DEVELOPMENT OF PERVIOUS CONCRETE

by

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CERTIFICATE OF AUTHORSHIP

I certify that the work in this thesis has not previously been submitted for any degree nor has it been submitted as part of requirements for a degree except as fully acknowledge within the text.

I also certify that the thesis has been written by me. And help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of Candidature

(Yukari Aoki)
June 2009

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ABSTRACT

In many developed countries, the use of pervious concrete for the construction of pavements, car parks and driveways is becoming popular. In order to develop material specification for pervious concrete, it is necessary to conduct testing to evaluate the performance of this new type of high-performance concrete. In addition, carbon dioxide emission from Portland cement production is significant and contributes to global warming which leads to undesirable climate change. Therefore, it is necessary minimise the use of Portland cement in pervious concrete mixes by partially replacing the cement with industrial by-product, such as fly ash and slag which have been used successfully as supplementary cementitious materials in structural concrete mixes.

The pervious concrete is produced by using conventional cementitious materials, aggregates, and water. This concrete is tested for its properties, such as density, porosity, compressive strength, water permeability and drying shrinkage. The most important property of pervious concrete is its water permeability. Currently, there is no standard experimental procedure to determine to this property. A method was therefore developed to determine the water permeability. Fly ash is used as a supplementary cementitious material to partially replace Portland cement in pervious concrete mixes up to 50% by weight.

To improve the acceptance of pervious concrete, it is necessary to improve the surface texture. Due to the rough surface texture and bigger void content, it may be difficult for pervious concrete for wide acceptance by the construction industry. Therefore, fine textured pervious mortar is produced using cementitious materials, aggregate and water, and its properties are investigated. New type of pervious pavement, a combination of pervious concrete and pervious mortar, is developed and its properties are studied.

Pervious concrete having density around 1800 kg/m^3 shows the following properties, porosity 0.32 to 0.36, 28-day compressive strength between 5.7 MPa and 10.1 MPa, water permeability between 9.2 mm/s and 17.3 mm/s, and 56-day drying shrinkage between 470 and 600 microstrain.

The properties of pervious mortar having 0.35 water/cement ratio with hand compaction are as follows; density of 1690 kg/m^3, porosity of 0.34, 28-day compressive strength of 5.8 MPa, water permeability 2.6 mm/s, and 56-day drying shrinkage of 490 microstrain.

Combination of pervious concrete and pervious mortar is tested in density and water permeability. The density is around 1750 kg/m^3, while the water permeability between 2.3 mm/s and 3.0 mm/s. Further investigation on the development of this system to have adequate water permeability, strength and durability is recommended.

LIST OF PUBLISHED PAPERS

Y. Aoki and R. Sri Ravindrarajah (2008) *Shrinkage of Environmentally friendly sustainable pervious concr*ete, Proceeding of International Conference on Sustainable Concrete Construction, February, 2008, Ratnagiri, India

R. Sri Ravindrarajah and Y. Aoki (2008) E*nvironmentally Friendly pervious concrete,* Proceeding of 2nd International Conference on Advances in Concrete and Construction, February, 2008, Hyderabad, India

Y. Aoki, R. Sri Ravindrarajah and H. Khabbaz (2008) *Environmentally friendly sustainable pervious concrete,* Proceeding of the 20th Australasian Conference on the Mechanics of Structures and Materials, 2–5 December, 2008, Toowoomba, Queensland, Australia, pp. 567 – 570.

Y. Aoki, R. Sri Ravindrarajah and H. Khabbaz (2009) *Effect of fly ash performance of pervious concrete,* Proceeding of Tenth CANMET/ACI International Conference on Recent Advances in Concrete Technology and Sustainability Issue, 15-17 October, 2009, Seville, Spain.

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A	cross-sectional area of cylinder
A_1	cross-sectional area of the specimen
A_2	cross-sectional areas of the tube
A_B	total surface area of the pervious concrete block
A_c	continuous air void content
A_P	surface area of the pervious concrete block occupied by pores
A_s	specific surface area of materials
A_t	total air void content of porous concrete
C_0	empirical constant
C_c	percent volumetric compaction of the column
F_s	generalized factor to account for different pore shapes
G	gravimetric air void ratio
g	gravitational acceleration
h	total height
h	water head (head difference)
h_1	initial water head
h_2	final water head
k	water permeability (water permeability coefficient)
k_{eff}	theoretical effective permeability of sand-clogged or covered pervious concrete block system
k_s	hydraulic conductivity
k_{sand}	permeability of sand (cm/s)
$\mathrm{k_T}$	water permeability at Tc°
l	length of the specimen
M_1	buoyant mass of the saturated specimens in water
M_2	dry mass in the air for 24 hours
M_3	buoyant mass of the saturated specimens in water after 24 hours drying in the air
M_b	buoyant mass of the saturated specimens in water
M_d	oven-dry mass of the specimens

M_s	mass of saturated surface-dry specimens
P, p	average porosity
P_y	theoretical porosity at the hight ‘y’
Q	quantity of water
ρ_w	density of water
S_0	specific surface area of pores
T	mass of unit volume in the assumption of no air
t	time
v	kinematic viscosity of water
V_1	total volume of specimens
V_2	sum of absolute volume of all materials on the concrete of 1m^3
Vol	volume
V_r	porosity (void ratio)
W	mass of unit volume in the container
W_1	weight under water
W_2	oven dry weight
W_3	mass in the air after 24 hours
W_4	total mass of all materials on the concrete of 1m^3
y	height
β_H	hydraulic connectivity factor
τ	tortuosity
φ_P	porosity

Chapter 1

Introduction

1.1 Background

1.1.1 Pervious concrete

Conventional normal weight Portland cement concrete is generally used for pavement construction. The impervious nature of the concrete pavements contributes to the increased water runoff into the drainage system, over-burdening the infrastructure and causing excessive flooding in built-up areas. Pervious concrete has become significantly popular during recent decades, because of its potential contribution in solving environmental issues. Pervious concrete is a type of concrete with significantly high water permeability compared to normal weight concrete. It has been mainly developed for draining water from the ground surface, so that stormwater runoff is reduced and the groundwater is recharged. Figure 1.1 shows the typical pervious concrete used for the pavement. [1].

Figure 1.1 Pervious concrete pavement [1]

Pervious concrete has been developed in the USA in order to meet US Environmental Protection Agency (EPA) stormwater regulation requirements [2]. The American Society for Testing and Materials (ASTM) Concrete Committee (C09) has focused on this concrete and formed a subcommittee to deal exclusively with pervious concrete production, properties and usage [3]. European countries have developed pervious concrete, not only for water permeability but also for sound absorption [4]. In Japan, pervious concrete has been researched for the usage in not only for road surfaces but also to support vegetation along river banks [5,6].

In Australia, pervious concrete has been developed for key performance in relation to Water Sensitive Urban Design (WSUD) which seeks to improve required water quality and quantity in urban area. Pervious concrete blocks have been used as one of the permeable pavement systems [7]. Figure 1.2 shows an example of pervious concrete block used to meet WSUD requirements.

Figure 1.2 Pervious Concrete block [7]

1.1.2 Environmental effect of cement usage

In 2003, the world's Portland cement production reached 1.9 billion tonnes. The most populous countries on the earth, namely China and India, produced 41.9% and 5.2% respectively of the world's cement output [8]. As the demand for concrete increases, current Portland cement production will be substantially increased. Since one tonne of cement production releases 0.93 tonnes of CO_2 into the atmosphere [9], cement production contributes significantly to global warming which leads to undesirable climate change. Hence it is essential for the concrete industry to be aware of the consequences of utilising environmentally unfriendly cement. Every effort should be made to minimise the use of Portland cement in concrete mixes. In concrete mixes, Portland cement should be partially replaced with a variety of proven supplementary cementitious materials, such as natural pozzolans, fly ash and ground-granulated blast furnace slag. Substantial use of these cementitious materials will help to produce environmentally friendly concrete mixes.

1.2 Objectives of the investigation

The main objectives of this study are to:

1) Investigate the properties of pervious concrete with and without fly ash
2) Establish an experimental procedure to determine water permeability of pervious concrete and pervious mortar
3) Develop pervious mortar suitable for pavement application
4) Investigate the performance of a pervious concrete and pervious mortar combinative layer as a pavement system

1.3 Scope of the investigation

1) A number of pervious concrete mixes was produced with and without fly ash. The main properties studied include density, porosity, compressive strength, water permeability and drying shrinkage. These properties were compared with those for conventional concrete.
2) Although water permeability is the most important characteristic of the pervious concrete, there is no well-established method for its quantification. Therefore, an experimental procedure to assess the water permeability of pervious concrete is developed.
3) Pervious mortar is developed with modified pore sizes to make the pervious pavement surface smoother. Pervious mortars are evaluated for their physical and engineering properties similar to those for pervious concrete.
4) Pervious concrete and pervious mortar can be combined as a new type of pervious pavement system. Pervious mortar covers the surface of pervious concrete with two different thicknesses, namely, 20mm and 40mm of 80mm of the pervious pavement system. The water permeability of the pervious pavement system was evaluated.

1.4 Limitation

1) This study is limited to understand the properties of pervious concrete with selected materials of construction and compositions.
2) The performance of pervious concrete in the service environment is outside the scope of this study.

1.5 Thesis outline

Chapter 1 provides a brief introduction to pervious concrete and highlights the research objectives and scope of the investigation.

Chapter 2 provides a comprehensive literature survey associated with the present work. Specifications and engineering characteristics, materials used for pervious concrete, main durability and problems, application, and history of pervious pavement using pervious concrete are reviewed.

Chapter 3 presents the experimental details and the methodology adopted in this investigation. The experimental procedure of water permeability developed in this study is outlined.

Chapter 4 presents the results of the experimental investigation and discussion of the results. The properties of pervious concrete and pervious mortar are compared with those for conventional concrete.

Chapter 5 presents the conclusion of this study and others recommendations for further research, followed by the list of references and standards.

Chapter 2

Literature Review

2.1 Specification of pervious concrete and pervious mortar

2.1.1 Definition

Pervious concrete is a high performance concrete which has relatively high water permeability compare to conventional concrete due to interconnected pore structure. Pervious concrete is also termed as porous concrete and permeable concrete. It can be produced using conventional concrete-making materials, namely cement, cement supplementary materials, all types of coarse and fine aggregates, and water. Pervious mortar is produced with fine aggregate without the finest part, binder materials and water.

2.1.2 Advantages and disadvantages

Pervious concrete and mortar show several advantages and disadvantages over conventional concrete [2, 4, 10-14]. From the performance viewpoint, pervious concrete and mortar demonstrate the following advantages, benefiting the environment.

1. Decreasing flooding possibilities, especially in urban areas
2. Recharging the groundwater level
3. Reducing puddles on the road
4. Improving water quality through percolation
5. Sound absorption
6. Heat absorption
7. Supporting vegetation growth

On the other hand, pervious concrete also has some disadvantages:

1. Low strength due to high porosity
2. High maintenance requirement
3. Limited use as a load bearing unit due to its low strength

Pervious concrete cannot be used for the construction of roads that experience heavy traffic. The most significant problem for pervious concrete is clogging, so frequent maintenance is required. Clogging leads to a decrease in water permeability, and also causes a decrease in the advantages of using pervious concrete [15].

2.2 Properties of pervious concrete and mortar

2.2.1 General

Strength and permeability of pervious concrete are found to be affected by several factors including binder types, aggregate type, aggregate grading, mix combination and compaction [2, 6, 7, 13, 14, 16 -18].

(a) too little water (b) proper amount of water (c) too much water

Figure 2.1 Workability assessments for pervious concrete [2]

2.2.2 Workability

Even though a few researchers have reported slump values for pervious concrete, the standard slump test is not suitable for pervious concrete to assess its workability because of lightweight nature of pervious concrete was too small [2, 13, 16]. Tennis et. al. [2] recommended that workability for pervious concrete should be assessed by forming a ball with the hand to established mouldability of pervious concrete (Figure 2.1). Mouldability of pervious concrete is quite sensitive to water content, hence the amount of water should be strictly controlled.

2.2.3 Unit weight (density)

Due to high porosity, pervious concrete is a lightweight concrete. The unit weight of pervious concrete is between 1,500 kg/m^3 and 2,200 kg/m^3 [2, 7, 16, 19, 20].

2.2.4 Porosity (void content or void ratio)

Porosity for pervious concrete is ranged from 15 to 30%. Also, porosity of pervious concrete termed as void content or void ration in percentage. This high porosity leads to a high permeability for the pervious concrete [2, 4, 13, 14, 16-18, 20, 21].

2.2.5 Pore structure of pervious concrete

There are three different types of pores in the pervious concrete, namely, pores in cement paste, aggregate voids, and air voids, as shown in Figure 2.2. Gel pores in cement paste are smaller than capillary pores. Capillary porosity is affected by water/cement ratio and age. These types of pores are either discrete or connected. The air voids are bigger in size and may be connected and responsible for water permeability. It is mainly influenced by aggregate grading and degree of compaction. Aggregate voids vary in size and may or may not be connected and depending upon the types of aggregate used.

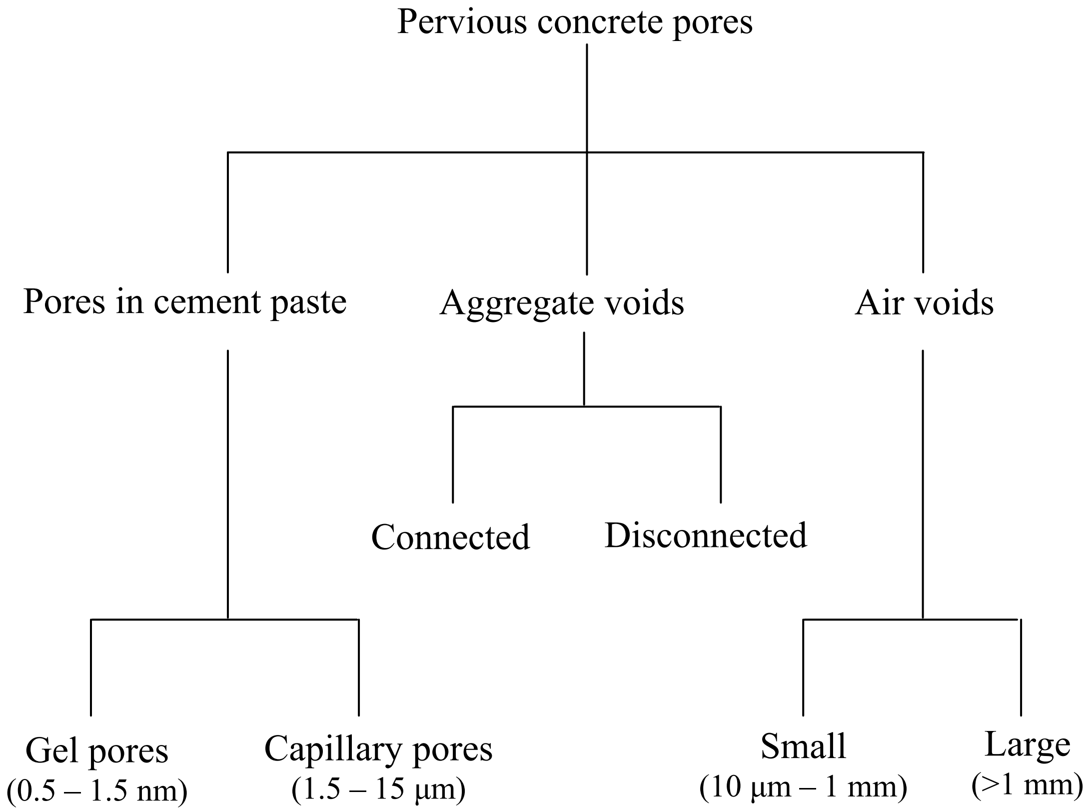


Figure 2.2 Types of pores of pervious concrete

2.2.6 Compressive strength

Because of the high void content, the compressive strength of pervious concrete is lower than that for conventional concrete. The average compressive strength of pervious concrete is around 20 MPa, while the lowest strength of 2.5 MPa and the highest strength of 34.5 MPa are reported [2, 13, 20]. The compressive strength for highly pervious concrete is half or one-third that of conventional concrete.

2.2.7 Water permeability

A wide range of values for water permeability of pervious concrete has been reported. Some researchers have claimed that water permeability of pervious concrete is 1 mm/s to 5 mm/s [16], and others have reported the permeability, between 20 mm/s and 45 mm/s [18, 22]. Hence, the permeability of pervious concrete is typically between 5 mm/s and 20 mm/s. The water permeability of pervious concrete was also reported as the permeability coefficient, intrinsic permeability and hydraulic conductivity.

2.3 Porosity of pervious concrete

2.3.1 Measurement of porosity

Naik and Kraus [23] measured the void ratios of hardened concrete, according to ASTM C137. Schaefer et. al. [12] used an equation reported by Park and Tia [24]. In this method, the void ratio is calculated based on the difference in weight between oven-dry and saturated weights. Safiuddin and Hearn [25] suggested that three types of saturation for pervious concrete influence permeability: (i) cooling-water saturation, (ii) boiling-water saturation (ASTM C 642) and (iii) vacuum saturation (ASTM C 1202). These three types of saturation were employed, and the permeable porosity was measured by the difference in weight between oven-dry, saturated surface-dry and buoyancy. The related equation is as shown below:

$$\text{Permeable Porosity} = \frac{M_s - M_d}{M_s - M_b} \times 100\% \tag{2.1}$$

where M_b = buoyant mass of the saturated specimens in water

M_d = oven-dry mass of the specimens

M_s = mass of saturated surface-dry specimens

According to Safiuddin and Hearn [25] results, vacuum saturation was shown to have the highest permeable porosity.

Matsuo et. al. [18] tested the total air void content and continuous air void content of pervious concrete, using ‘the experimental procedure’ recommended by Japan Concrete Institute (JCI) [26]. There are two methodologies to calculate the total porosity; first method is based on volume, and second one is based on mass. The void content determined by volume methodology is given by Equation 2.2,

$$A_t = 1 - \frac{(M_2 - M_1)/\rho_w}{V_1} \times 100 \tag{2.2}$$

where A_t = total air void content of porous concrete

M_1 = buoyant mass of the saturated specimens in water

M_2 = dry mass in the air for 24 hours

V_1 = total volume of specimens

ρ_w = density of water

The void content based on mass is methodology given by Equation 2.3,

$$A_t = \frac{T - W}{T} \times 100 \tag{2.3}$$

where A_t = total air void content of porous concrete

T = mass of unit volume in the assumption of no air

W = mass of unit volume in the container

Mass of unit volume in the assumption of no air (T) is given by Equation 2.4:

$$T = \frac{W_4}{V_2} \tag{2.4}$$

where W_4 = total mass of all materials on the concrete of 1m^3

V_2 = sum of absolute volume of all materials on the concrete of 1m^3

Absolute volume in this equation means each mass of every material divided by each density.

Mass of unit volume in the container (W) is calculated by Equation 2.5;

$$W = \frac{W_3}{V_1} \tag{2.5}$$

where W_3 = mass in the air after 24 hours

V_1 = total volume of specimen

There is one methodology given by JCI [26] to determine the continuous air void content of porous concrete and it is given by Equation 2.6,

$$A_c(\%) = A_t - \frac{(M_1 - M_{3)} / \rho_w}{V_1} \times 100 \tag{2.6}$$

Where A_c = continuous air void content

A_t = total air void content of porous concrete

M_1 = buoyant mass of the saturated specimens in water

M_3 = buoyant mass of the saturated specimens in water after 24 hours drying in the air

V_1 = total volume of specimens

ρ_w = density of water

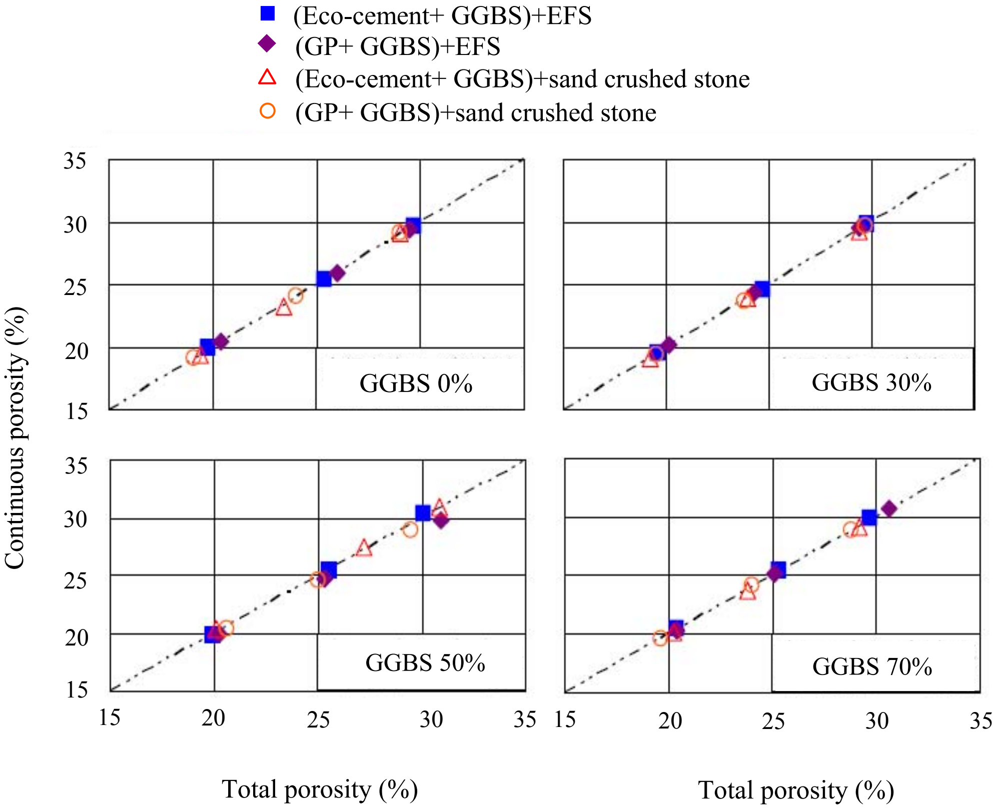


Figure 2.3 Linear relationships between total porosity and continuous porosity [18]

2.3.2 Relationship between continuous porosity and total porosity

Matsuo et al. [18] used electric arc furnace oxidising slag (EFS) aggregate and evaluated whether it could be used as aggregate for porous concrete. Even though there was EFS in concrete, the relationship between total air void content and continuous air void content was the same as that of the concrete made by natural aggregate as shown in Figure 2.3. Matsuo et al. [18] also compared the content of ground-granulated blast-furnace slag (GGBS) content: 0%, 30%, 50%, and 70%. There was no significant difference with or without GGBS. Total air void content increased with increased continuous air void content.

2.3.3 Vertical porosity distribution

Haselbach and Freeman [14] asserted that distribution of porosities of pervious concrete has serious influence on the water permeability, therefore the porosities need to be determined. They calculated the theoretical porosity distribution at the height of ‘y’ by the Equation 2.7,

$$P_y = P + \left(1 - \frac{2y}{h}\right)\left(C_c - \frac{PC_c}{100}\right) \tag{2.7}$$

where P_y = theoretical porosity at the height ‘y’

P = average porosity

C_c = percent volumetric compaction of the column

y = height

h = total height

Haselbach and Freeman [14] compared this theoretical vertical porosity distribution with experimental porosity, which is the weighted average porosity taken at three different heights: top quarter, middle half and bottom quarter. The relationship between vertical porosity and experimental porosity are shown in Figure 2.4. The top of the specimens shows the lowest porosity and the bottom of the specimens shows the highest porosity. It can also be predicted by a theoretical methodology. They concluded that this is significantly important to determine the physical characteristics of pervious concrete. For example, they claimed that the clogging location can be predicted by this theoretical procedure.

