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Vol 30 Nº3 2015   www.ricuc.cl

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Effect of recycled materials and compaction methods on the mechanical properties and solar reflectance index of pervious concrete

Efecto del uso de materiales reciclados y métodos de compactación en las propiedades mecánicas e índice de reflectancia solar del hormigón permeable

Cristian Gaedicke[1]*, Armando Marines**, Luis Mata***, Farel Miankodila*

* California State University, East Bay. USA
** Center of Technological Innovation for Construction, Holcim. MEXICO
*** University of Toledo, Toledo. USA

Abstract

This research project evaluated the effect of using recycled aggregate and ground granulated slag on pervious concrete specimens compacted using two different methods: fixed energy and fixed porosity. The permeability, compressive strength, and solar reflectance index were analyzed. When compacted to a fixed target porosity of 20%, mixtures using recycled aggregate had, on average, 12% less strength than virgin aggregate mixtures. The use of slag did not negatively affect permeability, or compressive strength and yet was useful in improving the solar reflectance index in mixtures made with limestone aggregate. Recycled aggregate mixtures exhibited a significantly higher solar reflectance index compared to the mixtures using virgin aggregates.

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

Resumen

En este proyecto de investigación se evalúa el efecto de los agregados reciclados y escoria de alto horno en diferentes probetas de hormigón permeable (poroso) sujetos a dos métodos de compactación: energía de compactación fija y porosidad fija. Se analizaron la permeabilidad, resistencia a la compresión e índice de reflectancia solar. En probetas compactadas a una porosidad fija del 20%, se observa que las mezclas que usan agregado reciclado poseen en promedio un 12% menos de resistencia a la compresión en comparación con las mezclas preparadas con agregado virgen. El uso de escoria de alto horno no afectó negativamente la permeabilidad o resistencia a la compresión y mejoró el índice de reflectancia solar en el hormigón con agregado calcáreo. Los hormigones con agregado reciclado presentaron mejores índices de reflectancia solar en comparación a los fabricados con agregado virgen.

Palabras clave: Hormigón permeable, hormigón poroso, agregado reciclado, escoria de alto horno, índice de reflectancia solar, sostenibilidad

1. Introduction

Pervious concrete has been successfully used in the U.S. for more than 20 years as an environmentally friendly stormwater management material (Ghafoori 1995, American Concrete Institute 2006, de Solminihac et al., 2007). The stormwater management benefits of pervious concrete are acknowledged by green building assessment systems such as U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED, 2013), which recognizes the importance of reducing impervious surfaces and stormwater runoff and promote infiltration within 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 (Schaefer et al., 2009). 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.

The thermophysical characteristics of a pavement play an important role in its effects on the environment, especially in urban areas due to the heat island effect. Research on conventional pavements (Deo and Neithalath, 2011; Gui et al., 2007) has shown that properties such as albedo and emissivity have significant positive effects on pavement maximum and minimum temperatures. Recent studies (Marceau and VanGeem, 2007; Boriboomsomsin and Reza, 2007) have also shown that the use of slag increases the solar reflectance of conventional pavements. The use of reflective surfaces is also addressed in green building assessment sytems Green Building Council's Leadership in Energy and Environmental Design (LEED, 2013). Studies on the effect of pervious concrete on pavement temperature (Kevern et al., 2009) have indicated that solar reflectance has a synergistic effect 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.

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[1] *Corresponding author:*

Assistant Professor, School of Engineering, California State University, East Bay. USA
E-mail: cristian.gaedicke@csueastbay.edu

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The inclusion of waste materials in pervious concrete mixtures has the potential to further 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 (U.S. Environmental Protection Agency, 2003). Li et al. (2009) and Rizvi et al. (2010) concluded that a substitution of 15% of virgin aggregate by recycled concrete aggregate did not affect the workability or mechanical properties of their mixtures. Butler et al. (2013) compared pervious concrete mixtures using virgin and recycled aggregate and concluded that the mixtures had equivalent strength, yet those made with recycled concrete had lower fracture energy. Bhutta et al. (2013) found that pervious concrete made with recycled aggregate had a higher total void ratio and water permeability. Their research also showed that mixtures using recycled aggregates had a slightly lower compressive strength.

Another venue for 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 (Prusinski et al., 2006) has shown that replacing 35% to 50% of cement with slag can help reduce CO_2 emissions by 29% to 46%, respectively. Recent research on the use of GGBFS in pervious concrete (Sriravindrarajah et al., 2012) showed no negative effect on compressive strength for mixtures that replaced 70% of cement with GGBFS. Slag also has the potential to mitigate the heat island effect by improving the solar reflectivity of concrete pavements.

