requirements for pavement sustainability, with pervious concrete being proposed as one of the leading materials to achieve this goal. The main characteristic of pervious concrete is its interconnected network of pores around the aggregate, which allows rainwater to percolate directly to the soil, potentially lowering pavement temperatures, improving skid resistance and reducing noise generation due to acoustic absorption. The purpose of this research is to further optimize the performance

and enhance sustainability of pervious concrete by using waste materials, particularly Ground Granulated Blast Slag (GGBS), to partially replace cement, and Recycled Concrete Aggregate (RCA) to replace virgin coarse aggregate. The proposed methodology will have two steps, focusing on each of the aforementioned materials. Each concrete mixture will be tested for compressive strength, permeability, unit weight and durability. The successful completion of this project would promote the use of pervious concrete in pavements by developing concrete mixtures with optimized properties, lower cost, reduced CO_2 footprint and high recycled material content.

I. INTRODUCTION

1.1 Background

The depletion of significant portions of natural land to allow for urban growth is altering entire ecosystems due to the large areas covered with flat and impervious surfaces such as parking lots and paved roads. Those areas covered by urban infrastructure can reach daytime temperatures of up to 150 °F, storing heat that is then released during the night, which contributes to the phenomenon known as urban heat island effect [1]. A decrease in the replenishment of ground-water along with the rise in temperature generate problems such as increased energy consumption, the need for higher capacity storm water sewer systems, impaired water quality, and contaminated local water streams. To minimize the negative impact of pavements, the U.S. Environmental Protection Agency has increased its regulations for storm water management and is also actively promoting the use of sustainable construction materials. One of the leading alternatives to conventional paving materials is pervious concrete.

Pervious concrete typically consists of coarse aggregate, Portland cement, water, and various admixtures. The absence of fine aggregates and a uniform coarse aggregate gradation creates an interconnected network of pores that allows rainwater to percolate through its structure and help replenish the underground water table (Figure 1) [2].

Contractors in the United States have taken advantage of this unique feature for more than 30 years to control stormwater pollution and runoff, eliminating the need for water-retention facilities and reducing the size of storm sewers [3]. The benefits of pervious concrete are not limited to its infiltration capacities. A number of studies have shown its potential to remove pollutants from water, reduce noise, improve skid resistance, and help mitigate the heat island effect [4,5,6,7].

One of the key properties of pervious concrete is its porosity, which ranges from 15% to 35% [2] and has been found to have a direct effect on other properties, such as permeability and strength. For instance, when porosity is high, the concrete tends to have higher permeability but lower strength and vice versa [2]. Therefore, the goal when designing a pervious concrete mixture is to provide the concrete with sufficient porosity to maintain a functional balance between the mechanical and the hydrological properties.

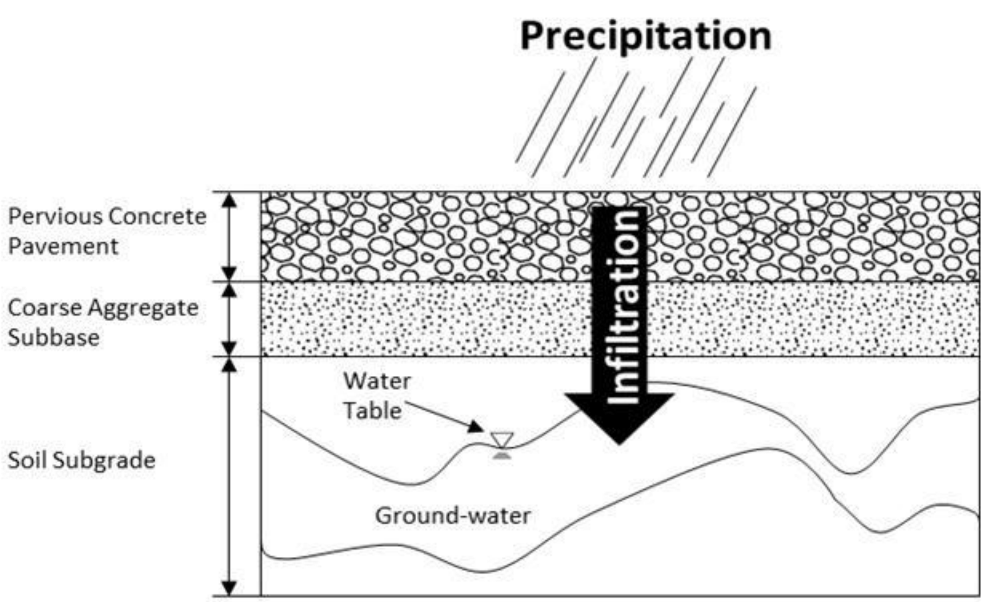


Figure 1 Cross Section of a Pervious Concrete Pavement

Nevertheless, a correctly designed concrete mixture is not a guarantee of an efficient pervious concrete pavement, as construction techniques, especially compaction, play a role that is equally as important to the overall performance of the pavement as the mix design [8]. For instance, insufficient compaction of the pavement in the field would lead to a higher permeability yet lower strength of the pavement, whereas excessive compaction would significantly reduce the permeability of the pervious pavement system.

Although pervious concrete has proven to be a sustainable alternative to conventional pavement, it has not been utilized to its maximum potential and has been limited to applications such as low vehicle traffic areas, parking lots, and sidewalks [9]. Some of the reasons for its limited use are the lack of a method to accurately assess its compaction level during construction in the field and the need for methods to accurately evaluate its mechanical and durability properties. The American Society of Testing and Materials (ASTM), through its subcommittee C09.49 on pervious concrete, has developed standards such as ASTM C1688 to evaluate the density and void content of fresh pervious concrete and ASTM C1701 to measure the infiltration rate of in-place pervious concrete; however, there is still a pressing need for more research to increase the competitiveness of such material.

1.1.1 Compaction of Pervious Concrete

The consolidation and compaction of pervious concrete in the laboratory and in the field is one of the key variables for maximizing the performance of pervious concrete. Meininger et al.[10] found that the amount of energy applied, as well as the method of compaction selected, can have a significant effect on the porosity of pervious concrete, consequently affecting the strength and permeability of the material. Ghafoori et al. [11] was one of the first researchers to investigate the physical and engineering characteristics of various pervious concrete mixtures using different levels of compaction. His research included the use of a 2.27 Kg (5lb) hammer to apply eight levels of compaction effort (from 13 J/m³ to 264 J/m³) and hand rodding as described in ASTM C192. They concluded that samples compacted at an energy of 33 J/m³ had similar properties to those obtained using the rodding method. Several authors have agreed that the conventional method for compacting cylinders using a ½-inch rod is not suitable for pervious concrete and does not replicate the compaction effort applied in the field [9,12].

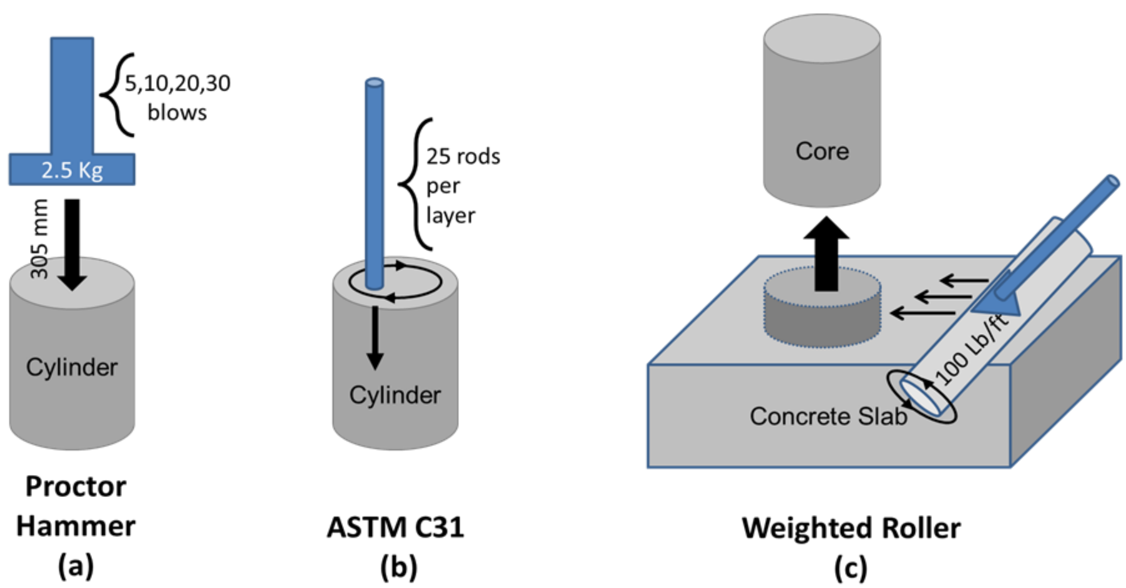


Figure 2 Compaction Methods. (a) Proctor Hammer. (b) ASTM C31. (c) Field Slab

Putman et al.[13] compared the engineering properties of laboratory-cast cylinders compacted using a Standard Proctor Hammer (Figure 3a) and the rodding method (Figure 2b). They found that rodded specimens showed greater variability than those compacted using a Standard Proctor Hammer and suggested the use of slabs of the same pavement thickness (Figure 2c). They also suggested the use of the same finishing technique as applied in the field to extract cores that effectively replicate the properties of in-place pavements. Despite the aforementioned efforts to study laboratory compaction methods that replicate the properties of field pavements, there is not an established methodology that could help to systematically reduce the variability of the desired permeability of any pervious concrete mixture throughout the entire process of design, mixing, placement, and finishing.

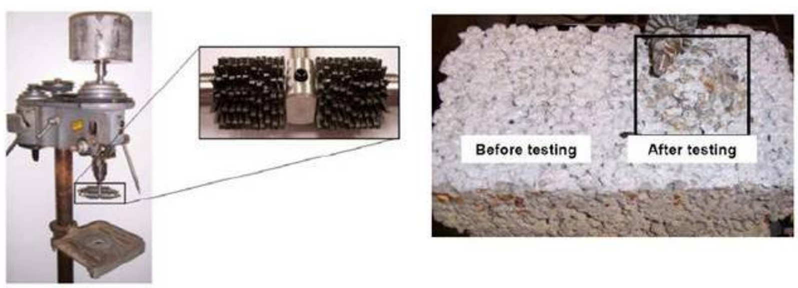
1.1.2 Pervious Concrete Surface Durability

The appropriate level of compaction is of key importance to obtaining the desired permeability and strength during construction of the pervious concrete pavement. However, the durability of its surface largely determines the operational life of the pavement. Surface durability is particularly critical in pervious pavements, as the rougher surface and open-graded structure can generate propitious conditions for the disaggregation of aggregate particles from the pavement surface, causing irregularities in its structure and uniformity [10]. This problem, commonly known in pavements as raveling, occurs when high shear stresses are applied to the pavement, such as when a truck suddenly brakes or performs a sharp turn, fracturing the bonding between the aggregate and the paste [14].

The surface abrasion and raveling resistance of a pervious pavement can be influenced by a number of factors related to the mixture proportioning, placement, and curing of the material. Therefore, a test method to help assess the surface durability of pervious concrete regardless of its specific conditions is needed [15]. Abrasion resistance in conventional concrete and mortars is commonly measured using the procedure described in ASTM C944.

(a) Los Angeles Abrasion Machine used in the Cantabro Loss test

(b) Asphalt Pavement Analyzer used in the Loaded wheel test



(c) Rotating-Cutter Drill Press used in the Surface Abrasion test

Figure 3 Abrasion Methods Performed by Dong et al. (a) Los Angeles Abrasion Machine. (b) Asphalt Pavement Analyzer. (c) Rotating Cutter Drill Press

Nevertheless, the specific characteristics of the surface of pervious concrete indicate that validation is needed to ensure the suitability of this test. A study comparing three different methods of evaluating abrasion resistance in pervious concrete was performed by Dong et al. [16]. They subjected eight different mixtures to three different methods as shown in Figure 2. These methods comprised the Cantabro test conducted in the Los Angeles Abrasion Machine (ASTM C131) and the Loaded Wheel Abrasion test using the Asphalt Pavement Analyzer (APA), both used to test rutting potential of asphalt mixtures, as well as the Surface Abrasion test (ASTM C944).The authors found that the Cantabro test achieved less variability and higher repeatability of the three methods studied. These findings provide information about the relationship between different surface durability tests and specimens cast in the laboratory. However, Offenberg et al. [14] stressed the need to correlate the performance of cores to the cylinders cast under laboratory conditions, which would give a better understanding of the behavior of pervious concrete pavements in the field.

1.1.3 Use of Recycled Materials in Pervious Concrete

One of the main advantages of pervious concrete pavements is improved sustainability by allowing the water to directly percolate to the ground; however, their construction can still generate additional substantial impacts on the environment. For instance, cement, which is used in relatively high quantities to produce pervious concrete, is a large contributor to carbon dioxide (CO_2) emissions. On average, for every ton of cement produced, there is an almost equal amount of CO_2 released into the air [17]. Also, the demolition of existing concrete structures, such as pavements, generates a substantial amount of debris, which amounts to one sixth of all waste in land fields in the U.S [18].

Densely populated areas concentrate considerable amounts of hardscape, preventing water from continuing its natural flow and increasing temperatures in urban areas. The U.S. Environmental Protection Agency claims that the difference in temperature between developed areas and nearby rural areas can be as much as 1 to 3 °C [1.8 to 5.4 °F], which directly translates into ecological and economical issues related to the higher energy consumption needed for cooling and ventilation [1]. The negative effects on the environment highlight the need for change in the form of more sustainable construction techniques and materials that help maintain the balance in natural cycles.

To mitigate the negative impacts of paved surfaces, the implementation of pervious concrete with a high percentage of recycled materials is a logical step to further enhance the environmental benefits of pervious concrete. However, this step cannot proceed without research to verify that recycled materials can be safely used without significantly affecting the concrete mechanical and physical properties.

Among the materials with a high potential to reduce environmental impact of pavements are Recycled Concrete Aggregate (RCA) and Ground Granulated Blast Furnace Slag (GGBFS), a waste product from ore. These materials could be used in pervious concrete mixtures to reduce greenhouse gas emissions, reduce mining and processing of virgin aggregates. Also, because GGBFS is generally whiter than Portland cement its use can potentially increase the solar reflectivity of pavements [19]. Rizvi et al. [20] performed preliminary research on RCA in pervious concrete that crushed and sieved concrete from old curbs and gutters, sidewalks, and sewers to substitute for virgin coarse aggregate. Based on the specific recycled concrete aggregate, they found that a substitution of 15% of recycled concrete aggregate produced properties that were similar to those of the control mixture.

Prusinski et al. [21] evaluated the potential of GGBFS as a material to reduce the CO_2 emissions associated with the construction of impervious concrete pavements. They found that replacing 35% to 50% of cement with GGBFS yielded a reduction of CO_2 emissions by 29% to 46%, respectively. Solar Reflectance Index measurements on conventional pavements using slag in concrete mixtures have shown the potential to mitigate the heat island effect by reducing the solar reflectivity of concrete pavements by 71% when 70% of cement was replaced by GGBFS [22, 23]. Despite the promising results seen in conventional pavements using GGBFS to replace cement, no research exists on the use of such material in pervious concrete.

In summary, pervious concrete pavements can significantly reduce the negative impact of having large surfaces covered by pavements in urban areas, yet there is still ample opportunity to further improve this material and reduce its carbon footprint by using large proportions of recycled materials such as RCA and GGBFS. Such improvements in pervious concrete sustainability, combined with enhanced methods to control previous concrete compaction and adequate means to evaluate its surface durability, could produce a synergistic effect that would lead to the widespread use of this environmentally friendly material.

1.2. Research Purpose

The purpose of this research project is to analyze the feasibility of producing highly sustainable previous concrete mixtures, evaluating the effect of the applied compaction on their properties and analyzing different test methods to assess their surface durability. This thesis is divided into three phases, each developed specifically to assess the following topics:

- Evaluate the feasibility of producing highly sustainable pervious concrete mixtures using large amounts of recycled materials without affecting their performance. Particularly, investigate the use of 50% of RCA and replacing cement with up to 30% of GGBFS. Solar Reflectance Indexes and CO_2 emissions of each mixture will be calculated to provide a basis for measuring sustainability.
- Investigate the effect of compaction techniques and efforts on pervious concrete properties. Permeability, porosity, unit weight, and compressive strength will be measured in field samples (cores) and laboratory cast specimens to compare their performance and determine correlations between properties.
- Characterize abrasion resistance of core samples and laboratory cast samples of pervious concrete to develop information about the efficiency, precision, and correlation of two different test methods used to evaluate durability: the Surface Abrasion test as determined by ASTM C 944 and Abrasion Resistance to Degradation of Pervious Concrete by Impact Abrasion as described in ASTM C1747.

1.3 Scope of Investigation

It is expected that the analysis of the test results shall address the following topics:

- *Effect of Recycled Materials:* the analysis of experimental results will determine the effect of use of large portions of recycled materials on the hydraulic and mechanical properties of pervious concrete. As the gradation of the recycled aggregate will be similar to virgin aggregate, and as GGBFS will replace cement (therefore not altering the concrete paste content), it is expected that the pervious concrete using recycled materials will exhibit hydraulic and mechanical properties similar to those mixtures using 100% virgin materials.

- *Effect of Raw Materials on the Concrete Solar Reflectance Index:* the effect of GGBFS and different aggregate types on the Solar Reflectance Index will be analyzed. It is expected that raw materials of lighter color will yield significantly higher values of solar reflectance of pervious mixtures, especially in those mixtures made with lighter aggregates (limestone and RCA blend).
- *Effect of Paste and Compaction:* the effect of paste contents at different void and compaction levels will be analyzed. Two particularly relevant scenarios that will be analyzed are concrete mixtures subjected to constant compaction levels versus mixtures with a constant void content.
- *Surface Durability:* abrasion resistance measured on core samples using the method described by ASTM C1747 (Abrasion Resistance to Degradation of Pervious Concrete by Impact Abrasion) and the method described by ASTM C944 (Surface Abrasion Resistance Test) will be compared and correlated. The suitability of each of these test methods for use on pervious concrete will be assessed.

1.4 Thesis Organization

The thesis is organized as a collection of journal papers joined together by a common introduction, conclusion, and references. Chapter 1 is the introduction and scope statement. Chapter 2 is a report on the effect of use recycled materials in pervious concrete mixtures to improve sustainability. Chapter 3 is a paper evaluating the abrasion resistance on pervious concrete. Chapter 4 is a paper discussing the characteristics and performance of pervious concrete core samples. General conclusions are provided in Chapter 5.