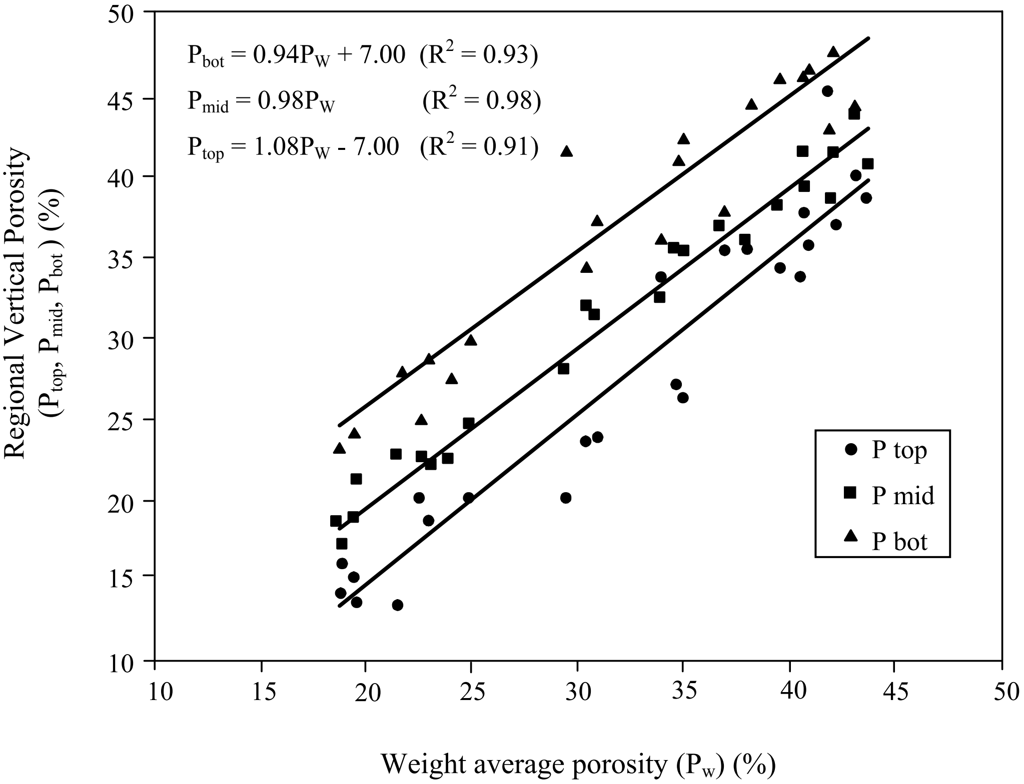


Figure 2.4 Weighted average porosity versus regional vertical porosities [14]

2.3.4 Porosity of theoretical pervious concrete

Bentz [27] illustrated the virtual pervious concrete microstructure using the NIST hard core/soft shell (HCSS) model. These virtual models are shown in Figure 2.5. This HCSS model can illustrate the three-phase materials, such as hard core spherical particle, soft shell, and bulk phase. In Bentz's research [27], the pervious concrete aggregates are shown as hard core materials, cementitious materials are demonstrated as soft shell, and voids are presented as bulk phase. In this model, the hard core models are surrounded by soft shell and put into the bulk phase. In Figure 2.5, four different porosities are shown; (a) 27.3%, (b) 22.4%, (c) 18.0% and (d) 14.1%. In this figure, aggregates are shown as dark circles, cementitious materials are shown as white, and voids are shown as black.

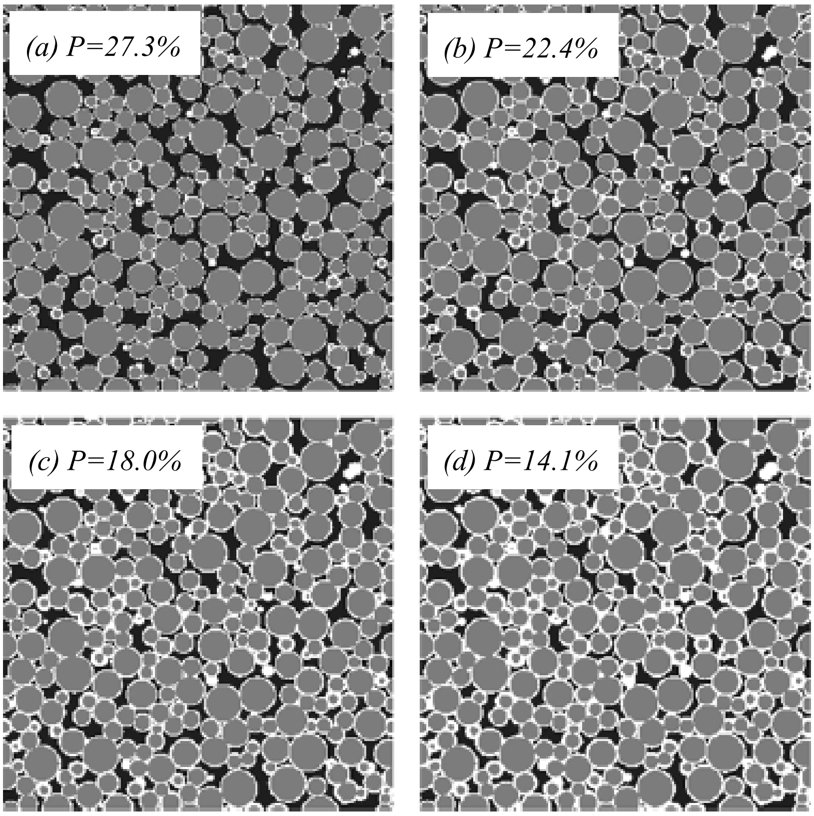


Figure 2.5 Two-dimensional images from 3D virtual pervious concrete microstructures based on hybrid HCSS model [27]

Bentz [27] also demonstrated another virtual microstructure of pervious concrete to compare with the HCSS model. This methodology is calculated by filtered correlation reconstruction models and is shown in Figure 2.6. In this model, percolation and transportation are emphasised, rather than the aggregate structures which can be shown in the HCSS model. Therefore, the porosities are illustrated as black areas in Figure 2.6, while aggregate and cementitious materials are shown as white areas. The porosities of Figure 2.6 are similar to Figure 2.5. Visually, the HSCC model demonstrates more detail than the filtering model, due to the fact that the HCSS model can show the three phases. It is similar to real porosities in pervious concrete. This methodology is critical to predict porosities.

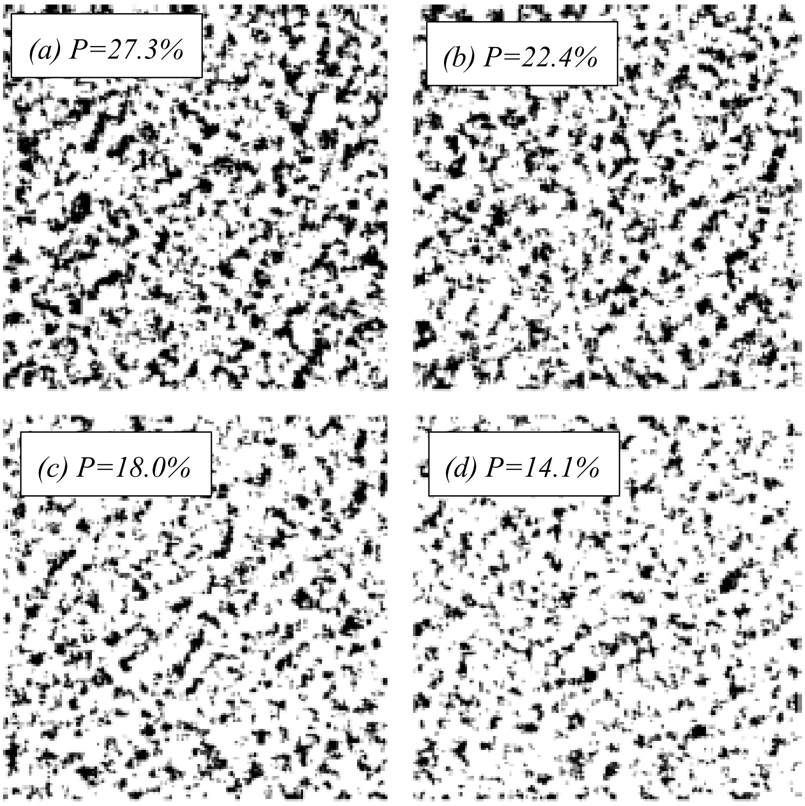


Figure 2.6 Two-dimensional images from 3D virtual pervious concrete microstructures based on correlation field reconstruction algorithm [27]

2.4 Compressive strength of pervious concrete

2.4. 1 Effect of porosity on compressive strength

Schaefer et al. [12] found a linear relationship between the compressive strength and the void ratio (Figure 2.7). According to this correlation, the low void content leads to the high compressive strength. They also developed a relationship between compressive strength and void content as shown in Equation 2.8.

$$\text{Compressive strength (MPa)} = 4762.1 - 97.16 \times [\text{void ratio (\%)}] \quad (2.8).$$

Matsuo et al. [18], who used electric arc furnace oxidising slag (EFS) aggregate, performed the compressive strength test developed by the Japan Concrete Institution [26]. Figure 2.8 shows the relationship between compressive strength and total void ratio. There is no significant effect GGBS on the strength-void ratio relationship was noted. The compressive strength decreases from 20 MPa to 10 MPa when the total porosity content was increased from 20% to 30%.

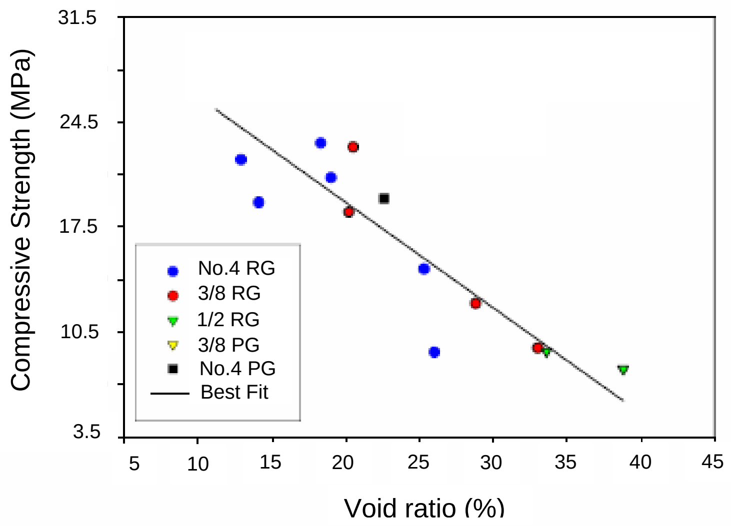


Figure 2.7 Relationship between compressive strength and void content [12]

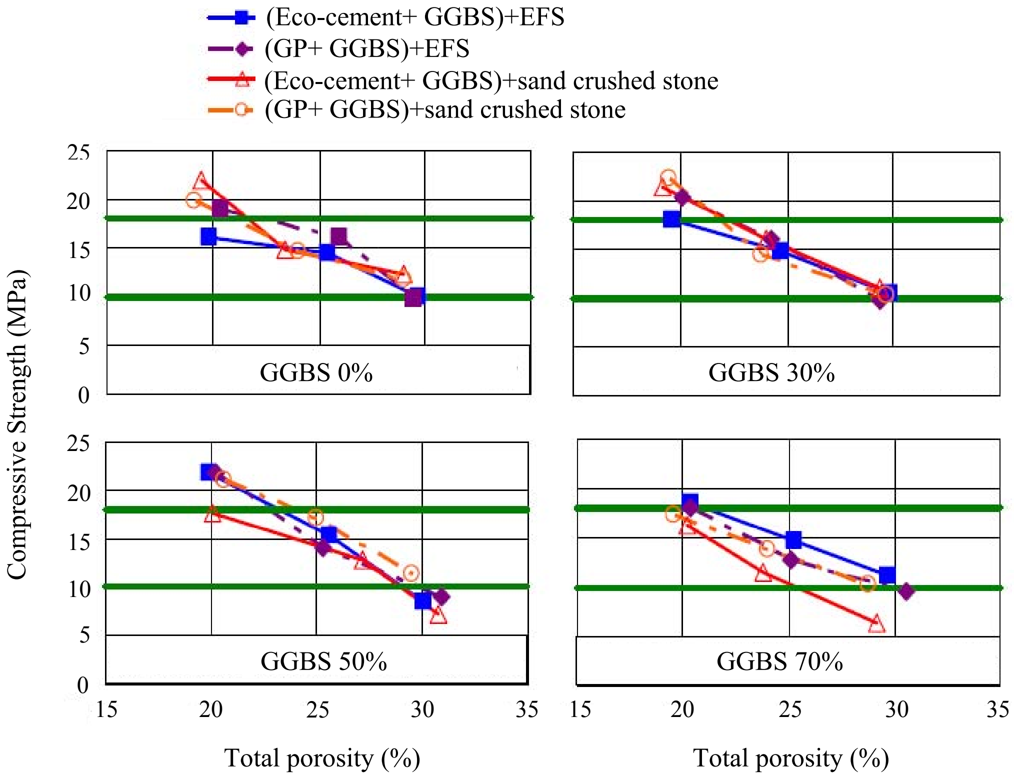


Figure 2.8 Effect of total porosity content on compressive strength [18]

2.4.2 Effect of compaction energy on compressive strength

Ghafoori and Dutta [16] showed the relationship between the compaction energy and compressive strength for no-fines concrete having different aggregate to cement ratios, as shown in Figure 2.9. They reported that increased compaction energy can lead to improved compressive strength.

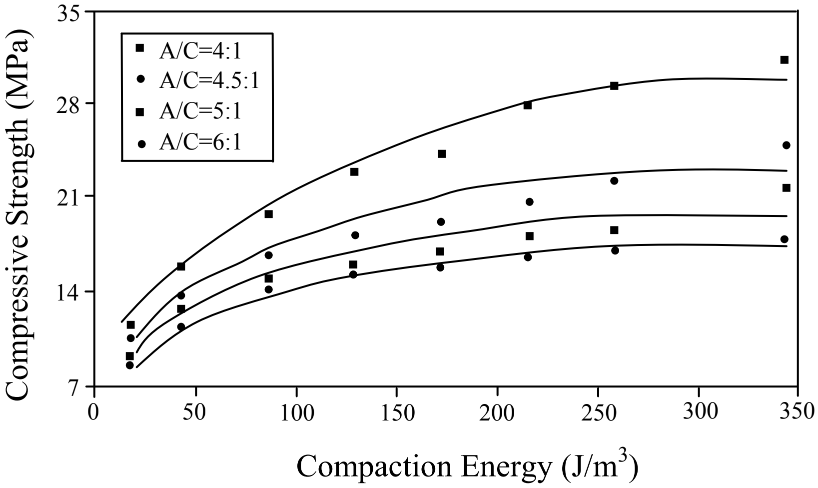


Figure 2.9 Effect of compaction energy on compressive strength for no-fines concrete [16]

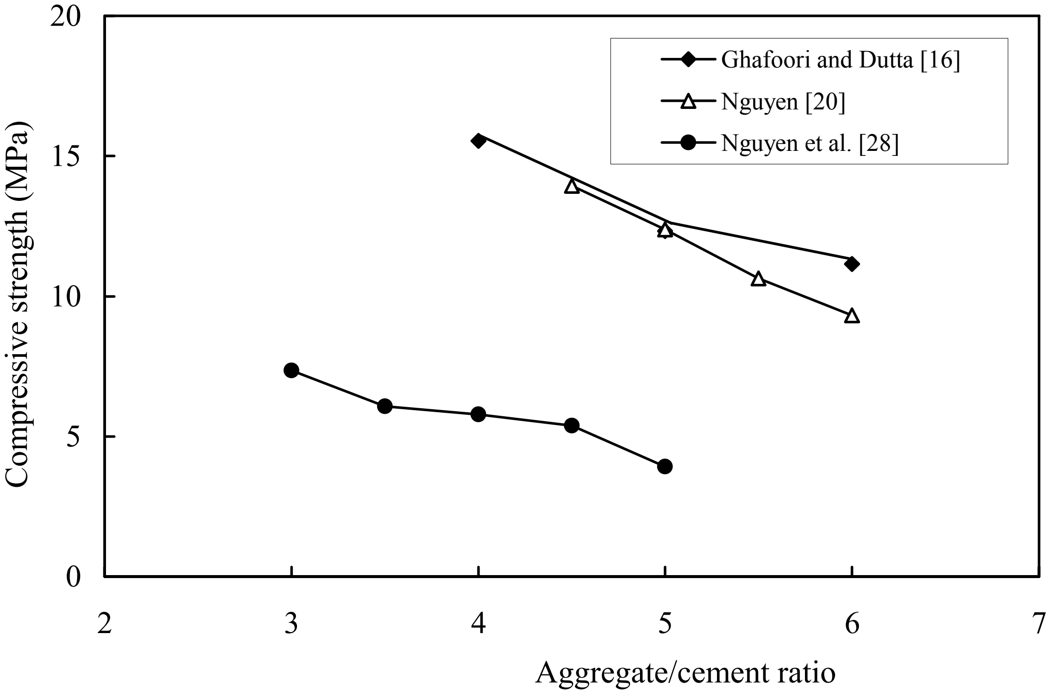


Figure 2.10 Effect of aggregate/cement ratio on compressive strength [16, 20, 28]

2.4.3 Effect of aggregate/cement ratio on compressive strength

Figure 2.10 shows the relationship between compressive strength and aggregate/cement ratio [16, 20, 28]. When the aggregate to cement ratio was increased, the compressive strength of pervious concrete was decreased. Moreover, the increased cementitious materials content can result in increased compressive strength.

2.4.4 Effect of binder materials on compressive strength

Naik and Kraus [23] showed unique results of compressive strength using three kinds of Coal Combution Products (CCP) ash, as binder materials. The physical properties of CCPs are shown in Table 2.1. Some of the results showed a decrease in compressive strength, and others showed the opposite.

Table 2.1: Physical properties of Coal Combution Products (CCPs) [23]

Test Parameter	Ash Source Number			ASTM C 618	
	CCP-1	CCP-2	CCP-3	CLASS C	CLASS F
Retained on 45μm sieve (%)	23.7	29.5	21.7	34Max	34Max
Strength Activity Index with (%)					
3-day	-	-	108	-	-
7-day	60	87	110	75 min	75 min
28-day	61	116	130	75 min	75 min
Water Requirement (% of control)	107	112	92	105 Max	105 Max
Autoclave Expansion (%)	0.05	0.26	0.05	±0.80	±0.80
Specific Gravity	2.64	2.17	2.58	-	-
Variation from Mean (%)					
Fineness	2.3	2.0	5.3	5.0 Max	5.0 Max
Specific Gravity	1.1	6.0	1.9	5.0 Max	5.0 Max

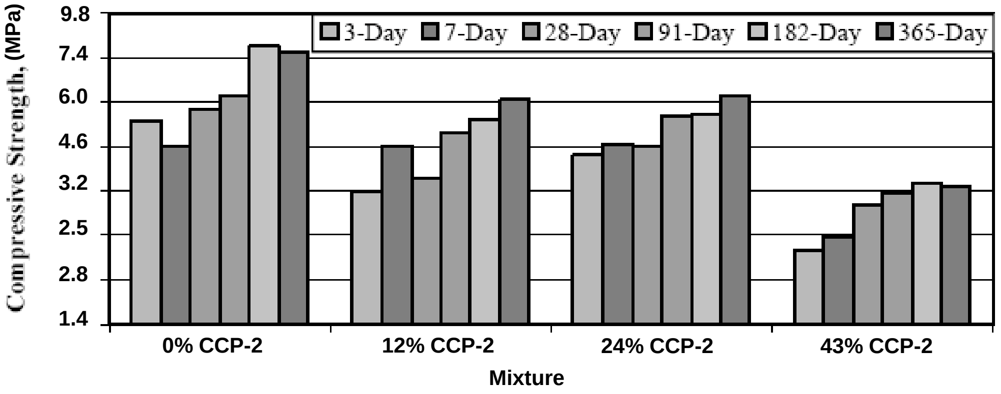


Figure 2.11 Compressive strength of pervious concrete with CCP-2 [23]

The effect of binder material types on compressive strength is shown in Figure 2.11. This is a result of CCP-2 (which is a high-carbon, sulfate-bearing coal combustion product) concrete without fine sand. According to this research, an increase in the CCP-2 content causes a decrease in compressive strength.

2.5 Water permeability of pervious concrete

2.5.1 Falling head test method

ACI [11] recommended that the falling head method developed by Neithalath et al. [4] could be used to determine the water permeability of pervious concrete. The schematic diagram of the falling head method for permeability testing is given in Figure 2.12.

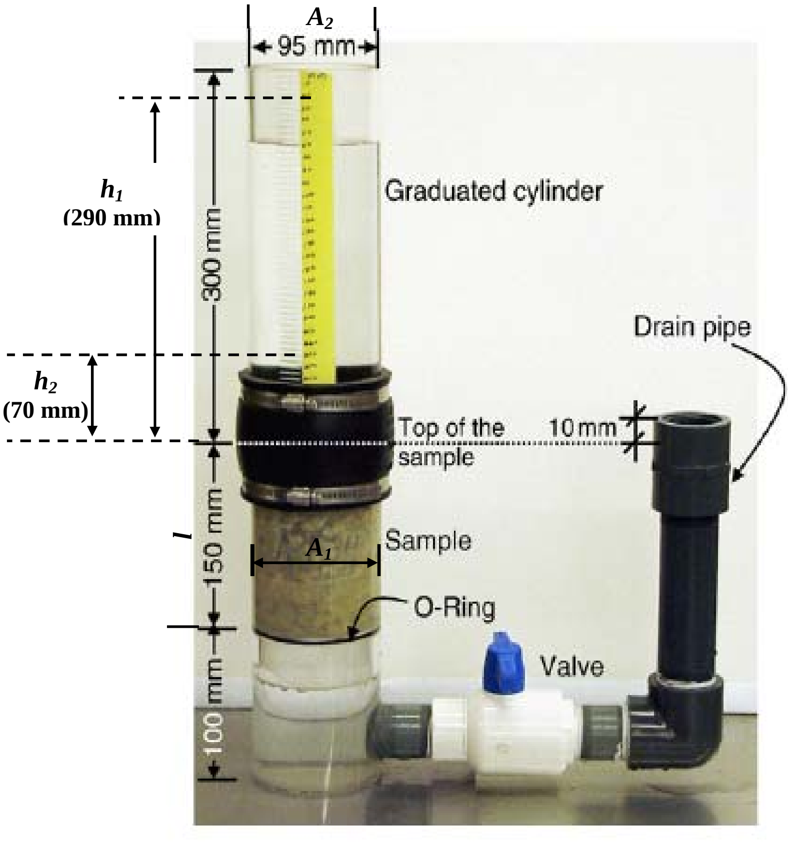


Figure 2.12 Falling head method for permeability testing [4]

The falling head method, illustrated by Neithalath et al. [4], measures the time taken by water level to fall from initial water head to the final water head, and water permeability is then calculated using Darcy’s First Law. The equation is as follows:

$$k = \frac{A_1 l}{A_2 t} \log \left(\frac{h_2}{h_1} \right) \tag{2.9}$$

where k = water permeability

A_1 =cross-sectional area of the specimen

A_2 = cross-sectional areas of the tube (95 mm)

l = length of the specimen (150 mm)

t = time

h_1 = the initial water head (290 mm)

h_2 = the final water head (70 mm)

For a given specimen geometry, and same cross-sectional area, the permeability coefficient is given as Equation 2.10,

$$k = \frac{A}{t} \tag{2.10}$$

where A = constant (= $\frac{A_1 l}{A_2} \log\left(\frac{h_2}{h_1}\right)$ =0.084 m)

t = time required for water to fall from an initial head to a final head

Schaefer et al. [12] also determined permeability by using the falling head method, and calculated it by the Equation 2.9.