2. Research objective

The purpose of this study was to evaluate the effect of the inclusion of large contents of recycled materials in pervious concrete with the aim of enhancing its environmental properties without significantly affecting its performance. Specifically, 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 methods, fixed porosity and fixed compaction energy, to examine 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.

3. Experimental program

3.1 Materials

Three different types of coarse aggregate with a nominal size of 3/8 in. were used in this study. Table 1 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 (Boriboomsomsin and Reza, 2007). 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 (2012a). 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.

3.2 Mixture Proportions

Two series of mixtures were produced as presented in Table 2. 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 GGBFS per aggregate. These mixtures were produced to evaluate the sustainability potential of using recycled materials in pervious concrete.

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.

Table 1. Physical Properties of Aggregates

Property	Unit	Pea Gravel	Limestone	RCAB
Unit Weight	kg/m³	1,588	1,471	1,411
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

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3.3 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. (2005). 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.

Cylinder specimens were fabricated to determineporosity, permeability, and strength. The specimens 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). Each testing sample consisted of 3 cylinder specimens. 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 specimens to be compacted as many times as necessary to reach a porosity of 20%. The porosity was controlled by placing a fixed amount (by weight) 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 for potential use 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 specimens 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 Index (SRI) 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) (Mahboub et al., 2009). 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 83 mm by 102 mm tall (5 in. x 3 in. x 4 in.).

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							
	Pea Gravel	G-0	0%	5.2	1453	284	-	85
		G-15	15%		1453	242	43	85
		G-30	30%		1453	199	85	85
I	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							
	Pea Gravel	G-0 LP	0%	6.0	1643	276	-	82
		G-15 LP	15%		1643	233	42	82
II		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: HP=High Paste Content, LP=Low Paste Content, MP=Medium Paste Content

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3.4 Test Procedures

Compressive Strength: Compressive strength tests were performed in accordance with ASTM C39 (2012b). All cylinders were sulfur capped before tested.

Porosity: The specimen dimensions, air-dried weight, and submerged weight were measured for each cylinder. Porosity was calculated in Accordance to the procedure proposed by Montes et al. (2005). Each specimen was left to air dry for 24 hours under laboratory conditions, and the exact dimensions of each cylinder were measured.

Permeability: A falling-head permeability test apparatus was used to measure permeability of concrete cylinders (Kevern et al., 2005). A flexible polyethylene foam membrane was carefully wrapped around the cylinder specimen to impede water infiltration between the surface of the specimen and the apparatus. The time for water to flow through the specimen was recorded at two different heights. The initial and final 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.

Solar Reflectance Index (SRI): 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 (Marceau and VanGeem, 2007). 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. The solar reflectance index was determined on three different randomly located spots on the top surface of each prismatic specimen (Figure 1b) previously obtained from the slabs. A portable solar reflectometer (Figure 1a) was used in accordance with ASTM C 1549. One set of three specimens was tested for each mixture, and the SRI was determined in accordance with ASTM E 1980 – 01.

(a)

(b)

Figure 1. Solar reflectance testing; (a) Solar Spectrum Reflectometer, (b) Test Specimens

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4. Results and discussion

4.1 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. 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. 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.