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II. EFFECT OF RECYCLED MATERIALS AND COMPACTION METHODS ON THE SUSTAINABILITY AND PROPERTIES OF PERVIOUS CONCRETE

2.1 Abstract

Pervious concrete allows rainwater to flow through its structure and pass into the soil, mitigating multiple negative environmental effects of urban pavements and parking areas. This study aims to further increase the environmental benefits of pervious concrete by using up to 50% of recycled aggregate and up to 30% of slag to reduce its carbon footprint and the depletion of existing aggregate sources while maintaining its hydrological, mechanical, and thermophysical properties. The effects on compaction energy, porosity, permeability, compressive strength, solar reflectance index, and carbon dioxide emissions were evaluated under two different specimen compaction scenarios, namely fixed compaction energy and fixed porosity. When compacted to a fixed porosity, recycled aggregate mixture specimens required the same or less energy compared to virgin aggregate, while their permeability was larger yet their compressive strength was 12% lower. In contrast, for specimens subjected to fixed compaction energy, the permeability and compressive strength varied in accordance with their measured porosity. Recycled aggregate mixtures had 22% lower porosity compared to limestone, yet their permeability and compressive strength were comparable, highlighting the relevance of the compaction technique in the laboratory and field. The use of slag proved to be beneficial as it did not negatively affect porosity, permeability, or compressive strength

and yet was critical in reducing carbon dioxide emissions by means of reducing the cement dosage and in effectively increasing the solar reflectance in some measured specimens.

Keywords: pervious concrete, recycled concrete aggregate, ground granulated blast-furnace slag, solar reflectance index, sustainability.

2.2 Introduction

Construction and the development of new infrastructure are essential for economic progress, yet these activities significantly impact the environment. For instance, cement production is one of the largest contributors to carbon dioxide (CO_2) emissions. On average, for every ton of cement produced, there is an almost equal amount of CO_2 released into the air [1]. Also, the construction industry is responsible for generating one third of all waste in land fields in the U.S., and concrete accounts for almost 50% of that amount [2]. Densely populated areas concentrate considerable amounts of hardscape, preventing water from continuing its natural flow and increasing temperatures in urban areas. The U.S. Environmental Protection Agency claims that the difference in temperature between developed areas and nearby rural areas can be as much as 1 to 3 °C (1.8 to 5.4 °F), directly translating into ecological and economic issues related to the higher energy consumption needed for cooling and ventilation [3]. The negative effects on the environment highlight the necessity for change in the form of more sustainable construction techniques and materials that help maintain the balance in natural cycles.

Pervious concrete has been successfully used in the U.S. for more than 20 years as an environmentally friendly stormwater management material [4], as it has porosity values ranging from 15% to 35% and a coefficient of permeability of 0.14 to 1.22 cm/s [5]. The stormwater management benefits of pervious concrete are acknowledged by Leadership in Energy and Environmental Design (LEED) [6], which grants points to projects that reduce impervious surfaces and stormwater runoff and promote infiltration in their sites. Several studies have evaluated other benefits of pervious concrete, such as noise reduction, water purification properties, and mitigation of the urban heat island effect [7,8,9]. Thus, the use of pervious concrete for parking lots, for example, has the potential to decrease multiple negative effects of concrete on the environment, particularly in urban areas.

Researchers have found porosity to be one of the key features of pervious concrete, having a direct effect on other properties, such as permeability and compressive strength. The goal when designing a pervious concrete mixture, then, is to provide the material with sufficient porosity to maintain a functional balance between the mechanical and hydrological properties. Although mix design is a major contributing factor, the amount of compaction applied during placement also plays an essential role in the level of porosity accomplished by a pervious mixture. Therefore, a range of desired characteristics in mixtures with various material properties and paste contents can be achieved through different levels of compaction [10].

The thermophysical characteristics of a pavement also play an important role in its effect on the environment, especially in urban areas due to the heat island effect. Research on conventional pavements [11] has shown that properties such as albedo and emissivity have the highest positive effects on pavement maximum and minimum temperatures, while increasing thermal conductivity, diffusivity, and volumetric heat capacity help in mitigating the maximum--but not the minimum--surface pavement temperature. Recent studies [12,13] have also shown that the use of slag increases the solar reflectance of conventional pavements.

The importance of solar reflectance is recognized by LEED [6], which awards credits for the use of pavement surfaces with a solar reflectance index (SRI) equal to or greater than 29. Studies on the effect of pervious concrete on pavement temperature [9,14] have indicated that solar reflectance should be used in combination with other properties, such as the cooling effect generated by moisture loss on a porous pavement system and the lesser heat-storing capacity of the pervious pavement. Also, the porous surfaces in pervious concrete may limit its reflectivity by creating a shadowing effect. Researchers emphasize the fact that more studies are needed to fully understand the interaction between reflectance, porosity, and heat storage as well as to evaluate the materials and construction methods that increase reflectance in pervious concrete [14].

The inclusion of waste materials in pervious concrete mixtures has the potential to enhance the environmental benefits of pervious concrete without significantly affecting its mechanical and physical properties. Recycled concrete aggregate has been used in pervious concrete mixtures to reduce greenhouse gas emissions, as less mining and processing of virgin aggregates is required [15]. Li and Rizvi et al.[16,17] crushed and sieved concrete from old curbs and gutters, sidewalks, and sewers to substitute for virgin coarse aggregate. Based on the specific recycled concrete aggregate quality used, a substitution of 15% of recycled concrete aggregate in their mixtures showed similar properties to those of the control mixture.

Another avenue for further improving the sustainability of pervious pavement is the use of supplementary cementitious materials such as ground granulated blast-furnace slag (GGBFS). For instance, research in conventional concrete [18] has shown that replacing 35% to 50% of cement with slag can help reduce CO_2 emissions by 29% to 46%, respectively. Slag also has the potential to mitigate the heat island effects by improving the solar reflectivity of concrete pavements [19]. Furthermore, owners pursuing a LEED certification can also achieve extra points by using waste materials such as recycled concrete aggregates and slag [6].

2.3 Research Objective

The purpose of this study was to evaluate the effect of the inclusion of large contents of recycled materials in pervious concrete to enhance its sustainability without significantly affecting its performance. Particularly, the use of a large percentage (50%) of recycled concrete aggregate and replacement of cement with up to 30% of GGBFS was investigated. The effect of the recycled materials was evaluated under two different compaction scenarios, fixed porosity and fixed compaction energy, to determine the method of compaction that yields the best performance under these conditions. The properties measured were porosity, permeability, compressive strength, and SRI of the pervious concrete mixtures produced. Also, the CO_2 emissions associated with both the raw materials and the manufacturing process were calculated for each mixture.

2.4 Experimental Program

2.4.1 Materials

Three different types of coarse aggregate with a nominal size of 3/8 in. were used in this study. Table 2 summarizes the properties of each aggregate. Pea gravel and limestone were obtained locally in central Texas. The recycled concrete aggregate blend (RCAB) was produced by mixing 50% of crushed virgin limestone aggregate and 50% of recycled concrete aggregate. Portland Cement Type I was used in this study. GGBFS, a by-product of steel manufacturing, was specifically selected for this study based on previous research that demonstrated its ability to improve strength and increase solar reflectivity [22]. The GGBFS had a Blaine fineness equal to 560.5 m^2/kg (835.7 ft^2/lb) and a slag activity index at 7 and 28 days of 98 and 123, respectively; it met the chemical and physical requirements of ASTM C989 and AASHTO M-302 for grade 120. A mid-range water-reducing admixture (ASTM C 494/C 494M type A) and a viscosity-modifying admixture (ASTM C 494/C 494M type S) were used in this study with a dosage of 392 and 261 ml/100 kg (6 and 4 fl oz/cwt) of cementitious material, respectively.

Table 1 Physical Properties of Aggregates

Property	Unit	Pea Gravel	Limestone	RCAB
Unit Weight	kg/m^3 (lb/ft^3)	1,588 (99.1)	1,471 (91.8)	1,411 (88.0)
Water Absorption	%	0.95	2.47	4.12
Bulk Specific Gravity$_{ssd}$[a]	------	2.61	2.57	2.42
Bulk Specific Gravity$_{od}$[b]	------	2.59	2.50	2.32
Voids	%	38.48	41.15	41.57

[a]*ssd, saturated surface dry condition*
[b]*od, oven dried condition*

2.4.2 Mixture Design

Two series of mixtures were produced as presented in Table 3. Series I consisted of nine mixtures with an intermediate paste content (aggregate-to-paste ratio of 5.2). The set consisted of one control mixture per type of aggregate and two levels of cement replacement by GGBS per aggregate. These mixtures were produced to evaluate the sustainability potential of using recycled materials in pervious concrete.

Table 2 Mixture Proportions

Series No.	Type of Aggregate	Mix No.	Slag Content	Aggregate -Paste Ratio	Aggregate (kg/m³)	Cement (kg/m³)	Slag (kg/m³)	Water (kg/m³)
	Medium paste content mixtures							
I	Pea Gravel	G-0	0%	5.2	1453	284	-	85
		G-15	15%		1453	242	43	85
		G-30	30%		1453	199	85	85
	Limestone	L-0	0%	5.2	1453	284	-	85
		L-15	15%		1453	242	43	85
		L-30	30%		1453	199	85	85
	RCAB	R-0	0%	5.2	1453	284	-	85
		R-15	15%		1453	242	43	85
		R-30	30%		1453	199	85	85
	Low paste content mixtures							
II	Pea Gravel	G-0 LP	0%	6.0	1643	276	-	82
		G-15 LP	15%		1643	233	42	82
		G-30 LP	30%		1643	193	82	81
	High paste content mixtures							
	Limestone	L-0 HP	0%	4.5	1519	334	-	101
		L-15 HP	15%		1519	284	50	100
		L-30 HP	30%		1519	234	100	100
	RCAB	R-15 HP	15%	4.5	1519	307	54	108

NOTE: LP=Low Paste Content, HP= High Paste Content

An additional set of mixtures (Series II) was prepared to evaluate the effect of paste content on the properties of pervious concrete. Four mixtures made with limestone and RCAB had a higher paste content (aggregate-to-paste ratio of 4.5), and three pea-gravel mixtures had a lower paste content (aggregate-to-paste ratio of 6.0). The type of cement (Type I), water-cementitious ratio (0.30), and aggregate size (3/8 in.) were kept constant for all mixtures.

2.4.3 Specimen Preparation and Compaction

Each pervious concrete mixture was prepared on an 85-liter (3 ft^3) rotating drum mixer by first mixing the aggregates, cement, and slag for one minute, as suggested by Kevern et al.[20]. Then, the water along with the mid-range water-reducing admixture was added and mixed for three minutes. Finally, the concrete was allowed to rest for one minute and then mixed again for three minutes while the viscosity-modifying admixture was added to the mixture.

Cylinders for porosity, permeability, and strength tests were cast in 100-mm diameter by 200-mm tall (4 in. x 8 in.) plastic molds and were compacted in two layers using a 2.5-kg (5.5 lb) Proctor hammer with a fall of 305 mm (1 ft). Two consolidation approaches, fixed porosity and fixed compaction energy, were used in this research to provide comparable results between samples using different material types and dosages and also to analyze the effect of compaction energy on the properties of pervious concrete. The first approach was fixed porosity, which required the samples to be compacted as many times as necessary to reach a porosity of 20%. The porosity was controlled by placing a fixed amount of material in the concrete cylinder. Consolidation varied across mixtures ranging from 45 KN*m/m^3 to 242 KN*m/m^3 (5 to 30 Proctor hammer blows, respectively). The measurement of the required compaction energy to reach a fixed porosity is also a useful parameter for comparing the compaction needs of different mixtures in the laboratory and eventually in the field.

The second approach was fixed compaction energy, in which a constant amount of compaction energy was applied to each cylinder, namely 20 Proctor hammer falls per layer (181 KN*m/m^3). As expected, the porosity of samples compacted under this approach ranged more widely, from 12% to 23%. The analysis of this compaction approach is relevant for assessing the implications for permeability and strength of using the same amount of compaction energy (i.e. a fixed number of roller passes) regardless of the concrete mixture, which in some cases is the practice in the field.

The specimens used to evaluate the solar reflectance of pervious concrete were cut from a 432 mm by 356 mm by 102-mm tall (17 in. x 14 in. x 4 in.) slab. The slab was compacted in one layer using a weighted roller at a constant pressure of 148 kg/m (100 lb/ft) [21]. The roller was used to ensure that the surface finishing method was close to the one normally used in the field.

Cylinders were covered with plastic caps while the slabs were covered with tight-fitting plastic sheeting to prevent moisture loss. All of the specimens were demolded and striped after 24 hours and placed in a curing room at 98% humidity for 28 days. The slabs were cut using a water-cooling masonry saw as determined by ASTM C42 to obtain specimens of approximately 125 mm by 83mm by 102 mm tall (5 in. x 3 in. x 4 in.).

2.5 Test Procedures

2.5.1 Compressive Strength

Compressive strength tests were performed in accordance with ASTM C39. All cylinders were sulfur-capped before tested.

2.5.2 Porosity

The specimen dimensions, air-dried weight, and submerged weight were measured for each cylinder. Porosity was calculated [20,22] using the following equation:

$$P = \left[1 - \left(\frac{W_2 - W_1}{P_w Vol}\right)\right] 100(\%) \quad (1)$$

Where:
P=porosity, %
W_1=weight under water, g
W_2=air dried weight, g
Vol=volume of sample, cm^3
P_w=density of water @ 21^o C, kg/cm^3

To guarantee accurate measurements, special care was taken to ensure stable underwater weight of the specimens. Each specimen was left to air dry for 24 hours under laboratory conditions, and the exact dimensions of each cylinder were measured.

2.5.3 Permeability

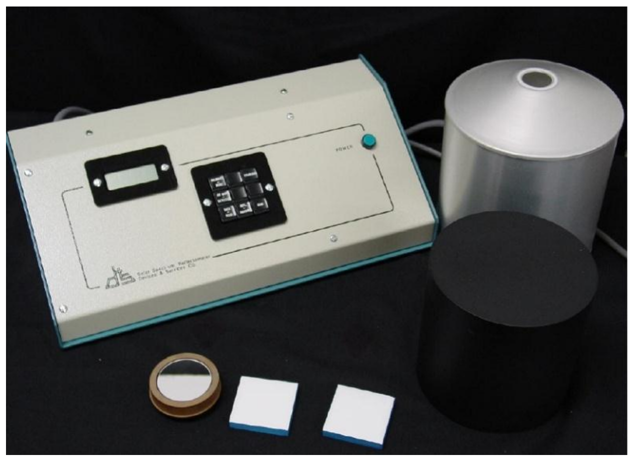
A falling-head permeability test apparatus was used to measure permeability of concrete cylinders [20]. A flexible polyethylene foam membrane was carefully wrapped around the sample to impede water infiltration between the surface of the sample and the apparatus. The time for water to flow through the sample was recorded at two different heights. The initial (h_1) and final (h_2) levels were set at 50 cm and 25 cm, respectively. Finally, the average coefficient of permeability was determined using Darcy's law that assumes laminar flow:

$$K = \frac{aL}{At} ln\left(\frac{h_1}{h_2}\right) \quad (2)$$

Where:
K=coefficient of permeability, cm/s
a=cross-sectional are of the standpipe, cm^2
L=length of sample, cm
A=cross-sectional area of specimen, cm^2
t =time in seconds from h_1 to h_2
h_1=initial water level, cm
h_2=final water level, cm

2.5.4 Solar Reflectance Index

Using highly reflective and light-colored construction materials reduces the amount of solar energy that is absorbed by urban infrastructure and is a common practice for reducing the heat island effect [12]. The SRI is a method that evaluates the thermal emittance and solar reflectance of surfaces. Solar reflectance represents the fraction of incident solar radiation upon a surface that is reflected from the surface.



(a)Solar Spectrum Reflectometer

(b)Test Specimens

Figure 4 Solar Reflectance Testing. (a) Solar Spectrum Reflectometer. (b) Test Specimens

It was measured on three different randomly located spots on the top surface of each prismatic specimen (Figure 4 b) previously obtained from the slabs. A portable solar reflectometer (Figure 4 a) was used in accordance with ASTM C 1549. One set of three specimens was tested for each mix, and the SRI was calculated according to ASTM E 1980 – 01.

2.6 Results and Discussion

2.6.1 Compaction Energy

The number of Proctor hammer blows necessary to reach a porosity of 20% was recorded for all cylinders and then used to calculate the compaction energy for each mixture as presented in Figure 5. Results revealed that the compaction energy needed to achieve 20% porosity was affected by the type of aggregate and the paste content of the mixture. For instance, in mixtures with medium paste content, the amount of compaction energy applied to pea gravel was 52% lower than that needed in a mixture made with limestone aggregate to achieve the same porosity. This difference can be explained by the rounded shape of the pea gravel, which facilitates the flow of its particles, whereas a crushed aggregate such as limestone requires more energy to flow.

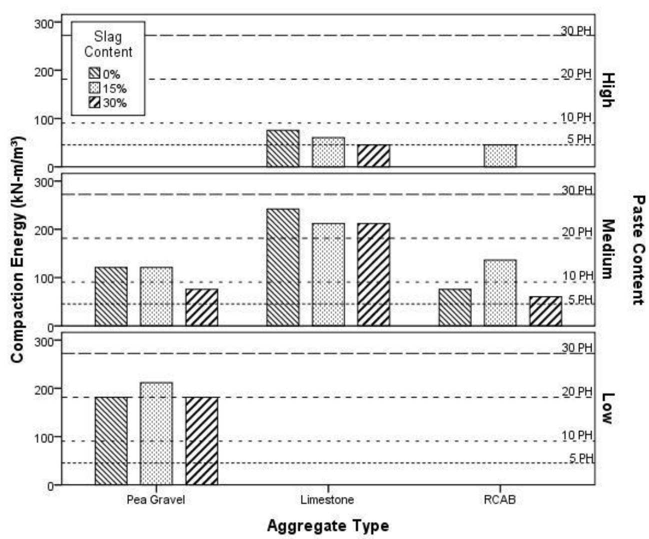


Figure 5 Compaction Energy Applied to Concrete Samples Using a Standard Proctor Hammer to Achieve 20% Porosity

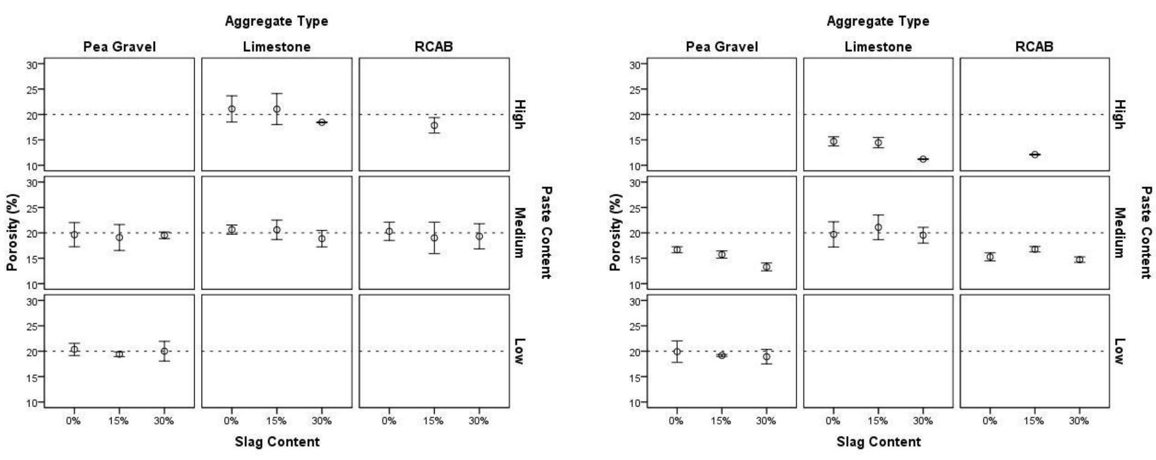
In contrast, mixtures using RCAB were more workable and required just 61% of the compaction energy to achieve 20% porosity compared to limestone mixtures. Further comparison between RCAB and limestone aggregate particles showed that the latter was more angular, which may have increased the aggregate interlock, decreasing its compactability. In contrast, the use of slag did not have a statistically significant effect on the compaction energy needed to achieve 20% porosity. The effect of paste on required compaction energy for a fixed porosity was analyzed. It was observed that the 20% porosity could be reached with 72% less compaction energy in limestone mixtures with higher paste content (aggregate/paste ratio of 4.5) compared to medium paste content (aggregate/paste ratio of 5.2). In contrast, pea gravel mixtures made with lower paste content (aggregate/paste ratio of 6.0) required 44% more compaction energy compared to mixtures made with medium paste content.