2.5.2 Constant head test method

Matsuo et al. [18] investigated the constant head method suggested by the Japan Concrete Institute [26]. The method is illustrated in Figure 2.13. The average water permeability of pervious concrete is 20 mm/s for 20% void content, and increased to 40 mm/s for a 30% void content [18].

Matsuo et al. [18] calculated the water permeability by constant head method using Darcy's First Law shown as Equation 2.11.

$$k_T = \frac{l}{h} \times \frac{Q}{A(t_2 - t_1)} \tag{2.11}$$

where k_T = water permeability at Tc°

l = length of specimen

Q = quantity of water

h = head difference

$t_2 - t_1$ = time

A = cross sectional area of specimen

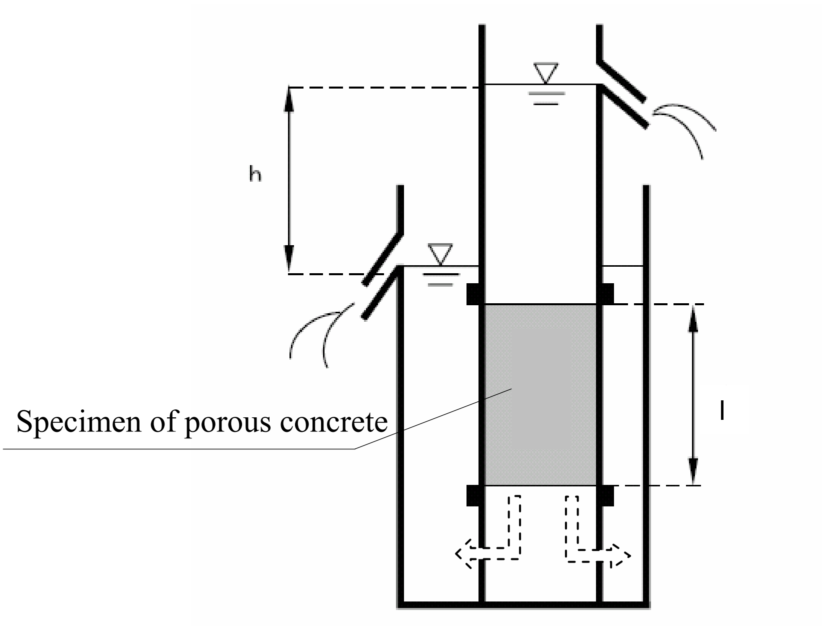


Figure 2.13 Constant head method for permeability testing [18]

2.5.3 Relationship between water permeability and porosity

The water permeability can be related to void ratio as shown in Figure 2.14. According to Schaefer et al. [12], the Equation 2.12 can be used for estimating permeability based on the void ratio.

$$\text{Permeability (mm/s)} = 13.74\times e^{(13.68\times\text{void ratio})} \qquad (2.12).$$

Ghafoori and Dutta [16] defined a numerical relationship between permeability and the air content of pervious concrete. This is shown in Figure 2.15. The permeability can be given by the following Equation 2.13:

$$k = 0.00091(\mathrm{G})^{3.72} \qquad (2.13).$$

where k = water permeability

G = gravimetric air void ratio

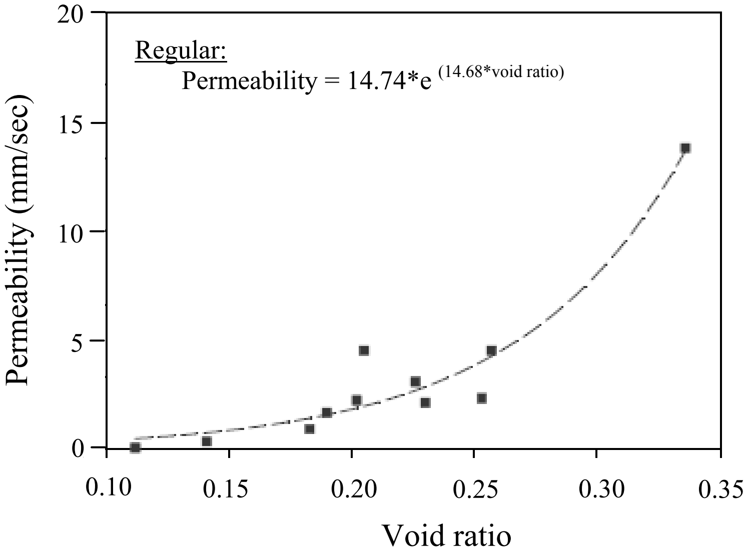


Figure 2.14 Relationship between permeability and void ratio [12]

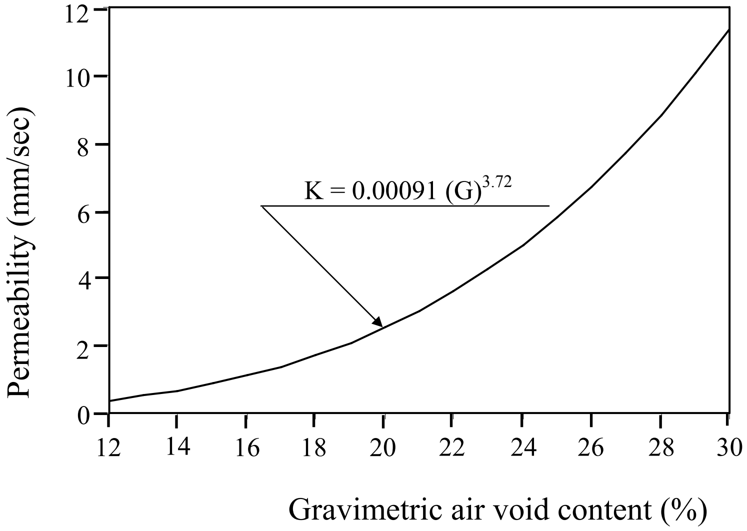


Figure 2.15 Relationship between permeability and air void content [16]

2.5.4 Water permeability by Kozeny-Carman Equation

Neithalath et al. [4] considered that they had found a quite unique fact. They expressed that even though permeability can normally be determined by using Darcy's First Law, there is no definitive relationship between porosity and permeability. The distribution of pores has also a significant influence on permeability, as well as porosity as shown in Figure 2.16.

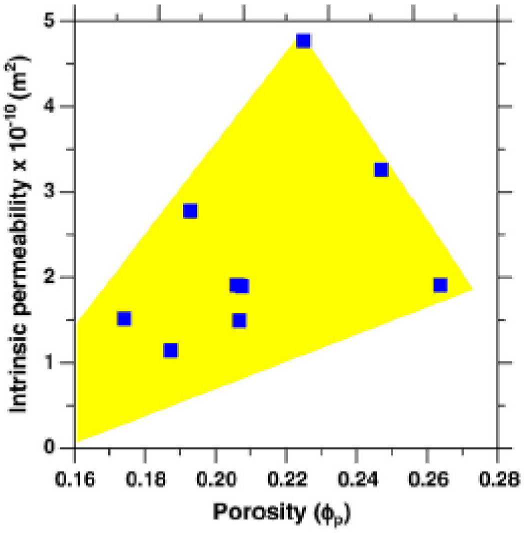


Figure 2.16 Relationship between porosity and permeability [4]

Neithalath et al. [4] conducted that the Kozeny-Carmen Equation shows a more specific relationship between water permeability and porosity, because it includes the influential factors for permeability, such as porosity, pore-size, distribution, pore roughness, construction of the pore space, and the tortuosity and connectivity of the internal pore channel. The Kozeny-Carman Equation is as follow:

$$k = \frac{\phi_P^3}{F_s \tau^2 S_0^2 (1-\phi_P)^2} \tag{2.14}$$

where k = water permeability

φ_P = porosity

F_s = generalized factor to account for different pore shapes

τ = tortuosity

S_0 = specific surface area of pores

This equation shows the relationship between k and the hydraulic connectivity factor (β_H). The hydraulic connectivity factor is shown as following equations.

$$\beta_H = \frac{1}{F_s S_0^2} \left[\sigma^*_{norm}\right]^2 \tag{2.15}$$

where σ^*_{norm} is

$$\sigma^*_{norm} = \left[\frac{\phi_P}{\tau}\right]^2 \tag{2.16}$$

Therefore, the hydraulic connectivity factor is a combination of the pore space volume and geometry, whereas the intrinsic permeability is the relation between porosity and the hydraulic connectivity factor. Figure 2.17 shows the relationship between the hydraulic connectivity factor and intrinsic permeability.

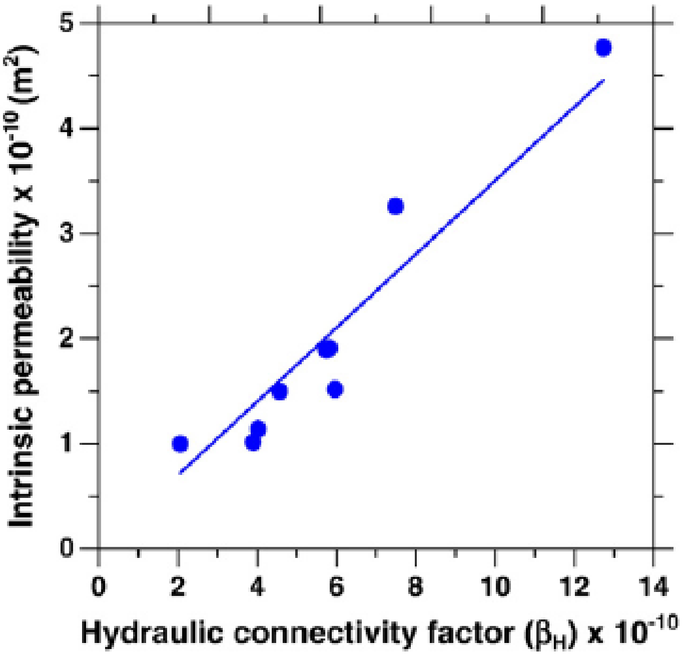


Figure 2.17 Intrinsic permeability (*k*) versus hydraulic connectivity factor (β_H) [4]

Montes and Haselbach [29] established the relationship between hydraulic conductivity and porosity by using the Kozeny-Carman Equation. They simplified the Equation 2.14 to Equation 2.17:

$$k_s = \alpha \left[\frac{p^3}{(1-p)^2} \right] \tag{2.17}$$

where k_s = hydraulic conductivity

p = porosity

α is given by Equation 2.18;

$$\alpha = \frac{gC_0}{vA_s} \tag{2.18}$$

where g = gravitational acceleration

C_0 = empirical constant

v = kinematic viscosity of water

A_s = specific surface area of materials

Montes and Haselbach [29] determined the factor α experimentally, due to the fact that some of the factors are difficult to define. They measured the water permeability by the falling head method which was shown as Equation 2.19 in Section 2.5.2. Table 2.2 summarises their results on water permeability for pervious concrete. The samples which were used to investigate hydraulic conductivity were taken from different field areas.

Table 2.2: Porosity and hydraulic conductivity for pervious concrete [29]

Sample number	location	porosity (%)	Hydraulic conductivity (mm/s)
A5b	Edisto	0.15	0.1
A5d	Edisto	0.16	0.3
B20b	Spartanburg	0.17	1.3
B20c	Spartanburg	0.19	2.4
B20d	Spartanburg	0.15	1.8
B22a	Spartanburg	0.24	2.7
B22b	Spartanburg	0.18	1.5
B22c	Spartanburg	0.22	1.5
B22d	Spartanburg	0.25	4.0
C4a	Charleston	0.25	4.6
C4b	Charleston	0.30	7.8
C4d	Charleston	0.27	8.7
C11a	Charleston	0.30	9.4
C11b	Charleston	0.32	13.2
C11d	Charleston	0.31	11.9

The relationship between hydraulic conductivity and porosity are shown in Figure 2.18 which was derived using the Marquadt method of the NLIN procedure in the SAS/STAT version 8.2 statistical software [30]. According to this model, the factor of α is well fitted as 17.9±2.3. Therefore, Montes and Haselbach [29] defined the Kozeny-Carman Equation as Equation 2.19:

$$k_s = 18 \left[\frac{p^3}{(1-p)^2} \right] \tag{2.19}$$

They suggested that this equation could be used as a design form for pervious concrete stormwater systems.

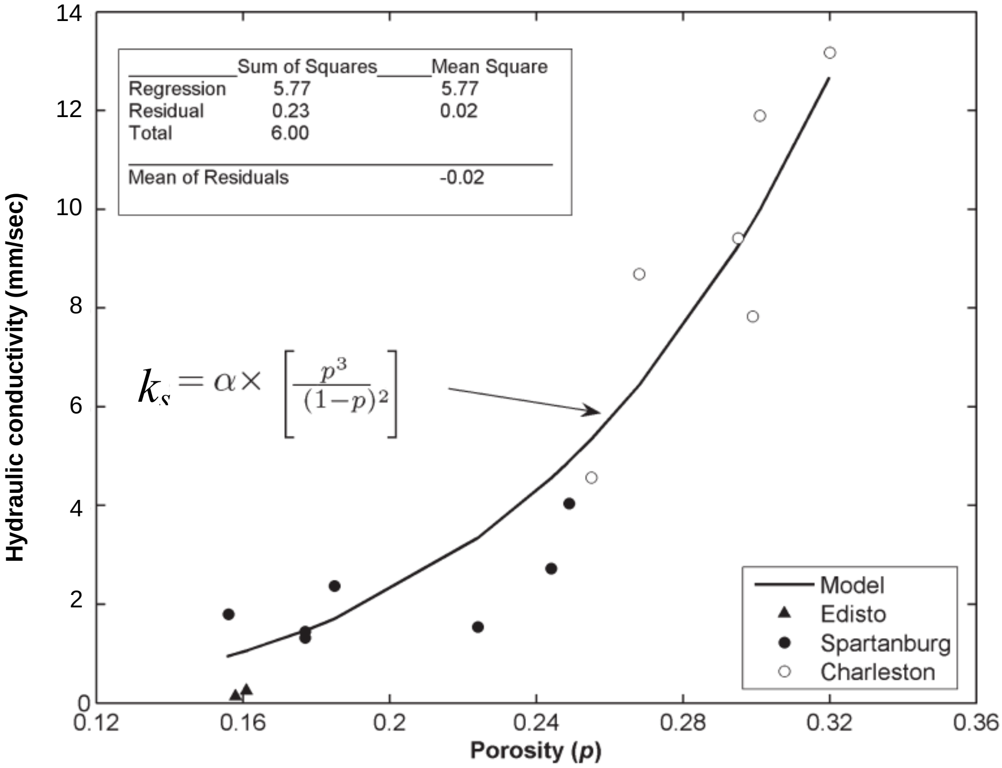


Figure 2.18 Model resulting from the nonlinear fitting of the saturated hydraulic conductivity and total porosity data to the Kozeny-Carman Equation [29]

2. 6 Drying shrinkage of pervious concrete

According to Tennis et al. [2], shrinkage of pervious concrete occurs rapidly but it is much lower than that of conventional concrete. They suggested that this might be due to the low cement paste and mortar content in pervious concrete.

Ghafoori and Dutta [16] suggested that the rapid drying shrinkage is influenced by the large surface area. The drying shrinkage of pervious concrete is half that of conventional concrete. In addition, the effect of aggregate/cement ratios on drying shrinkage is also reported (Figure 2.19). Similar to conventional concrete, an increase in aggregate content reduces the shrinkage of pervious concrete.

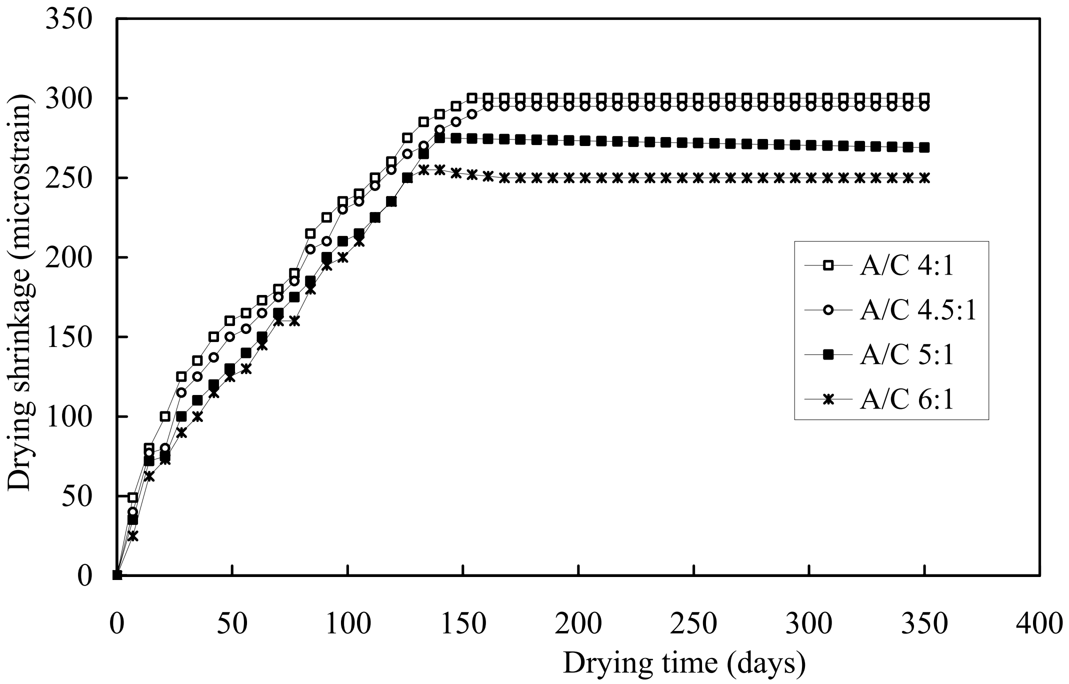


Figure 2.19 Drying shrinkage of pervious concrete [16]

2.7 Materials for pervious concrete and pervious mortar

2.7.1 Binder materials

For pervious concrete, Portland cement is used as the cementitious material. Eco-cement or blended cement have also been used. Matsuo et al. [18] used eco-cement and normal Portland cement, and claimed that there was no significant difference between them.

Supplementary cementitious materials such as fly ash, natural pozzolans, ground-granulated blast furnace slag, and silica fume were used in some studies. The use of latex and silica fume led to decreased compressive strength [12]. However, latex showed higher permeability, compared to other cementitious materials. Naik and Kraus [23] used three types of Coal-Combustion Product (CCP); some CCPs have higher compressive strength or better durability than others. Also, Yang and Jiang [13] used vinyl acetate-ethylene emulsion (VAE) and polyvinyl alcohol formaldehyde hydrosol (PAF). VAE produced high compressive strength, while decreasing permeability. On the other hand, PAF decreased the compressive strength and increased the permeability.

2.7.2 Coarse aggregate

Rounded gravel and angular crushed stone or crushed limestone are used as coarse aggregate for pervious concrete, in single size or narrow gradation size. The average sizes of coarse aggregate are 3.75 mm to 9.5 mm and 9.5 mm to 12.5 mm. Some researchers used fine aggregate such as 0.5 mm to 1.18 mm; other researchers used coarser aggregate, such as 25 mm to 30 mm. Tennis et al. [2] used a narrow gradation size aggregate, sized between 3.75 mm and 19.0 mm, 2.36 mm and 9.5 mm, or sized from 0.5 mm to 1.18 mm. Schaerer et al. [12] used two types of gradation aggregate, known as pea gravel. Yang and Jiang [13] investigated different sizes of coarse aggregate. They concluded that finer aggregate leads to increased compressive strength, with decreased permeability. In the case of Matsuo et al. [18], they developed an electric arc furnace oxidising slag (EFS) as a coarse aggregate. No significant difference was observed between crushed stone and EFS. Therefore, they claimed that EFS can be used for pervious concrete.

Zhuge [31] used recycled aggregate as coarse aggregate for permeable concrete base-course materials. The pervious concrete using recycled aggregate were compared with the pervious concrete using marble or dolomite. As a result, the recycled aggregate pervious concrete showed significantly low compressive strength with similar void content and water permeability. Regarding the other condition of the coarse aggregate, Tennis et al. [2] suggested that coarse aggregate requires a saturated surface-dry condition or moist condition, because properties of pervious concrete are very sensitive of amount of water in the mix.

2.7.3 Fine aggregate

Normally, fine aggregate is not used in pervious concrete mixes. However, some researchers have used it to improve the compressive strength of pervious concrete. Neithalath et al. [4] and Naik and Kraus [23] added fine sand to pervious concrete. According to Neithalath et al. [4], they added various amount of fine river sand, 2.5, 4.0 and 6.5% of total aggregate by weight, respectively. In Naik and Kraus's research [23], the coarse aggregate replaced not only the fine sand but also CCPs. They found out that adding fine aggregate can result in higher strength than in no-fines pervious concrete, but it also can result in lower permeability.

2.7.4 Admixture

Several chemical admixtures can be applied to pervious concrete to obtain special properties, including retarders, hydration-stabilising admixture, water-reducing admixture and air-entraining admixture. These admixtures are also used for the same reasons in conventional concrete. For example, retarders are used to stabilise and control cement hydration, and an air-entraining admixture is used for freeze–thaw durability. ACI [11] recommended that accelerators should be used for cold weather, and a retarding admixture should be used for hot weather. Styrene butadiene rubber (SBR) has been used to improve the cement paste aggregate bond strength and the freeze–thaw durability [12].

2.7.5 Water

Water quality used in pervious concrete should be the same as that used in conventional concrete: potable water, recycled water from the concrete industry, or tap water. Due to the sensitivity of pervious concrete, water quality control is very important [2].

2.8 Mix proportion of pervious concrete

According to Tennis et al. [2] and Ghaffori and Dutta [16], the water/cementitious-materials ratio for pervious concrete is normally around 0.3 to 0.4. It is lower than for conventional concrete. Tennis et al. [2] recommended that a water/cement ratio of 0.27 to 0.30 is possible when it is made by adding an admixture. The optimum water/cement ratio for pervious concrete is very important due to the mouldability of pervious concrete.

The optimum aggregate/cement ratio ranges from 4:1 to 4.5:1 by mass [2]. Ghaffori and Dutta [16] tried four different aggregate cement ratios such as 4:1, 4.5:1, 5:1, and 6:1. According to their results, a high amount of aggregate led to increased permeability and dramatically decreased compressive strength.

