Performance of pervious recycled aggregate concrete with reduced cement content

Abstract

Pervious concrete is a tailored concrete to have very high water permeability. The presence of interconnected pores of different sizes and shapes allow the passage of water to flow through easily. Permeable concrete pavement was shown to have significant advantages in stormwater management over impervious pavements and minimizing the risk of flooding in urban environment. This paper reports the results of an experimental investigation into the development of pervious concrete with reduced Portland cement content and recycled concrete aggregate. The performance of pervious concrete was evaluated through strength development, density, void content and permeability. The use of recycled concrete aggregate was found to affect the compressive strength of pervious concrete without influencing the permeability. The relationships between strength and void content, and permeability and porosity are reported. Through the empirical relationship presented, pervious concrete mixes with either natural aggregate or recycled concrete aggregate to meet the strength and permeability requirements could be designed.

Keywords: Pervious concrete, slag, strength, permeability, porosity

1. Introduction

Regular flooding in many cities in several countries is not uncommon during the rainy season. Impervious surfaces, resulting from infrastructure construction due to increased urbanization, block the infiltration of natural rainwater to the ground and increase the stormwater runoff. With the absence of sufficient drainage flash flooding becomes inevitable. In USA, the pervious pavements are increasingly used for the construction of secondary roads, parking lots, driveways, walkways and sidewalks. By capturing a significant amount of stormwater and allowing it to seep into the ground, the pervious concrete pavement is instrumental in recharging groundwater and reducing stormwater runoff, as recognised by the US Environmental Protection Agency.

Pervious concrete is a tailored concrete with a high proportion of large sized interconnected pores, typically 2 to 8mm, with the porosity ranged from 15 to 30% (ACI Committee 522, 2006). Typical pervious concrete mixes in US consists of the following mix compositions: cement from 180 to 355 kg/m^3, aggregate from 1420 to 1600 kg/m^3 and water to cement ratio between 0.27 and 0.43. For the hardened concrete, compressive strength ranges from 5.6 to 21.0 MPa, porosity ranging from 14 to 31 %, and permeability ranges from 0.25 to 6.1 mm/s (Schaefer et. al., 2006).

Malhotra (1976), Meininger (1988), Tennis et. al. (2004), Otani et. al. (2005) reported the influence of the mix composition, aggregate size and cement type on the strengths of pervious concretes. Since 2007, pioneering research on pervious concrete has been conducted at the University of Technology, Sydney, Australia and the results were reported by Sriravindrarajah and Aoki (2008, 2010), Aoki and Sriravindrarajah (2008), Aoki et. al. (2008 and 2009) and Sriravindrarajah et. al. (2010). The permeability of the pervious fly ash concrete was high as 15mm/s with the strength of about 10MPa. Both the strength and permeability are directly related to the porosity and the shrinkage for pervious concrete is lower than that for the normal weight concrete. Sriravindrarajah et. al. (2010) reported that the high pressure water cleaning is capable of restoring the permeability of pervious concrete. Otani et. al. (2005) studied the compressive strength of pervious concrete with four types of aggregates, namely natural, recycled concrete, blast-furnace and artificial lightweight. At a given porosity, a low density aggregate produced pervious concrete with reduced strength. The cement type had no significant effect on the strength of pervious concrete at a given porosity.

In order to improve the environmental sustainability, modern concrete standards such as EN206-1 allow the use of recycled concrete aggregates in structural grade concrete mixes. Sriravindrarajah and Tam (1985) reported that the replacement of natural aggregate with recycled concrete aggregate had reduced the strength and modulus of elasticity and increased the shrinkage of concrete. Although the strength can be recovered with the reduction in water to cement ratio and/or the addition of pozzolanic materials, it is not possible to increase the modulus of elasticity and to decrease the shrinkage of concrete (sriravindrarajah and Tam, 1988). Sriravindrarajah et. al. (2001) reported that the variability of the quality of recycled coarse aggregate had limited influence on the variability of the properties of recycled aggregate concrete. Murao et. al. (2002) reported that at a given porosity, the pervious concrete with recycled concrete aggregate showed significantly reduction in strength compared to the control concrete with natural aggregate.