2.6.2 Porosity

Fixed Porosity Samples. Figure 6 a shows the mean porosity measured in samples where compaction energy was applied to achieve a fixed porosity of 20%. The variability between the individual specimens of the measured properties is shown by error bars that represent one standard deviation. The mean porosity in samples compacted to achieve a fixed porosity was 19.7%, with a coefficient of variation of 9%. A one-sample T-test conducted at a 95% level of confidence confirmed that the difference between the porosity of the cylinders and the 20% target was non-significant ($P=0.267>0.05$), therefore validating the proposed compaction method. This verification is important for ensuring proper evaluation of the direct effects of materials on the properties of concrete without the effect of porosity as a variable.

Fixed Compaction Energy Samples. On the other hand, the mean porosity for samples compacted under the same energy (20 proctor hammer blows) ranged from

11.9% to 23.2% for all mixtures, as shown in Figure 6b. Medium paste mixtures (aggregate/paste ratio of 5.2) using limestone aggregate had a 24% and 22% higher porosity compared to pea gravel and RCAB, respectively. The increase of paste content from medium to high (aggregate/paste ratio of 4.5 to 5.2) in limestone mixtures decreased porosity by 33%, whereas decreasing medium to low paste content in pea gravel increased porosity by 21%. An analysis of variance confirmed that both aggregate type and paste content significantly affected porosity. The analysis also showed that replacing cement with GGBFS did not have a statistically significant effect on porosity for fixed compaction energy. Consequently, when placing pervious concrete in the field under a fixed level of compaction (i.e. a fixed number of roller passes), significant discrepancies in permeability and compressive strength may be expected as a result of the wide range of porosity values if variables such as aggregate type and paste content are altered in the mixture design [10].

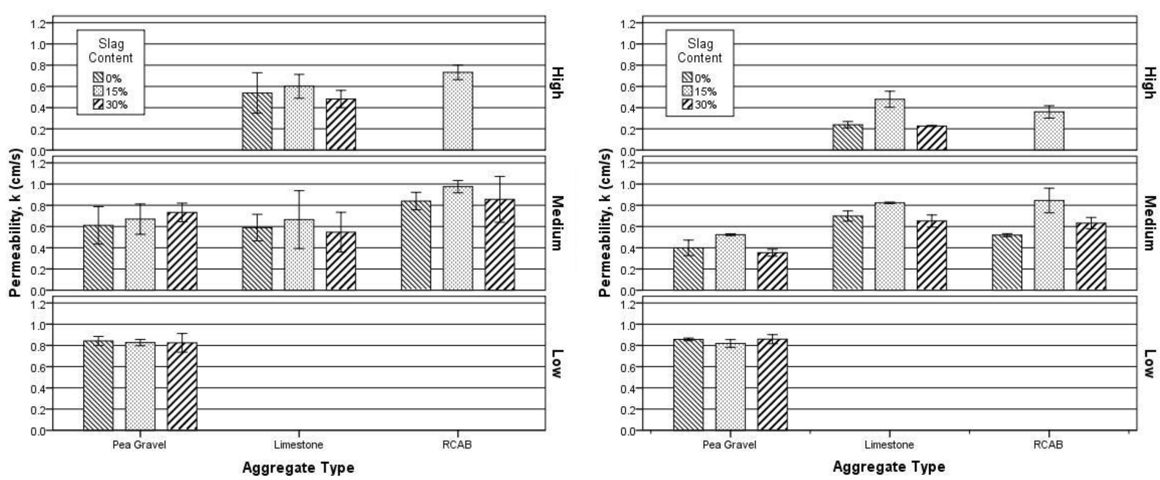


(a)Fixed Porosity (b)Fixed Compaction

Figure 6 Mean Porosity Values for (a) Samples Compacted to Achieve 20% Porosity and (b) Samples Compacted 20 Proctor Hammer Blows per layer. Error Bars Represent One Standard Deviation

2.6.3 Permeability

Fixed Porosity Samples. The permeability was measured for all mixtures compacted to a fixed porosity of 20%. As shown in Figure 7a, pea gravel and limestone mixtures with medium paste content had similar permeability of k=0.67 ± 0.13 cm/s and k=0.60 ± 0.18 cm/s, respectively. This difference of 0.07 cm/s is well within the variability of the test and therefore not statistically significant. In contrast, the permeability for RCAB mixtures (0.89 ± 0.14 cm/s) was higher than the virgin aggregates, which may be associated with an enhanced interconnectivity of the voids in RCAB mixtures due to the lower required compaction energy (compared to mixtures with limestone aggregate) needed to achieve the fixed porosity. The variations in slag did not have a significant effect on the measured permeability. The permeability was not significantly altered when lower paste contents were used in pea gravel, yet the use of higher paste content in limestone mixtures did slightly reduce the material permeability.



(a)Fixed Porosity (b)Fixed Compaction

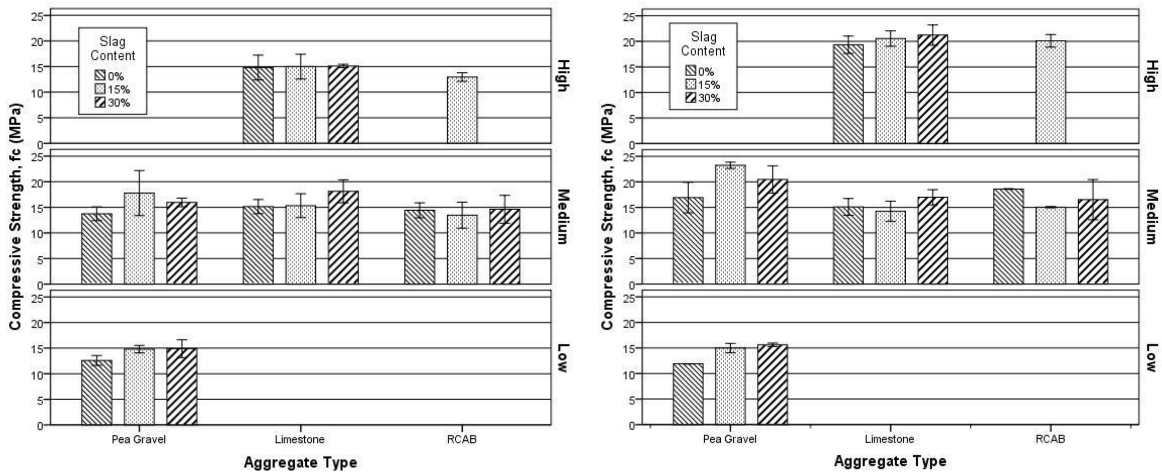
Figure 7 Permeability Results for (a) Samples Compacted to Achieve 20% Porosity and (b) Samples Compacted 20 Proctor hammer blows per layer. Error Bars Represent One Standard Deviation. (Note: 1 cm/s = 23.6 in/min.)

Fixed Compaction Energy Samples. The permeability for samples subjected to constant compaction energy (i.e. 20 Proctor hammer falls per layer) ranged from 0.26 cm/s to 0.89 cm/s, as shown in Figure 4b. For mixtures with medium paste content, the permeability of pea gravel mixtures was 40% lower than limestone mixtures, in line with their lower measured porosity. In contrast, the permeability of the RCAB and limestone mixtures was close in spite of the fact that the porosity of the RCAB mixtures was lower. Of note, these results are consistent with the fixed porosity scenario, where RCAB mixtures had higher permeability than limestone aggregates in spite of their equal porosities. As expected, the paste content had an effect on the permeability of pervious concrete mixtures subjected to constant compaction energy. Limestone concrete mixtures with higher paste had 56% lower permeability, which was correlated to their 33% higher porosity. The opposite was true in mixtures such as low-paste pea gravel, which showed the largest capacity for water infiltration with an average permeability value of 0.84 cm/s. The findings for fixed compaction energy were further analyzed by a two-way ANOVA, which indicated that the slag content was not a significant variable for permeability, whereas the aggregate type and paste content did affect the permeability. This finding confirmed that permeability is highly influenced by the porosity of the mixtures but also showed that other factors, such as the aggregate type, should be considered to achieve the desired permeability [23].

2.6.4 Compressive Strength

Fixed Porosity Samples. The effect of aggregate type, slag, and paste content on compressive strength for all mixtures compacted at a fixed porosity of 20% is shown in Figure 8a. The compressive strength results for medium paste content (paste/aggregate ratio of 4.5) show an average difference between pea gravel and limestone mixtures of just 2.4%. By comparison, average compressive strength of mixtures using limestone and RCAB was, on average, 12% lower than limestone. The use of slag did not generate statistically significant differences in compressive strength for mixtures with a fixed porosity of 20%. This finding is confirmed in Figure 8a, which shows that compressive strength remained almost unchanged as the slag content increased. The paste content had a moderate effect on compressive strength of the mixtures. For instance, the compressive strength values for pea gravel mixtures with a low paste content (14.09 ± 1.54 MPa) were 11% lower than the ones measured in pea gravel mixtures with a medium paste content (15.83 ± 2.92 MPa). The compressive strength for limestone mixtures with high (14.94 ± 1.85 MPa) and medium (16.20 ± 2.28 MPa) paste increased by 8%. The analysis confirms that, under controlled porosity, there is a negligible difference in compressive strength among the mixtures using virgin aggregates (pea gravel and limestone). However, the use of RCAB can reduce compressive strength by 12%, and the increase or decrease in paste can increase or decrease strength by approximately 8 to 12%.

Fixed Compaction Energy Samples. Figure 8b shows the compressive strength results for the different mixtures when the amount of compaction energy is kept constant (i.e. 20 Proctor hammer blows per layer) and consequently the porosity of the mixtures is different. These results confirm previous research by and Deo and Neithalath [10], Neptune and Putman [24], and Mulligan [25], which established porosity as one of the key properties affecting compressive strength. For instance, in mixtures with medium paste content, mixtures using pea gravel had, on average, 24% higher strength compared to limestone mixtures, which was closely tied to their lower porosity. In contrast, the compressive strength of mixtures using RCAB was 7.6% higher than limestone aggregate, but this result was strictly tied to the 22% lower porosity of RCAB mixtures.



(a)Fixed Porosity (b)Fixed Compaction

Figure 8 Compressive Strength Results for (a) Samples Compacted to Achieve 20% Porosity and (b) Samples Compacted 20 Proctor Hammer Blows per Layer. Error Bars Represent One Standard Deviation. (Note: 1 MPa = 145.04 psi.)

These findings highlight the conclusion that, under a constant level of compaction energy, the ease of placement and compactability of the mixture can play a role that could be as influential as the raw materials and mix design in achieving a specified compressive strength.

The effect of paste content on compressive strength was also closely tied to the porosity of each mixture. Limestone mixtures with high paste content had 24% higher strength (and 33% lower porosity) compared to those with medium paste content. A similar phenomenon was seen in pea-gravel mixtures, where the ones with low paste had 30% less strength (and 21% higher porosity) compared to the ones with medium paste content. These results, which are closely correlated to the porosity of the mixtures (i.e. the lower the paste, the higher the porosity, and vice versa), imply that if a constant amount of compaction energy is applied to pervious concrete in the field, then variations in paste content may significantly affect compressive strengths. In contrast, the analysis also showed that the use of slag up to 30% did not have a negative effect on compressive strength, regardless of the type of aggregate and paste content.

2.6.5 Solar Reflectance Index

The SRI was measured in nine selected mixtures, as shown in Figure 9. The objective was to assess the effect of aggregate type and slag on the SRI of pervious concrete compared to LEED requirements [6]. Results indicate that the SRI of two mixtures using pea gravel were below 29 (G-0 LP, G-30 LP), which is the minimum required by LEED to achieve credits in the category of Sustainable Sites-Heat Island Effect, for non-roof surfaces [6]. The use of slag seemed to improve the SRI, but the effect was not consistent when 30% of slag was used. While the aggregate color may have been a significant factor on the lower SRI of these mixtures, the fact that these mixtures had lower paste content may have also reduced the potential of the slag to increase the SRI. Therefore, more extensive research is needed to determine if pea gravel consistently generates mixtures with lower SRI and if slag can improve this property. In contrast, the use of slag did consistently improve the SRI of mixtures made with limestone aggregate. As seen in Figure 9, only the limestone mixture with no slag replacement was below the SRI threshold of 29. The SRI of pervious concrete made with limestone aggregate and 30% slag was 38% higher than the one containing no slag. These results are in line with findings by Boriboonsomsin and Reza [13] for conventional concrete made with limestone aggregate, where a replacement of 70% of cement by slag increased their albedo by 71%.

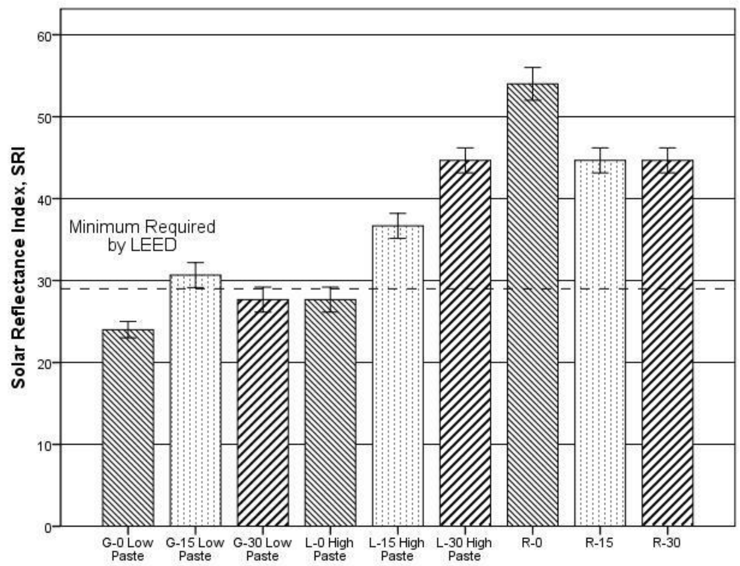


Figure 9 Solar Reflectance Indexes for Different Aggregates With Increasing Slag Replacement. Error Bars Represent One Standard Deviation.

The SRI for pervious concrete mixtures made with RCAB was, on average, higher than those made with pea gravel or limestone, while the dosage of slag did not have a consistent effect on the SRI. Whereas the relatively high SRI found in RCAB mixtures may be related to the specific demolished concrete used to create this particular recycled aggregate, the results are still encouraging, as all samples using this aggregate were well above the minimum value established by LEED [6]. Considering that pervious concrete features exposed coarse aggregate and a porous surface that could generate a shadow effect when measuring the SRI, other thermophysical properties should be studied in the future to fully assess the impact of pervious concrete on the heat island effect [9,11].

2.6.6 Carbon Dioxide Emissions

CO_2 emissions generated by each of the pervious concrete mixtures were calculated based on raw materials emissions published by Flower and Sanjayan [26] for cement, slag, and virgin aggregate and by McIntyre et al. [27] for recycled aggregates, respectively. The CO_2 emissions calculation also incorporated processes such as concrete batching and transportation [26]. Table 3 presents the CO_2 emission factors associated with each raw material or process, expressed in kilograms of CO_2 emissions per weight or volume of the produced material (kg CO_2/t or kg CO_2/m³). The literature shows that mix designs for conventional concrete produce 290 to 320 kg of CO_2 emissions per cubic meter of concrete [26]. The total emissions per mix were calculated by multiplying the mix proportions by the emissions generated by each raw material and by further adding concrete batching, transportation, and concrete placement.

Table 3 Carbon Dioxide Emission Factors for Concrete Manufacturing, Transportation, and Placement

Activity	Emission	Unit
Coarse aggregate – limestone	35.7	kg CO_2/t
Coarse aggregate – RCAB[a]	19.7	kg CO_2/t
Coarse aggregate – pea gravel	13.9	kg CO_2/t
Cement	820.0	kg CO_2/t
GGBFS	143.0	kg CO_2/t
Concrete batching	3.3	kg CO_2/m³
Concrete transport[b]	9.4	kg CO_2/m³

[a] *Calculated for the blend of limestone and recycled concrete aggregate*
[b] *Based on a metropolitan area scenario (100 Km radius) consuming on average 3.1 liters of diesel per cubic meter of concrete transported*

The benefits of using slag are demonstrated in Figure 10. The CO_2 emissions were reduced by approximately 20% in all of the three types of aggregate when 30% of cement was replaced by slag. Although there is limited literature evaluating the CO_2 emissions in pervious concrete, it has been observed that a replacement of 40% of cement with slag in conventional concrete mixtures concrete can help reduce the amount of CO_2 emissions by 22% [26].

Also, researchers from the Slag Cement Association [19] found that replacing 35% of cement by slag can reduce up to 30% of CO_2 emissions in conventional concrete. Because the processing of crushed aggregates like limestone and RCAB required more energy compared to pea gravel, mixtures prepared with the latter generated the least amount of CO_2 emissions of all the mixtures in this study. In contrast, the total CO_2 emissions for mixtures made with limestone and no cement replacement (L-0) were the highest, as its aggregate requires crushing and it used a full dose of cement.

A pervious concrete mixture made with RCAB and 30% of slag has a total recycled content of 45% and generates 38% less CO_2 emissions compared to a high-paste limestone mixture with no slag. It should be noted that the benefits of RCAB will vary depending on the project, especially if the impacts associated with the disposal of old concrete and use of landfills are considered as well.