2.9 Durability of pervious concrete

According to ACI [11], there is little research associated with the resistance of sulfate-bearing or acidic water on the durability of pervious concrete. Meanwhile, there is inadequate documentation regarding the freeze–thaw resistance of pervious concrete.

2.9.1 Freeze–thaw resistance

Pervious concrete has a high level of inter-connected air voids. When runoff water flows into pervious concrete in cold weather, it freezes inside the pervious concrete. This can lead to pressure on the thin cement paste coating area of the pervious concrete; pervious concrete is therefore not suitable for dry-freeze conditions. Some authors have researched the freeze–thaw durability of pervious concrete. Naik and Kraus [23], Kevern et al. [32] and Schaefer et al. [12] performed laboratory experiments, according to ASTM C665. Figure 2.20 shows the specimens for freeze-thaw durability testing [32].

Figure 2.20 Freeze-thaw resistance test for pervious concrete [32]

ACI [11] does not recommend this standard, because it is difficult to simulate field performance of pervious concrete. Naik and Kraus [23] reported that pervious concrete with sand, latex or other special aggregates, such as coal combustion products (CCP), can demonstrate better performance than typical pervious concrete. Adding these aggregates improved not only the strength, but also the freeze-thaw durability. In contrast, NRMCA [33] conducted a case study of freeze-thaw durability in several field locations in the USA, where the freeze-thaw cycle occurs 50 to 90 times per year. The pervious concrete showed acceptable results in wet-freeze conditions, but ACI [11] has suggested that pervious concrete should not be used in a freeze–thaw condition, particularly in areas with a high groundwater level.

2.9.2 Sulfate resistance

According to Tennis et al. [2], aggressive chemical resistance such as acid and sulfate resistance of pervious concrete is similar to that of conventional concrete. Nevertheless, pervious concrete can be influenced more than conventional concrete, because of its structural characteristics. Naik and Kraus [23] performed a sulfate resistance test, following ASTM C 1012. The concrete was mixed with three types of CCPs. According to their results, the pervious concrete mixed with CCP showed lower sulfate resistance than that without CCP. They did not conduct any permeability test or void content tests, and accordingly, the relation between CCP, sulfate resistance and permeability is not clear.

2.9.3 Abrasion resistance

Tennis et al. [2] suggested that abrasion and ravelling might be problems for pervious concrete, because of its rough surface. They also pointed out that pervious concrete has limits to its use, because of this low abrasion resistance. Ghafoori and Dutta [16] reported the abrasion resistance of pervious concrete is influenced by compaction energy and aggregate/cement ratio. The low compaction energy and high aggregate/cement ratio led to low abrasion resistance.

Figure 2.21 Pervious concrete blocks in Lake Eacham (Northern Queensland)

2.10 Long term performance of pervious concrete

ACI [11] indicated that there is limited information about the long-term performance of pervious concrete. The performance of pervious concrete refers to clogging, surface ravelling and so on. Visual observation of precast pervious concrete blocks used in Lake Eacham where about 70 km from Cairns, Australia, shows the effective functioning of concrete of pervious concrete for a number of years (Figure 2.21).

2.10.1 Clogging

The most significant problem for pervious concrete is clogging (Figure 2.22), because of its high porosity. Mallen [15] undertook a field test of pervious concrete pavement in Kogarah municipality, which is located approximately 15 km from Sydney central business district. This field test had been carried out for 21 months. According to Mallen's results, the water permeability was reduced by 97% over 21 months, because of clogging by sediments and organic matters. This shows that performance of pervious concrete can be significantly affected by the surface condition.

Figure 2.22 Pervious concrete clogging [2]

Haselbach et al. [17] have investigated the effect of sand clogging on permeability, both theoretically and experimentally. In the case of theoretical analysis, they simplified the porosity structure (Figure 2.23) and calculated the permeability of the pervious concrete by the following Equation 2.20:

$$k_{eff} = \left(\frac{A_p}{A_B} \right) k_{sand} \tag{2.20}$$

where k_{eff} = theoretical effective permeability of sand-clogged or covered pervious concrete block system (cm/s)

k_{sand} = permeability of sand (cm/s)

A_P = surface area of the pervious concrete block occupied by pores (cm^2)

A_B = total surface area of the pervious concrete block (cm^2)

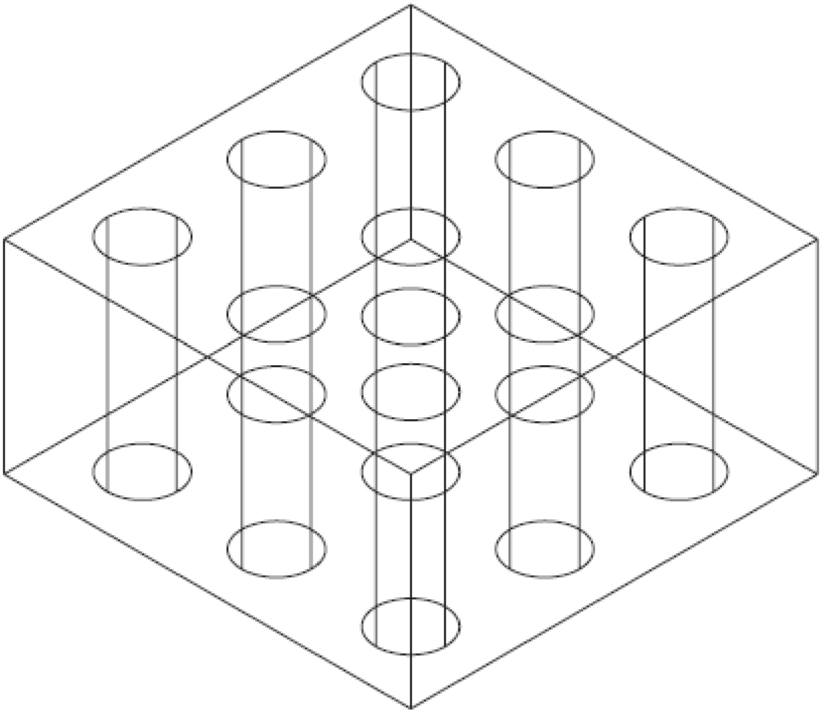


Figure 2.23 Block section of pervious concrete with exaggerated pore structure representing approximately 20% porosity [17]

Haselbach et al. [17] simulated the rainfall and sand clogging of the pervious concrete blocks experimentally. They claimed that clogging simulation of pervious concrete is a challenging research, because it is not possible to fill all the porosity in pervious concrete. Therefore, they assumed that the surface fully covered by sand is the worst situation of sand clogging. The experimental set-up is shown in Figure 2.24.

According to their results, sand clogging reduced the permeability significantly in both theoretical and experimental approaches. Conventional pervious concrete block showed a permeability of 0.2 mm/s, whereas the sand clogging block showed 0.04 mm/s. Therefore, they recommended proper care in the design and maintenance of pervious concrete.

Figure 2.24 Experimental set-up for clogging test [17]

2.10.2 Surface ravelling

Tennis et al. [2] made clear that the surface ravelling of pervious concrete happens at a very early stage. They also stated that there might be optimum compaction and curing techniques to reduce the ravelling. The cause of surface ravelling is heavy loads [11]. Wingerter and Paine [34] conducted a field test in Florida and concluded that surface ravelling is caused by unsuitable water/cement ratio or compaction energy.

2.11 Placing pervious concrete pavement

Two criteria should be considered in the design of pervious concrete. The first criterion is associated with hydraulic factors, such as the permeability and the void content, and the second criterion concerns the engineering properties, such as strength and durability.

The placing method of pervious concrete is different from those for conventional concrete. The significant difference in placement between pervious concrete and conventional concrete is that the pervious concrete cannot be pumped. Since the water/cement ratio of pervious concrete needs to be strictly controlled, pervious concrete placement should be undertaken as quickly as possible. For optimum strength and density, vibrating screeding is used. Steel pipes are then used to compact the pervious concrete. Normally, a bullfloat or trowels are not used for placement, because this would seal the surface. If joints are required, they should be made immediately after consolidation. If they are not made immediately, sawing equipment could be used. Some pervious concrete is made without joints. After placement, pervious concrete should be covered with plastic sheeting as soon as possible, and this is continued for at least seven days.

Figure 2.25 Placing pervious concrete [2]

2.12 Application of pervious concrete

The most typical applications for pervious concrete are for the construction of pavements [2], parking lots [35], light traffic roads [36], river banks and tollgates [37]. Figures 2.26 to 2.30 show the application of pervious concrete. Although pervious concretes have been used in many areas, applications are limited because of its relatively low strength.

Pervious concrete can absorb runoff water, and can percolate pollutants. Some researchers have investigated water quality where pervious concrete blocks have been used [2].

Figure 2.26 Pervious concrete pavement [2]

Figure 2.27 Pervious concrete parking lot [35]

Figure 2.28 Light traffic road [37]

Figure 2.29 River bank [37]

Figure 2.30 Tollgate [37]

2.13 History of pervious pavement

Pervious concrete has been used as one of the main materials for permeable pavement. Permeable pavement systems have become popular in the past decade due to their notable contribution to sustainable drainage systems. Since 19th century, the drainage system has been developed as a pipeline system. However, this traditional system quite often leads to stormwater runoff, especially in urban areas. Thus, this pipeline drainage system is not really efficient. Permeable pavement systems can play a significant role in controlling stormwater runoff, especially in urban areas. Water Sensitive Urban Design (WSUD) has claimed that this system has benefits such as a reduction in the potential for flooding, recharging the groundwater level, and improvement of the water quality [38].

According to EPA [39], the main advantages of pervious pavement are as follows:

1. Water treatment by pollutant removal
2. Less need for curbing and storm sewers
3. Improved road safety because of better skid resistance
4. Recharge to local aquifers.

On the other hand, the disadvantages include:

1. Engineers' lack of experience
2. Clogging if improperly installed and poorly maintained
3. High rate of failure
4. Some risks of contaminating groundwater, depending on soil conditions and aquifer susceptibility
5. Fuel may leak from vehicles, and toxic chemicals may leach from asphalt and/or binder surface. Porous pavement systems are not designed to treat these pollutants
6. Some building codes may not allow for its installation
7. Anaerobic conditions may develop in underlying soils if the soils are unable to dry out between storm events. This may impede microbiological decomposition.

2.14 Specification of pervious pavement

A typical pervious pavement design is shown in Figure 2.31. As a permeable paver unit, pervious concrete block is used as a common practice. In Australia, many researchers have developed various types of paver concrete blocks. HydroSTON [40], shown in Figure 2.32, has been developed by HydroCon Australia Pty Ltd. HydroSTON 50 and 60 can be used for residential areas, such as footpaths, patios and courtyards, while HydroSTON 80 can be used for vehicle areas, such as car parks, car parking bays and minor roads. HydroSton80 shows the highest breaking load, namely 14.0 kN, while HydroSTON50 and 60 shows 4.3 kN and 6.0 kN respectively. However all of them have adequate water permeability, which is approximately 1 mm/s.

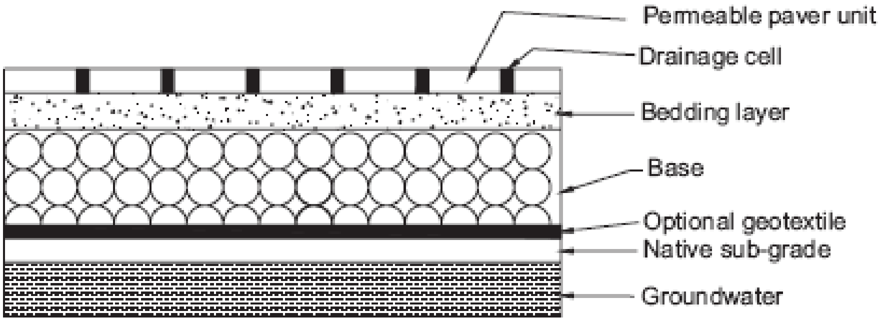


Figure 2.31 Schematic diagram of permeable pavement [38]

Figure 2.32 HydroSTON [40]

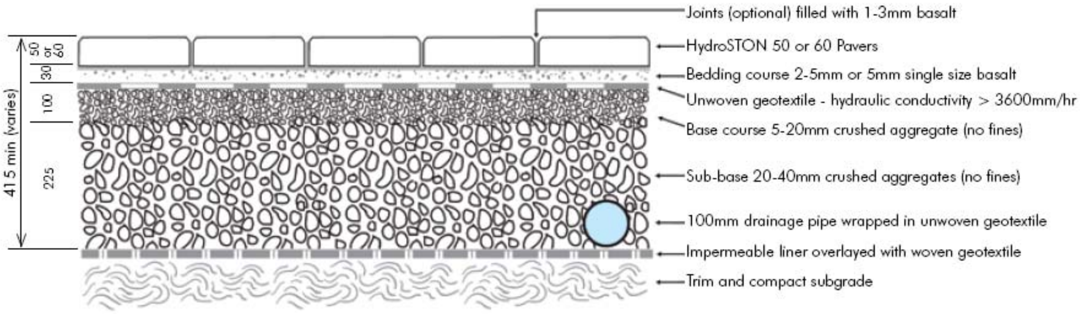


Figure 2.33 Use of HydroSTON for pavement [36]

Shackel and Pearson [19] also investigated eco-paving with pervious concrete blocks. Their findings related to eco-paving were applied in many pavement projects such as

Homebush Olympic Park in Sydney, Smith Street in Manly, and in the town of Kiama. Figure 2.34 shows a general view of the eco-paving employed at Sydney Olympic park. This eco-paving system can lead to a number of environmental benefits, such as minimising water runoff and trapping pollutants.

It can be noted that there are several types of pervious pavement systems, such as porous asphalt, pervious concrete, concrete paving blocks, gravel paving systems, and grass paving system [41]. Pervious concrete is one of the main materials for the construction of pervious pavements.

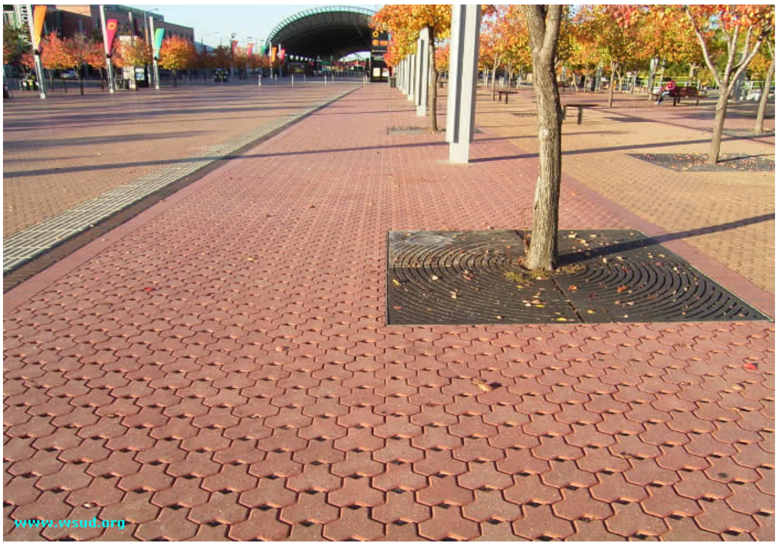


Figure 2.34 Sydney Olympic Park eco paving [19]

2.15 Summary

Pervious concrete is a special type of concrete having relatively high water permeability and porosity with low compressive strength and density. In this section, the engineering properties of pervious concrete were highlighted. The reviewed literatures on pervious concrete are used in the including of the results obtained in the experimental study of the investigation.

Chapter 3

Experimental Investigation

3.1 Introduction

For defining the basic characteristics of pervious concrete, pervious mortar and pervious pavement systems, an experimental investigation was conducted to study the following properties: density, porosity, water permeability, compressive strength, and drying shrinkage. The materials, mixture proportions, measurements and test method used in this study are described in this chapter.

3.2 Materials and mix proportions

3.2.1 Pervious concrete and conventional concrete

Two types of binder materials were used in this study; the first is Type GP Portland cement (AS3972 1997), and the second is fly ash conforming to AS3582 (1998). 10 mm crushed gravel, which is single-size, was used as coarse aggregate. The specific gravity of this aggregate is 2.69. Fine sand and coarse sand were used in equal weight proportion as fine aggregate. The specific gravity of fine and coarse sand is 2.5.

Table 3.1: Mix proportions for pervious and conventional concrete mixes, by weight

Mix	C (%)	F (%)	W/B Ratio	CA/B Ratio	FA/B Ratio
C1	100	0	0.35	2.8	1.4
C2	80	20	0.35	2.8	1.4
P1a	100	0	0.35	4.0	-
P2a	80	20	0.35	4.0	-
P3a	50	50	0.35	4.0	-

C: cement; F: fly ash; B: binder (cement plus fly ash);
W: water: CA: coarse aggregate; and FA: fine aggregate

The basic mix proportion for no-fines pervious concrete is binder materials, coarse aggregate and water: 1.0:4.0:0.35 respectively. Mix P1a contained 100% Portland cement. Mix P2a had 80% of the Portland cement and 20% fly ash by weight. Mix P3a had Portland cement and fly ash in equal weight proportion.

The water/cement ratio was determined by a trial test [2], which consisted of forming a concrete ball with hand, as shown in Figure 3.1. Water/binder ratio of 0.35 is found to be suitable to produce mouldable pervious concrete. Hence, for all pervious concrete mixes this water/ binder ratio was used.

(a) 0.25 (b) 0.30

(c) 0.35 (d) 0.40

Figure 3.1 Mouldability of pervious concrete at different water/cement ratios

Conventional concrete was produced to allow properties comparison with those for pervious concrete. The mix proportion of conventional concrete was binder materials, coarse aggregate, fine aggregate, and water: 1.0:2.8:1.4:0.35, respectively. Mix C1 and Mix C2 had the same definition as the pervious concrete.

Table 3.2: Mix proportions for pervious concrete mixes
with and without fine aggregate by weight

Mix	FA (%)	C (%)	F (%)	W/B Ratio	CA/B Ratio	FA/B Ratio
P1a	0	100	0	0.35	4.0	-
P1b	7.5	100	0	0.35	3.7	0.3
P1c	10	100	0	0.35	3.6	0.4
P2a	0	80	20	0.35	4.0	-
P2b	7.5	80	20	0.35	3.7	0.3
P2c	10	80	20	0.35	3.6	0.4

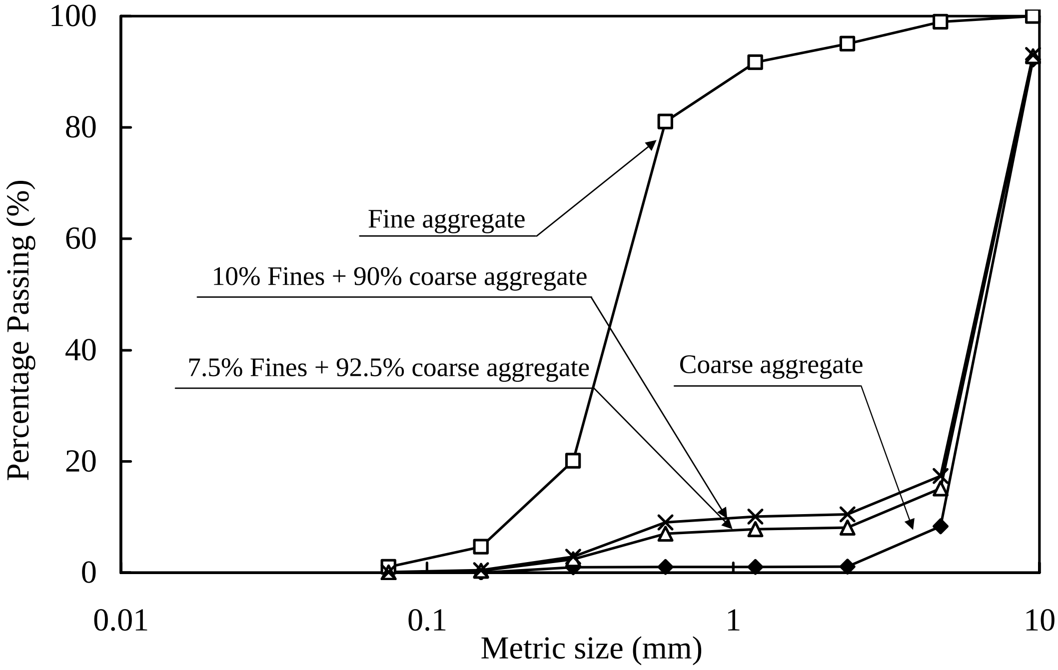


Figure 3.2 Grading curves for pervious concrete containing fine aggregate

In addition, two pervious concrete mixes were used in this study. The grading curves of aggregate combinations used in pervious concrete are shown in Figure 3.2. The first mixes (Mix P1b and Mix P2b) were made by adding 7.5% of fine aggregate of total aggregate by weight. The mix proportion of this was Portland cement, coarse aggregate, fine aggregate, and water, 1:3.7:0.3:0.35, respectively. The second mixes (Mix P1c and P2c) were produced with 10% fine aggregate of total aggregate. The mix proportion was 1:3.6:0.4:0.35, respectively. Figure 3.3 shows a pervious concrete cylindrical specimen produced for compressive strength test and water permeability test.

Figure 3.3 Pervious concrete cylinder

3.2.2 Pervious mortar

Type GP Portland cement was used for production of pervious mortar mix. Based on trial tests, coarse sand, particles mostly fall between 3.75 mm and 0.60 mm, and fine sand particles mostly fall below 0.60 mm used as aggregate. The gradations for both fine sand and coarse sand are shown in Figure 3.4.

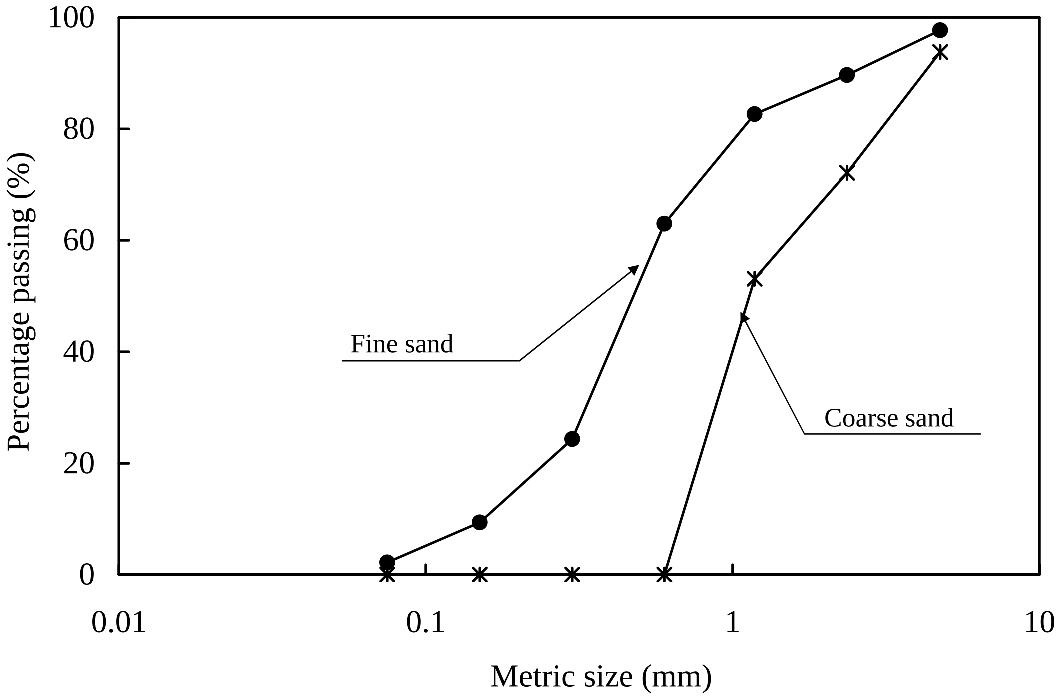


Figure 3.4 Grading curves for fine sand and coarse sand used in pervious mortar

Table.3.3: Mix proportions for pervious mortar mixes by weight

Mix	W/B Ratio	CS/B Ratio	FS/B Ratio	Compaction
PM1	0.35	4.0	-	No
PM2	0.60	4.0	-	No
PM3	0.35	3.6	0.4	No
PM4	0.35	4.0	-	25 times/layer (3 layer)

The mix proportions are summarised in Table 3.3. Four mix proportions were used for the pervious mortar. The water/binder ratio of 0.35 without compaction is called Mix PM1, the water/cement ratio of 0.6 without compaction is called Mix PM2, the water/cement ratio of 0.35, with the addition of 10% finest sand without compaction is called Mix PM3, and the water/cement ratio of 0.35 with compaction is called Mix

PM4. The compaction method consisted of 25 times tamping with wooden rod per one layer for three layers. Figure 3.5 shows the specimen of pervious mortar.

