Development of a Simplified Method of Designing Pervious Concrete Mixes using chip aggregate

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ABSTRACT

Pervious concrete can be referred to a sustainable paving material which reduces urban runoff, heat-island effect and improves the ground water quality. Due to the lack of awareness and the unavailability of a simplified design method, the applications are limited in the local context. In this research study, a new method of preparing pervious concrete mixes using commercially available chip aggregate together with coarse aggregate was developed. Five volume based binary combinations were prepared with varying coarse aggregate and chip aggregate proportions. A simple mix design method which is based on the porosity of the pervious concrete was used to determine the required cement paste content. For each aggregate combination, cement paste contents were calculated for four different design porosities. Overall, twenty pervious concrete mixes were prepared and test specimens for compressive strength, bending strength and permeability tests were conducted. Based on the test results, relationships between aggregate combination, compressive strength, permeability, and cement paste content were identified and a simplified graphical method of designing pervious concrete mixes to achieve required strength and permeability characteristics was introduced. Further, the addition of chip aggregate enhanced the strength characteristics while retaining adequate permeability.

KEYWORDS: *Chip aggregate, Coarse aggregate, Pervious concrete, Cement paste, Mix design.*

1 INTRODUCTION

Pervious concrete [PC] is a special concrete which has a higher void content with interconnected pore structure that allows water to pass through. With rapid urbanization, most of the earth's surface is covered with impermeable pavements reducing the storm water infiltration which results in ponding and excessive runoffs while affecting ground water quality. PC is used as a pavement material which is an effective remedy for controlling excessive runoff, flash floods and ponding. Also, PC differs from the conventional concrete as it contains little or no fine aggregate which leads to sustainable aspects as it saves natural resources. PC has excellent antiskid properties. The presence of interconnected pore structure ensures improved heat and humidity exchange than conventional pavement hence the possibility of a considerable reduction in the "Heat-Island effect". (Tun et al.,2014).

Considering the properties, PC has relatively lower density in a range of 1600kg/m^3 – 2000kg/m^3. Typically, the porosity of PC varies between 15%-35%. Relatively lower values of W/C ratio than conventional concrete are selected for PC mixes which vary between 0.27-0.4 in general. The coefficient of permeability of PC varies between 0.2 mm/s-5.4 mm/s (Nguyen, 2014). Due to high porosity, the compressive strength of PC is lower than the compressive strength of conventional concrete hence applicable where lesser loads are applied. It is used as a paving material for parking lots, walkways, foot paths, light traffic areas, slope stabilisation systems etc. (Tun et al.,2014). Typically, the compressive strength of PC generally varies between 5 MPa- 30MPa and flexural strength varies between 1 MPa- 3.5 MPa (Mohammed, 2016).

Lower compressive strength and the absence of a simplified mix design method have limited the applications of PC. Though many studies have been carried out globally, there are limited studies in the

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local context. Development of a simplified mix design method is difficult due to the lack of data obtained by experimental studies. The objective of this research is to study the variation of strength and permeability with aggregate content and cement paste content and how chip aggregate can be used to enhance the strength characteristics of PC.

2 STRATEGIES TO ENHANCE STRENGTH CHARACTERISTICS

To improve the performance of PC which can expand its applications, it is mandatory to enhance the compressive strength of PC. The strength characteristics depend on the microstructure of PC as it governs the load transferring mechanism. Figure 1 shows a generalized model of Pervious Concrete.

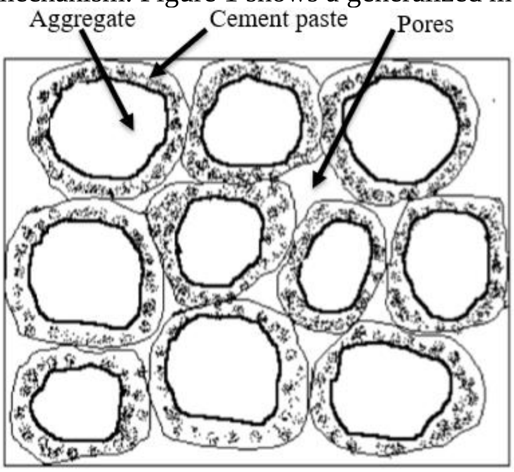

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Figure 1: Pervious Concrete model

Quantified results about the microstructure of PC can be obtained by means of X-ray microtomography. Experimental studies have concluded that mechanical properties of PC primarily depend on the properties of the aggregate (Ayda, 2013). Coarse aggregate effectively contributes to form the skeleton structure. A study on crack pattern using X-ray microtomography has shown, a higher tendency to develop cracks through the cement paste when the used aggregate is finer (Cosic, 2015). Based on the literature survey, the following strategies can be adopted to enhance the strength characteristics of PC (Jing, 2003).