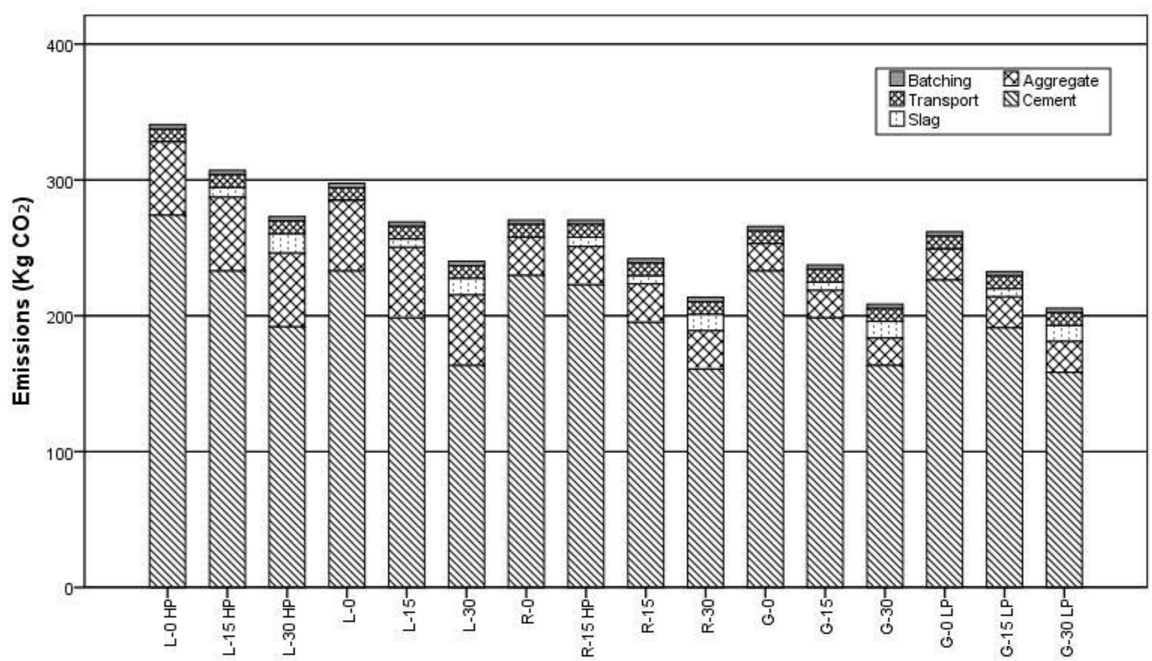


Figure 10 Kilograms of Carbon Dioxide Emissions per Cubic Meter of Concrete Produced for Mixtures with Different Aggregates, Increasing Levels of Slag Replacement, and Varying Paste Content

2.7 Conclusions

The following conclusions can be drawn from this study:

1. The type and shape of coarse aggregate had an effect on the required compaction energy needed to achieve a fixed porosity. Rounded aggregate such as pea gravel mixtures required less compaction energy compared to limestone or RCAB. The mixtures using RCAB aggregate required less compaction energy than mixtures using limestone, which may be associated with the angularity of the latter. While this phenomenon may be circumscribed to our particular RCAB, this finding highlights the potential of RCAB as an aggregate that can generate mixtures that are as workable and compactable as the ones with virgin aggregates if proper gradation, measurement of the aggregate absorption capacity and mixture design is achieved. The paste content of pervious concrete mixtures influenced its required compaction energy to achieve a constant porosity, where mix design with higher paste content required less compaction energy and vice versa. The use of slag did not affect the compaction energy needed by a pervious concrete mixture to achieve a given porosity.
2. The porosity of the pervious concrete mixtures subjected to a fixed amount of compaction energy was affected by both the aggregate type and the paste content. For instance, for medium paste content, limestone aggregate mixtures had 24% and 22% higher porosity than pea gravel and RCAB mixtures, respectively. As expected, mixtures with higher paste content had lower porosity and vice versa. The use of slag did not affect the porosity of the mixtures. These findings highlight the importance of properly determining the compaction energy needed for each mixture when placing pervious concrete in the field. If a fixed level of compaction (i.e. a fixed number of

roller passes) is applied regardless of the raw materials or mixture design, then significant discrepancies in porosity and, by extension, permeability and compressive strength may occur.

3. The effect of aggregate type and paste content on permeability was greatly reduced when porosity was controlled at 20%. Both limestone and pea gravel had similar permeability, while RCAB had higher permeability under such conditions. The use of lower paste content in pea gravel mixtures did not affect permeability, while the use of higher paste content in limestone mixtures did, suggesting that, at high paste contents, the permeability may be reduced even if the porosity is held constant. Under fixed compaction energy, the permeability of the specimens was closely tied to their measured porosity for mixtures using virgin aggregate. The RCAB mixtures also followed their measured porosity but trended to produce higher permeability, as evidenced by RCAB and limestone mixtures showing almost the same permeability in spite of RCAB having a lower porosity.
4. The compressive strength of mixtures compacted at a fixed porosity of 20% was not affected by the aggregate type when virgin aggregates such as limestone and pea gravel were used. Conversely, mixtures using RCAB had, on average, 12% less strength, indicating that the recycled aggregate may have some detrimental effect on compressive strength. The analysis for mixtures having different paste contents showed that, in spite of having the same porosity, an increase in paste content generated an increase of 8% in compressive strength, whereas a reduction in paste content reduced the compressive strength by 12%.

5. The compressive strength of mixtures subjected to a constant level of compaction energy was closely tied to their porosity. Under such conditions, the pea gravel had the highest compressive strength as it had the lowest porosity. The compressive strength of mixtures using RCAB was 7.6% higher than limestone aggregate, but these results were strictly tied to the 22% lower porosity of the RCAB mixtures. Therefore, these findings highlight the conclusion that, under a constant level of compaction energy, the ease of placement and compactability of a concrete mixture plays a role that may be as influential as the raw materials and mix design in achieving a desired compressive strength.
6. The SRI was found to be affected by the aggregate type, where darker aggregates such as pea gravel exhibited lower SRI compared to mixtures using RCAB or limestone aggregate. The use of GGBFS to replace cement in pervious concrete mixtures made with limestone had a significant effect on SRI, which was increased by 38% by replacing 30% of cement with GGBFS.
7. Replacing cement with GGBFS is an effective means of reducing CO_2 emissions associated with pervious concrete. For mixtures made with the same type of aggregate, the use of 30% of GGBFS reduced the pervious concrete CO_2 emissions by 18% to 21%. Moreover, the combined effect of 30% GGBS and RCAB further reduced the emissions by 35% compared to a mixture made with only cement and virgin limestone aggregate.

2.8 Acknowledgements

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III. COMPARISON OF THE EFFECT OF THE SPECIMEN TYPE ON PERVIOUS CONCRETE ABRASION RESISTANCE

3.1 Abstract

Abrasion resistance of pervious concrete was evaluated on core and cast specimens using two different abrasion test methods, namely the ASTM C944 - Standard Test Method for Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating-Cutter Method and the ASTM C1747 - Standard Test Method for Determining Potential Abrasion Resistance to Degradation of Pervious Concrete by Impact Abrasion. Sixteen mixtures were produced using limestone, pea gravel, and recycled concrete aggregate, and up to 30% of cement was replaced by ground granulated blast-furnace slag. The analysis of the core specimens indicated that the ASTM C1747 test had a low within-test coefficient of variation and was able to differentiate among mixtures. The effect of aggregate type, evaluated on core specimens with equivalent porosity, indicated that the ASTM C1747 abrasion resistance of mixtures made with pea gravel was significantly lower than the ones prepared with crushed aggregates. The use of recycled aggregate and ground granulated blast-furnace slag did not have any detrimental effect on the durability of pervious concrete. Core specimens had a 42% greater mass loss than cast cylinders of equivalent porosity. The ASTM C944 surface abrasion had a high within-test variability, and its correlation with ASTM C1747 was significantly affected by the aggregate type.

Keywords: pervious concrete, surface abrasion, recycled aggregate, core.

3.2 Introduction

Pervious concrete is characterized by an interconnected network of pores [1], which represent 15% to 35% [2] of the total volume of the mixture. This property makes it an environmentally friendly paving material, permitting easy passage of water through its porous structure, allowing for infiltration and deep percolation [3]. The benefits of using this material include, but are not limited to, the reduction of storm water runoff, removal of pollutants from water, reduction of noise, improved skid resistance, and potential to mitigate the heat island effect [4, 5, 6, 7, 8]. However, its lower strength compared to conventional pavements and the lack of standardized test methods for quality control have limited the use of pervious concrete to low-traffic applications such as parking lots, roads with minor use, sidewalks, and bicycle trails [9, 11, 12, 13, 14].

Whereas the lower strength of a pervious concrete mixture may be alleviated by improving the base or the pervious pavement layer thickness, its surface durability can still be affected by a number of factors [9]. For instance, a poor paste bond can often lead to the disjointing of aggregate particles in the surface of the material [15]. This problem, known as raveling, normally occurs when shear stress is applied to a pavement surface causing the paste-aggregate bond to fail, thus affecting its uniformity and structure. The mixture design, curing method, and placement techniques are some of the other variables that can have a direct effect on the abrasion resistance of a pervious pavement, which determines the likelihood of a raveling incident [16].

A limited number of studies have evaluated the raveling and abrasion resistance of pervious concrete. Henderson et al. [17] performed a visual pavement surface evaluation on pervious concrete pavement test sections that had been subjected to a variety of applications, loadings, rehabilitation maintenance methods, and environmental conditions. They observed that the worst raveling occurred at joints and corners and attributed this finding to the placing of the concrete under colder-than-suggested conditions. Kevern et al. [18] investigated the effect of various curing methods on pervious concrete durability. Surface abrasion was tested using a rotary cutter device according to ASTM C944 on beams constructed to simulate the field construction conditions. They found that the rotary cutter surface abrasion method differentiated between curing methods, allowing for relative comparison of the surface durability. They also found that mixtures cured under plastic sheets achieved higher abrasion resistance than the other surface treatments such as soybean oil, white pigment, and a non-film evaporation retardant.

Several studies have attempted to identify a method that can properly evaluate abrasion resistance on pervious concrete. Wu et al. [19] compared three different test methods, namely the ASTM C944 Surface Abrasion Test, the Cantabro Test using an ASTM C131 Los Angeles Abrasion Machine, and the Loaded Wheel Abrasion Test using the Asphalt Pavement Analyzer [20]. To evaluate surface durability based on the Cantabro loss test, they placed three cylinder specimens, measuring 150 mm in diameter by 100 mm in height (6 in by 4 in), in the ASTM C131 Los Angeles Abrasion Machine (no steel balls) and then subjected them to 300 revolutions. Mass loss ranged from 35% to 80%. The abrasion resistance was also measured on 300 mm by 125 mm by 75 mm (12 in by 5 in by 3 in) beam specimens in accordance with ASTM C944. Additional specimens were used to measure abrasion resistance using the Asphalt Pavement

Analyzer, which is commonly used to test the rutting potential of asphalt mixtures. The authors concluded that all three abrasion tests were able to measure pervious concrete abrasion resistance and differentiate among the various mixtures. They also found that the ASTM C944 Surface Abrasion Test demonstrated lower repeatability and higher variability (CV=32%) compared to the Cantabro Test (CV=11%) and the Loaded Wheel Abrasion Test (CV=19%). Finally, they concluded that using 4.75 mm (No. 4) single-sized gradations with latex admixture and polypropylene fibers can improve the abrasion resistance of pervious concrete.

Offenberg et al. [16] evaluated surface durability of pervious pavements with a Los Angeles Abrasion Machine, commonly used to evaluate abrasion resistance in aggregates. In this study, laboratory-cast specimens of 100 mm by 100 mm (4 in by 4 in) were cured for seven days and compacted to achieve the design porosity. The specimens were placed in the drum of the Los Angeles Abrasion Machine and rotated for 50, 100, and 500 revolutions. The initial weight of a set of three samples was measured before and after the rotation cycles. Finally, the mass loss was calculated. The authors observed that, after 50 revolutions, there was a modest abrasion of the coarse aggregate. Significant loss of the aggregate was observed after 100 and 500 revolutions. They concluded that an increase in porosity resulted in a higher mass loss percentage for the samples studied.

Finally, Shu et al.[21] evaluated the abrasion performance of pervious concrete in-situ. Cantabro mass loss measured in cores extracted from field slabs was compared to the values obtained from cylinders compacted with the standard rodding compaction method. Cores were found to have higher values of porosity compared to the cast cylinders, which resulted in lower strength and higher values of mass loss.

While the aforementioned research projects provided valuable information on pervious concrete abrasion resistance, additional research is needed to analyze the effect of aggregate type and sustainable materials on the surface durability of pervious concrete. It is also necessary to establish a correlation of the abrasion resistance between cores and cylinders with similar properties.

3.3 Research Objective

The main objective of this project was to characterize abrasion resistance on core samples of pervious concrete made with virgin and recycled aggregates at different levels of cement replacement with ground granulated blast-furnace slag (GGBFS). Both the ASTM C944 - Standard Test Method for Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating-Cutter Method and the recently developed ASTM C1747 - Standard Test Method for Determining Potential Resistance to Degradation of Pervious Concrete by Impact and Abrasion were used to evaluate their effectiveness in pervious concrete and to determine if a correlation between them exists. The effect of specimen type was also analyzed in limestone mixtures by comparing the mass loss of cores against Proctor hammer compacted cylinders of equal porosity.

3.4 Experimental Program

3.4.1 Materials

The cementitious materials used in this research were Type I Portland Cement and GGBFS. GGBFS is a by-product of steel production and was specifically selected for this study based on previous research that demonstrated its ability to improve workability, increase durability, reduce heat generation, and increase strength for concrete mixtures with a low water cement ratio [22]. The GGBFS had Blaine Fineness equal to 560.5 m^2/kg (835.7 ft^2/lb) and a slag activity index at 7 and 28 days of 98 and 123, respectively; it met the chemical and physical requirements of ASTM C989 and AASHTO M-302 for grade 120.

Three different types of coarse aggregate, namely pea gravel, limestone, and a recycled concrete aggregate blend (RCAB), were used for this study. All aggregates had a nominal maximum aggregate size of 9.5 mm (3/8 in) and met the requirements of ASTM C33/C33M. Their properties are summarized in Table 5. The RCAB was obtained by mixing 50% virgin limestone aggregate with 50% recycled concrete aggregate. Type A mid-range water-reducing admixture and a type S viscosity modifying admixture were also used in this study in accordance with ASTM C 494/C 494M. The admixture dosage used was 392 and 261 ml per 100 kg of cementitious material (6 fl oz/cwt and 4 fl oz/cwt) for the mid-range water-reducing admixture and the viscosity-modifying admixture, respectively.

Table 4 Physical Properties of Aggregates

Property	Unit	Pea Gravel	Limestone	RCAB
Unit Weight	kg/m^3 (lb/ft^3)	1,588 (99.1)	1,471 (91.8)	1,411 (88.0)
Water Absorption	%	0.95	2.47	4.12
Bulk Specific Gravity$_{ssd}^{a}$	------	2.61	2.57	2.42
Bulk Specific Gravity$_{od}^{b}$	------	2.59	2.50	2.32
Voids	%	38.48	41.15	41.57

[a] *ssd, saturated surface dry condition*
[b] *od, oven dried condition*

3.4.2 Mixture Proportioning

A total of sixteen mixtures with a water-cementitious ratio of 0.3 were proportioned using the method recommended by ACI 522-R10 [9]. Two series of batches were produced as shown in Table 6. Series I consisted of nine mixtures with an aggregate-paste ratio of 5.2. One control mixture and two mixtures with increasing levels of slag content were produced per aggregate for Series I. Series II consisted of three mixtures with high paste content for limestone, three mixtures with low paste content for pea gravel, and one mixture with high paste content for the RCAB.

3.4.3 Mixture Preparation, Casting, and Curing of Specimens

Mixtures were prepared in a rotating drum mixer. First, the aggregate and the cementitious materials were placed in the drum and mixed for one minute to ensure a better bond between the cement paste and the aggregate. Second, part of the water with the mid-range water-reducing admixture was added slowly to the rest of the materials and was mixed for three more minutes and then allowed to rest for one minute. Finally, the viscosity-modifying admixture was added during the last three minutes of mixing.

A concrete slab with a 100 mm (4 in) thickness was cast per mixture using wooden molds. The concrete was poured into the mold in a single layer and compacted using a weighted roller applying a constant pressure of 148 kg/m (100 lb/ft) [23]. The weight of each slab was monitored to achieve comparable levels of porosity in mixtures with equal paste contents. In addition, 100 by 100 mm (4 in by 4 in) cylindrical specimens were cast under laboratory conditions for all limestone mixtures. To achieve a unit weight that was comparable to the slabs, the mass of the fresh concrete necessary to fill the cylindrical mold to a height of 100 mm was determined. The concrete was placed in the mold and then compacted with a standard Proctor hammer until the specified height of 100 mm was achieved. A metal plate was placed between the hammer and the surface of the concrete cylinder while the compaction was applied to ensure an even surface finish.

Table 5 Mixture Proportions

Series No.	Type of Aggregate	Mix No.	Slag Content	Aggregate -Paste Ratio	Aggregate (kg/m³)	Cement (kg/m³)	Slag (kg/m³)	Water (kg/m³)
	Medium paste content mixtures							
I	Pea Gravel	G-0	0%	5.2	1453	284	-	85
		G-15	15%		1453	242	43	85
		G-30	30%		1453	199	85	85
	Limestone	L-0	0%	5.2	1453	284	-	85
		L-15	15%		1453	242	43	85
		L-30	30%		1453	199	85	85
	RCAB	R-0	0%	5.2	1453	284	-	85
		R-15	15%		1453	242	43	85
		R-30	30%		1453	199	85	85
	Low paste content mixtures							
II	Pea Gravel	G-0 LP	0%	6.0	1643	276	-	82
		G-15 LP	15%		1643	233	42	82
		G-30 LP	30%		1643	193	82	81
	High paste content mixtures							
	Limestone	L-0 HP	0%	4.5	1519	334	-	101
		L-15 HP	15%		1519	284	50	100
		L-30 HP	30%		1519	234	100	100
	RCAB	R-15 HP	15%	4.5	1519	307	54	108

NOTE: LP=Low Paste Content, HP= High Paste Content

All specimens were covered by a plastic film and demolded after 24 hours. They were placed in a fog room at 98% relative humidity to cure for 28 days as determined by ASTM C192-02. Drilled cores measuring approximately 95 mm by 100 mm (3.7 in by 4 in) and additional beam specimens for ASTM C944 surface abrasion were extracted.