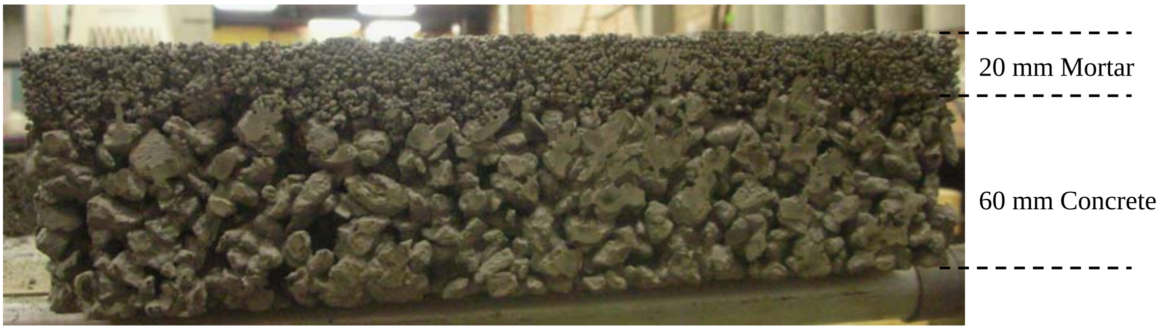
Figure 3.5 Pervious mortar slab specimen

3.2.3 Combination of pervious concrete and pervious mortar

In this study, a pervious pavement system is constructed with pervious concrete and pervious mortar. Pervious concrete mixes had 80% cement and 20% fly ash and Mix PM4 pervious mortar were used. The specimen of pervious pavement system is shown in Figure 3.6.

Figure 3.6 Specimen of pervious pavement system

Consistent with some research discussion about pervious pavement system, the best thickness for a pervious pavement system is 80 mm to 100 mm. (Scholz and Grabowiecki [38]; HydroCon Pty Ltd [40]) The total thickness of the pavement system is 80 mm, while there are two different combinations between pervious concrete and pervious mortar; the first combination is 20 mm pervious mortar with 60 mm pervious concrete, and the second combination is 40 mm of pervious concrete and 40 mm mortar. These are shown in Figure 3.7.



(a) Combination of pervious concrete and mortar Mix PCM1

(b) Combination of pervious concrete and mortar Mix PCM2

Figure 3.7 Combination of pervious concrete and mortar

3.3 Mixing of concrete, casting and curing of test specimens

Concrete mixes were produced in a pan-type mixer. Immediately after mixing, the wet density of concrete was determined. A number of standard 100 mm diameter by 200 mm high cylinders were cast in steel moulds for compressive strength testing and water permeability tests on hardened concrete at appropriate ages. Two standard prisms 5 mm high by 75 mm wide and 280 mm long, were cast in steel moulds for shrinkage testing.

Mortar batches were mixed in a small Hobart mixer. Six 50 mm cube were moulded for compressive strength testing and water permeability testing.

For the combination of pervious concrete and mortar, pervious concrete and pervious mortar were mixed separately and 80 mm thick, 300 mm square specimen were cast. For each batch the same standard specimens were cast for the determination of compressive strength, water permeability and drying shrinkage. Hand compaction was applied using wooden plastic shown in Figure 3.8. All specimens were demoulded after 24 hours and stored in water at 20°C until testing.

Figure 3.8 Casting of combination of pervious concrete and mortar

3.4 Measurements of pervious concrete and mortar properties

3.4.1 Compressive strength

Compressive strength test was performed according to AS 1012.9. For the pervious concrete, three cylindrical specimens 200 mm high and 100 mm in diameter were used. The specimens were capped with dental plaster on both loading surfaces. The specimens were cured in water (20°C) until the testing. The compressive strength reported are the average of three results taken from three identical cylinders.

For the pervious mortar, 50 mm cubes were used for strength testing. Both sides of the specimens were capped with dental plaster, and the compressive strength represented the average of three results taken from three identical specimens.

3.4.2 Drying shrinkage

Drying shrinkage was measured according to AS 1012.12. Two prismatic specimens, sized 75 mm by 75 mm by 285 mm, were used. The shrinkage specimens were water cured at 20°C for 7 days, followed by drying in an unsaturated uncontrolled laboratory environment having the mean temperature of 20°C and 65% relative humidity. The shrinkage of each specimen was monitored over a 200 mm gauge length using a demountable mechanical strain gauge on the opposite longitudinal sides, over 56 days of drying period. The reported results are the average of two readings taken on both sides of a shrinkage specimen. The shrinkage specimens were also weighed when the shrinkage measurement was made. For the pervious mortar, the same sizes and methodology were used.

3.4.3 Porosity

The porosity of the hardened concrete was calculated from the oven-dry and saturated weights, using the following equation [24]:

$$V_r = \left[1 - \left(\frac{W_2 - W_1}{\rho_w Vol}\right)\right] \; 100(\%) \tag{3.1}$$

where V_r = porosity

W_1 = weight under water

W_2 = oven dry weight

Vol = volume of sample,

ρ_w = density of water.

3.4.4 Water permeability

For the pervious concrete, the constant head method was used to measure the water permeability. Figure 3.9 shows the schematic diagram of the permeability test. Three water heads were adopted, namely 100, 150, or 200 mm.

For the pervious mortar, the same procedures were used as those for pervious concrete. However, the pervious mortar cubic specimens, each sized 50 mm, were small. Hence, the mortar specimens were wrapped with polyethylene and cast in dental plaster as shown in Figure 3.10.

Water permeability of the pervious pavement system was measured under constant water head method. Due to the large specimen sizes, a new experimental set-up was created as shown in Figure 3.11.

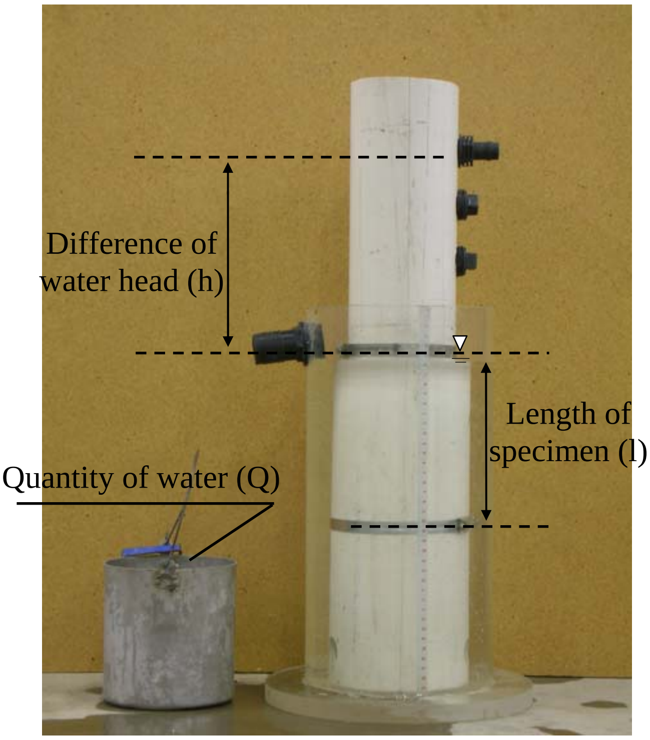


Figure 3.9 Constant head water permeability test

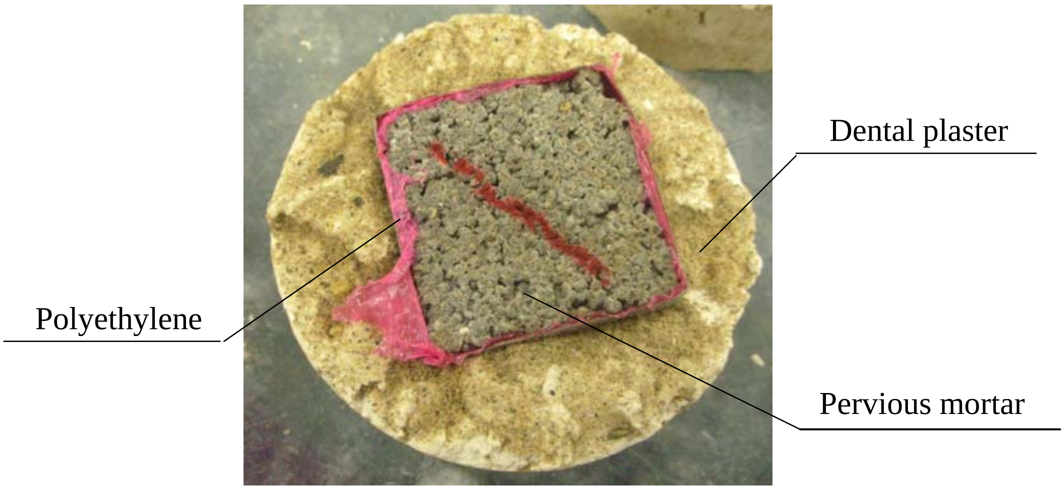


Figure 3.10 Pervious mortar specimen for water permeability

To stop the water leakage from the side, the specimens were covered with wax, as shown in Figure 3.12.

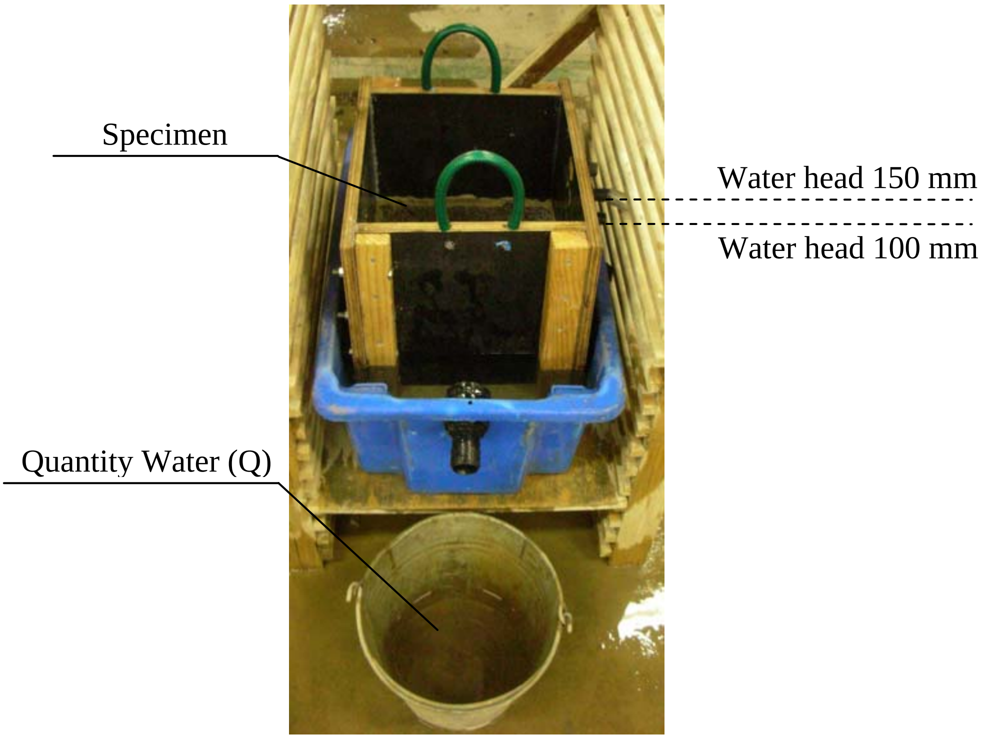


Figure.3.11 Constant head water permeability test for pervious pavement system

Figure 3.12 Pavement specimens covered by wax

The test cylinders were covered with sponge rubber to prevent water leakage in the transverse direction. The cylinders were placed in the hard plastic pipe and tightened by circular clamps. Under a given water head, the permeability testing was carried out when a steady state of flow was reached. The amount of water flowing through the specimens over 30 seconds was measured and the permeability coefficient was calculated using Darcy’s First Law as given below:

$$\frac{Q}{At\rho_w} = k\frac{h}{l} \tag{3.2}$$

where A = cross-sectional area of cylinder (mm^2)
Q = quantity of water collected over 30 seconds (g)
ρ_w = density of water (1.0×10^{-3} g/mm^3)
t = time (30s)
k = water permeability coefficient (mm/s)
h = water head (mm)
l = length of specimen (mm).

Chapter 4

Results and Discussion

4.1 Introduction

The results of the experimental investigation are presented in this chapter. Section 4.2 provides the results of pervious concrete without fine aggregate and the conventional concrete. The results associated with the pervious concrete samples mixed with two different percentages of fly ash are presented in Section 4.3. Section 4.4 presents the pervious concrete containing fine aggregate. The relationships among density, porosity, compressive strength and water permeability of all pervious concrete are discussed in Section 4.5. Section 4.6 discusses the results obtained with the pervious mortar. Section 4.7 presents the density and water permeability of the combined pervious concrete and pervious mortar system.

4.2 No-fines pervious concrete and conventional concrete

4.2.1 Density

The densities at the age of 7 days and 28 days of the pervious concrete and conventional concrete with and without cement replacement with fly ash are shown in Table 4.1. The density for each specimen, the mean value, the standard deviation and the coefficient of variation are presented in Table 4.1.

The mean density for conventional concrete varied between 2370 and 2430 kg/m^3, while pervious concrete has a density between 1800 and 1830 kg/m^3. Therefore, the pervious concrete showed nearly 25% lower density than conventional concrete. The age of concrete does not influenced to the density of pervious concrete and conventional concrete. The cement replacement with fly ash had marginal affected the density for both pervious and conventional concretes. Moreover, the density of both conventional and pervious concretes does not show wide range. The coefficient of valuation of density for pervious concrete are around 1%, while the smallest is 0.61% in 28 days pervious concrete and the largest is 1.6% in 7 days for pervious concrete with 100% cement.

Table 4.1: Density for conventional concrete and pervious concrete
with and without cement replacement with fly ash

	100% cement				**80% cement & 20% fly ash**			
	Conventional concrete (Mix C1)		**Pervious concrete (Mix P1a)**		**Conventional concrete (Mix C2)**		**Pervious concrete (Mix P2a)**	
Age (days)	**7**	**28**	**7**	**28**	**7**	**28**	**7**	**28**
Density (kg/m^3)	2397	2499	1835	1800	2367	2354	1826	1829
	2385	2403	1794	1782	2386	2380	1787	1837
	2395	2393	1778	1802	2387	2360	1789	1811
Mean (kg/m^3)	2392	2432	1803	1795	2380	2365	1800	1826
Standard deviation	6.1	58	29	11	12	14	22	13
Coefficient of variation (%)	0.25	2.4	1.6	0.61	0.49	0.58	1.2	0.71

4.2.2. Porosity

The porosities for conventional and pervious concretes having different binder materials combinations are shown in Table 4.2. The porosity of each specimen, the mean value, the standard deviation and the coefficient of value of each age are reported.

Pervious concrete shows considerably higher porosity than conventional concrete at 7 and 28 days. The average porosity of pervious concrete is 0.34, whereas corresponding porosity for these conventional concrete is 0.08. The porosity of pervious concrete are within the value of porosity reported in Section 2.2.4.

The porosity of the conventional concrete decreased with the increase of age, due to continuous hydration of the cement. In contrast, the porosity of the pervious concrete was independent on the age of concrete. The different types of pore structure are responsible for this phenomenon. As shown in Section 2.2.5, the porosities in conventional concrete are affected by age of concrete. However, the porosity in pervious concrete is mainly large size air voids which are bigger than the pores in cement paste. The porosity of pervious concrete is influenced by aggregate grading and compaction. Hence, the porosity of pervious concrete is not noticeably changed with an increase in the age of concrete.

The results showed that cement replacement with fly ash has no significant influence in the porosity for either conventional concrete or pervious concrete at 7 and 28 days.

Table 4.2: Porosity for conventional concrete and pervious concrete with and without cement replacement with fly ash

	100% cement				**80% cement & 20% fly ash**			
	Conventional concrete (Mix C1)		**Pervious concrete (Mix P1a)**		**Conventional concrete (Mix C2)**		**Pervious concrete (Mix P2a)**	
Age (days)	**7**	**28**	**7**	**28**	**7**	**28**	**7**	**28**
Porosity	0.12	0.07	0.32	0.37	0.13	0.08	0.36	0.30
	0.10	0.07	0.33	0.34	0.11	0.06	0.32	0.36
	0.13	0.05	0.32	0.36	0.11	0.09	0.38	0.33
Mean	0.12	0.07	0.33	0.36	0.12	0.08	0.35	0.33
Standard deviation	0.02	0.01	0.01	0.02	0.01	0.01	0.03	0.03
Coefficient of variation (%)	16	18	2.4	4.6	7.6	17	9.7	8.5

4.2.3 Compressive strength

Table 4.3 summarises the compressive strengths of each specimen, the mean value, the standard deviation and coefficient of value. The specimens were tested at the age of 7 days and 28 days for water cured conventional concrete and pervious concrete with and without cement replacement with fly ash. The compressive strengths develop with age for conventional concrete and pervious concrete with and without fly ash.

In Table 4.3, the pervious concrete showed significantly lower strength than that for the conventional concrete. The mean value of the compressive strength of conventional concrete with 100% cement had 50.6 MPa, whereas pervious concrete had the compressive strength of 10.1 MPa. At the same age of conventional concrete with 20% fly ash had the strength of 41.2 MPa, while the strength of pervious concrete is 8.78 MPa, which is only 20% of the conventional concrete. As expected, pervious concrete resulted in low compressive strength due to its higher porosity compare to that for conventional concrete.

Table 4.3: Compressive strength for conventional concrete and pervious concrete with and without cement replacement with fly ash

	100% cement				**80% cement & 20% fly ash**			
	Conventional concrete (Mix C1)		**Pervious concrete (Mix P1a)**		**Conventional concrete (Mix C2)**		**Pervious concrete (Mix P2a)**	
Age (days)	**7**	**28**	**7**	**28**	**7**	**28**	**7**	**28**
Compressive strength (MPa)	44.3	49.9	7.51	10.4	27.2	41.6	6.61	8.85
	46.4	50.9	6.54	9.22	30.4	42.2	7.25	8.38
	45.1	51.0	8.66	10.6	28.6	39.7	6.84	9.12
Mean (MPa)	45.3	50.6	7.57	10.1	28.7	41.2	6.90	8.78
Standard deviation	1.1	0.62	1.1	0.73	1.6	1.3	0.33	0.37
Coefficient of variation (%)	2.4	1.2	14	7.2	5.6	3.1	4.8	4.2

Figure 4.1 shows the development of compressive strength with age for conventional concrete and pervious concrete with and without fly ash. As shown in Figure 4.1, all concrete mixes showed improvement in strength with the increase in the age. In the case of conventional concrete, 20% cement replacement concrete showed significant improvement from 7 to 28 days. In contrast, the strength of pervious concrete increased slightly in both mixes during the same period. Cement hydration is an important factor for justifying these trends. The pozzolanic reaction rate of fly ash is slower than the hydration rate for cement. For the pervious concrete, the increases in rates of both mixes are quite similar. It can be noted that cement hydration has strong influence on conventional concrete properties.

The results also indicated that cement replacement with fly ash reduced the strength by 37% at 7 days and by 18% at 28 days for the conventional concrete (Mix C2). The pervious concrete showed 13% reduction in strength at 7 days (Mix P2a), while it decreased by 18% at 28 days. Therefore, replacement fly ash leads to decrease the compressive strength at early ages of concrete. However, presence of slow reactive fly ash can improve the compressive strength of water-cured concrete for several days.

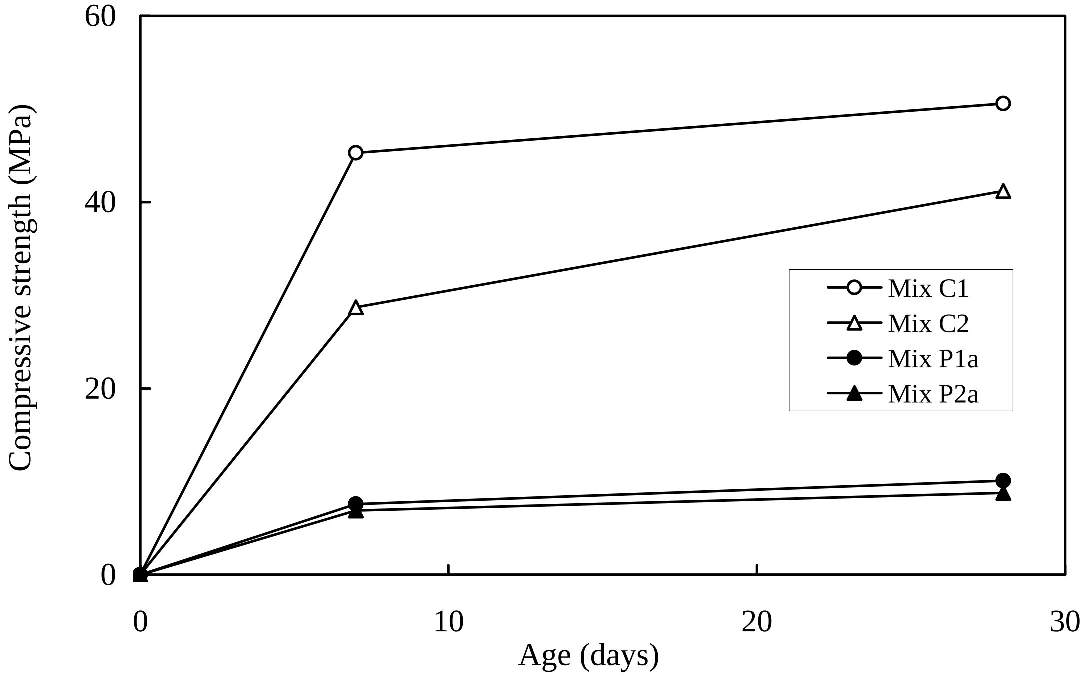


Figure 4.1 Development of compressive strength by age
for conventional and pervious concrete

4.2.4 Drying shrinkage

Figure 4.2 shows the development of drying shrinkage with time for the pervious concrete and conventional concrete. The drying shrinkage at 56-days for all mixes are compared in Figure 4.3.