In order to reduce the environmental impact of pervious concrete, the investigation is aimed to reduce the cement content by 70% by weight with the use of ultra fine slag and to replace the natural aggregate fully with recycled concrete aggregate. This paper discusses the results of an investigation into the compressive strength, density, porosity and permeability of pervious concrete with ultra-fine slag and recycled concrete aggregate.

2. Experimental Investigation

2.1 Materials and mix proportions

Ordinary Portland cement and ultra-fine granulated blast furnace slag were used as the binder materials. The mean particle size and fineness for the cement were 14.7μm were 300m^2/kg, respectively and those for the slag were 4.1μm were 870m^2/kg, respectively. The strength activity index for the slag was 1.64, 1.20 and 1.16 at the ages of 3, 7 and 28 days, respectively. The aggregate size was ranged either from 5 to 13mm (small) or from 13 to 20mm (large). The density of natural aggregate was 2650kg/m^3, whereas that for the recycled concrete aggregate was 2190 and 2040kg/m^3 for large and small sizes, respectively. The small-sized aggregate had the highest water absorption and lowest particle density, due to the increased amount of attached mortar component. The water absorption for the large and small sized aggregates was 5.3 and 8.2%, respectively, compared to 1.0% for the both sizes natural aggregate.

Table 2: Mix details for the pervious recycled aggregate concrete mixtures

Mix	*Aggregate*	*Cement (kg/m^3)*	*Slag (kg/m^3)*	*Cement (%)*	*Slag (%)*	*A/(C + S)*
NA20	*Natural*	*270*	*0*	*100*	*0*	*5.00*
NA13	*Natural*	*320*	*0*	*100*	*0*	*3.70*
RA20	*Recycled*	*335*	*0*	*100*	*0*	*4.00*
RA13	*Recycled*	*440*	*0*	*100*	*0*	*2.80*
RA13S35	*Recycled*	*230*	*124*	*65*	*35*	*3.00*
RA13S70	*Recycled*	*120*	*280*	*30*	*70*	*3.00*

Table 2 summarises the compositions of the pervious concrete mixes. The free water to binder ratio was 0.33, by weight, for all the mixes. The cement replacement levels in recycled aggregate concrete with slag were 0%, 35% and 70%, by weight. The aggregate to binder (cement plus slag) ratio for mixes with 20mm aggregate was 5.0 and 4.0, by weight, for natural and recycled aggregate concretes, respectively. In order to maintain the same porosity of 20%, the aggregate to binder ratio was reduced to 3.7 and 2.8, respectively, for the mixes with 13mm sized natural and recycled aggregate. The aggregates were kept in water for over 24 hours prior to concrete mixing and batched in the saturated surface dry condition. The concrete mixes had the suitable workability as assessed by hand-ball rolling test (Sriravindrarajah and Aoki, 2008).

2.2 Casting and curing of test specimens

The mixes were produced in a tilt-drum type concrete mixer in the laboratory environment. Firstly, the aggregate and binder materials were dry mixed for few minutes. The water was then added gradually and the mixing was continued until a uniform mix was obtained. The fresh concrete was tested for its wet density. For each mix, 14Nos. of 100mm diameter by 200mm high cylinders and 3Nos. of 150mmm cubes were cast in the standard steel moulds. The concrete was placed layers in the moulds and minimum hand compaction was applied to each layer. The cast specimens were demoulded after 24 hours and stored in water at the room temperature (28^{o}C) until testing. The ages of testing were 7 days and 28 days for compressive strength and for each age three identical cylinders or cubes were tested. The testing procedures adopted were in accordance with the relevant Euro-standards. The porosity of pervious concrete, based on volume, was determined using the void free density (T) and measured density (D) of the concrete mixes, using the eq. (1)

$$\text{Porosity (\%)} = 100 \times (T - D) / T \qquad \text{…………….. (1)}$$

Figure 1: Water permeability test set-up for pervious concrete

2.3 Water permeability test for pervious concrete

The water permeability for pervious concrete was determined under a falling head method, using a specially made permeability apparatus (Figure 1). The test specimen (100mm diameter by 150mm high) was firstly wrapped with a rubber membrane to stop the water leak along the edges and to allow the water to flow through the cross-section of the specimen. The top and bottom of the specimen were fitted to perspex tubes. A valve was attached at the end of the bottom tube where as the top tube was left open to accept the water. The water permeability test was conducted under the falling heads of 500 to 400mm; 400 to 300mm; 300 to 200mm and 500 to 200mm. For each concrete mix, two identical specimens were tested and the mean values of three runs are reported. The coefficient of permeability (k) is given in the Eq. (2).

