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Comparing Design Void Content with Actual Void Content of Laboratory Prepared Pervious Concrete

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Abstract

The goal of this study was to compare the predicted void content with the actual void content of pervious concrete cylinders. All pervious concrete systems are designed with a void content in mind to facilitate a specific permeability; however, due to variable placing techniques and inherent issues with the material, the actual in place void content often varies from designed. This study quantifies this difference and attempts to develop a correction factor, such that design values are more approximate to in place pervious concrete systems. The analysis included multiple mixtures with three design void contents (15%, 25%, 35%), two aggregate types (angular and rounded), and three different water-to-cement ratios (0.33, 0.37, 0.41). These samples were methodically designed to contain a desired void ratio, then casted in the laboratory, in which the compaction of each sample was controlled for consistency. Following casting, the in-place void content was determined using ASTM C1754 and compared to the predicted. The difference was then averaged to create a correction factor requiring more or less cement paste, which was used to redesign the mixtures. The new mixtures were then compared to the predicted void content. The results of this study show that initial designs can vary from 3% - 15% on average from initial designed void content and that a correction factor can be used to obtain within 3% on average of the target void ratios.

Keywords

Pervious Concrete, Void Content, Permeability, Compaction

1. Introduction

1.1. Background

Pervious concrete is a type of concrete that has a high interconnected pore structure with a void content ranging between 15% and 35% [1] [2]. Pervious concrete is comprised of cement, water, and uniform size of coarse aggregate. This type of concrete typically has no fine aggregate, as it likely limits the permeability of the material. Due to its porous structure and ability for water penetration, pervious concrete allows efficient drainage through its interconnected pores, therefore offering sustainable drainage solutions [3] [4]. With the increase in population and urbanization of cities, pavement surfaces are mostly covered by impervious material, therefore the storm water is not drained properly causing rapid overflow. In addition, with impervious surfaces, it is difficult for water to drain into soil where the temperature and humidity of the surface of earth cannot be balanced. Whereas pervious concrete allows rain water to run through, therefore avoiding flooding and overflow. Due to its environmental benefits such as filtration of storm water runoff, the area also benefits from superior ground water recharge. Pervious concrete has been used in construction of parking lots, drive ways, low-volume pavements, residential roads, tennis courts, well linings, swimming pool decks, hydraulic structures, floors for green house and pavement edge drains [1] [2].

One of the important parameters in pervious concrete is the void percentage, as it associates directly with the permeability as well as compressive strength [1] [2] [3]. The compressive strength of conventional concrete is mostly determined by its water-to-cement ratio (w/c) whereas pervious concrete strength is controlled by both w/c and void content [5] [6]. Due to the presence of voids in pervious concrete, there lacks binding between the aggregate compared to conventional concrete, which results in lower strength and higher permeability. Due to the unique void structure in pervious concrete, this material is affected by the size and gradation of the aggregate, cement paste thickness, and compaction method used to prepare the concrete. In fact pervious concrete cannot be handled, placed, vibrated, and finished with traditional methods similar to conventional concrete. Placing and compacting pervious concrete in the field consist of first placing the concrete, then screeding the concrete surface even with the forms, then using a handheld roller to compact the concrete [1] [2] [3]. Researchers are using a breadth of compaction techniques for laboratory prepared pervious concrete specimens that includes a Marshall hammer of varied weights, lifts, and blows from the hammer, and a tamping rod of varied sizes, lifts, and a varied number of strokes [1] [2] [3] [5]-[11]. All of these techniques provide varied levels of compaction, which affect the properties of pervious concrete, and are different to what is often done in the field. These compaction techniques can drastically change the void content of the hardened pervious concrete resulting in a different void content and performance than what was initially designed.

Therefore there is a need for better design control such that pervious concrete designs are closer to what is fabricated in the laboratory and in the field. This study focuses on laboratory fabricated pervious concrete specimens and demonstrates the difference between design (what is created on paper) and actual (what is placed in the field) and suggests a method to correct for this difference. This study also developed a novel compaction technique for laboratory prepared specimens that is more realistic to what is often done in the field. A superior characterization of design void content versus actual void content combined with a more realistic laboratory compaction technique can lead to better designs in the field and enhanced quality control.

1.2. Research Approach

The objective of this study is to compare the designed void content of pervious concrete mixtures with the actual void content of casted pervious concrete cylinders. In order to complete a similar placing procedures of field placed pervious concrete, the pervious concrete specimens were compacted using a roller in one lift, as is done in the field. Three design void contents, 15%, 25%, and 35%, were used. After comparing the design with actual void contents using ASTM C1754 Drying Method A (38˚C ± 3˚C [100 ± 5 ˚F]) [12], the difference per sample type (aggregate type, aggregate size, and w/c) was used as a "correction factor" to determine how much more/less cement paste was needed to produce a closer void content comparison. Lastly, pervious concrete samples were casted based off the new corrected designs and their void contents determined also using ASTM C1754 Drying Method A (38˚C ± 3˚C [100 ± 5 ˚F]) [12]. The new samples' void contents were then compared and analyzed. **Figure 1** provides a flow chart of the research approach used in this study.