The drying shrinkage for both concrete types increased with time at a decreasing rate. Drying shrinkage developed sooner for the pervious concrete than that for the conventional concrete. The drying shrinkage at 7 days of pervious concrete reached 350 microstrain for mix with 100% Portland cement and 290 microstrain for mix with 80% cement and 20% fly ash. These are nearly half of the total shrinkage. The drying shrinkage at 7 days of conventional concrete reached 160 microstrain for mix with 100% Portland cement and 130 microstrain for mix with 80% cement and 20% fly ash. These are only one quarter of the total shrinkage. The drying shrinkage of pervious concrete is 600 microstrain which is smaller than for the conventional concrete of 700 microstrain. Tennis et al. [1] also reported that the drying shrinkage of pervious concrete occurred sooner and was smaller.

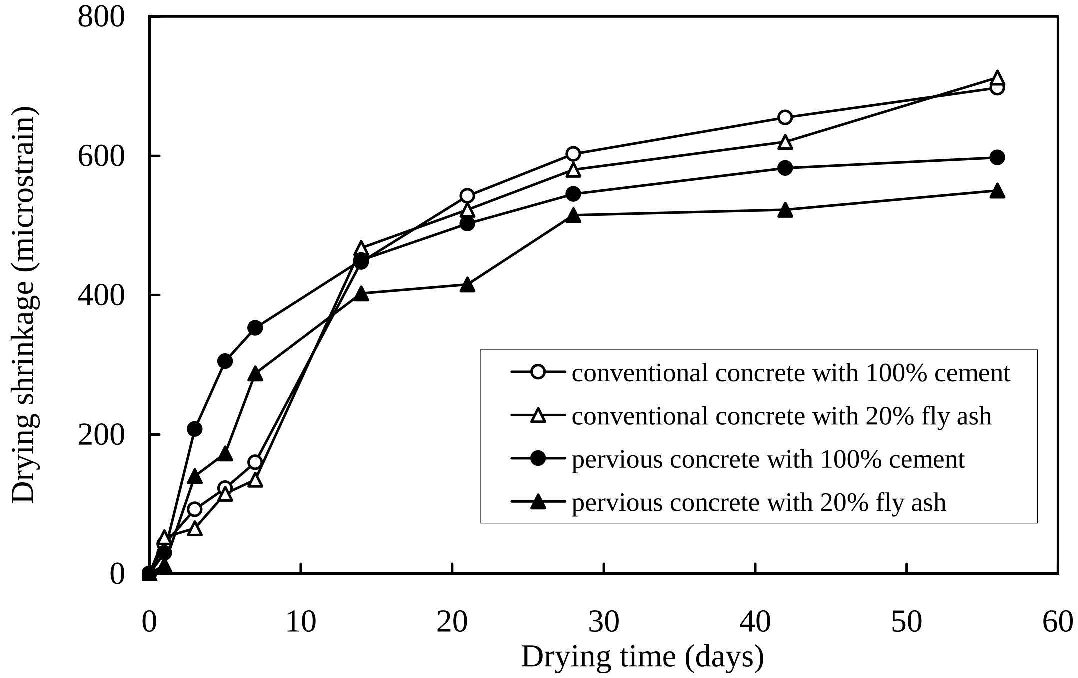


Figure 4.2 Development of drying shrinkage with time
of conventional concrete and pervious concretes

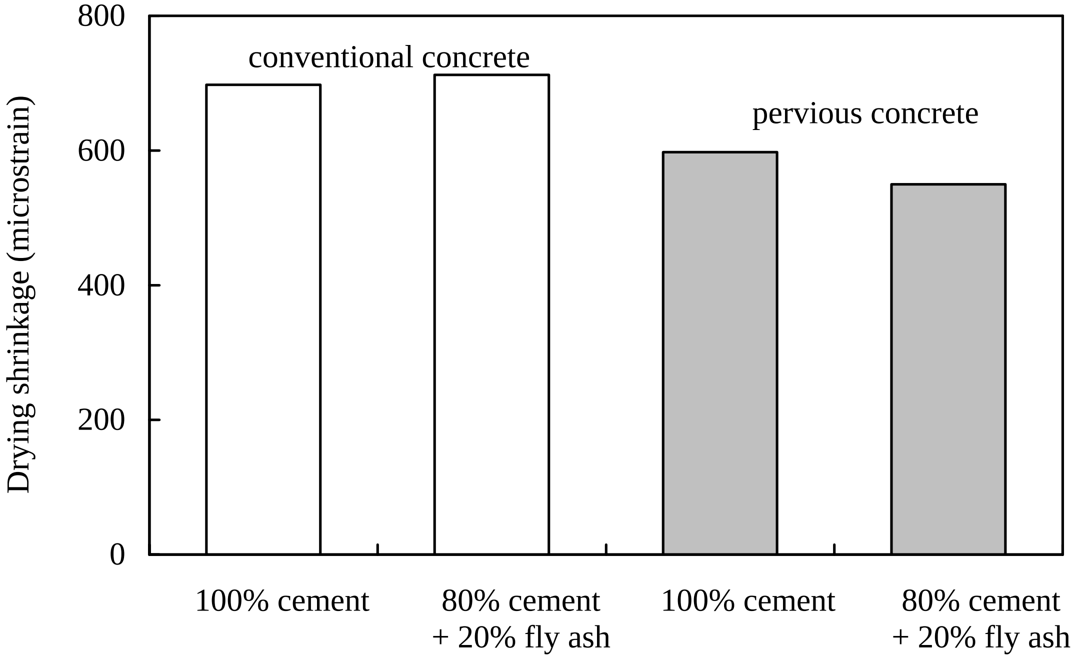


Figure 4.3 56-day drying shrinkage for conventional and pervious concretes

Figure 4.4 shows the relationship between the drying shrinkage and weight loss for the pervious concretes and conventional concrete mixes with 100% cement, and 80% cement and 20% fly ash.

There are significant differences in the shrinkage-weight loss relationship between the pervious concrete and the conventional concrete. The pervious concrete showed significant weight loss, expressed as a percentage of the concrete's weight, compared to that for the conventional concrete. For pervious concrete, the total weight loss was 3.1% for mix with 100% cement and 3.4% for mix with 80% cement and 20% fly ash. For conventional concrete, the weight losses were only around half of that, i.e. 1.8% and 2.2% respectively. When the pervious concrete lost 1.5% of its weight, the drying shrinkage reached less than 30 microstrain. However, for the conventional concrete, the same amount of weight loss produced the drying shrinkage of about 700 microstrain.

Most of the water loss from the pervious concrete is free non-bonded water type from the large air void structure and hence its effect is low in the development of drying shrinkage.

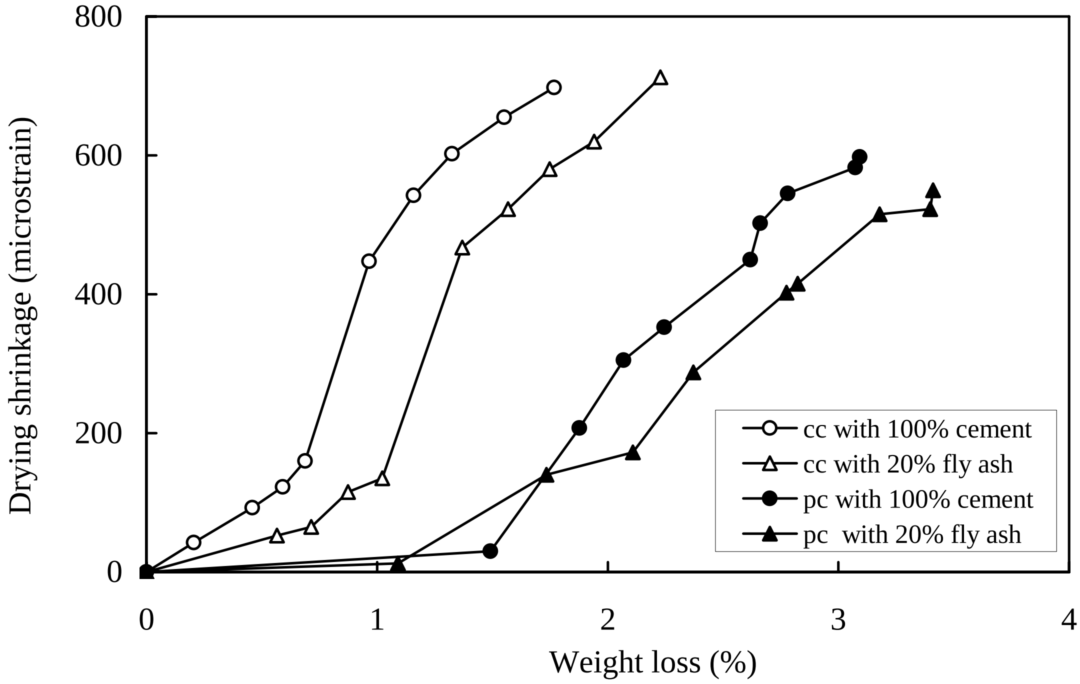


Figure 4.4 Relationship between drying shrinkage and weight loss for conventional and pervious concretes

4.3 Pervious concrete containing fly ash

4.3.1 Density

7 days and 28 days of densities for all pervious concrete samples are summarised in Table 4.4. In this table, density of each specimen, mean value, standard deviation and coefficient variation are presented.

The mean density of pervious concrete with 100% cement (Mix P1a) and 80% cement and 20% fly ash (Mix P2a) are similar and around 1800 kg/m^3. For the pervious concrete with 50% cement replacement (Mix P3a), the mean density was around 1750 kg/m^3. Therefore, high amount of fly ash cause of marginal decrease in density.

Table 4.4: Density for pervious concrete with and without containing fly ash

	100% cement pervious concrete (Mix P1a)		**80% cement + 20% fly ash Pervious concrete (Mix P2a)**		**50% cement + 50% fly ash Pervious concrete (Mix P3a)**	
Age (days)	**7**	**28**	**7**	**28**	**7**	**28**
Density (kg/m^3)	1835	1800	1826	1829	1774	1747
	1794	1782	1787	1837	1709	1753
	1778	1802	1789	1811	1754	1751
Mean (kg/m^3)	1803	1795	1800	1826	1746	1751
Standard deviation	30	11	22	13	33	3.1
Coefficient of variation (%)	1.6	0.61	1.2	0.71	1.9	0.18

4.3.2 Porosity

Table 4.5 presented the porosity of all pervious concrete with and without cement replacement with fly ash at 7 and 28 days.

The mean porosity of all mixes in 0.33, although some differences are noted for various mixes. 7 days porosity for 100% cement pervious concrete is 0.03 smaller than that at 28 days. As explained in Section 2.2.4, the porosity of pervious concrete are relatively high and they are not affected by age. Comparing 100% cement pervious concrete with the other two mixes which cement partially replaced with fly ash, there is no significant difference, (i.e. 0.01 difference). The coefficient value ranges from 0.56% to 15%. This is also caused by the porosity structure. The porosity is depended on more likely construction methodology such as compaction energy rather than mix properties. Thus, it can be concluded that the partial cement replacement up to 50% with fly ash does not influence the porosity of pervious concrete.

Table 4.5: Porosity for pervious concrete with and without containing fly ash

	100% cement pervious concrete (Mix P1a)		**80% cement + 20% fly ash Pervious concrete (Mix P2a)**		**50% cement + 50% fly ash Pervious concrete (Mix P3a)**	
Age (days)	**7**	**28**	**7**	**28**	**7**	**28**
Porosity	0.32	0.37	0.36	0.30	0.35	0.32
	0.33	0.34	0.32	0.36	0.38	0.32
	0.32	0.36	0.38	0.33	0.29	0.33
Mean	0.33	0.36	0.35	0.33	0.34	0.32
Standard deviation	0.01	0.02	0.03	0.03	0.05	0.00
Coefficient of variation (%)	2.4	4.6	9.7	8.5	15	0.56

4.3.3 Compressive strength

Compressive strength for pervious concrete mixes at 7 and 28 days are given in Table 4.6. Pervious concrete having 50% cement replacement with fly ash (Mix P3a) showed the lowest compressive strength among the all pervious concrete. The mean compressive strength was 2.68 MPa at 7 days and 5.66 MPa at 28 days. Pervious concrete with 100% cement (Mix P1a) presented the highest compressive strength at both ages, namely 7.57 MPa at 7 days and 10.1 MPa at 28 days. Pervious concrete having 20% cement replacement with fly ash showed marginally lower compressive strength than pervious concrete with 100% cement. The strength was 6.90 MPa at 7 days and 8.78 MPa at 28 days. Thus, it is clear that increased cement replacement with fly ash had reduced the compressive strength of pervious concrete.

The measured compressive strength varied considerably in all concrete mixes. The highest coefficient variation is 16% in 7 days compressive strength for 50% fly ash pervious concrete (Mix P3a), while the smallest number is 4.2% in 28 days compressive strength for 20% fly ash pervious concrete (Mix P2a).

Table 4.6: Compressive strength for pervious concrete
with and without containing fly ash

	100% cement pervious concrete (Mix P1a)		**80% cement + 20% fly ash Pervious concrete (Mix P2a)**		**50% cement + 50% fly ash Pervious concrete (Mix P3a)**	
Age (days)	**7**	**28**	**7**	**28**	**7**	**28**
Compressive strength (MPa)	7.51	10.4	6.61	8.85	2.19	5.54
	6.54	9.22	7.25	8.38	2.92	4.93
	8.66	10.6	6.84	9.12	2.93	6.51
Mean (MPa)	7.57	10.1	6.90	8.78	2.68	5.66
Standard deviation	1.1	0.73	0.33	0.37	0.42	0.79
Coefficient of variation (%)	14	7.2	4.8	4.2	16	14

4.3.4 Water permeability

The range of water permeability under different water heads for pervious concrete are summarised in Table 4.7. Figure 4.5 shows the effect of water head and fly ash content on the permeability of pervious concrete. Determination of water permeability for pervious concrete is shown in Figure 4.6.

Table 4.7: Water permeability of different water head for pervious concrete
with and without containing fly ash

	100% cement pervious concrete (Mix P1a)			**80% cement + 20% fly ash Pervious concrete (Mix P2a)**			**50% cement + 50% fly ash Pervious concrete (Mix P3a)**		
Water head (mm)	**100**	**150**	**200**	**100**	**150**	**200**	**100**	**150**	**200**
Permeability (mm/s)	13.7	19.2	15.7	8.0	6.3	5.9	12.7	14.4	13.4
	15.1	15.7	11.3	13.3	15.6	9.9	15.1	13.8	10.9
	15.9	17.1	13.9	15.0	11.6	11.9	19.9	23.5	14.7
Mean (mm/s)	14.9	17.3	13.6	12.1	11.1	9.2	15.9	17.2	13.0
Standard deviation	1.1	1.8	2.2	3.7	4.7	3.1	3.6	5.4	2.0
Coefficient of variation (%)	7.3	10	16	30	42	33	23	32	15

The range of water permeability of pervious concrete is quite wide for all mixes under all three water heads used as shown in Table 4.7. The coefficient of variation ranges from 7.3% to 42%. The water permeability under 100 mm water head for 100% cement pervious concrete is between 13.7 mm/s to 15.9 mm/s. The water permeability of pervious concrete is significantly influenced by pore structure which is affected by compaction and grading.

The mean water permeability under different water heads for each pervious concrete mixes is shown in Figure 4.5. The water permeability of pervious concrete is relatively high, especially for pervious concretes with 100% cement and with 50% cement and 50% fly ash. The water permeability coefficient under 200 mm water head showed the lowest value for all pervious concrete mixes, while the water permeability under 150 mm water head had the highest value for pervious concrete with 100% cement and with 50% cement and 50% fly ash. This is an unexpected result, since higher water permeability is expected under the highest water head of 200 mm. This is probably caused by change in water flow pattern from steady to turbulent. The sizes of pores in pervious concrete are large; hence high water head may lead to turbulent flow.

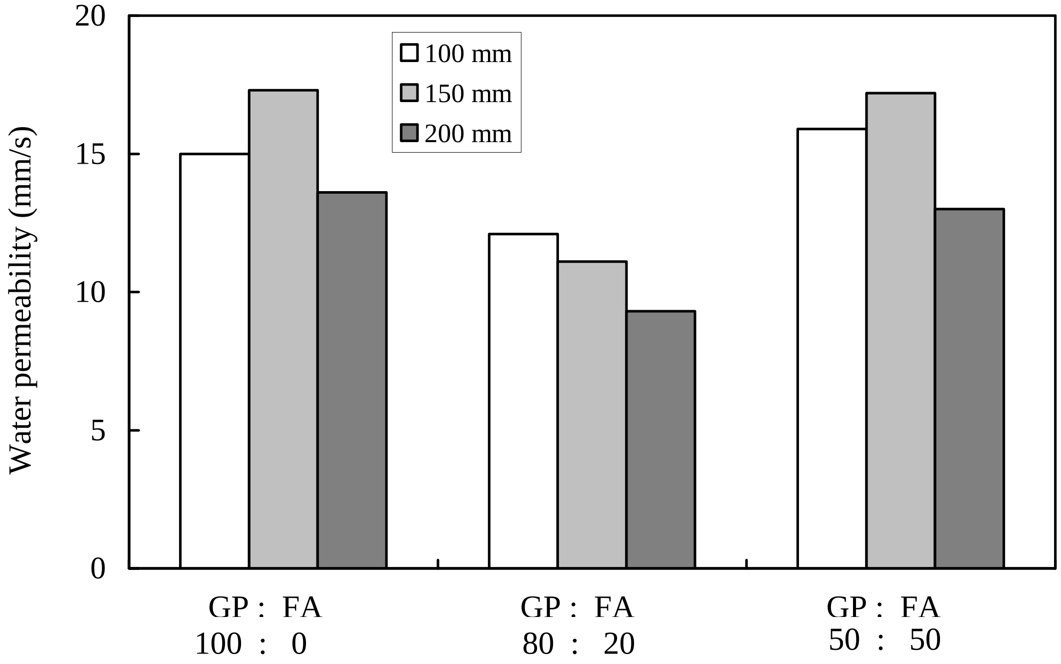


Figure 4.5 Effect of water head and fly ash content on the permeability of pervious concrete

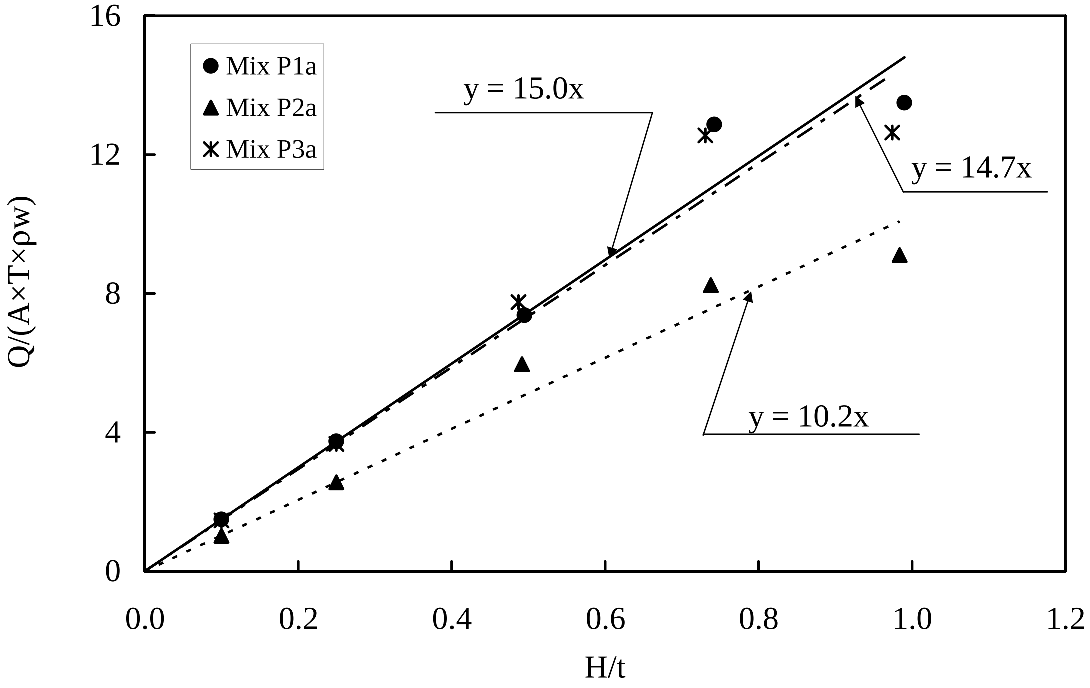


Figure 4.6 Determination of water permeability for pervious concrete

In Figure 4.6, the X-axis and Y-axis are presented from the Equation 3.2. The coefficient of permeability, *k*, is obtained form slope of the linear line. The permeability coefficient for 100% cement pervious concrete and for pervious concrete with 50% cement and 50% fly ash is 15.0 mm/s and 14.7 mm/s, while for pervious concrete with 80% cement and 20% fly ash is 10.2 mm/s. The observed permeability coefficients are within the values of water permeability for pervious concrete shown in Section 2.2.7.

4.3.5 Drying shrinkage

Figure 4.7 shows the development of free drying shrinkage with time for the pervious concrete mixes with and without cement replacement with fly ash. Figure 4.8 shows the relationship between the drying shrinkage and the weight loss for pervious concrete mixes.

In Figure 4.7, the drying shrinkage of pervious concrete increased at a decreasing rate with drying time. 56-day drying shrinkage was ranged from 470 to 600 microstrain. The pervious concrete having 50% fly ash (Mix P3a) showed the lowest shrinkage of 470 microstrain compared with the pervious concrete with only cement (Mix P1a) of 600 microstrain. The results indicate that the cement replacement with fly ash increased the dimensional stability of pervious concrete due to the reduction in the shrinkable cement paste content.