$$k = (a \,.\, L / A \,.\, t) \ln (h_o / h_1) \qquad \text{………………} \ (2)$$

where,
- a: cross-sectional area of the reservoir (7857 mm^2)
- L: length of the specimen (150 mm)
- A: cross-sectional area of the specimen (mm^2)
- T: time taken for the head to fall from h_o to h_1
- h_o: initial water head (500, 400 or 300 mm)
- h_1: final water head (400, 300 and 200 mm)

Table 3: Porosity and compressive cylinder strength of pervious concrete

Mix	*Age (days)*	*Porosity (P) (%)*	*Strength (f) (MPa)*	P_{av} *(%)*	f_{av} *(MPa)*	(f_{28}/f_7)
NA20	7	*30.9 – 36.7*	*6.16 - 8.53*	*42.1*	*7.41*	*1.00*
	28	*33.3 – 36.1*	*6.69 – 7.79*	*34.3*	*7.41*	*1.00*
NA13	7	*25.5 – 29.3*	*11.1 – 13.1*	*27.7*	*11.8*	*1.00*
	28	*26.8 – 28.1*	*12.0 – 15.8*	*27.5*	*13.9*	*1.18*
RA20	7	*23.5 – 25.4*	*6.03 – 6.80*	*27.7*	*6.47*	*1.00*
	28	*24.6 – 28.8*	*4.48 – 6.96*	*27.5*	*6.06*	*0.94*
RA13	7	*13.8 - 16.1*	*6.42 - 12.1*	*14.4*	*11.1*	*1.00*
	28	*7.0 - 13.2*	*10.4 - 13.3*	*9.87*	*12.1*	*1.09*
RA13S35	7	*22.1 – 27.0*	*4.99 – 6.81*	*24.4*	*5.79*	*1.00*
	28	*22.8 – 28.4*	*5.09 – 7.00*	*25.5*	*6.19*	*1.07*
RA13S70	7	*13.7 – 16.0*	*8.55 – 10.8*	*15.0*	*10.0*	*1.00*
	28	*13.9 – 19.7*	*10.2 – 11.1*	*16.7*	*10.6*	*1.06*

4. Results and discussion

Table 3 shows the porosity and compressive cylinder strength at the ages of 7 and 28 days for the pervious concrete mixes. For a concrete mix at the same age, the porosity of the three test specimens was varied notably due to the variation in the degree of compaction. This has influenced the measured strength. Figure 2 shows the relationship between strength and porosity for pervious recycled aggregate concrete at 7 and 28 days, using the individual results.

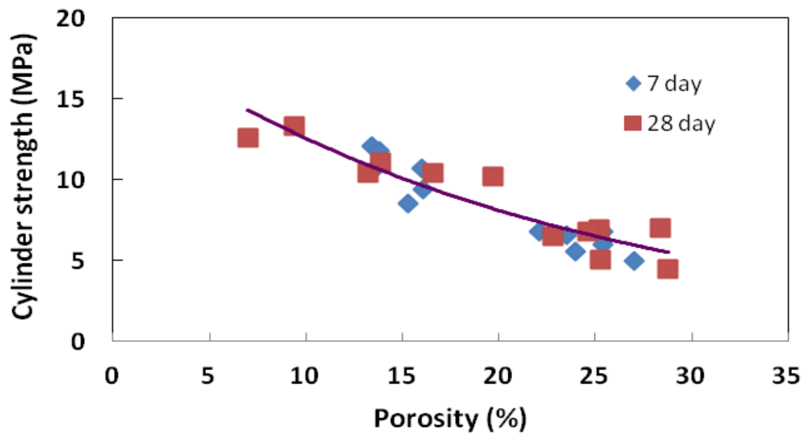

Figure 2: Relationship between strength and porosity for pervious recycled concrete

4.1 Binder type and age on concrete strength

The results show that the strength of pervious recycled concrete is marginally increased with age (Table 3). Due to the variability in the porosity of the specimens, the strength improvement with age is difficult to estimate. However, the relationship between strength and porosity is not significantly affected by either age or binder type (Figure 2), similar to that reported by Mahboub et. al. (2009). The strength is primarily is influenced by the porosity of concrete and other factors had marginal influence.