The other variable investigated in this study was the impact of the w/c, as additional water content will affect the viscosity of the paste, which can in turn affect the void content of the samples. The three w/c investigated were 0.33, 0.37, and 0.41, which are all within the range of recommended w/c for pervious concrete and are commonly used in practice [1] [2] [13] [14]. As this study focuses

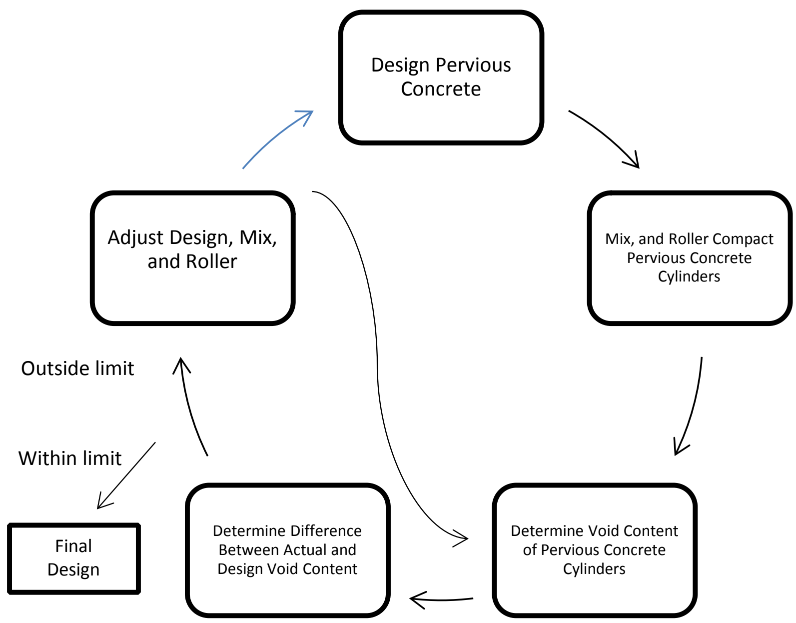

Figure 1. Proposed mix design development procedure.

on comparing void contents, other variables, including cement type, admixtures, and supplementary cementitious materials (SCMs), etc., were minimized as much as possible. Therefore, only one cement type, no SCMs, and no admixtures were used for this study.

Due to the high impact that the void content has on the performance of pervious concrete, the actual void content of the mixtures produced was also compared to the permeability, compressive strength, and splitting tensile strength.

2. Experimental Program

2.1. Materials

Two types of aggregate (angular and rounded) were used in this study in order to determine if the shape of aggregate have an impact on design versus actual void content. The two types of aggregates were limestone and pea gravel with a single size of 9.5-mm (3/8-in.). The two aggregates were obtained from local quarries in Hays County, Texas and were chosen to reflect typical pervious concrete coarse aggregate types and sizes [1] [2] [13] [14]. Type I/II cement was used, which was obtained locally. The specific gravity, water absorption, voids, and unit weight of each aggregate size is shown in **Table 1**.

2.2. Mixture Proportions

Mixtures were designed for three specified void contents (15%, 25%, 35%) per w/c (0.33, 0.37, 0.41) and aggregate type (limestone, pea gravel, yielding a total of 18 different mixtures). Each concrete mixture was proportioned based on the methods described in ACI 522 R-10 [1]. The amount of cement needed for each mixture was based on the specific gravity of cement (3.15) and the three w/c ratios.

Mixtures were prepared using a rotating drum mixer and mixed in accordance to ASTM C192 [15]. The initial mixture proportions can be seen in **Table 2**.

2.3. Laboratory Compaction Techniques

A unique compaction method was used in this study to compact the pervious concrete. As previously described, there is no consensus on the proper technique to compact laboratory prepared pervious concrete specimens. Pervious concrete, when placed in the field, is typically roller compacted to help densify the concrete, while maintaining the void structure and creating an even flat surface. The approximate weight of roller compacters used in the field is 148.82 kg/m (100 lbs/ft) [1] [2]. To mimic this in the laboratory, a smaller, hand-held, roller was built out of steel and used to roller compact the pervious concrete in a 101.6-mm (dia.) × 203.2-mm (4-in. (dia.) × 8-in) steel cylinder mold. The hand-held roller had the following dimensions; 152.4-mm (6-in) in diameter and 139.7-mm (5.5-in) in length and weighed 16.42 kg (36.20 lbs). The weight of the roller was determined by using the diameter of the steel cylinder mold (101.6-mm (4-in.)), in which the hand-held roller was rolled over the top of, and the weight of a common in-the-field roller; therefore the 148.82 kg/m (100 lbs/ft) was used to back calculate the size and weight needed for the hand-held roller. A photograph of the hand-held roller can be seen in Figure 2.

Table 1. Physical properties of aggregates.

Property	Standard	Unit	Limestone	Pea Gravel
Dry Rodded Unit Weight	ASTM C29	kg/m^3 (lb/ft^3)	1442 (90.0)	1586 (99.0)
Water Absorption	ASTM C127	%	2.33	1.45
Solid Specific Gravity$_{SSD}$[a]	ASTM C127	-	2.57	2.62
Solid Specific Gravity$_{OD}$[b]	ASTM C127	-	2.51	2.60
Voids	ASTM C29	%	44.86	39.48

[a]SSD, saturated surface dry condition. [b]OD, oven dried condition.

Table 2. Initial mixture proportions.