3.5 Test Procedures

3.5.1 Porosity

A number of key properties in pervious concrete, including permeability and compressive strength, have been directly related to the porosity of the material. Therefore, it was very important to obtain the porosity of all of the mixtures produced and compare it to the results of abrasion resistance [1,3]. Porosity was measured on all concrete specimens including cores and cast cylinders. The diameter and length of the specimens was measured and recorded first. The air-dried weight and the underwater weight were obtained and were used to calculate porosity using the following equation [24]:

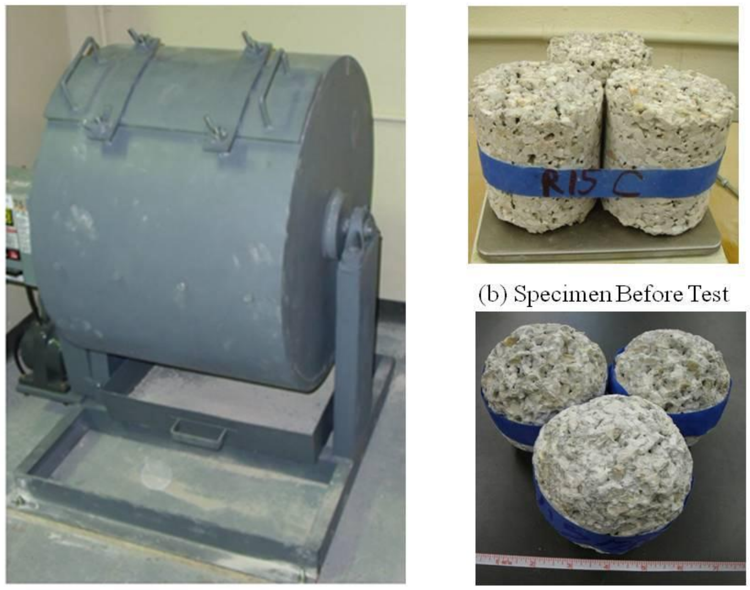
$$P = \left[1 - \left(\frac{W_2 - W_1}{P_w Vol}\right)\right] 100(\%) \qquad (1)$$

Where:
P= Porosity, %
W_1= Weight under water, g
W_2= Air-dried weight, g
Vol= Volume of sample, cm^3
P_w= Density of water @ 21^o C, kg/cm

To guarantee accurate measurements, special care was taken to ensure stable underwater weight of the specimens. Each specimen was left to air dry for 24 hours under laboratory conditions, and the exact dimensions of each cylinder were measured.

3.5.2 Abrasion Resistance to Degradation of Pervious Concrete by Impact Abrasion (ASTM C1747)

A Los Angeles machine was used to evaluate abrasion resistance of pervious concrete following the procedure described in ASTM C1747. Two sets of core samples per mixture were evaluated. In addition, two sets of cast 100 x 100 mm (4 x 4 in) cylinders compacted by a Proctor hammer were tested per limestone aggregate mixture.



(a) Los Angeles Abrasion Machine (b) Specimen Before Test (c) Specimen After Test

Figure 11 Test Method for Determining Potential Abrasion Resistance to Degradation of Pervious Concrete by Impact Abrasion ASTM C1747.

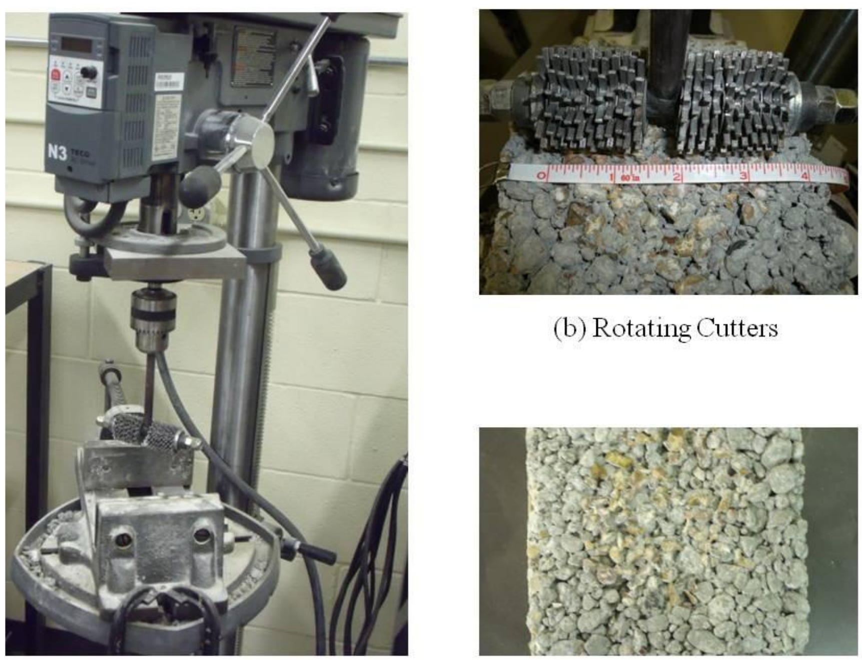
The testing procedure for cores and cylinders began by measuring the initial mass (W_1) of a set of three specimens as shown in Figure 11 b. Once the weight was recorded, the next step consisted of placing three specimens at once inside the drum of the Los Angeles Abrasion machine (Figure 11a). Then, the machine was rotated up to 500 times at a constant rate of 30 revolutions per minute. No steel balls were used during this test. After the loose debris passing the 25 mm sieve (1 inch) was removed and discarded, the final mass (W_2) of the specimens was recorded (Figure 11c). Finally, the percentage of mass loss was calculated using the following formula:

$$ML = \frac{W_1 - W_2}{W_1} \times 100 \tag{2}$$

Where:
ML= Mass loss, %
W_1= Initial weight of test specimen, gr
W_2= Final weight of test specimen, gr

3.5.3 Surface Abrasion Resistance Test (ASTM C944)

Surface abrasion was measured on the top surface of the beam specimens cut from the slab in accordance with ASTM C944. First, the specimen was placed in the rotating-cutter drill press shown in Figure 12a. The device was set to rotate for two minutes at a frequency of 200 revolutions per minute exerting a constant load of 98 N (22 lbf).



(a) Rotating-Cutter Drill Press
(b) Rotating Cutters
(c) Abraded Specimen

Figure 12 Surface Abrasion Test ASTM C944

The total diameter of the cutter shown in Figure 11b was 82.5 mm (3.5 in). After each cycle of abrasion, loose material was removed, and then the mass of the specimen was measured to the nearest 0.1 gr. The three results of mass loss measured in the different locations were averaged, and the abrasion resistance was determined using Equation 3:

$$SA = \frac{W_1 - W_2}{W_1} \times 100 \tag{3}$$

Where:
SA = Surface abrasion %
W_1= Initial weight of test specimen, gr
W_2= Final weight of test specimen, gr

3.6 Results and Discussion

3.6.1 Porosity

Porosity was measured on all cores and cylinders to determine which pervious concrete mixtures had equivalent porosity and thus could be compared in the analysis. Figure 13 shows the results for cores, with each mixture's average porosity and standard deviation represented by an error bar. The analysis for medium paste mixtures indicated that excluding mixture G-0, the porosities were close to the 24% target. The value of porosity measured in mixture G-0 was found to affect the equality of variances and was identified as an outlier; therefore, it was not included in subsequent analyses. In contrast, the remaining gravel mixtures (G-15 and G-30) had a porosity of 25.3 ± 2.5%, and the limestone mixtures had a porosity of 25.4 ± 2.0%. The porosity of mixtures made with RCAB was slightly lower at 23.1 ± 2.1%, yet further tests showed that this difference was not statistically significant ($p>0.05$) compared to pea gravel or limestone.

Additional analysis confirmed that, for all three aggregates used in this study, there was no significant difference in porosity between the control mixture and the subsequent mixtures that had increasing levels of slag. This finding facilitated a comparison of the properties between mixtures made with the same aggregate with increasing levels of slag content. The porosity for gravel mixtures with low paste content was 25.3 ± 1.4% and equivalent to the set of pea gravel mixtures with medium paste content. On the contrary, both the high paste limestone mixtures' and recycled mixtures' porosities were lower at 17.6 ± 1.4% and 14.2 ± 2.4%, respectively. Consequently, the abrasion resistance of mixtures using high paste content is not fully comparable to that of mixtures with medium or low paste, as their porosities are significantly lower.

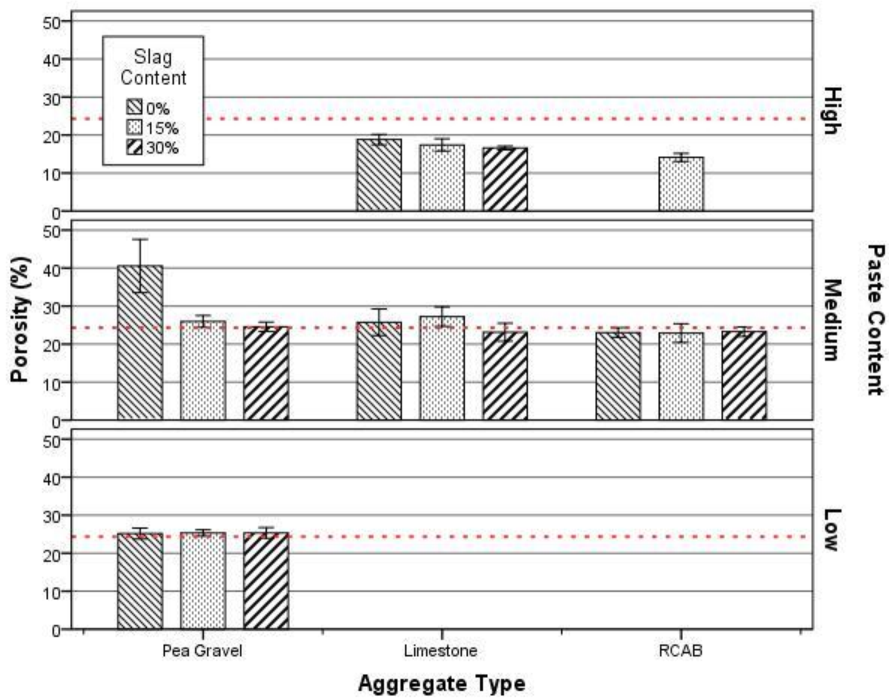


Figure 13 Comparison of the Average Porosity Between Core Samples. Error Bars Represent One Standard Deviation

3.6.2 Abrasion Resistance of Pervious Concrete Cores by Impact Abrasion

The mass loss was measured for two sets of cores per concrete mixture. Each set of cores consisted of three specimens as specified by ASTM C1747. Figure 14 shows the average mass loss after 500 revolutions and standard deviation for each concrete mixture produced. The test was capable of differentiating among mixtures as indicated by the measurements between 25.5% and 65.3%. The precision of the test was evaluated by measuring the within-test range (difference between the largest and smallest mass loss) for each mixture, the within-test range-to-mean ratio (difference between the largest and smallest mass loss divided by the mean of the two measured mass losses multiplied by 100) for each mixture, and the within-test coefficient of variation (CV_1, based on ACI 214R-02). For all evaluated mixtures, the average within-test range was 4.5%, the average within-test range-to-mean ratio was 9.5%, and the within-test coefficient of variation was 8.5%, indicating that the test generates precise results over a wide range of results. As represented by the error bars in Figure 14, the mixtures made with pea gravel had the greatest variability, which could be associated with their higher mass loss, yet even in this scenario the within-test range and within-test range-to-mean ratio did not exceed 8.8% and 14.4%, respectively.

The analysis for medium paste content indicates that pea gravel mixtures had the highest mass loss of 58.6 ± 4.7%, while crushed aggregates such as limestone and RCAB had significantly lower measured mass loss at 46.1± 3.8% and 36.1 ± 3.8%, respectively. The limestone and RCAB had mass loss that was, on average, 21% and 38% lower than pea gravel mixtures, respectively. It is hypothesized that this difference may be associated with the shape of the crushed aggregates, which facilitates interlock, and the superficial roughness of the limestone and RCAB particles, which may improve their bond to the paste. In contrast, the smooth round surfaces of the pea gravel may create a weaker bond between the paste and the aggregate [25]. Of note, the RCAB mixtures had the lowest mass loss compared to virgin limestone aggregate. Although this difference may be associated with the specific RCAB used in this study and also partially explained by the slightly lower porosity of RCAB mixtures, the results are very encouraging in terms of the potential of RCAB when it comes to surface durability. This finding is also consistent with previous research that has observed improved bonding of the interfacial transition zone for some of the recycled aggregate used in pervious mixtures [26].

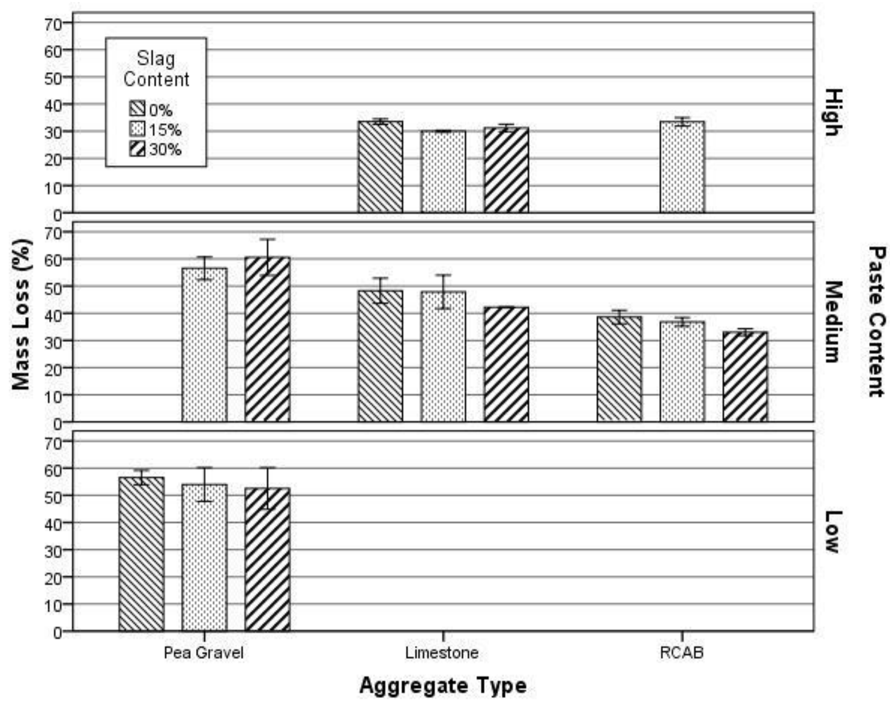


Figure 14 Mass Loss Evaluated as per ASTM C1747 for Different Aggregate Types and Increasing Levels of Slag, and Paste Content Measured After 500 Revolutions. Error Bars Represent One Standard Deviation

The GGBFS was able to effectively replace up to 30% of cement without generating any negative effect on the surface durability of the pervious concrete mixtures. In fact, the opposite was true, as GGBFS was able to reduce mass loss by 13% and 14% in limestone and RCAB, respectively. While these reductions in mass loss were not statistically significant (p=0.331), the ability to replace such a large portion of cement by a recycled material without affecting the concrete performance is by itself a very desirable outcome.

The analysis of the effect of paste content showed that low paste content mixtures made with pea gravel reached a mass loss of 54.4 ± 6.1%, which was equivalent to medium paste mixtures G-15 and G-30. These results suggest that paste content may have a limited effect on abrasion resistance if the porosity and aggregate type are maintained constant. In contrast, high paste content mixtures had a mass loss which was on average 22% lower than medium paste content mixtures, but these results cannot be associated with the paste content itself as their significantly lower porosities were not comparable to medium paste mixtures.

3.6.3 Abrasion Resistance of Cores versus Cast Cylinders

Understanding the effect of the specimen type, namely cast cylinders versus cores, is relevant to implement the ASTM C1747 test for quality control in the field. To accomplish this goal, two sets of 100 by 100 mm cylinders were cast for each limestone mixture made with medium paste content. These cylinders were cast at the same time that the slabs were poured, ensuring that the same mixture was used. The cylinders' compaction was monitored to achieve similar values of porosity to those expected in core specimens. The comparison between cores and cylinders is shown in Figure 15. An independent sample T-Test found that cores and cylinders had statistically similar porosities for the three levels of slag content.

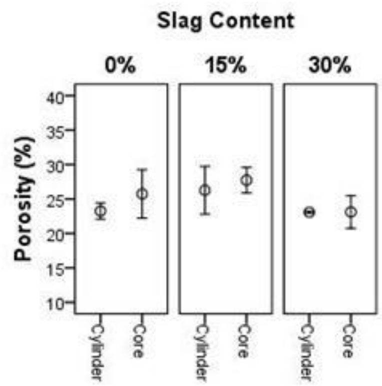
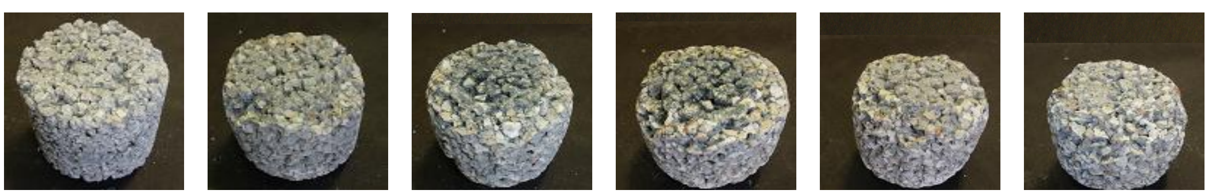


Figure 15 Comparison Of Porosity Between Field Cores And Cylinder Specimens For Limestone Mixtures With Medium Paste Content. Error Bars Represent One Standard Deviation.

After ensuring that the porosities were equivalent, a total of ten mass loss values were obtained for each set of samples every 50 revolutions until the specified 500 revolutions were reached, as shown in Figure 16.



Before Test 50 Cycles 100 Cycles 150 Cycles 200 Cycles 250 Cycles

300 Cycles 350 Cycles 400 Cycles 450 Cycles 500 Cycles

Figure 16 Specimen In ASTM C1747 Test At Various Revolutions

Results showed that even though the porosities were equivalent, the cores consistently had higher values of mass loss compared to cast cylinders. This difference may be linked to the micro-cracks and damage induced by the core drill during the core extraction.

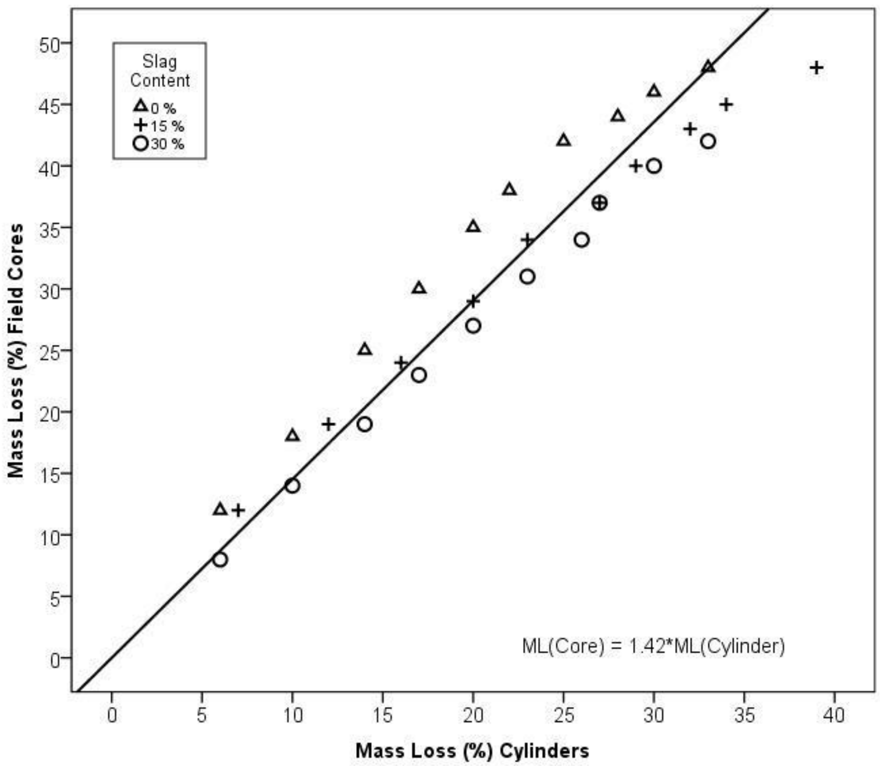


Figure 17 Comparison Of Mass Loss Measured Every 50 Revolutions Between Field Cores And Cylinder Specimens For Limestone Mixtures With Medium Paste Content.