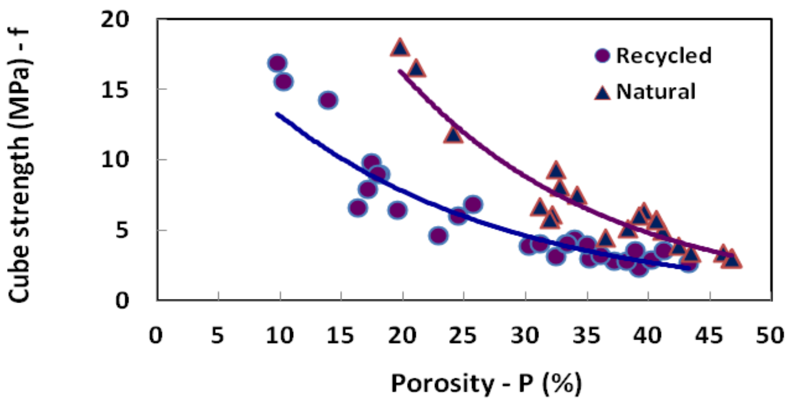

Figure 3: Aggregate type on strength of pervious concrete

4.2 Aggregate type and size on concrete strength

Figure 3 shows the relationship between cube strength and porosity for pervious concrete with natural and recycled concrete aggregates. At a given porosity, the strength of pervious recycled concrete is lower than that for the similar concrete with natural aggregate. Otani et. al. (2005) showed a similar decrease in strength for pervious concrete with recycled concrete aggregate. The results also show that the extent of strength reduction is reduced with the increase in the porosity of pervious concrete.