- **Enhancing the binder strength**

With the presence of pores, cement paste becomes thinner which results in lower compressive strength. There are micro-pores and microcracks in cement paste and the presence of those in transition zone significantly contributes to the reduction of strength. Mineral admixtures and intensifiers such as Silica fume, fly ash can be used to improve the micro-structure which enhance bond properties (Jing, 2003).

- **Increasing the binder area**

Using a smaller aggregate, particle density can be increased in order to increase the specific surface area.. This increases the binder area resulting in an improvement of the strength (Tiejun et al., 2019).
A majority of studies used a narrow range particle size of coarse aggregate. In this study, the full range of commercially available coarse aggregate was used considering the practical means. Particles finer than 4mm were removed as well as particle greater than 20mm, to avoid the reduction of permeability and strength respectively. To enhance the strength by increasing the binder area, commercially available aggregates smaller than 10mm which is known as chips were also added to remove particles finer than 4mm. In the design of PC, strength and permeability are the major considerations and the cement paste content and aggregate content are the governing factors for these properties.

3 METHODOLOGY

3.1 Materials

- Cement: Rapid flow cement with strength class 42.5 N/mm^2
- Coarse Aggregate (CA): Commercially available coarse aggregate in the size range of 4mm - 20mm
- Chips: A type of commercially available coarse aggregate having smaller size range (< 10mm). For this study, particles finer than 4mm were removed.
- No fine aggregate was used in this study.

3.2 Mix design

Five volume based binary combinations of CA and chips were used in this study. CA and chips were volumetrically proportioned as 0%:100%. 25%:75%, 50%:50%, 75%:25% and 100%:0% which were coded as combination A, B, C, D, and E respectively. PC was designed using a simple approach which is mainly based on the porosity of PC (Sumanasooriya, 2012). Porosity of the relevant compacted sample of CA and chips was found to be approximately 40% for every combination.

Table 1: Porosity of the compacted aggregate

Chips: CA	Code	Porosity of compacted aggregate sample (%)
100:0	A	40.10
75:25	B	41.17
50:50	C	38.68
25:75	D	39.40
0:100	E	41.98

The design porosity of PC was varied as $0.1m^3/m^3$, $0.15\ m^3/m^3$, $0.2\ m^3/m^3$ and $0.25\ m^3/m^3$. After the selection of design porosity value and determination of the porosity of the compacted aggregate, the required paste content per 1 m^3 of PC can be calculated as follows.

$$\textit{Total Void Volume} = \textit{Design porosity} + \textit{cement paste content} \quad (1)$$

Since the total void content per $1m^3$ of the compacted aggregate is known, if the design porosity is decided, the design cement paste content can be determined using the above equation. Throughout this study, W/C ratio was kept constant and W/C of 0.3 was used based on the literature (Cosic, 2015). Then, the required cement mass(x) can be calculated as follows.

$$V_{cement\ paste} = V_{cement} + V_{water} \quad (2)$$

$$V_{cement\ paste} = \frac{x}{Density\ of\ cement} + \frac{0.3x}{Density\ of\ water} \quad (3)$$

4 EXPERIMENTAL STUDY

As mentioned earlier, five volumetric combinations of CA and chips were used in this study and prior to mix design calculation, the porosity of the compacted aggregate sample must be determined. It can be determined using a simple water displacement test with an aggregate sample which has been

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compacted using a similar compaction method used for the trial mixes by filling 1/3 by 1/3 and giving 35 blows per each layer. Per each combination, four PC mixes were batched varying the design porosity as 25%,20%,15% and 10% hence the design paste content varied as well. However, for a particular aggregate combination, aggregate requirement does not vary with the paste content. Aggregate proportions used in this study for 1m^3 of PC and the numbering code for prepared trial mixes are shown in Table 2 and Table 3, respectively.