4.2 Permeability

Fixed Porosity Specimens: The permeability was measured for all mixtures compacted to a fixed target porosity of 20%. As shown in Figure 2a, pea gravel and limestone mixtures with medium paste content had similar permeability of $k=0.67 \pm 0.13$ cm/s and $k=0.60 \pm 0.18$ 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.
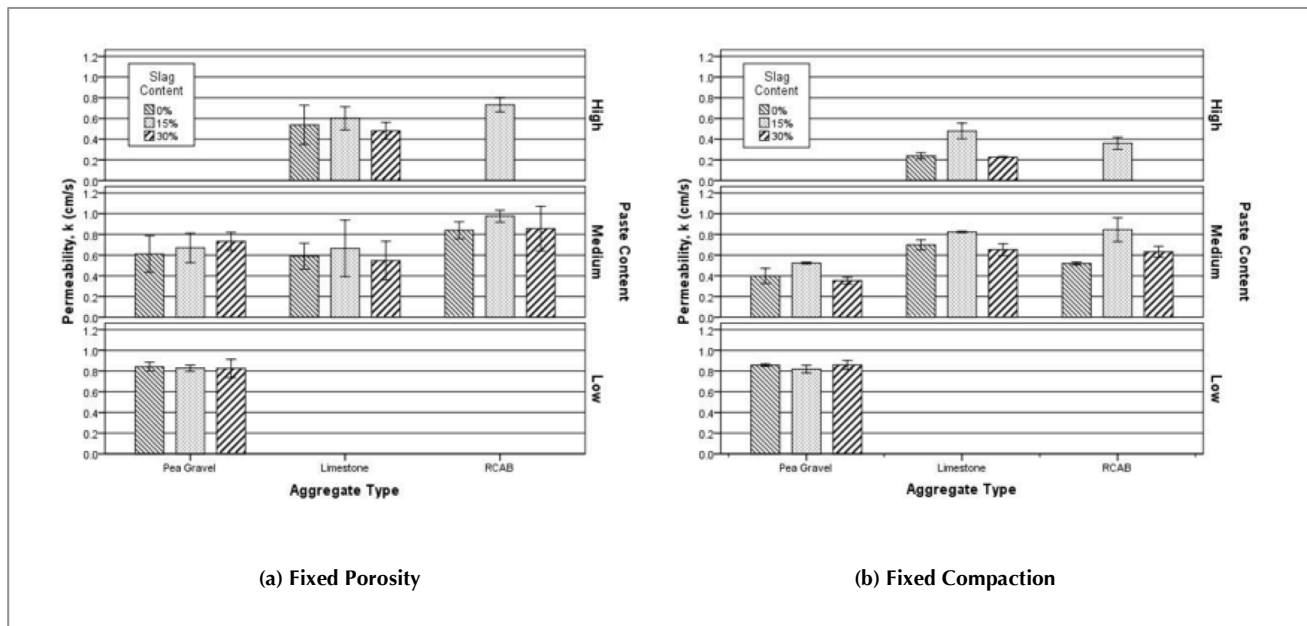

(a) Fixed Porosity   (b) Fixed Compaction

Figure 2. *Permeability results for (a) specimens compacted to achieve 20% porosity and (b) specimens compacted with 20 Proctor hammer blows per layer*

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Fixed Compaction Energy Specimens: The permeability for spceimens 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 2b. 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. 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 with 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. 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 (Crouch et al., 2007).

4.3 Compressive Strength

Fixed Porosity Specimens: 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 3a. 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 12% lower than limestone. The use of slag did not generate significant differences in compressive strength for mixtures with a fixed porosity of 20%. This finding is confirmed in Figure 3a, 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%.
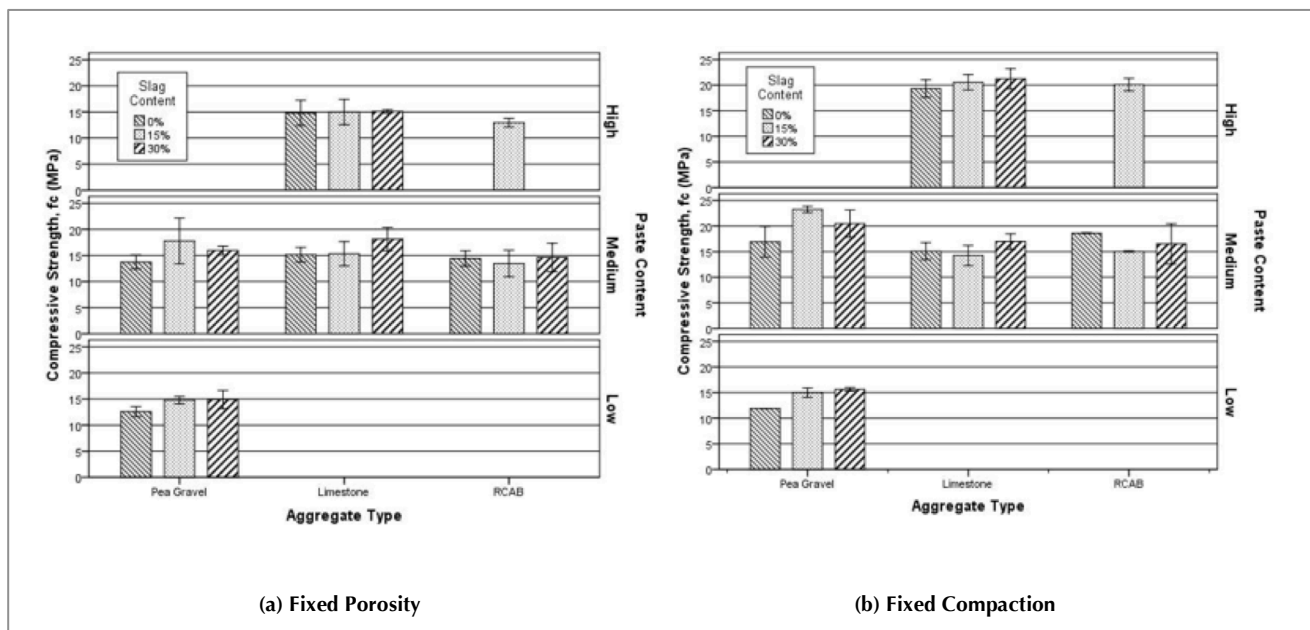