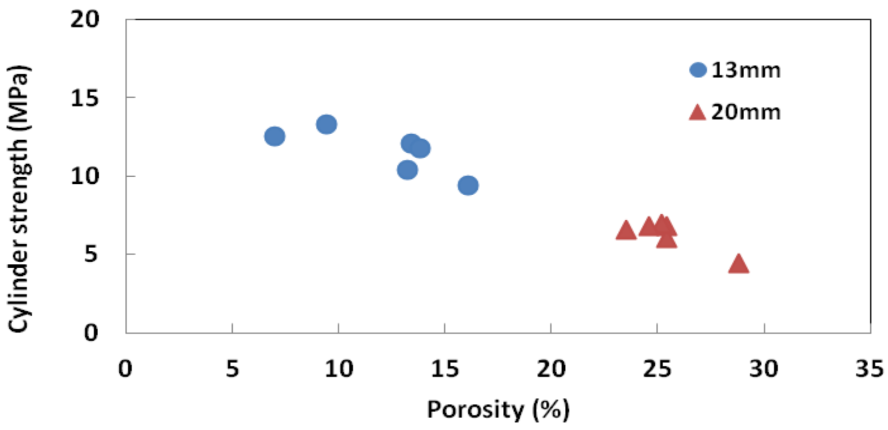

Figure 4: Aggregate size on the strength of recycled aggregate pervious concrete

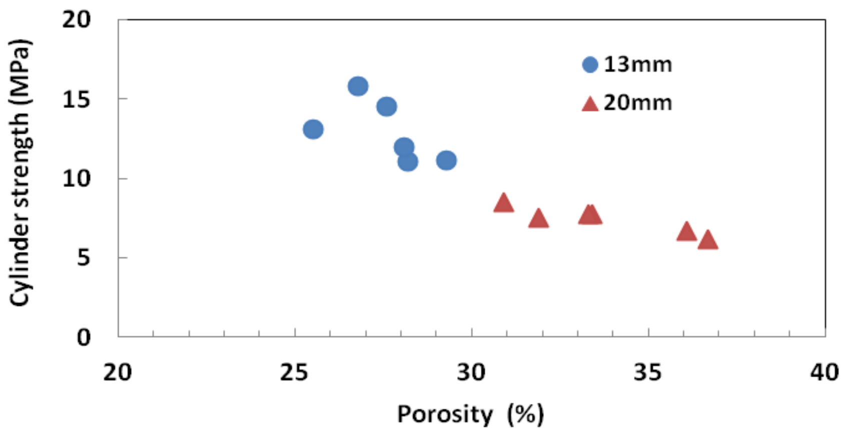

Figure 5: Aggregate size on the strength of natural aggregate pervious concrete

Figures 4 and 5 show the influence of aggregate size on the strength of pervious concrete, having recycled concrete aggregate and natural aggregate, respectively. As the aggregate size is increased the bulk density of aggregate is decreased and the porosity of pervious concrete is increased. Mahboub et. al. (2009) reported that the porosity of pervious concrete is linearly related to the bulk density of aggregate.

4.3 Shape of the test specimen on strength

Compressive strength of pervious concrete was determined using both standard cubes (100mm and 150mm) and cylinders (100mm diameter by 200mm high). The absence of fine aggregate resulted in uneven honeycombed type concrete surfaces, both cast and top. Therefore, to achieve smooth load bearing surface under loading, the test specimens were capped with dental plaster. Figure 6 shows the relationship between compressive cube/cylinder strength and porosity. The results show that the relationship between the compressive strength and porosity is not significantly affected by the specimen shape. This implies that cubes (preferably 150mm) could be used for the compressive strength testing of low strength pervious concrete.

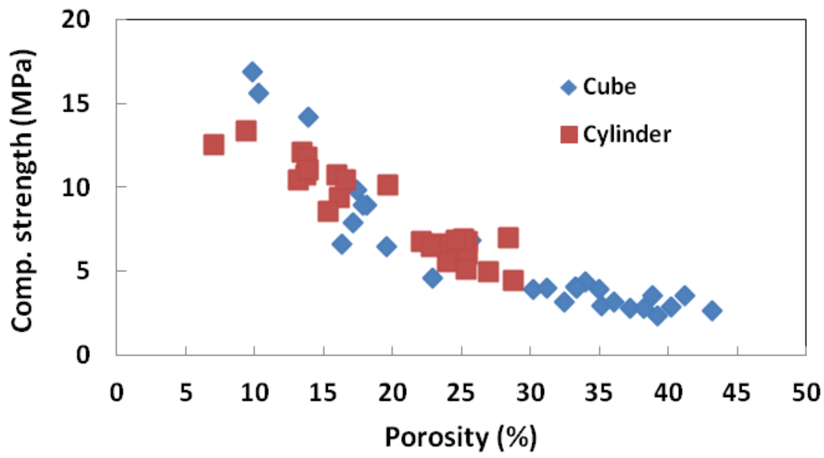

Figure 6: Specimens shape on the strength of recycled pervious concrete

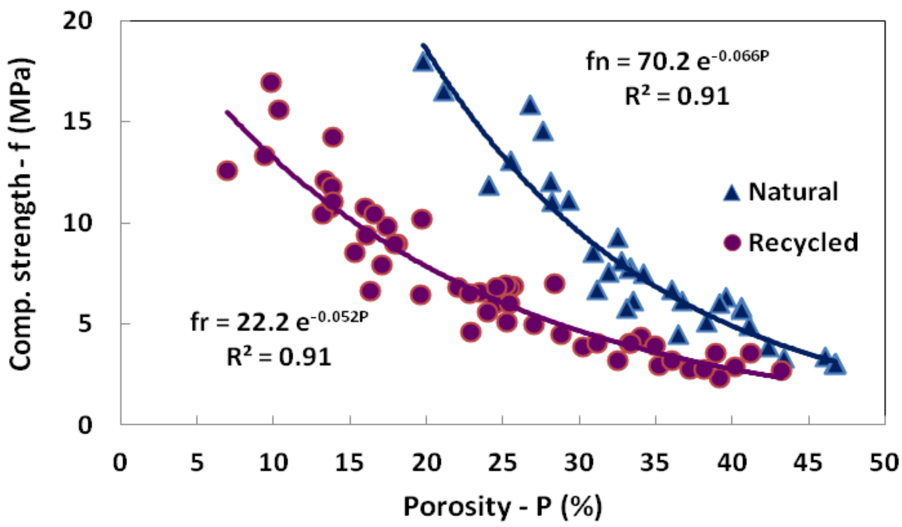

Figure 7: Aggregate type on the strength - porosity relationship for pervious concrete