The preliminary results depicted in Figure 17 indicate that cores made with the same concrete mixture and equal porosity may experience an average of approximately 42% larger mass loss compared to cast cylinders. The results also show some differences among mixtures with 0% slag and mixtures with 15% and 30% slag, but, due to the limited number of mixtures, further research is needed to evaluate potential effects of materials such as aggregates and GGBS on the core versus cylinder relation for abrasion tests.

3.6.4 Abrasion Resistance of Pervious Concrete by Surface Abrasion Test (ASTM C 944)

Surface abrasion was measured in three different areas by using rotating cutting wheels in accordance with ASTM C944. Figure 18 shows the average mass loss and standard deviation for each mixture, as indicated by the error bars. The measured results were between 0.55% and 0.18%, suggesting that the test is capable of differentiating among different concrete mixtures. The within-test coefficient of variation for all mixtures was 32%, which was similar to the value observed by Dong et al. for the same test method [20]. As represented by the error bars in Figure 18, the group of low paste content gravel mixtures had the highest within-test coefficient of variation, which was 53%. Based on the limited set of tests performed in this study, the within-test coefficients of variation suggest that this test may lack the level of precision needed for use in quality control of abrasion resistance on pervious concrete. This conclusion agrees with several authors who have concluded that the standard test for surface abrasion on conventional concrete (ASTM C944) does not fully represent the abrasion resistance of pervious concrete mixtures as it may not be capable of testing a representative area [16].

As shown in Figure 18, medium paste pervious concrete made with limestone aggregate had the highest mass loss of 0.48 ± 0.07% among medium paste content mixtures, followed by RCAB, which lost 0.25 ± 0.07%. The mass loss of pea gravel mixtures was the lowest at 0.19 ± 0.09%. While limestone and RCAB mixtures followed a similar trend compared to the ASTM C1747, the mass loss of pea gravel mixtures tested under ASTM C944 was significantly lower, while their mass loss measured under ASTM

C1747 was significantly higher. This discrepancy suggests that the surface abrasion test is more sensitive to the finished surface and that rounded aggregates allow the dressing wheels to roll without getting caught, therefore generating less mass loss, while crushed aggregates get caught by the wheels.

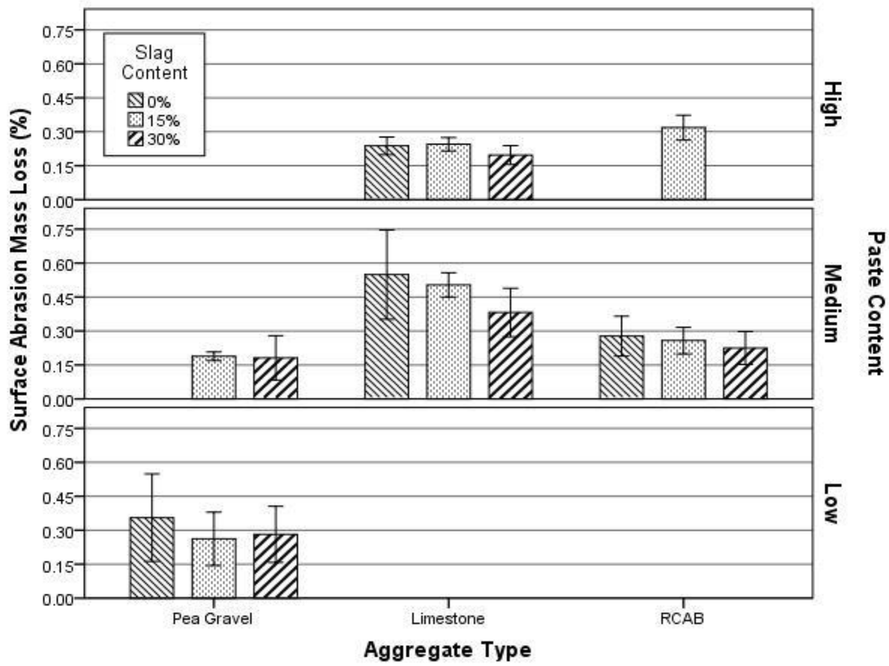


Figure 18 Surface Abrasion Mass Loss Results For Different Aggregate Types, Increasing Levels Of Slag, And Paste Content. Error Bars Represent One Standard Deviation.

The relation between surface mass loss and mass loss under ASTM C1747 can be observed in Figure 19. The coarse aggregates followed a trend that can be represented by a linear equation relating both tests, as depicted in Figure 19. In contrast, the pea gravel mixtures did not show any correlation between surface mass loss and mass loss under ASTM C1747. The effect of supplementary cementitious materials is shown in Figure 8. Increasing the levels of GGBFS to 30% had a beneficial effect, reducing the surface mass loss by 30% and 19% in medium paste limestone and recycled aggregate mixtures, respectively.

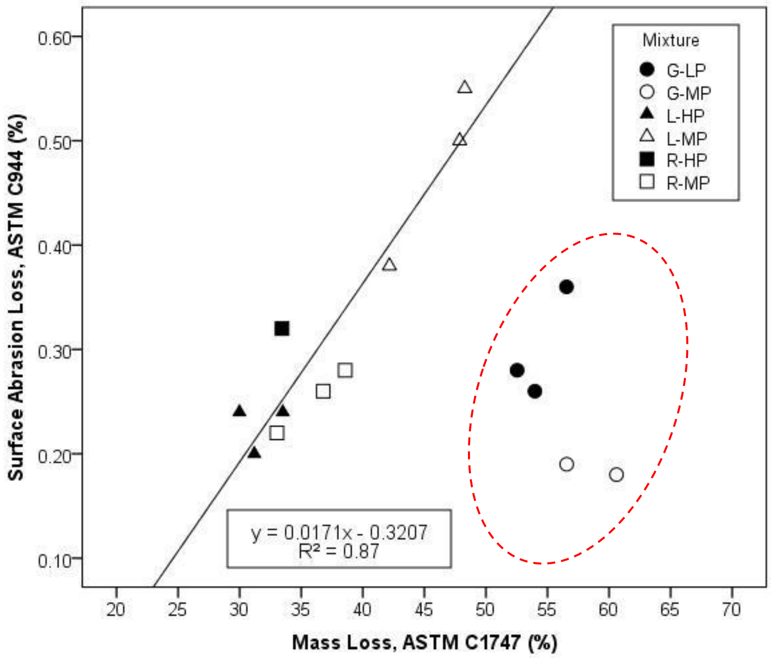


Figure 19 Relation Between The ASTM C1747 Impact Mass Loss Abrasion And ASTM C 944 Surface Abrasion Loss. Note: LP = Low Paste, MP = Medium Paste, And HP = High Paste.

Increasing the paste content in limestone aggregate mixtures had a beneficial effect, reducing the mass loss by 52%, yet this outcome is associated with the lower porosity of high paste mixtures.

3.7 Conclusions

The abrasion resistance test as specified by ASTM C1747 effectively differentiated among mixtures prepared with different aggregates, supplementary cementitious materials, and paste contents. The relatively low within-test range and within-test coefficient of variation of 4.5% and 8.5%, respectively, indicate that the test method has precision over a wide range of different pervious concrete mixtures. In contrast, the measurements for surface abrasion as specified by ASTM C944 had a within-test coefficient of variation of 32%. In addition, the within-test variability was significantly affected by the aggregate type and paste content, indicating that this test may lack the level of precision needed for use in quality control of abrasion resistance on pervious concrete.

The aggregate type had an important role in the ASTM C1747 abrasion resistance of mixtures with the same aggregate-to-paste ratio and equivalent porosity. Pea gravel mixtures had significantly less abrasion resistance than crushed aggregate mixtures. This difference, which was 21% for limestone and 38% for RCAB, may be associated with the enhanced interlock and the superficial roughness of both crushed aggregates, which may have improved their bond with the paste. The RCAB aggregate mixtures analyzed in this study had an abrasion resistance that was comparable to, and even slightly lower than, virgin limestone aggregate mixtures. The paste content did not significantly alter the abrasion resistance if the porosity was kept constant.

A preliminary comparison between the ASTM C1747 abrasion resistance of field cores and cast cylinders of equivalent porosity was performed on three limestone mixtures. The mass loss of cores was, on average, 42% higher than the mass loss measured in cast cylinders of the same porosity. While it was clear that core specimens had higher mass loss than cast specimens, further research is needed to evaluate potential effects of materials such as aggregates and GGBS on the core versus cylinder relation.

The surface abrasion test prescribed by ASTM C944 had a within-test coefficient of variation of 32%, which was 3.8 times larger than the coefficient of variation of measurements using ASTM C1747. The comparison between the aforementioned tests shows that their measurements can be correlated by a linear regression when crushed aggregate is used, yet no significant relation was found for pea gravel.

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IV. INFLUENCE OF TEST SPECIMEN TYPE ON THE STRUCTURAL AND FUNCTIONAL PERFORMANCE OF PERVIOUS CONCRETE MIXTURES

4.1 Abstract

In spite of its environmental advantages, pervious concrete is in limited use because of the variability observed during the handling of the material and the lack of standardized protocols that could help establish effective quality control. The current project examined the properties of specimens produced in the laboratory by Proctor hammer and its correlation to the properties of pervious concrete cores. The experimental design was chosen to evaluate the effect of the aggregate type and ground granulated blast-furnace slag on pervious concrete. Different levels of compaction were achieved using a standard Proctor hammer to produce a range of porosities. Unit weight, permeability, and compressive strength were obtained for all of the specimens produced as well as for a set of core specimens. For equivalent porosity, there was no significant difference between the dry unit weight of cores and Proctor hammer compacted cylinders. In contrast, the permeability of cores was, on average, 20% lower than the cylinders compacted by Proctor hammer, and the compressive strength was 17% lower. The recycled aggregate mixtures were more sensitive to the core extraction process as indicated by lower core-to-cylinder ratios for permeability and strength.

Keywords: pervious concrete, core specimen, recycled aggregate, compaction.

4.2 Background

Pervious concrete has been used as a sustainable alternative to conventional paving materials during the last 30 years due to its ability to allow for water infiltration while maintaining structural performance [1]. Water passes through an interconnected network of voids in the pervious concrete structure resulting from constrained use of fine aggregates, uniform gradation, and low water-to-cementitious-material ratio [2]. In addition to its infiltration capacity, pervious concrete has been used to remove pollutants from stormwater runoff, improve skid resistance, and reduce the tire-pavement noise interaction [3-5]. Furthermore, pervious concrete has reduced heat storage capacity, which helps mitigate the urban heat island effect [6-8].

Porosity, which ranges from 18% to 25%, is one of the key properties of pervious concrete and directly influences the performance of the material [2]. For instance, pervious concrete mixtures with high porosity tend to demonstrate higher permeability but poor strength, whereas low-porosity mixtures show superior strength but allow less water conduction [9-13]. In addition to porosity, other essential pore structure features, such as pore size, volume fraction, specific surface area, mean free spacing, and connectivity of pores, strongly influence the properties of any open-grade structure material and need to be considered when studying the mechanical response and water infiltration capabilities of a pervious concrete pavement [14-17].

Pervious concrete mixtures are designed to achieve a design value of porosity that guarantees a balance between the water infiltration capacity and the desired mechanical properties [2]. For instance, Sumanasooriya et al. developed a novel methodology for mixture proportioning based on particle packing concepts to attain a desired porosity in pervious concrete mixtures [18]. The approach relies on relationships between material volume and amount of compaction effort applied. Although mixture proportioning is a major contributing factor, the compaction energy and construction methodology are also variables that affect the porosity, consequently influencing the properties and performance of pervious concrete [14]. Care must be taken during field placement to ensure a proper bond between the aggregates and the paste without compromising the hydrological abilities of the material.

The unique characteristics and behavior of pervious concrete make the sampling and evaluation methods used in conventional concrete difficult to apply in pervious mixtures as they may not be representative and consistent. As a result, the American Society of Testing and Materials (ASTM) through its subcommittee C09.49 on pervious concrete has developed a number of standards to measure such properties as infiltration rate, resistance to degradation, and fresh density. ASTM C1688, one of the most essential standards in quality control of pervious mixtures, was designed to evaluate the density and void content of fresh pervious concrete. However, the standard is used as means of verifying that the aforementioned properties correspond to those specified by the designer in the mix proportioning, and the results do not necessarily reflect the performance of the material-in-place.

A number of studies have compared the properties of laboratory cast specimens and core samples obtained in the field [19]. The conventional method for compacting cylinders using a ½-inch rod has been found to be inappropriate for the casting of laboratory specimens of pervious concrete. Instead, pervious concrete samples have been compacted using a Proctor hammer with more consistent results. Other tools and techniques, such as a pneumatic press, rollers, hand tamping, Marshall hammer, and vibration tables have also been evaluated [11, 20-23]. Table 1 summarizes the methods utilized and the most important findings from the studies.

Table 6 Compaction Techniques Evaluated from the Literature

Reference	Compaction Techniques	Observations
Ghafoori and Dutta 1995 [1]	• A 2.27-kg (5-lb) hammer was used to apply 8 different levels of compaction • Standard rodding method using a 12.7-mm (½-in) diameter steel bar	Hand-rodded specimens showed similar properties to those obtained in samples compacted at 33 J/m3
Suleiman et al. 2006 [20]	• Rodding 25 times in 3 layers and vibration for 5 seconds at 0.005-inch and 0.0024-inch amplitudes	Compaction significantly affects pervious concrete properties
Rizvi et al. 2008 [21]	• 3 layers with 25, 15, and 5 rods per layer • 2 layers with 20 and 10 blows of a standard Proctor hammer per layer	Samples compacted by 10 blows of the Proctor hammer per layer achieved the most consistent results
Mahboub et al. 2009 [22]	• Molds were filled in one layer and compacted at 10 psi (0.007 MPa) using a pneumatic press • Rodding as described in ASTM C192	The traditional method of rodding cylinders does not accurately represent the conditions of a roller-compacted slab
Brown 2010 [23]	• Rodding 25 times in 3 layers • Jigging method described in ASTM C29 • Compaction as a percentage of volume • Weight vs. volume method	The weight vs. volume method produced pervious specimens with the most consistent results
Putman and Neptune 2010 [19]	• 3 layers each rodded 10,15, and 25 times • 2 layers rodded 25 times • Dropping the mold from a height of 50 mm • Cores extracted from 600-mm square slabs compacted using the same technique and of the same thickness as the field slab	Rodded cylinders had a greater degree of variability than those compacted using the other methods. Cores extracted from the slabs had properties that were most similar to the in-place pavement

Despite the numerous efforts cited above, the method that best matches the properties of in-place pervious concrete varies with the characteristics of the mixture under consideration given a specific paste content, aggregate type, and size, along with the compaction techniques used in the field.

4.3 Objectives

For this study, laboratory cast samples were produced under different levels of compaction using a standard Proctor hammer, and their performance was compared to that of core specimens obtained from slabs compacted under conditions similar to those in the field (roller compaction). The effect of the aggregate type and percentage of cement replacement by slag were evaluated, and relationships between the porosity and (a) the compressive strength and (b) permeability of compacted cylinders were obtained. A series of adjustment factors that would account for discrepancies in performance related to the specimen type and compaction were developed.

4.4 Experimental Program

4.4.1 Materials

The cementitious materials selected for this study include: (i) *Portland cement Type I* and (ii) *ground granulated blast-furnace slag* (GGBFS), a by-product of steel production. GGBFS was specifically used to replace cement due to its ability to further enhance the sustainability of pervious concrete without compromising its performance. The GGBFS had a Blaine fineness equal to 5,605 cm^2/g and a slag activity index at 7 and 28 days of 98 and 123, respectively; it met the chemical and physical requirements of ASTM C989 and AASHTO M-302 for grade 120. Three types of single-sized 3/8-inch coarse aggregate were used in the study. Pea gravel and crushed limestone were obtained locally. The *recycled concrete aggregate blend* (RCAB) was obtained by mixing 50% of crushed virgin limestone aggregate and 50% of recycled concrete aggregate. The specific gravity, water absorption, voids, and unit weight of each aggregate are shown in Table 2. A viscosity-modifying admixture type S according to ASTM C 494 was used in all concrete mixtures with a dosage of 261 ml/kg of cementitious material. A non-chloride, mid-range water-reducing admixture with a dosage of 392 ml/kg of cementitious material was also used. It met ASTM C 494 requirements for Type A water-reducing admixtures.

Table 7 Physical Properties of Aggregates

Property	Unit	Pea Gravel	Limestone	RCAB
Unit Weight	kg/m³ (lb/ft³)	1,588 (99.1)	1,471 (91.8)	1,411 (88.0)
Water Absorption	%	0.95	2.47	4.12
Bulk Specific Gravity$_{ssd}$[a]	------	2.61	2.57	2.42
Bulk Specific Gravity$_{od}$[b]	------	2.59	2.50	2.32
Voids	%	38.48	41.15	41.57

[a]*ssd, saturated surface dry condition*
[b]*od, oven dried condition*

4.4.2 Mixture Proportions

Sixteen mixtures with a water-cementitious ratio of 0.30 were proportioned based on the method described in ACI 522 R-10 [2]. The experimental design comprised two series as shown in Table 3. Series I consisted of nine mixtures with an aggregate-to-cement ratio of 5.2. Specifically, one control mixture and two mixtures with 15% and 30% of cement replacement by slag for each type of aggregate were produced. These mixtures were used to evaluate the performance of, and compare the effect of using various aggregates and percentages of slag in, pervious concrete mixtures. Series II was mainly used to verify the factors that correlate cylinder and core specimens. All mixtures contained 15% GGBFS that replaced cement, specifically one pea gravel mixture, one limestone mixture, and one RCAB mixture with modified aggregate-to-paste ratios of 6, 4.5, and 4.2, respectively. Mixtures were prepared using a rotating drum mixer.