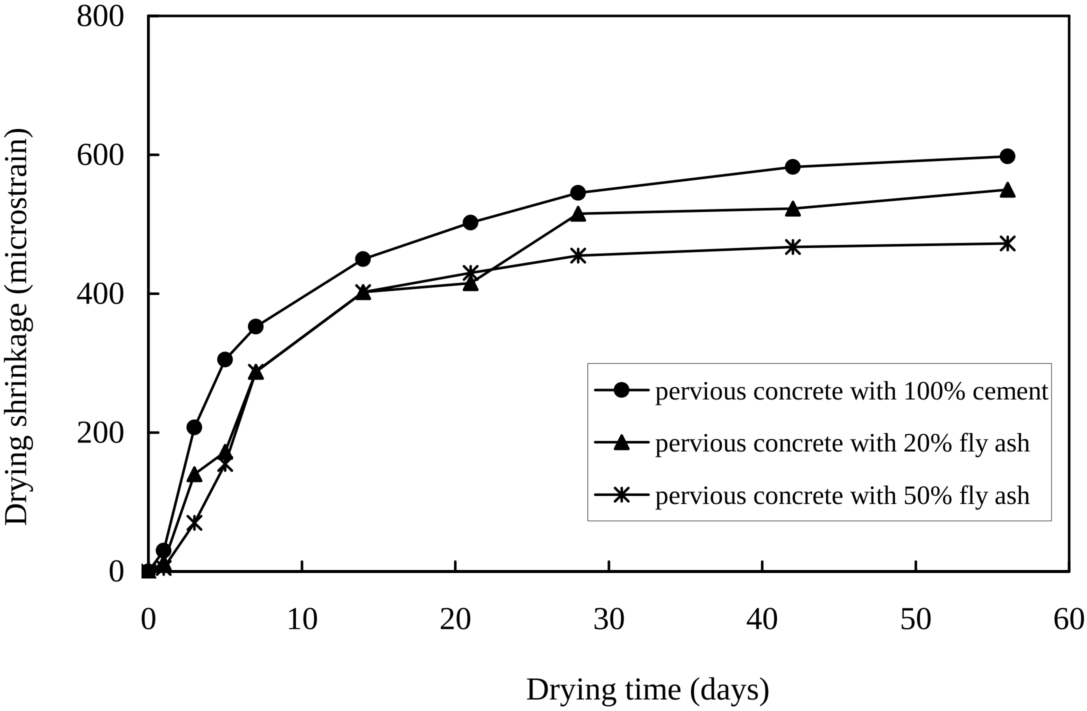


Figure 4.7 Development of drying shrinkage with time for pervious concrete

Significant weight losses, expressed as the percentage of concrete weight, were obtained in all mixes as shown in Figure 4.8. The mean total weight loss of the pervious concrete mixes due to drying for 56 days in the uncontrolled laboratory environment was 3.3%. The pervious concrete having 20% cement replacement with fly ash (Mix P2a) and having 50% fly ash (Mix P3a) showed the higher weight loss of 3.4% than that for the pervious concrete without cement replacement (Mix P1a) of 3.1%. This is due to the unbound water in hardened binder paste having 50% cement and 50% fly ash is significantly more than that in the cement paste. This is due to the increased water to cement ratio in the binder paste with significant fly ash content. The effect of this is clearly seen in the relationship between the drying shrinkage and weight loss as shown in Figure 4.8. For a given weight loss, the pervious concrete with cement only showed the maximum shrinkage compared to concrete having cement replacement with fly ash.

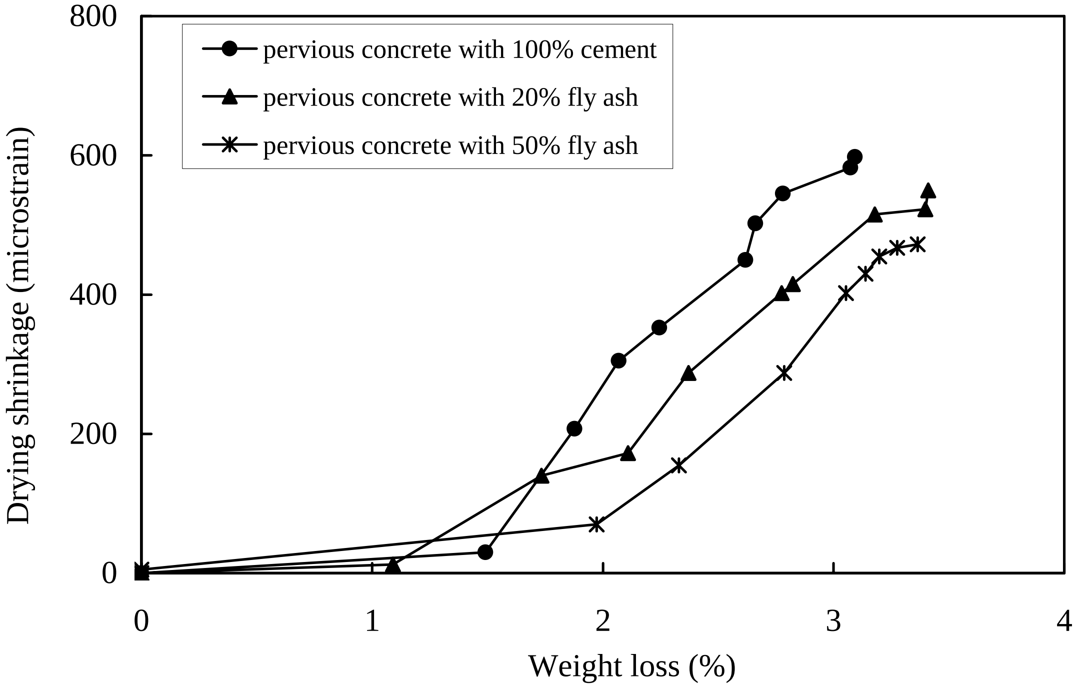


Figure 4.8 Relationship between drying shrinkage and weight loss for pervious concrete

4.4 Effects of aggregate grading on pervious concrete properties

4.4.1 Density

The densities of pervious concrete having different aggregate grading with and without cement replacement are given in Table 4.8.

In terms of 100% cement pervious concrete, pervious concrete with 10% fines showed higher density than that for no-fines and 7.5% fines content. The mean density of no-fines pervious concrete was 1790 kg/m^3. The densities for pervious concrete were 1800 kg/m^3 with 7.5% fines and 1910 kg/m^3 with 10% fines. Hence, the change in the fine aggregate content has affected the density of pervious concrete.

In contrast, the mean density of pervious concrete with 20% cement replacement was between 1800 kg/m^3 and 1830 kg/m^3. The results showed that fine aggregate content and fly ash content influenced the pore size distribution and hence the concrete density.

The coefficient of variation is less than 2.2% for all mixes. The density ranges within the value as pervious concrete show in Section 2.2.3, even in the case of the pervious concrete having fine aggregate.

Table 4.8: Density for pervious concrete with and without fine aggregate

100% cement pervious concrete						
	no-fines (Mix P1a)		**7.5% fines (Mix P1b)**		**10% fines (Mix P1c)**	
Age (days)	**7**	**28**	**7**	**28**	**7**	**28**
Density (kg/m^3)	1835	1800	1767	1775	1761	1751
	1794	1782	1745	1824	1786	1797
	1778	1802	1820	1800	1709	1775
Mean (kg/m^3)	1803	1795	1777	1799	1752	1774
Standard deviation	29	11	39	24	39	23
Coefficient of variation (%)	1.6	0.61	2.2	1.4	2.2	1.3

80% cement + 20% fly ash pervious concrete						
	no-fines (Mix P2a)		**7.5% fines (Mix P2b)**		**10% fines (Mix P2c)**	
Age (days)	**7**	**28**	**7**	**28**	**7**	**28**
Density (kg/m^3)	1826	1829	1783	1824	1827	1789
	1787	1837	1760	1813	1789	1819
	1789	1811	1792	1835		
Mean (kg/m^3)	1800	1826	1778	1824	1808	1804
Standard deviation	22	13	17	11	27	22
Coefficient of variation (%)	1.2	0.71	0.93	0.60	1.5	1.2

4.4.2 Porosity

Table 4.9 presents the porosity of pervious concrete having different aggregate grading with and without cement replacement with fly ash.

The mean porosity of no-fines pervious concrete (Mix P1a) was 0.36 which was the highest among the pervious concrete having different aggregate grading. Pervious concrete with 7.5% fines (Mix P1b) had the porosity of 0.32, while pervious concrete with 10% fines (Mix P1c) showed the porosity of 0.27. For the pervious concrete with 100% cement, the porosity is affected by aggregate grading. However, no particular trend for pervious concrete with 20% cement replacement was noted. The porosity of no-fines pervious concrete (Mix P2a) was 0.33. The pervious concrete with 7.5% fines (Mix P2b) was 0.37, and pervious concrete with 10% fines (Mix P2c) was 0.31. The coefficient of variation of pervious concrete with 20% fly ash is higher than that of 100% cement pervious concrete.

Table 4.9: Porosity for pervious concrete with and without fine aggregate

100% cement pervious concrete						
	no-fines (Mix P1a)		**7.5% fines (Mix P1b)**		**10% fines (Mix P1c)**	
Age (days)	**7**	**28**	**7**	**28**	**7**	**28**
Porosity	0.32	0.37	0.33	0.33	0.36	0.36
	0.33	0.34	0.33	0.32	0.34	0.36
	0.32	0.36	0.33	0.33	0.32	0.36
Mean	0.33	0.36	0.33	0.32	0.34	0.36
Standard deviation	0.01	0.02	0.00	0.00	0.02	0.00
Coefficient of variation (%)	2.4	4.6	0.31	1.5	5.8	0.21

80% cement + 20% fly ash pervious concrete						
	no-fines (Mix P2a)		**7.5% fines (Mix P2b)**		**10% fines (Mix P2c)**	
Age (days)	**7**	**28**	**7**	**28**	**7**	**28**
Porosity	0.36	0.30	0.31	0.37	0.30	0.31
	0.32	0.36	0.32	0.38	0.32	0.30
	0.38	0.33	0.29	0.36		
Mean	0.35	0.33	0.31	0.37	0.31	0.31
Standard deviation	0.03	0.03	0.02	0.01	0.01	0.01
Coefficient of variation (%)	9.7	8.5	5.0	2.9	3.3	2.4

4.4.3 Compressive strength

The compressive strength for pervious concrete containing fine aggregate are summarised in Table 4.10.

Compressive strength for all pervious concrete mixes increased in that increase of age except for 10% fines for both mixes. The smallest compressive strength is 4.30 MPa for 28 days Mix P1c, while the highest is 10.1 MPa for 28 days Mix P1a. The measured compressive strengths are within the range for pervious concrete as discussed in Section 2.2.6.

Table 4.10: Compressive strengths of pervious concrete with and without fine aggregate

100% cement pervious concrete						
	no-fines (Mix P1a)		**7.5% fines (Mix P1b)**		**10% fines (Mix P1c)**	
Age (days)	**7**	**28**	**7**	**28**	**7**	**28**
Compressive strength (Mpa)	7.51	10.4	5.87	6.53	7.88	2.15
	6.54	9.22	5.31	6.48	3.94	3.16
	8.66	10.6	6.43	6.16	5.71	7.59
Mean (Mpa)	7.57	10.1	5.87	6.39	5.84	4.30
Standard deviation	1.1	0.73	0.56	0.20	2.0	2.9
Coefficient of variation (%)	14	7.2	9.6	3.1	34	67

80% cement + 20% fly ash pervious concrete						
	no-fines (Mix P2a)		**7.5% fines (Mix P2b)**		**10% fines (Mix P2c)**	
Age (days)	**7**	**28**	**7**	**28**	**7**	**28**
Compressive strength (Mpa)	6.61	8.85	5.88	8.12	7.07	6.85
	7.25	8.38	3.90	7.24	6.52	5.23
	6.84	9.12	4.88	7.10	-	-
Mean (Mpa)	6.90	8.78	4.88	7.49	6.79	6.04
Standard deviation	0.33	0.37	1.0	0.55	0.39	1.2
Coefficient of variation (%)	4.8	4.2	20	7.3	5.7	19

The fine aggregate fills the gaps among the concrete aggregates in pervious concrete and might cause the increasing compressive strength. However, the results failed to confirm this. There is one acceptable reason for this observation. As shown in Table 4.10, the ranges of compressive strength are quite wide for all mixes. The coefficient of variation ranges from 3.1% in Mix P1b at 7 days to 67% in Mix P1c at 28 days. In terms of 100% cement pervious concrete with 10% fines, this is the particular case which should be considered, due to the highest coefficient of variation of 67%. This range is considerably high. This might be caused by aggregate grading, compaction and age.

4.4.4 Water permeability

Table 4.11 summarised the range of water permeability coefficient under of the water heads of 100, 150 and 200 mm for pervious concrete with no-fine, and for 7.5% and 10% fine aggregate content. Figures 4.9 and 4.10 showed the effect of water head and fly ash content on the permeability of pervious concrete. Furthermore, determination of water permeability for pervious concrete with different aggregate gradings is shown in Figure 4.11.

Table 4.11: Water permeability for pervious concrete
with and without containing fine aggregate

100% cement pervious concrete									
	no-fines (Mix P1a)			**7.5% fines (Mix P1b)**			**10% fines (Mix P1c)**		
Water head (mm)	**100**	**150**	**200**	**100**	**150**	**200**	**100**	**150**	**200**
Water permeability (mm/s)	13.7	19.2	15.7	12.8	11.4	10.3	16.7	15.1	13.5
	15.1	15.7	11.3	14.1	12.8	11.6	12.4	11.9	11.6
	15.9	17.1	13.9	14.1	13.4	12.6	12.1	11.4	10.4
Mean (mm/s)	14.9	17.3	13.6	13.7	12.5	11.5	13.7	12.8	11.8
Standard deviation	1.1	1.8	2.2	0.79	1.1	1.1	2.6	2.1	1.5
Coefficient of variation (%)	7.3	10	16	5.8	8.4	10	19	16	13

80% cement + 20% fly ash pervious concrete									
	no-fines (Mix P2a)			**7.5% fines (Mix P2b)**			**10% fines (Mix P2c)**		
Water head (mm)	**100**	**150**	**200**	**100**	**150**	**200**	**100**	**150**	**200**
Water permeability (mm/s)	8.0	6.3	5.9	9.7	8.9	7.7	16.6	14.6	13.9
	13.3	15.6	9.9	13.2	12.6	12.9	14.3	13.4	12.2
	15.0	11.6	11.9	10.9	9.8	9.1			
Mean (mm/s)	12.1	11.1	9.2	11.3	10.4	9.9	15.4	14.0	13.0
Standard deviation	3.7	4.7	3.1	1.8	2.0	2.7	1.6	0.81	1.2
Coefficient of variation (%)	30	42	33	16	19	27	11	5.8	9.4

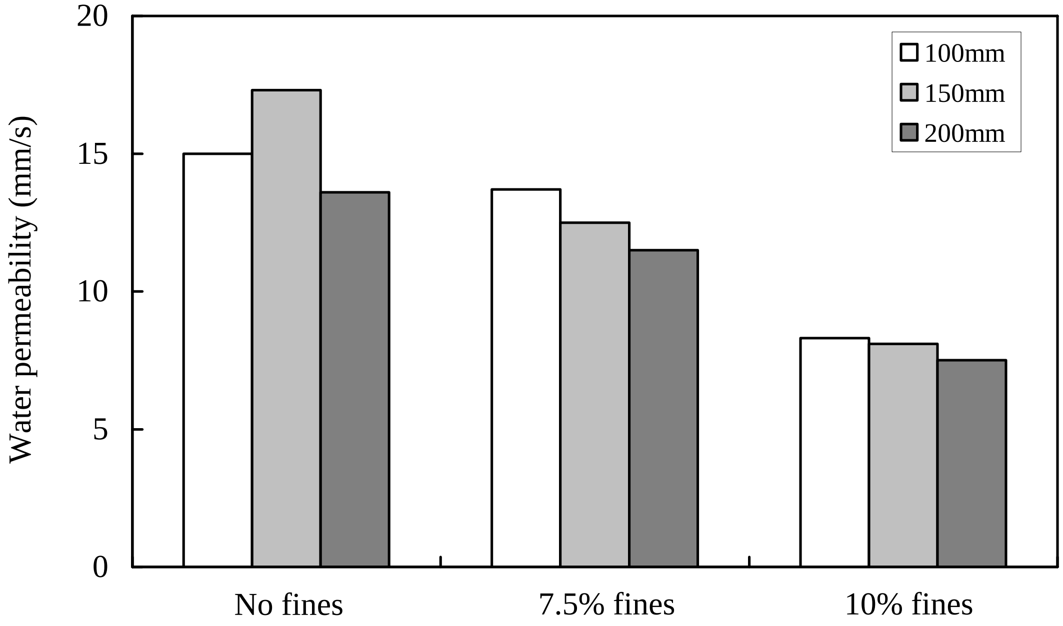


Figure 4.9 Effect of fine aggregate content on the water permeability for pervious concrete (100% cement)

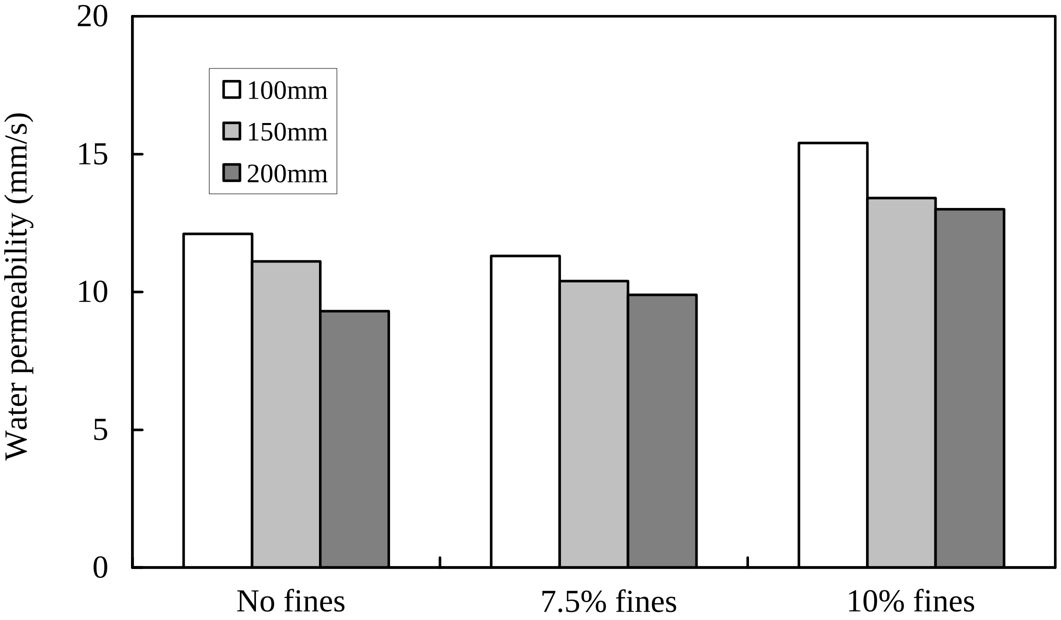


Figure 4.10 Effect of fine aggregate content on the water permeability for pervious concrete (80% cement and 20% fly ash)

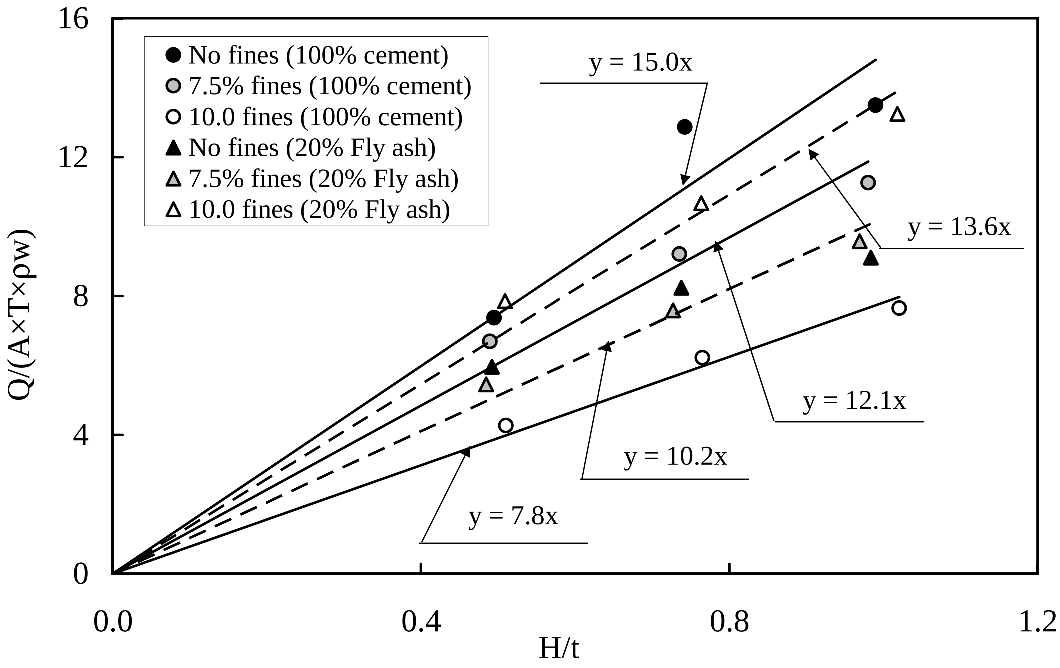


Figure 4.11 Determination of water permeability for pervious concrete with and without fine aggregate

The range of water permeability of pervious concrete is large for all mixes under all water heads due to the sensitivity of water permeability of pervious concrete to pore size and pore structure. The coefficient of variation is between 5.8% and 42%. However, the measured water permeability in this research is within the value of reported by others for water permeability as discussed in Section 2.2.7.

Figure 4.9 shows that the mean water permeability decreased by adding fine aggregate for pervious concrete with 100% cement. The water permeability of no-fines concrete was 13.6 mm/s under 100 mm water head. The water permeability was 11.5 mm/s and 7.5 mm/s when the fines content is increased to 7.5% and 10%, respectively. In contrast, the average water permeability increased by adding fine aggregate for pervious concrete with 20% cement replacement with fly ash as shown in Figure 4.10.

The water permeability decreased when the water head is increased from 100 mm to 200 mm. This trend can be seen for all mixes. It happened most probably due to the change in the water flow from steady to turbulent. Further research is needed to conform this observation and to identity the reason.

In Figure 4.11 the relationship between H/t, the ratio of water head (H) to length of specimen (t), and Q/TAρw, where Q is quantity of water, A is cross sectional area of the specimen, T is correction time and ρ_w is density of water. The constant slope of plot of Q/(ATρw) against H/t gives the permeability coefficient.

The water permeability coefficients for pervious concrete with 100% cement are 15.0 mm/s, 12.1 mm/s, and 17.8 mm/s, for 0%, 7.5% and 10% fine aggregate content respectively. The coefficient of water permeability decreases with increasing amount of fine aggregate. In contrast, the coefficients of pervious concrete with 20% cement replacement with fly ash are 10.2 mm/s for 0% and 7.5% fine aggregate content and 13.6 mm/s for 10% fine aggregate content respectively. Overall, the water permeability coefficient of pervious concrete with 100% cement is marginally greater than that for pervious concrete with 20% cement replacement.

4.4.5 Drying shrinkage

The development of drying shrinkage with time for pervious concrete having different aggregate grading and binder materials combinations is shown Figure 4.12.

Pervious concrete with 20% fly ash showed lower drying shrinkage than control cement pervious concrete (100% cement). Higher fine aggregate content in pervious concrete had lower shrinkage. Thus, the lowest of 510 microstrain is for 20% fly ash pervious concrete with 7.5% fine aggregate. The significant property of drying shrinkage for all pervious concrete mixes occurred during 7 days. The shrinkage reached half of its total shrinkage in the first 7 days. The mean total drying shrinkage for 100% cement pervious concrete was about 600 microstrain, while for 20% fly ash pervious concrete was between 500 microstrain and 550 microstrain.

Figure 4.13 shows the relationship between the drying shrinkage and weight loss for these mixes. It is clear that 20% cement replacement pervious concrete lost more weight than 100% cement pervious concrete. This trend was seen in Figure 4.7, higher cement replacement with fly ash and higher amount of fine aggregate content leads to higher weight loss. Total weight loss for 100% cement pervious concrete was 2.9%, while the total weight loss for 20% fly ash pervious concrete was 3.7%.