4.4 Relationship between strength and porosity

Figure 7 shows the correlation between compressive strength and porosity of pervious concrete with natural and recycled concrete aggregate. Both cylinder and cube compressive strength results for all six concrete mixes were plotted. The results indicate that the influence of age, specimen size and shape, binder type on the compressive strength of pervious concrete is not significant when compared with the influence of porosity of concrete. Exponential relationship between strength and porosity showed a very high degree of correlation, (square of the correlation coefficient of 0.91). Figure 7 clearly shows that the aggregate stiffness (porosity) has a significant influence on the relationship between compressive strength and porosity. The following empirical equations for compressive strength are obtained for pervious concrete with natural and recycled aggregates and these equations could be used for the design of pervious concrete mixes.

Natural aggregate: $f_n = 70.2\ e^{-0.066P}$ ………………… (3)

Recycled concrete aggregate: $f_r = 22.2\ e^{-0.052P}$ ………………… (4)

Table 4: Mean Porosity and permeability of pervious concrete

Mix	*Density (kg/m^3)*	*Porosity (%)*	*Permeability (mm/s)*
NA20	1610	35.9	26.7
NA13	1780	28.5	15.5
RA20	*1540*	*29.1*	*15.6*
RA13	*1650*	*22.0*	*7.45*
RA13S35	*1385*	*32.4*	*17.1*
RA13S70	*1535*	*24.6*	*9.78*

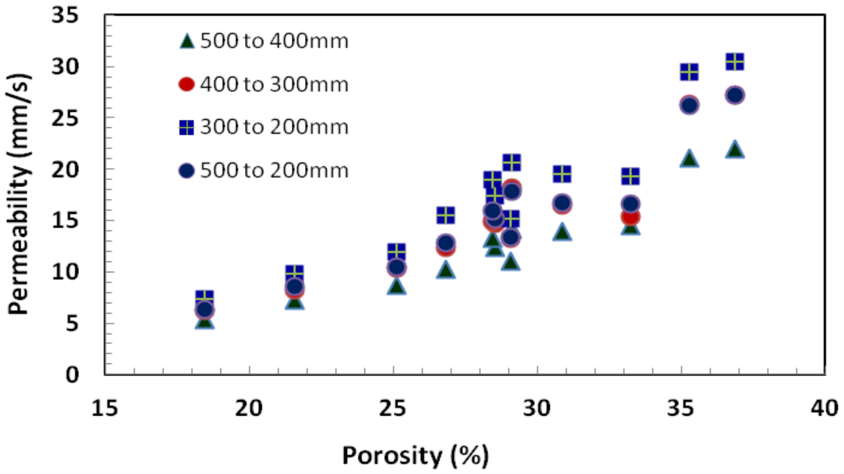

Figure 8: Effect of head on the permeability and porosity relationship for pervious concrete