Table 2: Aggregate proportions

Aggregate combination	**CA (kg)**	**Chips (kg)**
A	-	1581.36
B	401.51	1164.83
C	837.018	809.424
D	1240.785	399.96
E	1583.946	-

Table 3: PC trial mixes numbering

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="4">Design Porosity</td></tr>
<tr><td>25%</td><td>20%</td><td>15%</td><td>10%</td></tr>
<tr><td rowspan="5">Aggregate combination</td><td>A</td><td>A1</td><td>A2</td><td>A3</td><td>A4</td></tr>
<tr><td>B</td><td>B1</td><td>B2</td><td>B3</td><td>B4</td></tr>
<tr><td>C</td><td>C1</td><td>C2</td><td>C3</td><td>C4</td></tr>
<tr><td>D</td><td>D1</td><td>D2</td><td>D3</td><td>D4</td></tr>
<tr><td>E</td><td>E1</td><td>E2</td><td>E3</td><td>E4</td></tr>
</table>

In total, 20 mixes of PC were prepared and for each mix 150mm×150mm×150mm cube specimens and permeability test specimens (100mm radius and 200mm height) were made. To study the variation of the flexural strength of PC, 150mm × 150mm × 750mm beams were made for each aggregate combination. Trial mix A1 was not effective because of the insufficient coating of cement paste. Mixing and compaction method used in Wang et al. (2006) was used in this study (Wang, 2006). All the samples were cured for 28 days and tested for compressive strength, flexural strength, permeability, and porosity in accordance with relevant standards.

5 RESULTS AND DISCUSSION

5.1 Compressive strength

Variation of the compressive strength of PC with cement paste content for different aggregate combinations is plotted as shown in Figure 2. Results show that compressive strength increases with the cement paste content for all the aggregate combinations. Trial mix D4 yielded the highest compressive strength of 38MPa while A2 yielded the lowest strength of 9.9MPa. The compressive strength of B2 and B3 mixes exceeded 35MPa.

Results indicate that, compressive strength can be enhanced by introducing smaller particles which make the aggregate combination more likely well graded hence the formation of the well packed skeleton structure. .

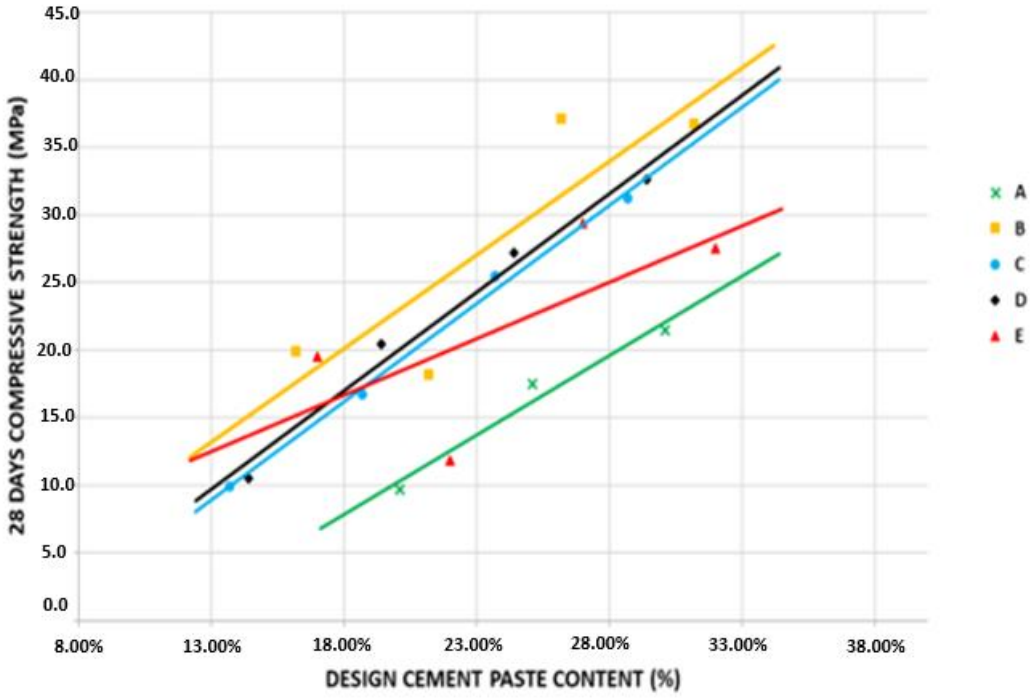

Figure 2 : 28 days compressive strength vs design cement paste content

However, PC mixes made only with smaller particles, show lower compressive strengths. In this study, the strength of the cement paste binder was not improved by using admixtures or intensifiers. Results confirm the fact that the cracks initiate and propagate through the cement paste when a higher fraction of smaller particles is present.