Mix ID	Type of Aggregate	w/c	Design Void Content	Aggregate kg/m^3 (lb/yd^3)	Type I/II Cement kg/m^3 (lb/yd^3)	Water kg/m^3 (lb/yd^3)
L-0.33-15			15%		464.9 (783.7)	154.2 (259.9)
L-0.33-25		0.33	25%		310.9 (524.0)	103.1 (173.8)
L-0.33-35			35%		156.9 (264.4)	52.0 (87.7)
L-0.37-15			15%		437.9 (738.0)	162.8 (274.5)
L-0.37-25	Limestone	0.37	25%	1403.4 (2365.4)	292.6 (493.2)	108.8 (183.4)
L-0.37-35			35%		147.7 (249.0)	54.94 (92.60)
L-0.41-15			15%		413.7 (697.3)	170.5 (287.3)
L-0.41-25		0.41	25%		276.5 (466.1)	113.9 (192.1)
L-0.41-35			35%		139.5 (235.2)	57.5 (96.92)
PG-0.33-15			15%		432.2 (728.4)	142.9 (240.9)
PG-0.33-25		0.33	25%		278.1 (468.8)	91.9 (155.0)
PG-0.33-35			35%		123.8 (208.7)	40.9 (69.0)
PG-0.37-15			15%		407.3 (686.5)	151.0 (254.6)
PG-0.37-25	Pea Gravel	0.37	25%	1458.6 (2458.4)	261.8 (441.2)	97.1 (163.6)
PG-0.37-35			35%		116.9 (196.9)	43.3 (73.0)
PG-0.41-15			15%		384.9 (648.8)	158.2 (266.6)
PG-0.41-25		0.41	25%		247.6 (417.3)	101.7 (171.5)
PG-0.41-35			35%		110.1 (185.6)	45.2 (76.2)

Figure 2. Hand-held roller for compacting pervious concrete cylinders.

The compaction technique consisted of first placing the wet pervious concrete into one 101.6-mm (dia.) × 203.2-mm (4-in. (dia.) × 8-in) steel cylinder mold in one layer (lift) until overfilled by approximately 12.7 mm (0.5-in.). Then the concrete was screeded off using a straight edge to achieve a flat surface, and then the hand-held roller was used to roll over the top of the concrete to compact the aggregate. The compaction was achieved by laying the roller on top of the concrete, beginning at one end of the mold and ending at the other first pushing away from the operator then pulling towards the operator. This processes was considered as one pass of the roller. Approximately 3 - 5 passes were completed to achieve a flat surface. **Figure 3** provides a visual representation of the process.

2.4. Test Procedures

2.4.1. Void Content

The void content of the pervious concrete samples was determined using the method outlined in ASTM C1754-12 [12]. ASTM C1754-12 Drying Method A (DMA) was followed in order to ensure accuracy with the underwater weight of the specimens. The void content is the main parameter investigated in this study in which the design versus the actual was compared. However, due to the significant impact the void content has on pertinent pervious concrete performance, the actual void content was compared to permeability, compression strength and splitting tensile strength.

2.4.2. Compressive Strength, Splitting Tensile Strength, and Permeability

The compressive strength tests were performed in accordance with ASTM C39-15a [16]. The specimens were capped on the ends using a sulfur compound to provide plane surfaces and ensure an even distribution of the compressive force, which was completed in accordance to ASTM C617-15 [17]. The compressive force was applied in accordance to ASTM C39-15a [16]. The compressive strength of the specimens was determined at the age of 28-day.

The splitting tensile strength tests were performed in accordance with ASTM C496-11 [18]. The specimens were tested using a constant load until the specimens displayed a well-defined fracture pattern. The splitting tensile strength of the specimens was determined for 28-day strengths. Three specimens were tested per mix type and the results were averaged and reported. A falling-head permeameter was used to measure the permeability of each sample as outlined by Neithalath *et al.* [19]. The procedures, developed by Neithalath *et al.* [19], were followed to determine the permeability of the pervious concrete samples. Three specimens were tested per mixture and the results were averaged.

3. Analysis of Results

3.1. Design vs. Actual Void Content

After the pervious concrete cylinders were fabricated using the previously described methods, the samples were cured (minimum of 98% relative humidity) and their void content was determined. The comparison between the design void content and the average measured void content for the limestone aggregate samples is shown in Figure 4.

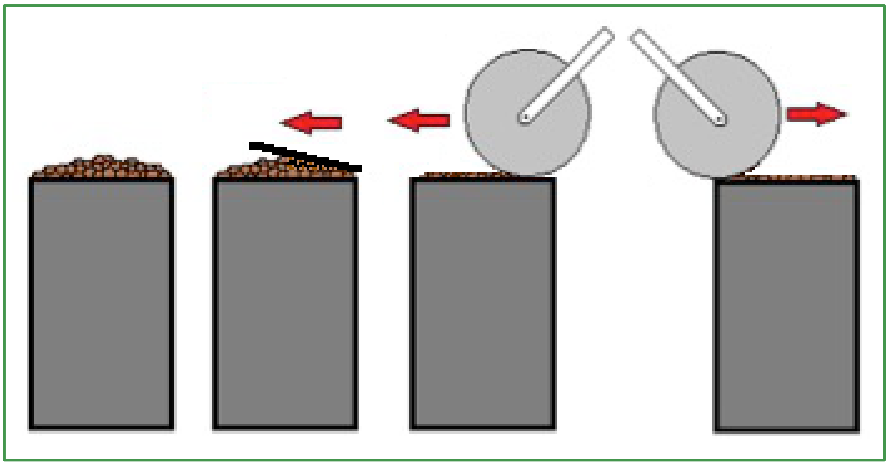

Figure 3. Visual example of roller compaction process.