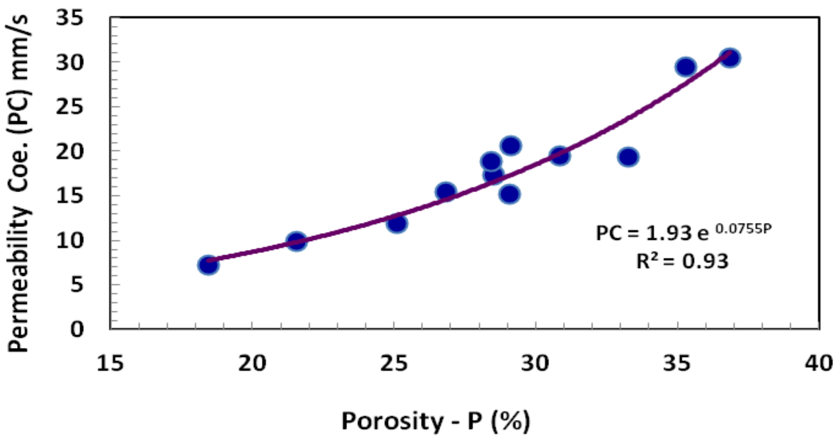

Figure 9: Relationship between permeability and porosity for pervious concrete

4.5 Water permeability of pervious concrete

Table 4 shows the mean water permeability for all six mixes. The permeability of pervious concrete with 20mm natural aggregate was 26.7 mm/s is the highest due to the highest porosity of 35.9%. The lowest permeability value of 7.45mm/s was obtained for the pervious concrete with 13mm recycled concrete aggregate which had the lowest porosity of 22%. Figure 8 shows that the relationship between porosity and permeability for pervious concrete is influenced by the water head. The permeability of pervious concrete having the porosity over 25% is found to be more sensitive to water head. This could be due to the change in the pattern of water flow from streamline to turbulence in the highly porous concrete with complicated interconnected pore structure. The permeability varied with water head for all pervious concrete mixes with natural and recycled concrete aggregates. Considering the water level of 300mm, the permeability of pervious concrete for the falling head from 300 to 200mm could be selected for pervious concrete mix design, to meet the specification requirements. Figure 9 shows the relationship between permeability coefficient (PC) and porosity (P) for pervious concrete under the water head of 300mm and the eq. (5) shows the empirical equation. The type of aggregate has no significant effect on the permeability of pervious concrete.

$$PC = 1.93\, e^{0.0755P} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

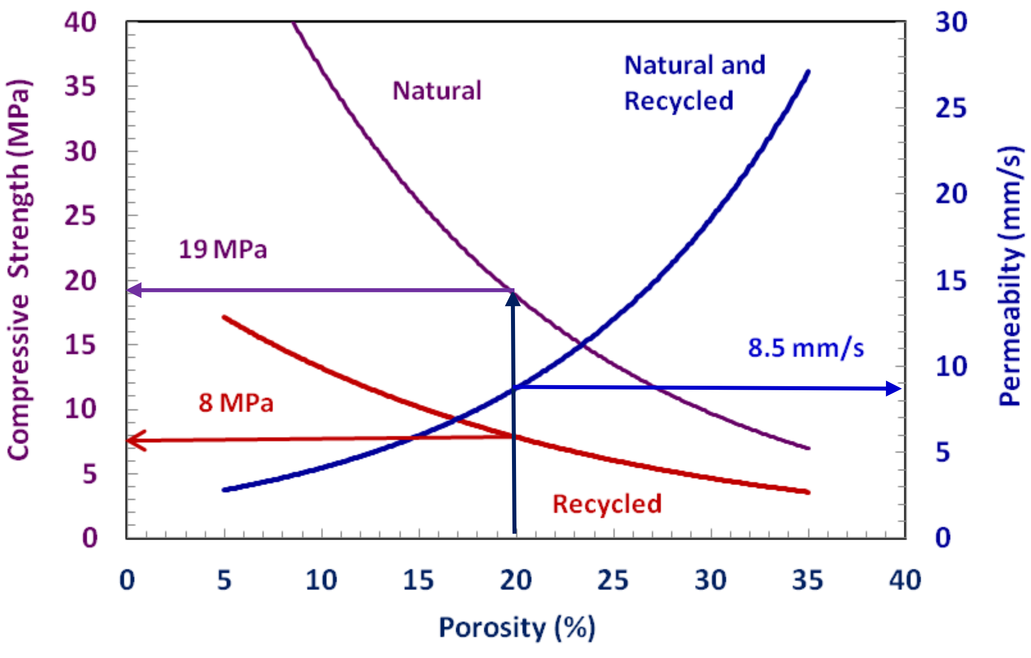

Figure 10: Relationship between strength and permeability for pervious concrete

4.6 Design guide for pervious concrete mix

Figure 9 shows the empirical relationships between strength and permeability for pervious concrete as a function of the aggregate type. From this plot, it is possible to estimate the strength and permeability of natural and recycled aggregate pervious concretes for a given porosity as demonstrated. These relationships could be used in determining the porosity of concrete needed to satisfy both strength and permeability requirements for the pervious concrete with either natural or recycled concrete aggregates.

5. Conclusions

Based on the results of the experimental investigation on the performance of pervious concrete the following conclusions can be made.