Table 8 Mixture Proportions

Series No.	Type of Aggregate	Mix No.	Slag Content	Aggregate-Paste Ratio	Aggregate (kg/m³)	Cement (kg/m³)	Slag (kg/m³)	Water (kg/m³)
	Medium paste content mixtures							
I	Pea Gravel	G-0	0%	5.2	1453	284	-	85
		G-15	15%		1453	242	43	85
		G-30	30%		1453	199	85	85
	Limestone	L-0	0%	5.2	1453	284	-	85
		L-15	15%		1453	242	43	85
		L-30	30%		1453	199	85	85
	RCAB	R-0	0%	5.2	1453	284	-	85
		R-15	15%		1453	242	43	85
		R-30	30%		1453	199	85	85
	Low paste content mixtures							
II	Pea Gravel	G-0 LP	0%	6.0	1643	276	-	82
		G-15 LP	15%		1643	233	42	82
		G-30 LP	30%		1643	193	82	81
	High paste content mixtures							
	Limestone	L-0 HP	0%	4.5	1519	334	-	101
		L-15 HP	15%		1519	284	50	100
		L-30 HP	30%		1519	234	100	100
	RCAB	R-15 HP	15%	4.5	1519	307	54	108

4.5 Methods

4.5.1 Slab Preparation and Core Extraction

Pervious concrete was poured into wooden forms of 200 mm (8-in.) height in a single layer and compacted using a weighted roller applying a constant pressure of 148 kg/m (100 lb/ft). The weight of each slab was monitored to achieve comparable levels of density among the mixtures produced. Core samples with a 100-mm (4-in.) diameter were extracted from the concrete slab and used for the determination of the in-place properties of the material.

4.5.2 Cylinder Specimen Preparation

Four compaction efforts were used in this study to cast cylindrical test specimens with an ample range of porosities. Cylinders of 200-mm length and 100-mm diameter were compacted in two layers using a 2.5-kg (5.5-lb) standard Proctor hammer having a height of fall of 30 cm (12 in.). The compaction energies shown in Table 4 were obtained by the product of the number of Proctor hammer blows by the number of layers by the height of fall by the weight of the hammer, divided by the volume of the mold. The slabs and the cylinder specimens were covered with a plastic sheet for a period of 24 hours. After that period of time, all of the samples including the slabs were demolded and stored in a curing room at 98% humidity for 28 days.

Table 9 Compaction Energies Applied to Compact Cylinders Using the Proctor Hammer

Number of Repetitions	Number of Layers	Compaction Energy (kN*m/m³)
5	2	45.4
10	2	90.8
20	2	181.6
30	2	272.4

4.6 Test Procedures

4.6.1 Porosity

Porosity of pervious concrete was determined using a method developed by Montes et al. [24]. The diameter and length of the sample were measured to obtain the total volume of the cylinder. The samples were weighted in dry condition (W_1) and submerged condition (W_2), and the porosity was calculated using the following equation:

$$P = \left[1 - \left(\frac{W_2 - W_1}{P_w Vol}\right)\right] \times 100(\%) \tag{1}$$

Where:
P=porosity, %
W_1=weight under water, g
W_2=air-dried weight, g
Vol=volume of sample, cm^3
P_w=density of water @ 21^oC, kg/cm^3

To guarantee accurate measurements, special care was taken to ensure stable underwater weight of the specimens. Each specimen was left to air dry for 24 hours under laboratory conditions, and the exact dimensions of each cylinder were measured.

4.6.2 Permeability

A falling-head permeability test apparatus was used to measure permeability [10]. A flexible polyethylene foam membrane was carefully wrapped around the sample to impede water infiltration between the surface of the sample and the apparatus. The time for water to flow through the sample was recorded at the initial (h_1) and final (h_2) levels, which were set at 500 mm and 250 mm, respectively. Finally, the average coefficient of permeability was determined using Darcy's law that assumes laminar flow:

$$K = \frac{aL}{At} ln\left(\frac{h_1}{h_2}\right) \tag{2}$$

Where:
K=coefficient of permeability, cm/s
a=cross-sectional area of standpipe, cm^2
L=length of sample, cm
A=cross-sectional area of specimen, cm^2
t =time in seconds from h_1 to h_2
h_1=initial water level, cm
h_2=final water level, cm

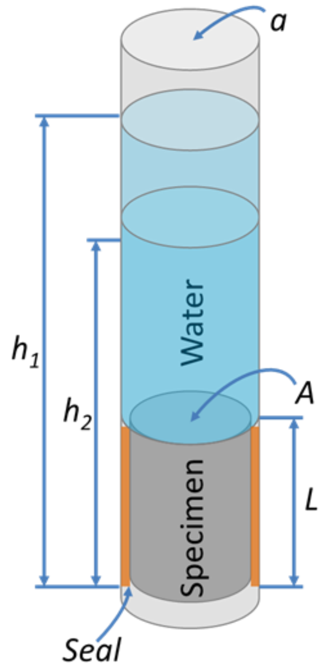


Figure 20 Falling-head Permeability Test

4.6.3 Compressive Strength

The compressive strength tests were performed in accordance with ASTM C39 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. The specimens were capped on the ends using a sulfur compound to provide plane surfaces and ensure an even distribution of the compression force, which was applied at a rate of movement of 0.25 ± 0.005 MPa/s (35 ± 7 psi/s) until the specimen displayed a well-defined fracture pattern.

4.7 Analysis of Results

4.7.1Unit Weight

The fresh concrete unit weight was determined for all Proctor-hammer-compacted cylinders using the cylinder mass measured immediately after being cast. Their dry unit weight was measured before the compressive test after 28 days of curing; each cylinder was allowed to dry for 24 hours. The relationship between fresh and hardened unit weight for all mixtures is shown in Figure 21. As expected, the fresh unit weight was slightly higher than the dry unit weight. An analysis of independent variables indicated that neither the aggregate type nor the slag content had a significant effect on the relationship between fresh and dry unit weight. The regression equation was:

$$UW_{dry} = 0.965 * UW_{fresh} \tag{3}$$

Where UW_{fresh} and UW_{dry} are the fresh and dry unit weights measured on the Proctor-hammer-compacted cylinders, respectively. This relationship means that for a wide range of unit weights, the fresh unit weight is 3.6% higher than the dry unit weight. The core specimens were not included in this relationship, as they were extracted from the slabs once hardened and cured.

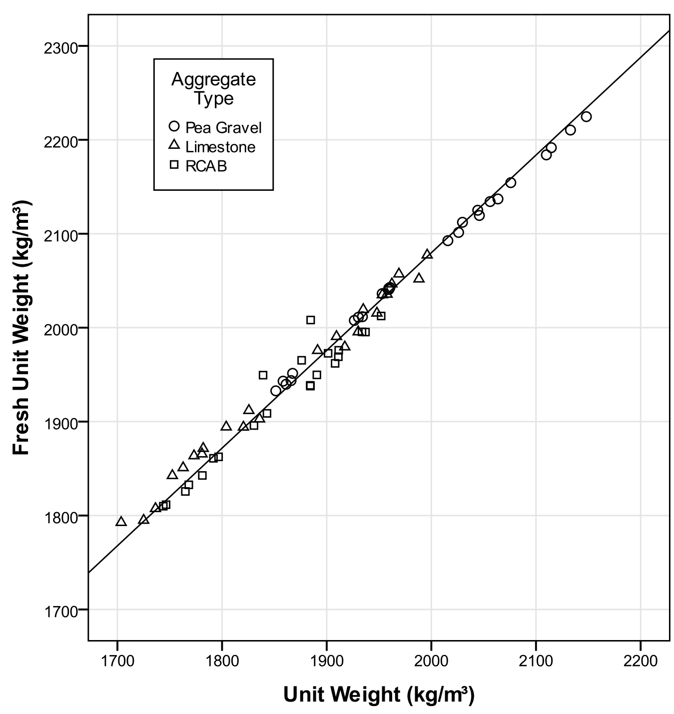
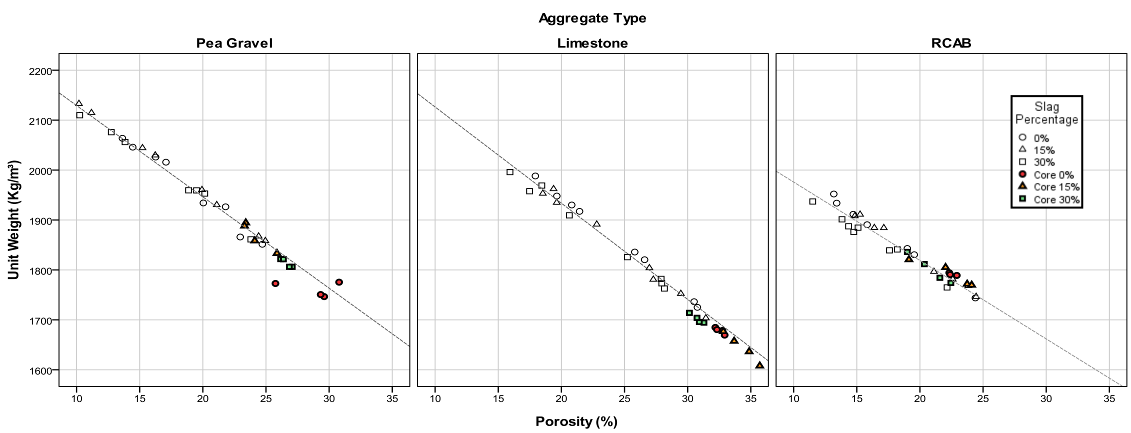


Figure 21 Relationship Between Fresh and Dry Unit

Weight of Proctor-Hammer-Compacted Cylinders.

The relationship between unit weight and porosity for cylinders and cores made with three different aggregates (pea gravel, limestone, and RCAB aggregate) and three different levels of cement replacement by slag (0%, 15%, and 30%), respectively, is presented in Figure 3. The cylinders are represented by hollow markers, whereas cores are represented by colored markers. A dotted line representing the regression for the Proctor hammer cylinders was added to each plot as a reference to visually compare the cast cylinders and cores.



(a) (b) (c)

Figure 22 Relationship Between Unit Weight and Porosity For Cylinders And Cores of (a) Pea Gravel; (b) Limestone; and (c) RCAB Aggregate Mixtures.

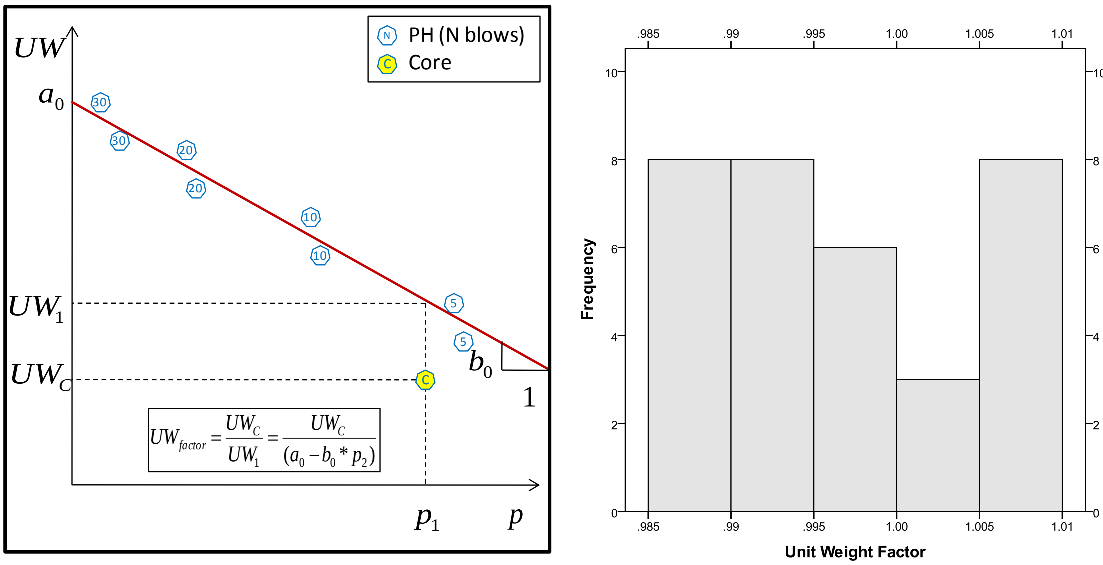
Figure 22 shows that the relationship between unit weight and porosity was affected by the type of aggregate. While all curves had a similar slope, the intercept differed. This finding was more pronounced when comparing the lower unit weight of RCAB mixtures with both virgin aggregate mixtures. In contrast, both limestone and pea gravel mixtures had a similar unit-weight-versus-porosity relationship. These differences are closely related to the bulk specific gravity (BSG) of each aggregate. For instance, limestone and pea gravel have similar BSG of 2.61 and 2.57, whereas RCAB has a much lower BSG of 2.42. The slag content did not show a specific effect in any of the plots, which was expected due to its similar density as compared to cement. A general linear model was applied to determine if the aggregate type and slag content had an effect on the relationship between unit weight and porosity. The following equation was obtained for Proctor-hammer-compacted specimens:

$$UW = 435 - 17.6 * p + 715.9 * BSG \tag{4}$$

Where:
UW=dry unit weight of the concrete, kg/m^3
p=porosity, %
BSG=bulk specific gravity (ssd) of the coarse aggregate.

The general linear model analysis confirmed that the slag content was not a significant variable affecting the unit weight-porosity relationship, whereas an increase in BSG did significantly increase the unit weight. While the high coefficient of determination equal to R^2=0.98 indicates that both variables can predict the unit weight, the results are limited to this particular set of mixtures, and more research with a wider array of mixtures is needed to derive a more general equation.

One of the main difficulties when comparing the effect of specimen type (i.e. cores and compacted cylinders) is obtaining specimens of the same porosity. While it is possible to prepare a very large set of cylinders compacted at different levels of energy by varying the number of hammer blows, this process is very time consuming. Another alternative is to measure the weight of a small cast slab and to prepare a set of cylinders of equivalent porosity by filling each cylinder to the mass and volume that would match the slab porosity or unit weight; however, this method is only feasible for smaller slabs and can still generate porosity values that can significantly differ among specimen types.



(a) (b)

Figure 23 (a) Calculation Of The Uwfactor To Relate Cores To Proctor Hammer Cylinders; (b) Statistical Distribution Of The Uwfactor.

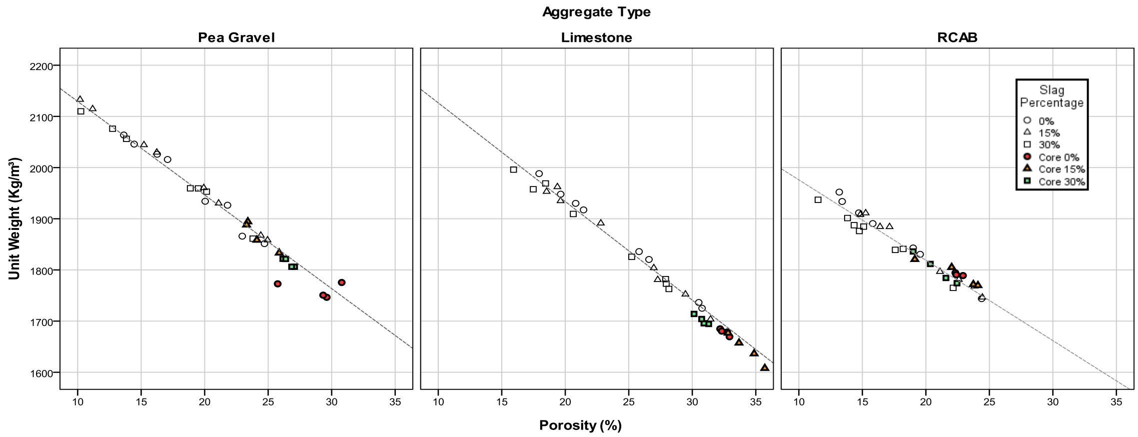
The proposed method, shown in Figure 23a, used four different levels of compaction at 5, 10, 20, and 30 Proctor hammer blows to calculate a linear master curve for each pervious concrete mixture. This master curve was then used to estimate the unit weight that a compacted cylinder of exactly the same porosity as the core would have had. After this step, both the measured core unit weight (UW_C) and the unit weight calculated for a Proctor hammer cylinder of the same porosity (UW_1) were compared, and a ratio (UW_{factor}) was obtained. After this process was repeated for all cores, the distribution of the UW_{factor} was obtained, as shown in Figure 23b.

The average UW_{factor} was 1.0 and had a very narrow range between 0.0985 and 1.010. Further verification with a t-test corroborated that the factor was equivalent to 1.0, confirming that the type of specimen (i.e. core or compacted cylinder) did not affect the unit weight versus porosity relationship. This finding is very important, as it indicates that the unit weight of cores and compacted cylinders can be directly compared without the need for an adjustment factor.

4.7.2 Permeability

As expected, permeability increased with an increase in the porosity for all pervious concrete mixtures produced. Figure 24 shows the relationship between porosity and permeability. For the range of porosities measured in the cylinders compacted using the Proctor hammer, a linear equation was found to appropriately represent the correlation. The figure demonstrates that the slope and the intercept varied according to the type of aggregate used in the mixture, whereas the percentage of slag used to replace cement did not have a particular effect on the relationship. The effect of porosity on permeability was higher for mixtures made with limestone aggregate. For instance, a 1% increase in the porosity improved permeability by 0.08 cm/s. Conversely, the same increment of porosity increased the permeability by 0.05 cm/s and 0.06 cm/s for the pea gravel and RCAB mixtures, respectively. It was also noted that RCAB mixtures showed higher values of permeability for a given porosity compared to the mixtures made with pea gravel and limestone aggregate.

Of note, for the same value of porosity, the core samples exhibited lower values of permeability compared to the laboratory cast specimens compacted using the standard Proctor hammer. For example, at a porosity of 20% in RCAB mixtures, permeability for laboratory cast specimens was around 0.9 cm/s, whereas the value of permeability for core specimens extracted from the slab was around 0.65 cm/s. To assess the influence of the specimen type (cylinders versus core) for mixtures made with different aggregates, an adjustment factor (K_{factor}) for permeability measured in the core samples was proposed.



(a) (b) (c)

Figure 24 Relationship Between Permeability And Porosity For Cylinders And Cores of (a) Pea Gravel; (b) Limestone; and (c) RCAB Aggregate Mixtures.