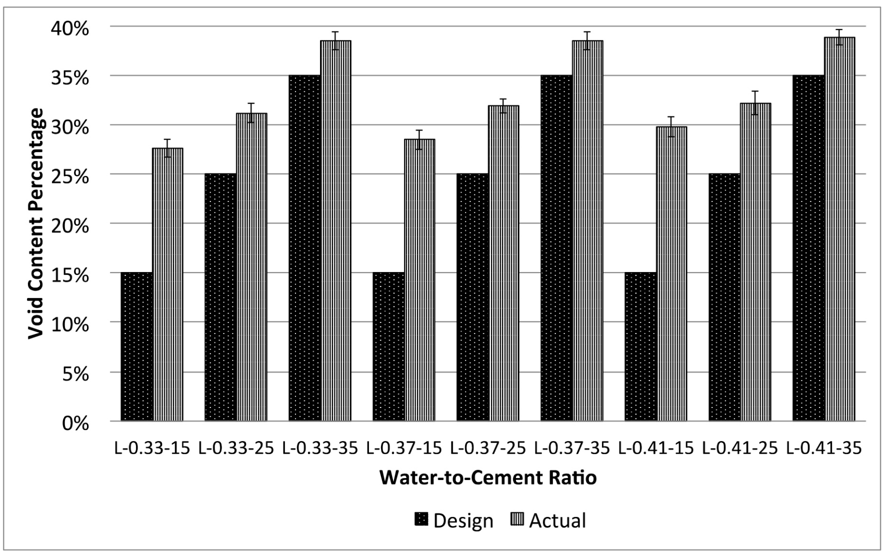

Figure 4. Comparison of design void content vs. average actual void content for limestone aggregate samples.

A preliminary analysis of **Figure 4** shows that the actual void content is always higher than the design void content for the limestone aggregate pervious concrete specimens. This can be attributed to high cement contents producing thicker paste bridging, which would displace the volume of aggregate in the concrete, in turn resulting in higher a void content than designed [7]. Furthermore, the comparison results from the limestone mixtures shows that as the design void contents increase, the difference between measured and design void content is reduced, such that the lowest void content investigated (15%) resulted in the largest difference between design and actual void content, whereas the largest void content investigate in each category (35%) resulted in the smallest differential. For instance, the average difference between design and actual for 15%, 25%, and 35% were 13.6%, 6.8%, and 3.6% respectively. Additionally, as the w/c content increases, it was observed that the difference between design and actual void content increases. The average difference between design and average for a w/c of 0.33 was 7.4%, whereas the difference for a w/c of 0.37 was 8.0%, and for a w/c of 0.41 was 8.6%. These two results suggest that; 1) the lower the design void content, the higher the difference between design and actual, and 2) the actual void content is always higher than the design void content. Therefore the more cement paste in a pervious concrete design (lower design void content) the greater the difference between design and actual, which will ultimately affect all performance properties. This result is supported by the findings of Torres, *et al.* (2015) [7], such that the higher the cement content in a pervious concrete mixture the thicker the cement paste and paste bridging between aggregates, thus causing a separation between the aggregates and resulting in a higher difference between the actual and design void content. In an ideal case, aggregates are the exact same size, shape, and have an even coating of paste and each aggregate particle would be separated by the same distance, and the void content results more predictable. However, Torres *et al.* (2014) [7] demonstrate that the paste thickness and the aggregate separation distance is a function of aggregate size, shape, compaction energy, cement content, and w/c, which results in varied void contents that are higher than expected. Torres *et al.* (2014) [7], A.M. Neville (2011) [20], and Albert K.H. (2014) [21] also reported that at any given location the paste thickness can be non-existent, *i.e.* the aggregates are touching without any cement paste between them, which often occurs at high compaction energies.

To determine if there is a statistical significant difference between the three w/c content results, a sample t-test was performed. The test was performed with a 95% confidence level and the statistical significance (p-value) considered at 0.05 level of confidence was used to analyze the data. All p-values recorded were greater than 0.05; therefore there was no significant difference among the w/c content at this level, which is expected as the average differences between the void contents was only 0.6%. However, the same statistical analysis was completed on the three different design void contents (within the same w/c content as well as across the different w/c contents) and the results do show a significant difference among the three design void contents. Although the w/c content does not show a statistically significant effect of this variable on the difference between actual and design void content, the results show an effect on the w/c on the difference between the design void content versus the actual void content.

The design versus actual void content analysis was also completed on the pea gravel samples and the results can be seen in Figure 5.

The analysis for the pea gravel samples shows similar results to the limestone sample analysis. The only minor difference is that the all samples' actual void contents were slightly closer to the design, with an overall average difference of 7.5% compared to the average of 8.0% from the limestone aggregate. As with the limestone aggregate the results showed that the design void content had an inversely proportional relationship with the actual average void content, such that the higher the void design, the smaller the percent difference between the design and actual void content. The results showed that the 15% design void content had an average difference of 13.0%, the 25% design had a difference of 6.2%, and lastly the 35% design had a difference of 3.3%. Similarly, as the w/c content increased, so did the average difference between void contents. For example, the average actual void content for the 0.33 w/c content was 6.9%, whereas the 0.37 and 0.41 w/c contents had a difference of 7.3, and 8.3% respectively. This is likely due to the increase in paste volume with the increase in w/c along with the paste being more flow-able, with the addition of more water. Therefore, the amount of paste surrounding and bridging between the aggregate is affected by the w/c. As with the limestone analysis these results also confirms the trend that with higher amounts of both cement and water, the higher the difference between actual and design void content. The same statistical analysis was completed on these results. There exists a statistically significant effect of the w/c content on the design versus actual void contents.