1. The compressive strength of pervious concrete is mainly depends on the porosity of concrete; the influences of binder type and age are marginal; and the maximum aggregate size influenced the strength through its effect on the porosity.
2. The size and shape of test specimen had marginal influence on the strength of pervious concrete and the use 150mm cubes is recommended for pervious concrete.
3. For a given porosity, the pervious recycled aggregate concrete had a significantly reduced the strength compared to the concrete with natural aggregate. The relationships between the strength and porosity for pervious concrete are given by the following empirical equations:
    - natural aggregate concrete: $f = 70.2\ e^{-0.066P}$;
    - recycled aggregate concrete: $f = 22.2\ e^{-0.052P}$
4. Permeability of pervious concrete is mainly influenced by the porosity and not affected by the use of recycled concrete aggregate. The relationship between permeability (PC) and porosity is given by the following empirical relationship: $PC = 1.93\ e^{0.0755P}$

References

ACI Committee 522 (2006) “Pervious Concrete”, Report No. 522R-06, American Concrete Institute. Detroit, USA.

Aoki Y and Sriravindrarajah R (2008) “Shrinkage of environmentally friendly sustainable porous concrete”, Proceedings of the International Conference on Sustainable Concrete Construction. Ratnagiri, India, February 2008.

Aoki Y., Sriravindrarajah R, and Khabbaz H (2008) “Environmentally friendly sustainable pervious concrete”, Proceedings of the 20th Australasian Conference on the Mechanics of Structures and Materials, Toowoomba, Australia, December 2008.

Aoki Y, Sriravindrarajah R and Khabbaz H (2009) “Effect of fly ash performance of pervious concrete”, Supplementary Proc. of Tenth CANMET/ACI International Conference on Recent Advances in Concrete Technology and Sustainability Issue. Seville, Spain, August 2009.

Malhotra V M (1976) “No-fines concrete – Its properties and applications”, *ACI Journal*, **73**: 628-644.

Meininger R C (1988) “No-fines pervious concrete for paving”, *Concrete International*, **10**: 20-27.

Mohhboub K C, Canler J, Rathbone R, Robl T and Davis B (2009) “Pervious concrete: Compaction and aggregate gradation” *ACI Materials Journal*, **106**: 523-528.

Murao K, Yuasu Y, Misima N, and Hatanaka S (2002) “Experimental study on the strength of porous concrete with low quality recycled aggregate” *Journal of Architectural Institute of Japan*, **8**: 823-824.

Otani T, Sato Y, and Kiyohara C, Murakami M, and Mitsui Y (2005) “An equation for predicting the compressive strength of porous concrete” *Journal of Structural and Construction Engineering*, **590**: 25-30.

Schaefer V R, Wang K, Suleiman M T and Kevern J T (2006) “Mix Design Development for Pervious Concrete in Cold Weather Climates” Center for Transportation Research and Education, Iowa State University, USA.

Sriravindrarajah R and Aoki Y (2008) “Environmentally friendly porous concrete”, Proceedings of the Second International Conference on Advances in Concrete and Construction, Hyderabad, India, February 2008.

Sriravindrarajah R and Aoki Y (2010) “Environmentally friendly pervious concrete for sustainable construction”, Proceedings of the 35th Conference on Our World in Concrete & Structures, August 2010.

Sriravindrarajah R, Nguyen L D, Do H M and Aoki Y (2010) “Effect of clogging on the water permeability of pervious concrete” Proceedings of the 21st Australasian Conference on the Mechanics of Structures and Materials, Melbourne, Australia, December 2010.

Sriravindrarajah R, and Tam C T (1985) “Properties of concrete made with crushed concrete as coarse aggregate” *Magazine of Concrete Research*, **37**: 29-38.

Sriravindrarajah R and Tam C T (1988) “Methods of improving the quality of recycled aggregate concrete”, Proceedings of the Second International RILEM Symposium on Demolition and Reuse of Concrete and Masonry, November 1988, Japan.

Sriravindrarajah R, Stewart M and Greco D (2001) “Variability of recycled concrete aggregate and its effects on the properties of concrete”, Proceedings of the Second International Conference on Engineering Materials, August 2001, San Jose, USA.

Tennis P. D, Leming M L and Akers D J (2004) "Pervious concrete pavements", Portland Cement Association and The National Ready Mixed Concrete Association, USA.