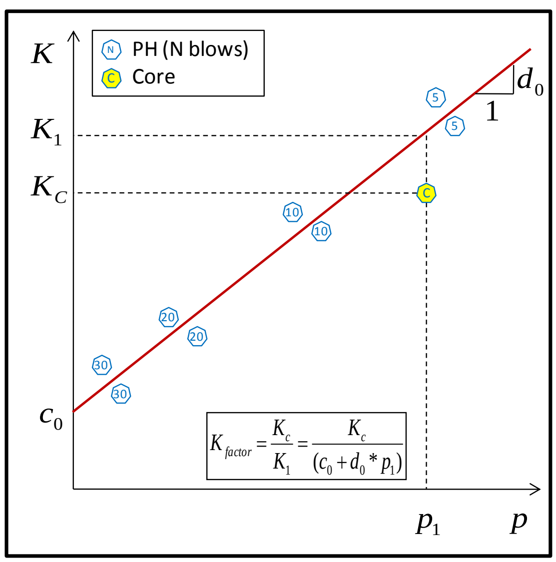
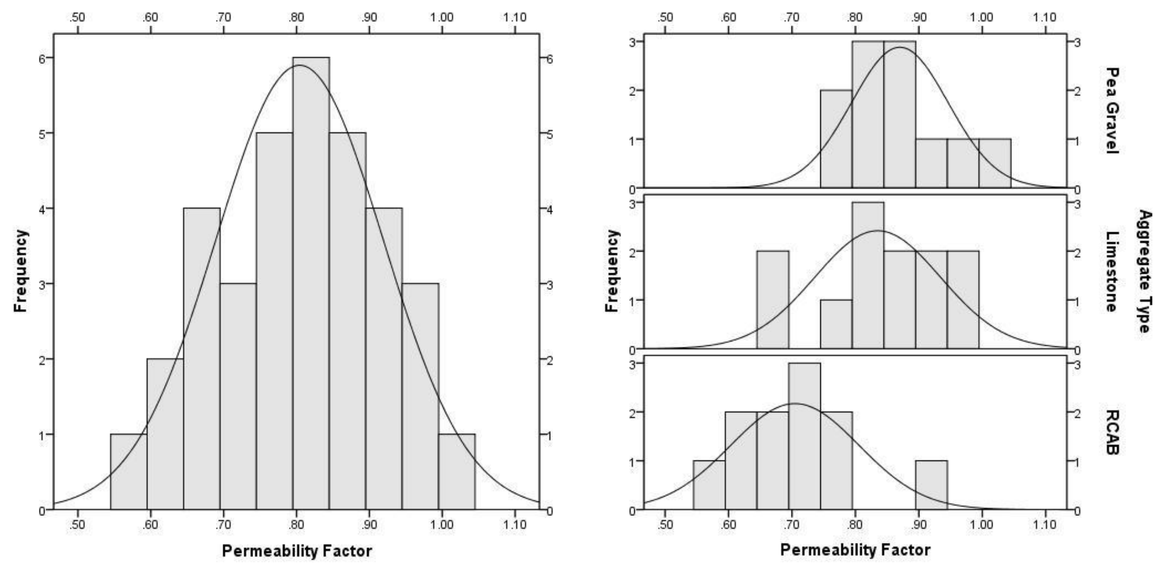


Figure 25 Calculation Of The K Factor To

Relate Cores To Proctor Hammer Cylinders.

The proposed methodology, shown in Figure 25, was very similar to the one used to determine the unit weight factor (UW_{factor}). First, the correlation between permeability and porosity was defined for each mixture using the values measured in the cylinders compacted with the Proctor hammer. An estimated permeability (K_1) was obtained by entering the value of porosity (p_1) measured in the cylinder in the correlation equation. The permeability ratio (K_{ratio}) between the estimated value (K_1) and the experimentally measured permeability (K_c) was calculated for all of the core samples.



(a) For All Specimens (b) Per Aggregate Type

Figure 26 Statistical Distribution of The K Factor (a) for All Specimens; (b) per Aggregate Type.

Figure 26a shows the distribution of the K_{factor} for all three aggregates used, which had a mean value of 0.80 with a coefficient of variation of 14%. Figure 26b shows the distribution of the factor for each of the aggregates. The permeability factor for RCAB had a mean and coefficient of variation of 0.70 and 14%, respectively. In contrast, the mean K_{factor} for limestone and pea gravel was higher at 0.83 and 0.87, respectively. Their variability was also lower than RCAB, with a coefficient of variation of 12% and 9% for limestone and pea gravel, respectively. A two-way analysis of variance confirmed a significantly lower factor for RCAB compared to the factor for limestone and pea gravel, which were statistically equivalent.

The aforementioned findings confirm that the permeability of cores is significantly lower than Proctor-hammer-compacted cylinders even when the porosity is the same. The lower permeability is most likely associated with the use of the roller, which tends to increase compaction and, consequently, lower the permeability of the upper layer of the slab. As the layer close to the surface of the slab is less permeable, the overall permeability is reduced, yet the overall porosity of the slab can stay the same by having greater porosity at its bottom. The difference in vertical distribution of porosity in pervious concrete has been previously reported by Haselbach et al. [25].

In terms of the application of the proposed permeability factors, the authors suggested the use of 0.80 for mixtures using virgin aggregates, meaning that, for the same porosity, a core extracted from the field has, on average, 20% less permeability compared to a cylinder compacted with a Proctor hammer. Special care should be taken when estimating the permeability of RCAB cores, due to its lower factor of 0.70 and higher variability.

To evaluate the proposed method, core specimens from Series II mixtures were evaluated to illustrate the effectiveness of the proposed model and the adjustment factors in predicting the permeability of pervious concrete cores under the conditions proposed in this paper. Results are shown in Figure 27, where the actual versus predicted permeability are presented for this set of mixtures. The plot confirms that each predicted permeability was close to the equality line, confirming the effectiveness of the proposed method.

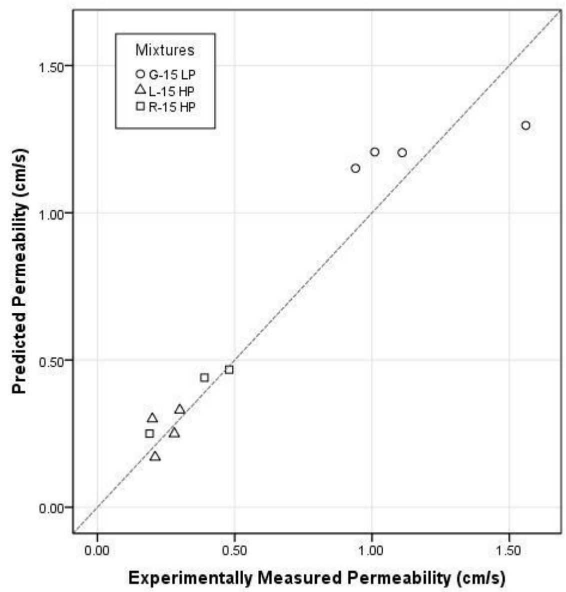


Figure 27 Predicted Vs. Actual Permeability For Series I Pervious Concrete Core Specimens.

4.7.3 Compressive Strength

Compressive strength tests were performed to evaluate the structural performance of the mixtures produced. A definite correlation between compressive strength and porosity was observed. Contrary to the behavior of permeability, compressive strength was found to be inversely proportional to the porosity. This relationship was true for all of the mixtures produced and can be observed in mixtures made with pea gravel, which had the lowest values of porosity but achieved compressive strengths of up to 25 MPa.

Figure 28 shows the relationship between porosity and compressive strength measured in cylinders and core specimens for the mixtures produced with the three aggregates and their corresponding levels of slag content. The figure indicates that the slope and intercept varied according to the aggregate. On the other hand, the use of 15% and 30% of slag to replace cement did not have a particular effect on this relationship. Mixtures made with pea gravel aggregate were the most sensitive to porosity, as they demonstrated that for a 1% increase in porosity, almost 0.94 MPa of compressive strength was lost.

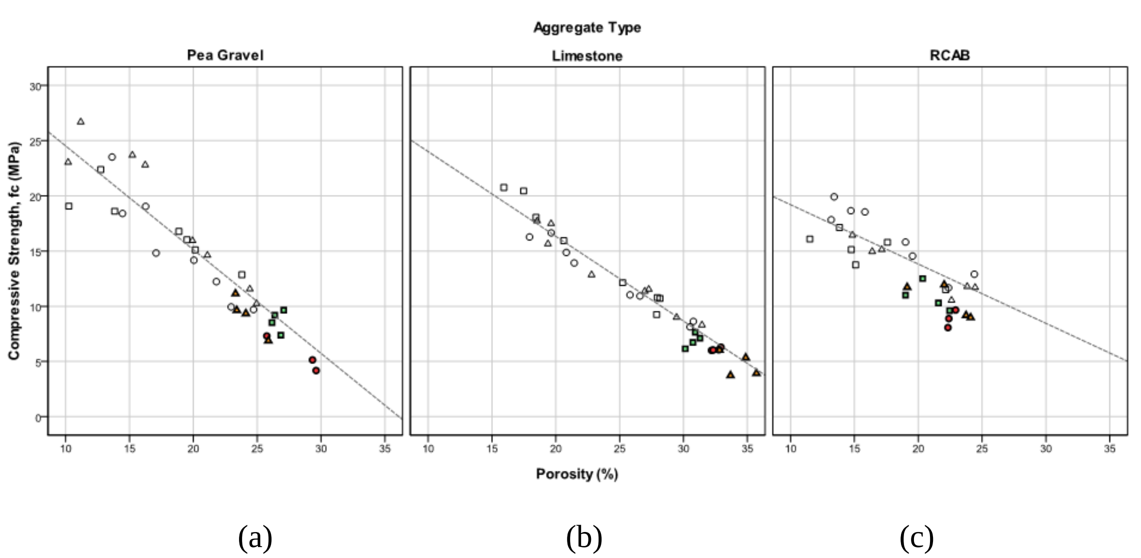


Figure 28 Relationship Between Compressive Strength And Porosity For Cylinders And Cores of (a) Pea Gravel; (b) Limestone; and (c) RCAB Aggregate Mixtures.

Limestone and RCAB showed reductions of 0.77 and 0.54 MPa, respectively. For the range of porosities from 10% to 23%, the use of recycled materials had an effect on the strength of pervious mixtures compared to the strength values seen in the other two virgin aggregates. Specifically, at 20% porosity, the compressive strength of RCAB mixtures was, on average, 8% and 15% lower than pea gravel and limestone compressive strength, respectively. Similar trends regarding the effect of the aggregate type and the recycled content on the mechanical properties of pervious concrete have been described by other researchers [26, 27].

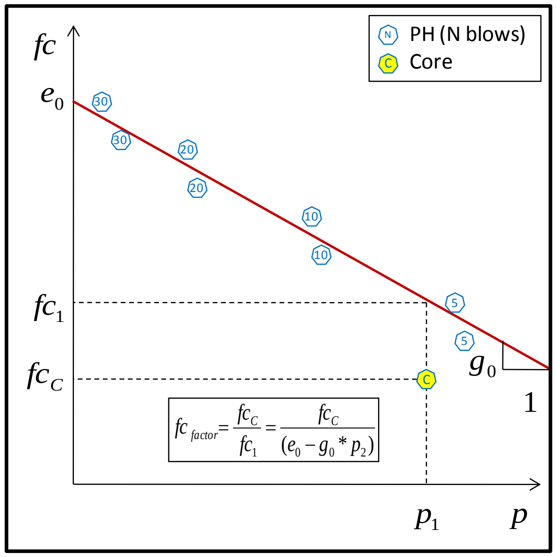
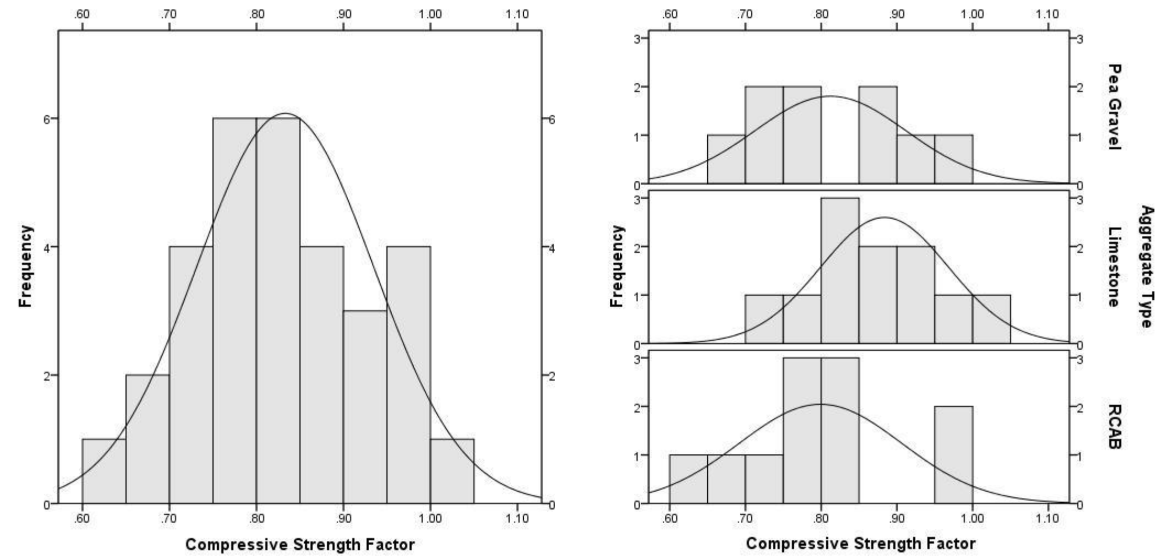


Figure 29 Calculation Of The Fc Factor To Relate Cores To Proctor Hammer Cylinders.

Similar to conventional concrete, core specimens had a lower strength than cast cylinders. This lower compressive strength in core samples was observed for all of the mixtures, regardless of the aggregate type or the level of cement replacement by slag. The performance of cores extracted from the slabs was evaluated using this relationship following the same methodology explained in previous sections, as shown in Figure 29. Individual ratios for each core specimen were obtained as the quotient between measured compressive core strength (fc_C) and the estimated compressive strength (fc_1). An average fc_{factor} of 0.83 was obtained as shown in Figure 30a. This factor had a coefficient of variation of 12%. For mixtures made with pea gravel, the factor had a mean value of 0.81 and coefficient of variation of 12%. Limestone and RCAB mixtures had ratios of 0.88 and 0.80, and their coefficients of variation were 10% and 13%, respectively. While the factor for RCAB was slightly lower, the analysis of variance showed that this difference was not significant.



(a) For All Specimens (b) Per Aggregate Type

Figure 30 Statistical Distribution Of The Fc Factor (a) For All Specimens; (b) Per Aggregate Type.

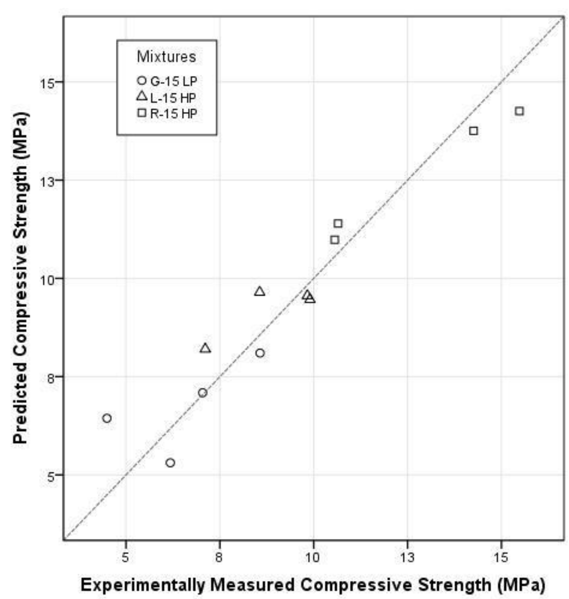


Figure 31 Predicted Vs. Actual Compressive Strength For Series I Pervious Concrete Core Specimens.

The fc_{factor} indicates that, on average, core specimens have 17% less compressive strength than cylinders cast under laboratory conditions. This observation compares to the factor observed in conventional concrete, where the strength results of cores are known to be potentially lower than the strength of cylinders with factors of 0.85 for the average and 0.75 for individual values of strength. The actual versus predicted strengths were plotted using the results for mixtures made in Series II. Figure 31 shows that the model was capable of accurately predicting the compressive strength using the factors obtained for the mixtures in Series I, as indicated by the predicted values located close to the equality line.

4.8 Conclusions

Based on the data obtained in this study, the following conclusions may be drawn:

- Neither the aggregate type nor the percentage of cement replacement by slag has a significant effect on the relationship between the unit weight measured in fresh concrete cylinders and their dry unit weight. On average, pervious concrete was found to suffer a 3.6% unit weight loss when going from a fresh to a dry state. This relationship could be used to predict the dry unit weight of a mixture based on the measurement of the fresh unit weight of a cylinder or slab.
- The bulk specific gravity of the aggregate was observed to be one of the factors affecting the porosity versus unit weight relationship. For a constant porosity, higher unit weights were achieved by mixtures made with pea gravel, followed by

those made with limestone and RCAB. There was no significant difference between the unit weight of cores and cast cylinders of the same porosity.

- Permeability and strength of core specimens were lower than those of cast cylinders. In general, permeability measured in cores was, on average, 20% lower than that in cast cylinders. Similar to conventional concrete, the compressive strength of pervious concrete cores was, on average, 17% lower than that of cast cylinders. The proposed factors were very similar for the virgin aggregates, yet the factors for RCAB were lower, suggesting that RCAB mixtures may be more sensitive to the core-cutting process.
- The type of aggregate had a significant effect on the properties measured and affected the proposed factors. For instance, regardless of porosity, the RCAB showed higher permeability and lower compressive strength compared to the virgin aggregates used. The use of slag to replace cement was found to have no negative effect on the performance of pervious concrete.

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GENERAL CONCLUSIONS

The use of recycled materials was evaluated in this research to optimize the performance and enhance the sustainability of pervious concrete mixtures with encouraging results. For the specific conditions of the experimental program and the particular characteristics of the materials used it was observed that the effect of aggregate type and paste content on pervious concrete performance was greatly reduced when porosity was controlled. Furthermore, it was feasible to produce pervious concrete mixtures containing up to 50% of recycled concrete aggregate and 30% ground granulated blast-furnace slag (GGBFS) without significantly affecting the compressive strength, permeability, and abrasion resistance of the material. Additionally, replacing cement with GGBFS and using recycled concrete are effective means of reducing CO_2 emissions associated with pervious concrete.

The abrasion resistance of pervious concrete mixtures was effectively evaluated using the method specified by ASTM C1747 Standard Test Method for Determining Potential Abrasion Resistance to Degradation of Pervious Concrete by Impact Abrasion. In contrast, the measurements for surface abrasion as specified by ASTM C944 were significantly variable, indicating that this test may lack the level of precision needed for use in quality control of abrasion resistance on pervious concrete.

It was also observed that the permeability and strength of core specimens were lower than those of cast cylinders. In general, permeability measured in cores was, on average, 20% lower than that in cast cylinders. Similar to conventional concrete, the compressive strength of pervious concrete cores was, on average, 17% lower than that of cast cylinders. The comparison of core samples and cast cylinders on abrasion resistance showed that the mass loss of cores was, on average, 42% higher than the mass loss measured in cast cylinders of the same porosity.

Finally, the bulk specific gravity of the aggregate was observed to be one of the factors affecting the porosity versus unit weight relationship. For instance, an equation was obtained to estimate the UW of a pervious mixture based on the porosity of the mixture and the bulk specific gravity of the aggregate with a high level of precision.

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