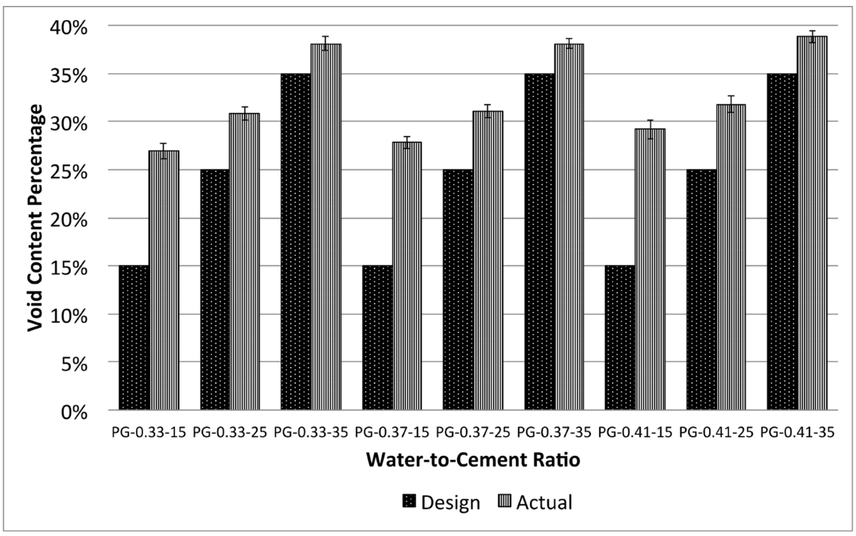

Figure 5. Comparison of design void content vs. average actual void content for pea gravel aggregate samples.

The analysis of the difference between the design and actual void content in the limestone and pea gravel mixtures clearly shows the need for a method to correct and adjust such differences. Therefore, following the results from the initially designed and produced pervious concrete samples, the average difference between the actual and designed void content was used to develop a corrected cement amount to re-design the same mixtures. **Table 3** shows the average percent difference between the actual and design void content for each aggregate type and w/c content.

Using the average difference outlined in **Table 3**, corrected pervious concrete mixtures were proportioned with the adjusted cement paste content while still maintaining a constant aggregate content and the same w/c ratio. The corrected mixture proportions are shown in **Table 4**.

Following the proportioning of the corrected mixture design of the pervious concrete mixtures, the specimens were mixed, compacted, cured, and the void content was determined exactly as previously outlined (ASTM C1754-12 [12]). The design versus average actual void content was then analyzed. The comparison for the adjusted mixtures produced with limestone aggregate can be found in **Figure 6**.

Table 3. Average void content difference between design and actual.

Type of Aggregate	w/c	Design Void Content	Actual Void Content	Average Difference
Limestone	0.33	15%	27.6%	12.6%
		25%	31.2%	6.2%
		35%	38.5%	3.5%
	0.37	15%	28.5%	13.5%
		25%	31.9%	6.9%
		35%	38.5%	3.5%
	0.41	15%	29.8%	14.8%
		25%	32.2%	7.2%
		35%	38.9%	3.9%
Pea Gravel	0.33	15%	26.9%	11.9%
		25%	30.8%	5.8%
		35%	38.1%	3.1%
	0.37	15%	27.8%	12.8%
		25%	31.1%	6.1%
		35%	38.1%	3.1%
	0.41	15%	29.2%	14.2%
		25%	31.8%	6.8%
		35%	38.8%	3.8%

Table 4. Corrected mixture proportions.

Mix ID	Type of Aggregate	w/c	Design Void Content	Aggregate kg/m³ (lb/yd³)	Type I/II Cement kg/m³ (lb/yd³)	Water kg/m³ (lb/yd³)
C-L-0.33-15			15%		595.8 (1004.4)	196.6 (331.4)
C-L-0.33-25		0.33	25%		375.4 (632.6)	123.9 (208.7)
C-L-0.33-35			35%		193.28 (325.7)	63.8 (107.5)
C-L-0.37-15			15%		595.2 (1003.3)	220.2 (371.2)
C-L-0.37-25	Limestone	0.37	25%	1403.4 (2365.4)	373.0 (628.7)	138.0 (232.6)
C-L-0.37-35			35%		188.5 (317.7)	69.7 (117.5)
C-L-0.41-15			15%		604.8 (1019.5)	247.9 (417.9)
C-L-0.41-25		0.41	25%		369.5 (622.7)	151.5 (255.3)
C-L-0.41-35			35%		189.9 (320.0)	77.8 (131.2)
C-PG-0.33-15			15%		555.9 (936.9)	183.4 (309.2)
C-PG-0.33-25		0.33	25%		338.4 (570.4)	111.6 (188.2)
C-PG-0.33-35			35%		156.0 (262.9)	51.5 (86.7)
C-PG-0.37-15			15%		556.5 (937.9)	205.9 (347.0)
C-PG-0.37-25	Pea Gravel	0.37	25%	1458.6 (2458.4)	332.9 (561.0)	123.1 (207.6)
C-PG-0.37-35			35%		153.0 (257.9)	56.6 (95.4)
C-PG-0.41-15			15%		567.9 (957.3)	232.8 (392.5)
C-PG-0.41-25		0.41	25%		335.4 (565.3)	137.5 (231.8)
C-PG-0.41-35			35%		159.1 (268.3)	65.3 (110.0)