5.2 Permeability

The coefficient of permeability was calculated using Darcy's equation.

$$v = kI \tag{4}$$

Where: v = velocity of the flow
k = coefficient of permeability
I = hydraulic gradient

Using the experimental results, permeability vs design cement paste graphs were plotted as shown in Figure 3.

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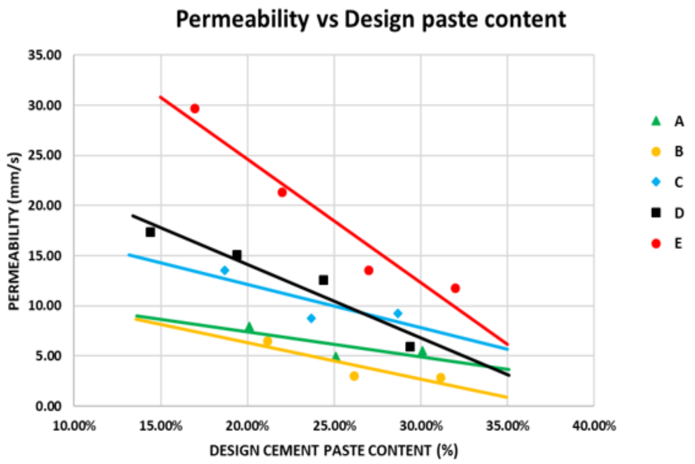

Figure 3: Permeability vs design cement paste content

Aggregate combination A shows the lowest coefficient of permeability whereas combination E has the highest. Permeability decreases when the chip content increases. In combination A, PC mixes were only made with the chip aggregate hence the particles are in a well packed structure, blocking the capillaries. Since combination E has the highest fraction of larger particles, larger sized and more connected pores can be expected. On the other hand, in all aggregate combinations, the coefficient of permeability reduces when the cement paste content increases as a result of the blockage of the interconnected pores.

As observed in the previous section, compressive strength increases with the cement paste content. Therefore, it implies that the higher the compressive strength, lesser the permeability is. However, the requirement of permeability from a PC mix totally depends on the permeability of the underlaying soil layer of the site unless a separate drainage is provided. It is not efficient to have a higher coefficient of permeability than that of the underlaying soil layer. General values of coefficient of permeability are shown in Table 4 (Das, 2015).

Table 4: Range of the Coefficient of permeability for various soils

Type of soil	Coefficient of permeability *k* (cm/sec)
Medium to coarse gravel	Greater than 10^{-1}
Coarse to fine sand	10^{-1} to 10^{-3}
Fine sand, silty sand	10^{-3} to 10^{-5}
Silt, clayey silt, silty clay	10^{-4} to 10^{-6}
Clays	10^{-7}

Referring to the experimental results, the least coefficient of permeability obtained was $2.81x10^{-1}$ cm/s which matches the range of medium to coarse gravel which is positively above the coefficient of permeability of all kinds of subgrades in the local context.

5.3 Flexural strength

A three-point bending test was performed on the specimens cast with a design porosity of 20% for all the aggregate combinations. Results show relatively lower flexural strength values than the typical flexural strength of conventional concrete. Combination C has the highest flexural strength value of 2.64MPa which is approximately half of the typical flexural strength of conventional concrete (Concrete in Practice, 2000). Figure 4 shows the variation between Modulus of rupture and chip percentage, and it indicates that the percentage of chips does not have a significant impact on flexural strength.