(a) Fixed Porosity   (b) Fixed Compaction

Figure 3. *Compressive strength results for (a) specimens compacted to achieve 20% porosity and (b) specimens compacted with 20 Proctor hammer blows per layer*

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Fixed Compaction Energy Specimens: Figure 3b 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 Deo and Neithalath (2011), Neptune and Putman (2010), and Mulligan (2005), 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. 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 with 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.

4.4 Solar Reflectance Index (SRI)

The SRI was measured in nine selected mixtures, as shown in Figure 4). The use of 15% of slag improved the SRI in pea gravel mixtures, but the effect was not consistent when 30% of slag was used. While the aggregate color may have been a significant factor in the lower SRI of these mixtures, the fact that the pea gravel mixtures had lower paste content may have also reduced the potential of the slag to increase their SRI. Therefore, more extensive research is needed to determine if pea gravel consistently generates mixtures with lower SRI and if slag can consistently improve this property.

In contrast, the use of slag did consistently improve the SRI of mixtures made with limestone aggregate. As seen in Figure 4, 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 (2007) for conventional concrete made with limestone aggregate, where a replacement of 70% of cement by slag increased their albedo by 71%.

The SRI for pervious concrete mixtures made with RCAB was, on average, higher than those made with pea gravel or limestone. The dosage of slag did not affect the SRI on such mixtures using recycled aggregate. Whereas the relatively high SRI found in RCAB mixtures may be related to the specific crushed concrete used to create this particular recycled aggregate.
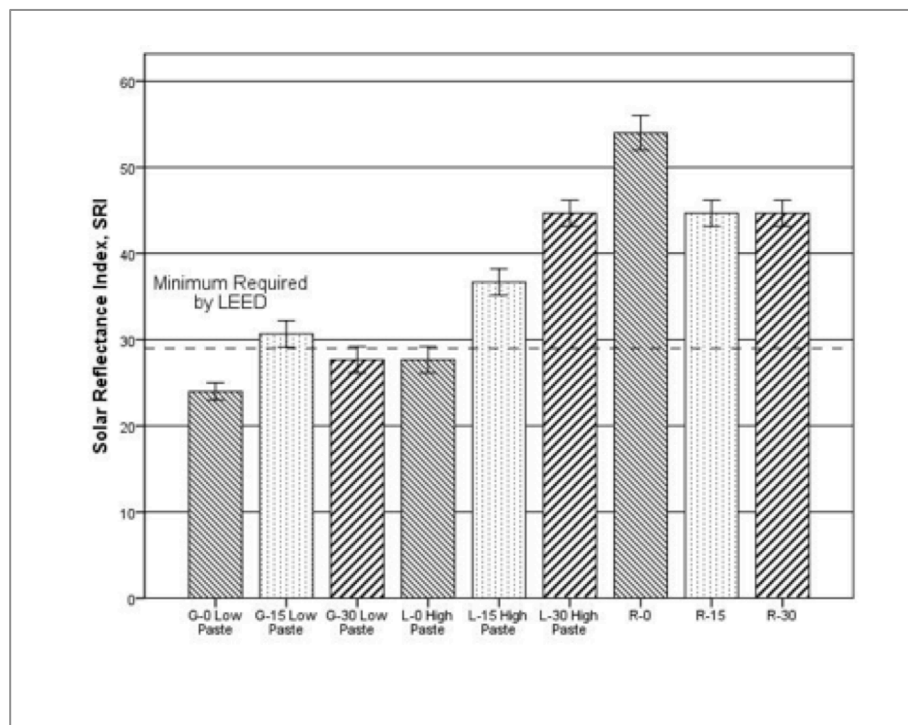

Figure 4. *Solar reflectance indexes for different aggregates with increasing slag replacement. Error bars represent one standard deviation*

5. Conclusions

1. 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 mixture proportions 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 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 RCAB mixtures 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.

3. 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 a slight 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%.

4. 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.

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