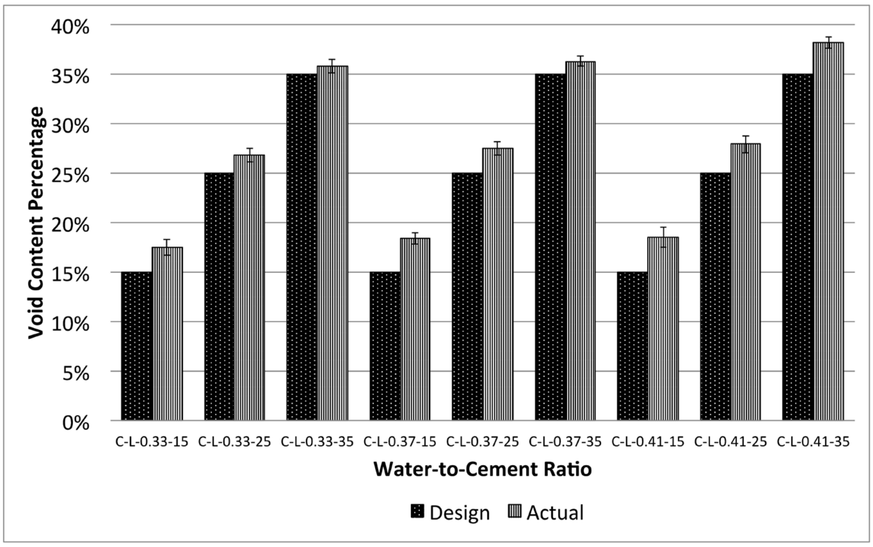

Figure 6. Comparison of design void content vs. average actual void content for corrected limestone aggregate samples.

As seen in Figure 6, the results of the adjusted pervious concrete specimens fabricated with limestone aggregate show a promising trend. All adjusted mixtures produced show an actual void content that is much closer to the design void content. For instance, the adjusted design to actual void content difference for all limestone mixtures was on average only 2.4%, which is a very tolerable result for designers. It is interesting to note that similar movements were noticed in the adjusted samples as compared to the initial design, such that the higher the design void content the closer the average actual was to the design and the higher the w/c content the higher the average actual was to the design. For example, the average actual void content for the 15%, 25%, and 35% design void content was 3.1%, 2.4%, and 1.8% respectively and the average actual for the w/c contents of 0.33, 0.37; and 0.41 was 1.7%, 2.4%, and 3.2% respectively. Thus showing that there is less than a 4% difference between all w/c used, demonstrating that the methodology outlined in this study has worked. A student t-test was also completed on the final results, which reveals that the design and actual final values are not significantly different between each other. These results suggest that the proposed method is effective in reducing the differences such that the corrected design void content and actual void content are too close to each other for any of the void contents to become statistically relevant. This conclusion makes sense as all results from the corrected designs were very close to each other.

Following the analysis of the limestone mixtures, the pea gravel samples were also analyzed and can be seen in Figure 7.

The corrected pea gravel mixtures also show positive results such that the overall difference between the design and the average actual void content was just 2.5%, which, again, shows control over the mixtures after the second design iteration. The results for the three design void contents of 15%, 25%, and 35%

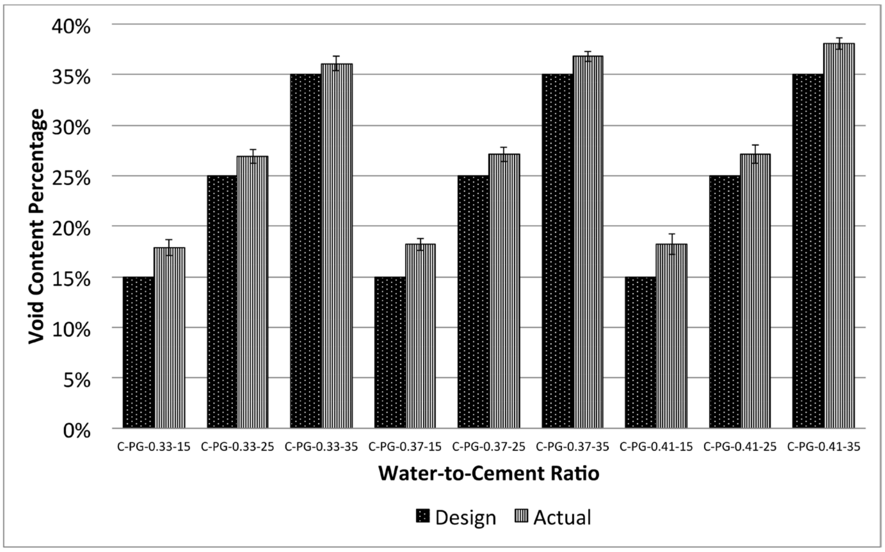

Figure 7. Comparison of design void content vs. average actual void content for corrected pea gravel aggregate samples.