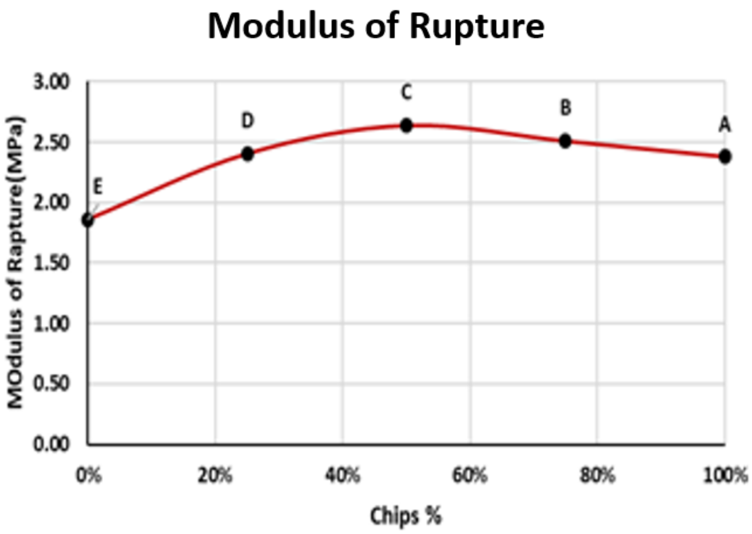

Figure 4: Flexural strength vs chips percentage

5.4 Actual porosity

Referring to the results, the actual porosity vs design porosity graph is plotted as shown in Figure 5. Results show that the actual porosity values are considerably lower than the design values. The porosity was determined using a water displacement method recording the amount of water required to fill the voids. However, the isolated voids may not be accounted for with this method, and it may lead to deviations.

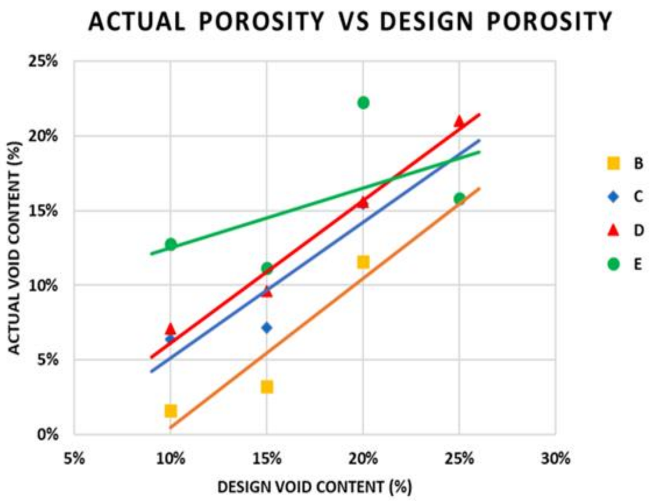

Figure 5: Actual porosity vs design porosity

6 PROPOSED CONCEPTUAL MIX DESIGN METHOD

Using the experimental data obtained and the patterns and relationships between the major parameters observed, a simplified concept of designing PC mixes was developed. The required compressive strength and the permeability are the key input parameters for the proposed method. In order to increase the strength characteristics, combinations of full range of particle sizes of CA and chips were used removing particles finer than 4mm and larger than 20mm. Prior to design, a basic idea about the required permeability which can be estimated considering the soil strata or provided drainage at the proposed site, is needed. Considering the application of the pavement, strength requirement can be obtained. The design concept is to determine a suitable aggregate combination and a cement paste content using the developed compressive strength vs design paste content graph. The selected combinations should be

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checked for the coefficient of permeability using the developed permeability vs design cement paste graph and the adjustment should be made to meet both compressive strength and permeability requirements.

7 CONCLUSION

Applications of PC are limited mainly because of the unavailability of a simplified mix design method which is suitable for local industry and the relatively lower strength characteristics. Enhancing the binder strength and increasing the binder area are the major methods of enhancing the strength characteristics of pervious concrete. In this research study, the full-size range of coarse aggregate and commercially available smaller version of coarse aggregate known as chips were mixed in order to enhance the strength characteristics by increasing the bond area between cement paste and aggregate particle with the means of practicality and simplicity. Results confirmed that PC can be made with relatively higher compressive strength exceeding 30MPa while obtaining adequate coefficient of permeability without using admixtures with this new method. A conceptual method of designing pervious concrete mixes was proposed using experimental results which simplify the design process.
It is recommended to conduct further experimental studies to improve the proposed design method and to further enhance the strength characteristics by enhancing the binder strength which was not studied in this research study.

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