show an average difference of 3.1%, 2.0%, and 2.4%, respectively. The results for the three w/c contents of 0.33, 0.37, and 0.41 show an average void content difference of 2.0%, 3.0%, and 2.5% respectively. Again a significant reduction from the initial design was noticed, such that the corrected specimens had less than a 4% difference between all w/c ratios investigated. The outcome of the statistical analysis (student t-test) of corrected pea gravel mixtures was similar to the corrected limestone aggregate analysis: the difference between measured and design void content became small to a point that other variables such as design void content and w/c content became statistically insignificant. Therefore, after a second design iteration, the variables investigated become controlled and their impact is diminished, which confirms the effectiveness of the proposed method.

This study has demonstrated a method that helps reduce the difference between designed void content and the actual void content of pervious concrete specimens. Without the intervention of this method, a difference of up to approximately 15% was shown between initially produced specimens, for both aggregate types, and w/c ratios. This difference was recorded at the 15% design void content, which resulted in mixtures actually having an approximate 30% void content. From the perspective of a designer and a user, this drastic difference can have negative consequences. It should be noted that 15% design void content is a common desired void content in practice as it produces a sufficient permeability with sufficient mechanical properties [1] [2] [4] [5] [22]. After the intervention of the methodology outlined in this study, the difference between the 15% designed specimens was only approximately 2.4%, which is more tolerable difference. Due to the observations made in this study, the data collected can be used to produce a linear regression equation to obtain the necessary adjustment factor for future pervious concrete cylinders. This unique equation was developed using the data obtained in this study and can be used without first producing trial pervious concrete cylinders.

$$\text{Adjustment Factor}(\%) = 20.2 - 0.492 \times (\text{DV}) \tag{1}$$

where DV is the designed void content and the adjustment factor is the amount of the initially designed cement paste needs to be increased by. The R^2 value of this equation was 91.4%. It should be noted that this unique equation does not include the w/c and the aggregate type as those variables were shown to be statistically insignificant. Since this equation is produced from regression analysis of 18 data points, and fits with this study, further study is still needed to validate and expand this equation to include a broader spectrum of pervious concrete mixtures.

3.2. Compressive Strength, Splitting Tensile Strength, and Permeability

An analysis on the compressive strength, splitting tensile strength and permeability is included in this study to further demonstrate the importance the void content has on these important performance properties and to further increase the continuing growth of pervious concrete understanding. **Figure 8** shows the results obtained for the compression strength of the initially designed and corrected samples made with both aggregate types.

The results from the compressive strength analysis confirm trends reported by other authors [1] [2] [22] such that as the void content increases the compression strength decreases. It can also be seen in the analysis that the corrected samples have higher compression strength than their initial sample counterparts, which is due to the higher cement content and lower void content used to correct the samples. In addition to the compression strength analysis, the splitting tensile strength was determined for all samples and the results were averaged and presented in **Figure 9**.

Similar to the compressive strength data, the data of the splitting tensile strength analysis demonstrate a trend that is similar to previous research [8]. As the void content increases, the splitting tensile strength decreases. It was also noticed that the corrected samples produce higher splitting tensile strengths than their initial sample counter part due to lower void contents and a higher cement content, with the highest splitting tensile strength of approximately 2.88 MPa (418 psi). It is also observed that there appears to be no effect on performance due to the aggregate type. It should be noted that due to the proportional relationship between both the compression strength and splitting tensile strength to the void content of pervious concrete, large unintended differences in the void content could have negative impacts on the desired mechanical proprieties. For example if the actual void content is off by approximately doubled the intended design (as with the 15% design specimens in this study) the compression strength will be reduced by approximately 10 MPa (1450 psi) and the splitting tensile strength will be reduced by approximately 2 MPa (290 psi). The last performance criteria investigated was the permeability of the samples. The results from this analysis can be found in **Figure 10**.

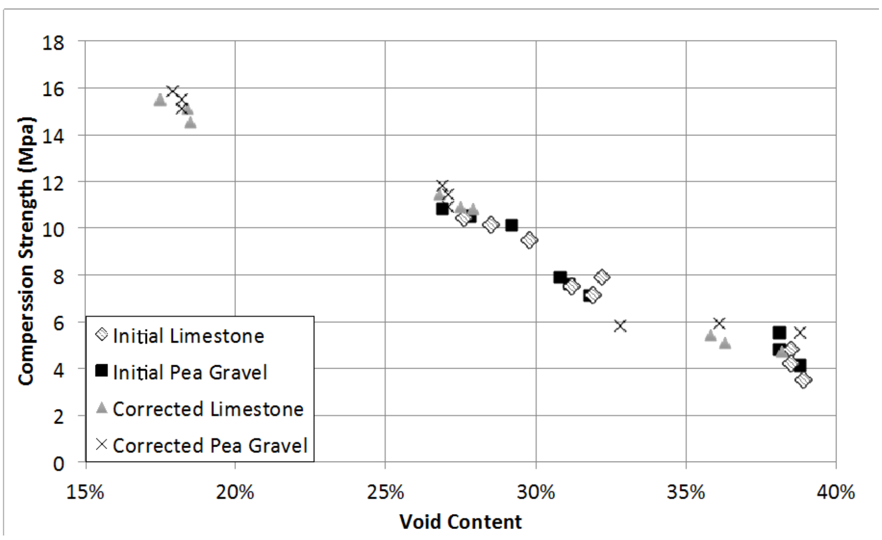

Figure 8. Compression (28-day) versus void content of all specimens.

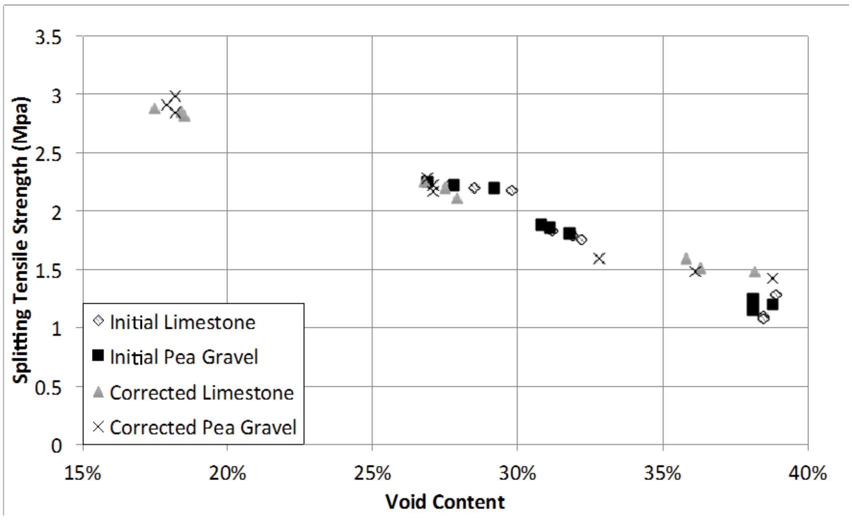

Figure 9. Splitting tensile (28-day) versus void content of all samples.

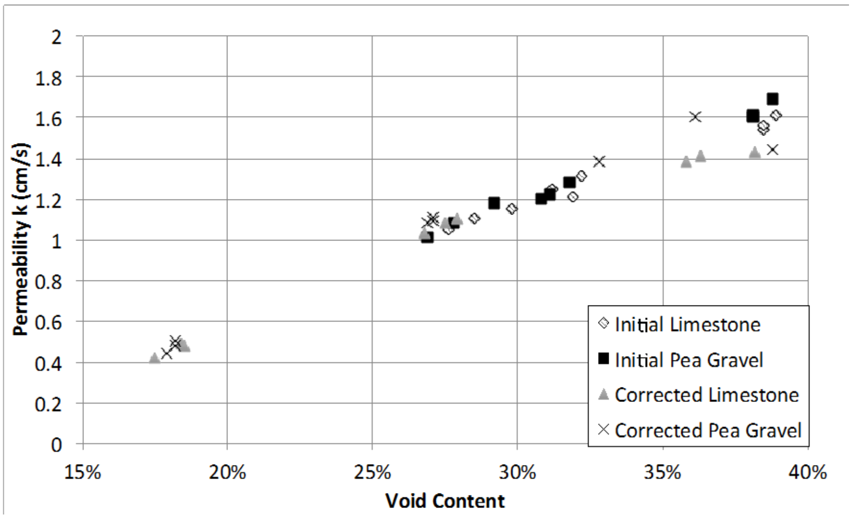

Figure 10. Permeability versus void content of all samples.

The permeability is one of the primary performance criteria of pervious concrete as it is the main purpose of pervious concrete. The results from this analysis demonstrated that as the void content increases in the samples the permeability also increases, which is consistent with published results [8]. The highest permeability reached came from the sample with the highest void content of 38.8%, which was 1.69 cm/s (0.67 in/s). The lowest permeability came from the lowest void content, which was the corrected limestone sample with a void content of 17.5% and a permeability of 0.42 cm/s (0.17 in/s). Similarly with the compression and splitting tensile strength results, if the intended design void content is doubled, the resulting permeability can increase by approximately 1.2 cm/s (0.47 in/s).

4. Conclusions

This study compares design versus actual void content and demonstrates a method to correct for any difference of laboratory prepared pervious concrete samples using a controlled systematic design sequence that mimics in place placing conditions. Multiple pervious concrete samples were prepared and their void contents were compared to the designed void content. The difference was determined and a cement content correction factor was developed and applied to produce new mixtures. Additionally, the primary performance criteria (compression strength, splitting tensile strength, and permeability) were investigated on all samples. Based on the data obtained in this study, the following conclusions may be drawn:

- Initial samples showed the difference between design and actual void content for non-adjusted mixtures can have a difference up to 15% with an average equal to approximately 9% based on the variables investigated.
- A method consisting of calculating a correction factor was proposed, which lead to a designed void content versus actual void content difference that was on average 2.4%, yet always below 4%.
- The higher the design void content the closer the actual void content will be to the design.
- The higher the w/c the higher the difference between design void content and actual void content.
- Compression strength, splitting tensile strength, and permeability results produced in this study are consistent with the literature review.
- A unique cylinder compaction method was developed that mimics in the field compaction.
- The results from this study can be used to improve pervious concrete through superior pervious concrete designs that produce expected performance values.
- This result from this study can be continued further through laboratory produced pervious concrete slabs and cores extracted from in-the-field pervious concrete.

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