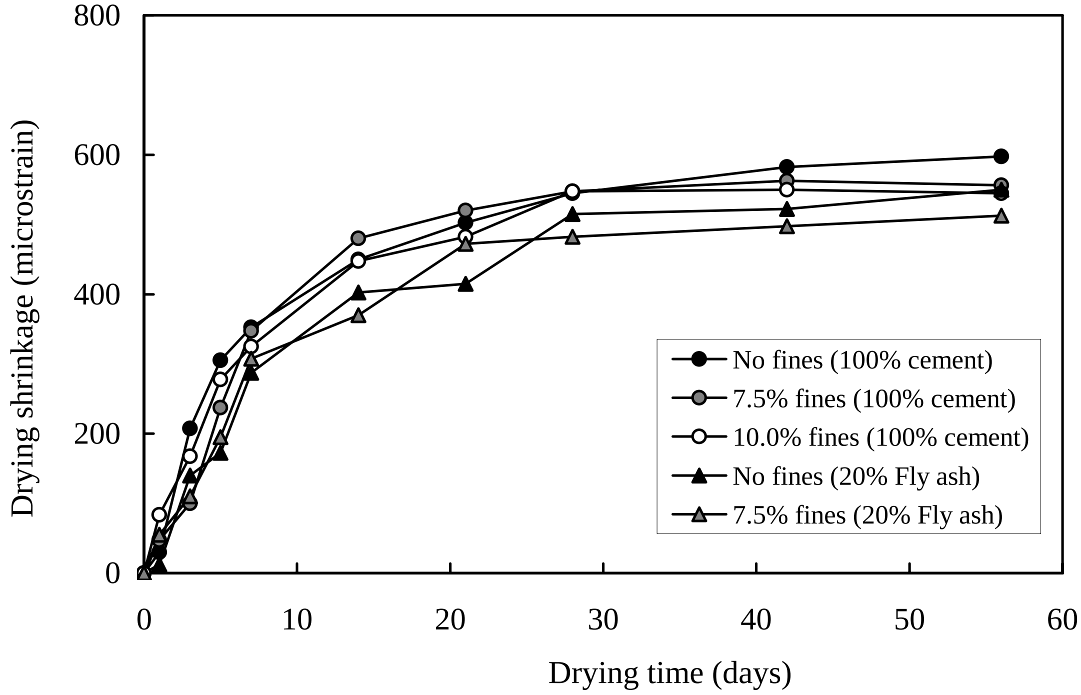


Figure 4.12 Development of drying shrinkage with time for pervious concrete with and without fine aggregate

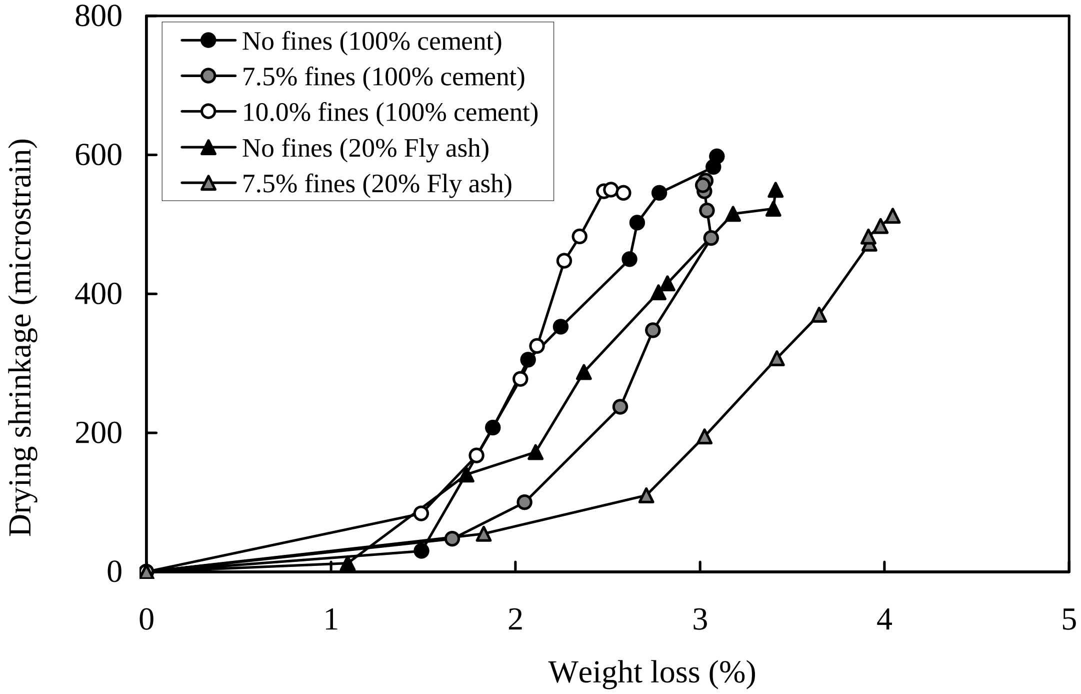


Figure 4.13 Relationship between drying shrinkage and weight loss for pervious concrete with and without fine aggregate

An examination of all results indicates that cement replacement with fly ash leads to decrease the drying shrinkage and increase the weight loss. However, fly ash can be used in pervious concrete without having significant influence on shrinkage of pervious concrete.

4.5 Relationships among the properties of pervious concrete

4.5.1 Density and porosity

The relationship between density and porosity for all pervious concrete mixes in this research and results from literature [12,20] are shown in Figure 4.14. The porosity decreased with an increase in the density for all pervious mixes. This trend is expected. The porosities of this research were higher than the results of Nguyen [20], although these were similar to Schaefer et al [12]. The densities of all mixes are between 1700 kg/m^3 to 1920 kg/m^3, when the porosities varied between 0.17 and 0.40.

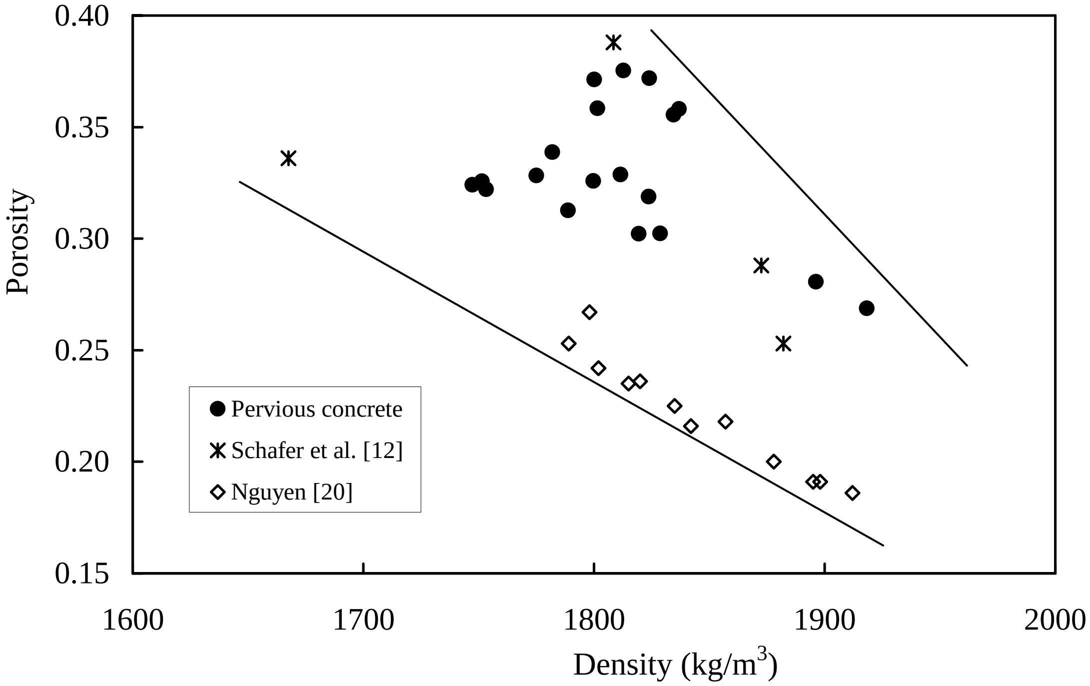


Figure 4.14 Relationship between density and porosity for pervious concrete

4.5.2 Density and compressive strength

Figure 4.15 shows the relationship between compressive strength and density for all pervious concrete mixes. A significant scatter in the relationship is noted. Generally, the compressive strength is improved when the density is increased. The compressive strength increased from 8 MPa to around 12 MPa, when the density increased by 100 kg/m^3. Pervious concrete results in this research showed both lower density and compressive strength compared with the concrete mix by other researchers, even the trend is matched.

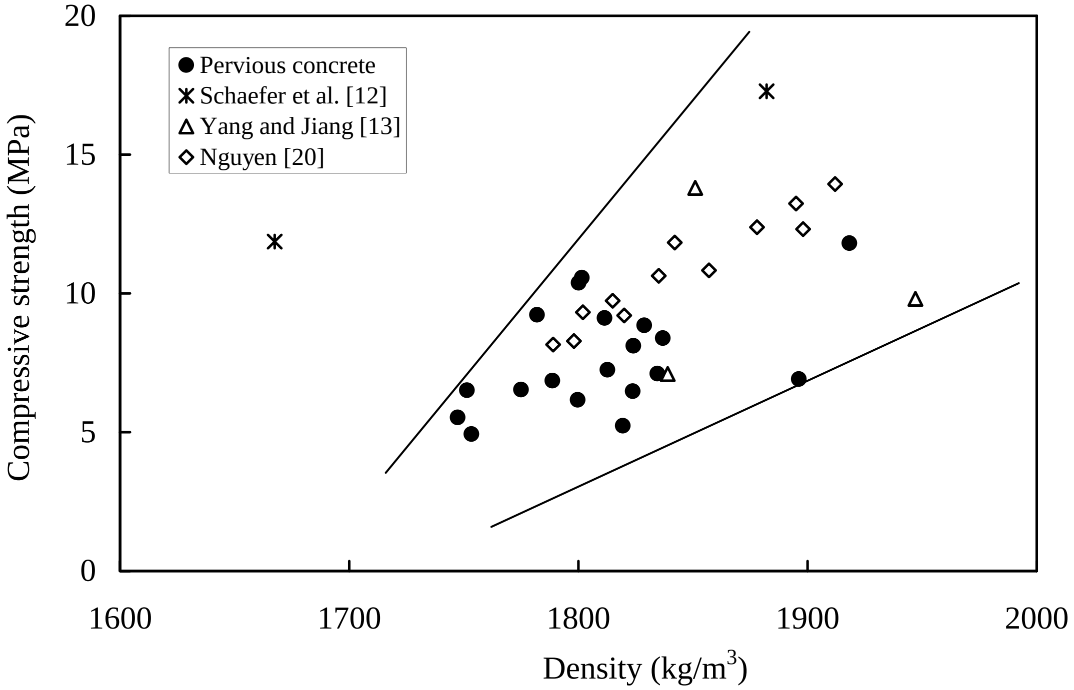


Figure 4.15 Relationship between compressive strength and density for pervious concrete

4.5.3 Density and water permeability

The relationship between density and water permeability for all pervious concrete is shown in Figure 4.16. The water permeability of pervious concrete obtained is marginally higher than that reported by others, for the same density. The water permeability decreased with an increase in density. For instance, the water permeability was approximately 15 mm/s when the density was 1800 kg/m^3. While the density was increased to 1900 kg/m^3, the water permeability was reduced to 10 mm/s.

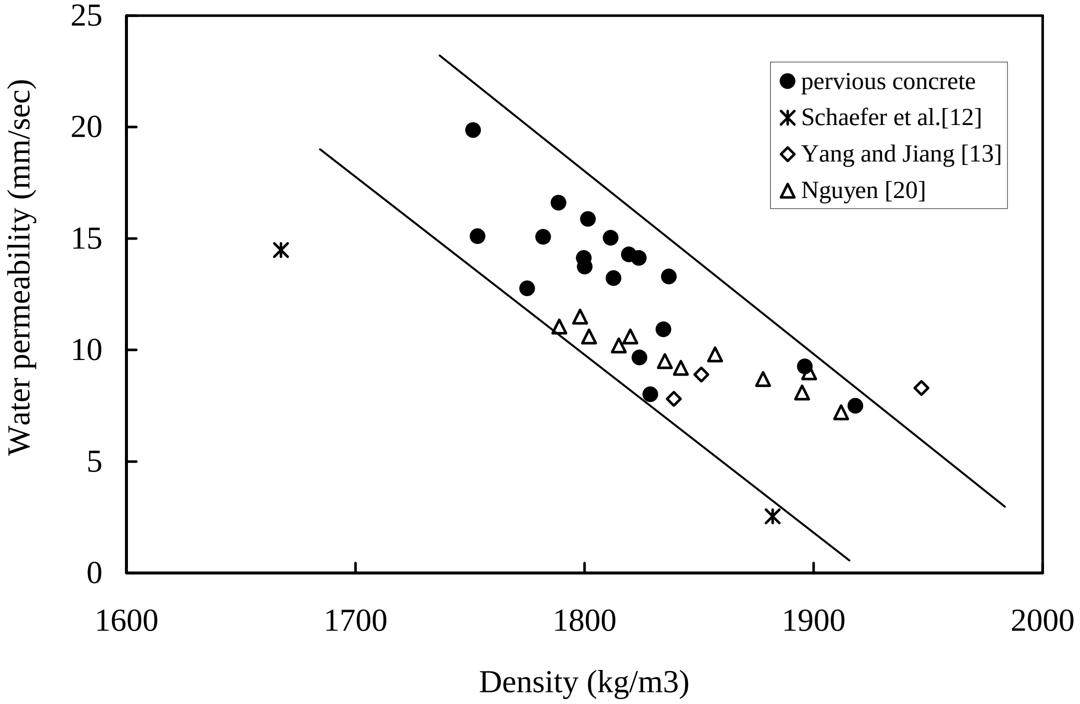


Figure 4.16 Relationship between density and water permeability for pervious concrete

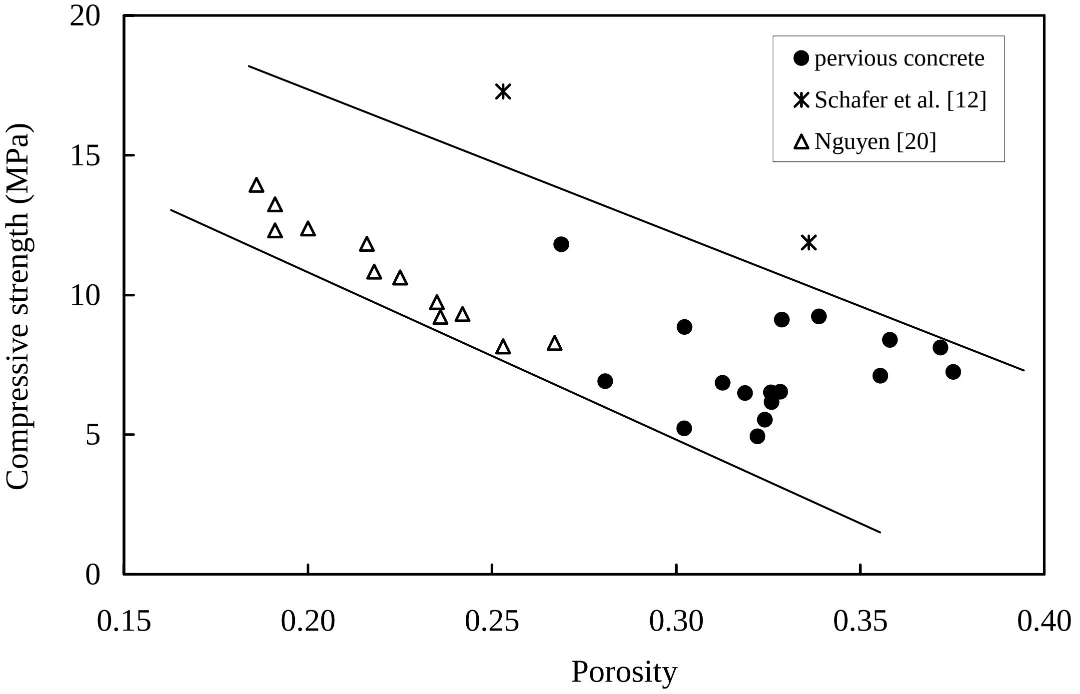


Figure 4.17 Relationship between porosity and compressive strength for pervious concrete

4.5.4 Porosity and compressive strength

Figure 4.17 shows the relationship between porosity and compressive strength for all pervious concrete mixes. The results from the literatures are also included [12, 20]. The porosity of pervious concrete affects the compressive strength. When the porosity increases, the compressive strength drops. The range of porosity of pervious concrete is between 0.15 and 0.40, while the range of compressive strength is between 5 MPa and 20 MPa. This trend has been pointed out by several researchers, as discussed in Section 2.4.1.

4.5.5 Porosity and water permeability

Figure 4.18 shows the relationship between porosity and water permeability for all pervious concrete mixes. The water permeability decreased significantly when the porosity is decreased. The water permeability with 0.35 porosity is around 15 mm/s.

The water permeability can be calculated by Kozeny-Carman Equation, discussed in Section 2.5.4. The trend line shown in Figure 4.18 is calculated based on equation when α equals 18 [29]. The experimental results are well matched with this trend line.

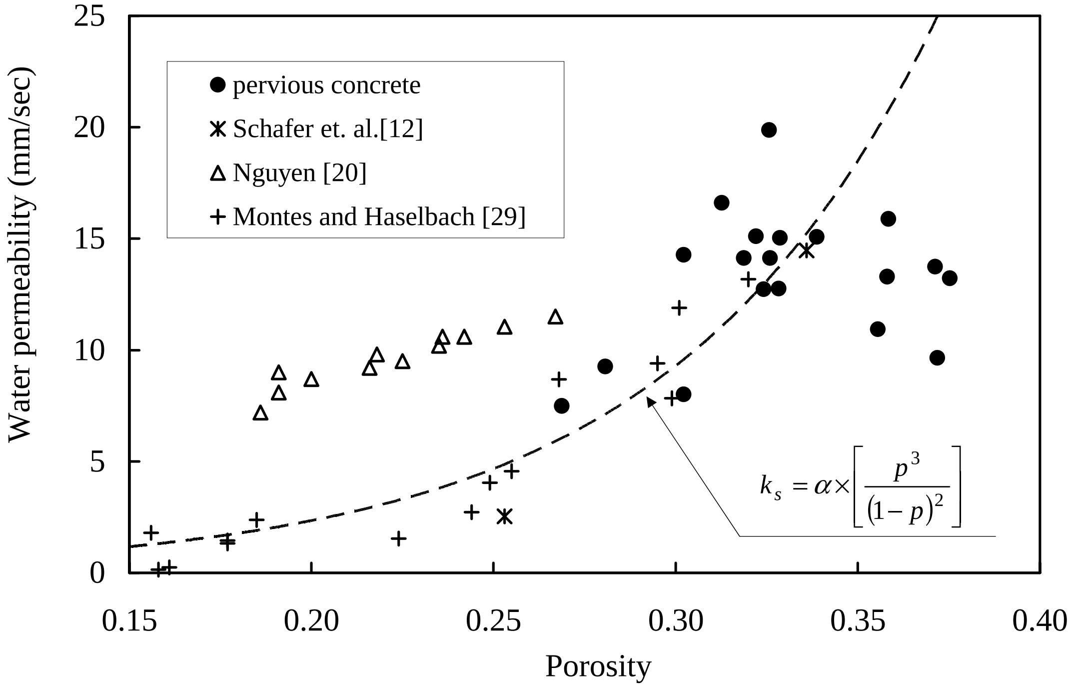


Figure 4.18 Relationship between porosity and water permeability for pervious concrete

4.6 Properties of pervious mortar

4.6.1 Density, porosity, strength and water permeability

The mix proportions and properties of all pervious mortar are summarised at 28 days in Table 4.14. All pervious mortar mixes were produced with 100% cement.

Density of pervious mortar was lower than pervious concrete. The lowest density is for Mix PM1 having water/cement of 0.35 and produced without compaction. In contrast, the highest density is for Mix PM4 having water/cement of 0.35 with compaction.

In the case of porosity, Mix PM1 and Mix PM3 showed high porosity of 0.54 and 0.55 respectively. Even though Mix PM3 contains fine aggregate, Mix PM3 has such a high porosity because of no compaction. Mix PM2 showed porosity of 0.31, due to high water/cement ratio. Moreover, Mix PM4 showed reduced porosity of 0.34, due to compaction. High water/cement ratio and compaction led to decrease the porosity.

Compressive strength of mortar mix, Mix PM1 and Mix PM3 having the high porosity of 0.54, were very low and not measurable. Mix PM2 showed 2.66 MPa at 28 days. Mix PM4 presented the highest compressive strength of 5.81 MPa among the pervious mortar mixes tested.

The water permeability of pervious mortar Mix PM1 under 100, 150 and 200 mm water heads are similar to pervious concrete due to high porosity. For the same reason, Mix PM3 shows high water permeability between 9.4 mm/s to 9.7 mm/s. This is led by no compaction and fine aggregate content does not affect to the water permeability. The water permeability of Mix PM2 was between 5.4 mm/s to 6.1 mm/s, while Mix PM4 showed the lowest water permeability which is between 2.5 mm/s and 2.7 mm/s. The water permeability of pervious mortar is lower than that for pervious concrete because of smaller pore structure.

Considering all strength and permeability results, pervious mortar having water/cement 0.35 and produced with compaction is the best mix among the pervious concrete due to the highest compressive strength. Although the water permeability of Mix PM4 is lower than that of pervious concrete, this is within the value of water permeability for pervious concrete. Moreover, density and porosity of Mix PM4 are similar to that of pervious concrete. Therefore, Mix PM4 was further investigated as pervious mortar in this research. The results are shown in Section 4.6.2.

Table 4.12: Properties of pervious mortar

Property		**Mortar**				**Concrete**
		PM1	**PM2**	**PM3**	**PM4**	**Mix P2**
Water/cement ratio		0.35	0.60	0.35	0.35	0.35
Coarse sand/cement ratio		4.0	4.0	3.6	4.0	4.0
Fine sand/cement ratio		-	-	0.4	-	-
Hand compaction		No	No	No	Yes	Yes
Density (kg/m^3)		1290	1590	1320	1690	1800
Porosity		0.54	0.31	0.55	0.34	0.34
Compressive strength (MPa)		-	2.66	-	5.81	8.78
Water permeability (mm/s)	**100 (mm)**	16.4	6.1	9.5	2.5	12.1
	150 (mm)	15.1	5.7	9.7	2.6	11.1
	200 (mm)	14.9	5.4	9.4	2.7	9.2

4.6.2 Drying shrinkage for pervious concrete and mortar

Figure 4.19 shows the development of drying shrinkage with time of pervious concrete and mortar. The drying shrinkage of pervious mortar after 56 days is smaller than that for pervious concrete. The shrinkage was 490 microstrain for mortar and 600 microstrain for concrete. Drying shrinkage for pervious concrete developed faster than that for pervious mortar. The drying shrinkage for both pervious concrete and mortar increased with time at a decreasing rate.

The relationship between drying shrinkage and weight loss of pervious concrete and mortar are shown in Figure 4.20. The mortar lost significant weight on drying. The weight loss for mortar was 7.1%, while the weight loss for pervious concrete is 3.1%. The pervious mortar lost 6.0% weight in first 7 days, when the shrinkage reached only one fourth of total drying shrinkage. Hence, the mortar has large amount of free unbounded water in the structure. Therefore, the shrinkage is low.

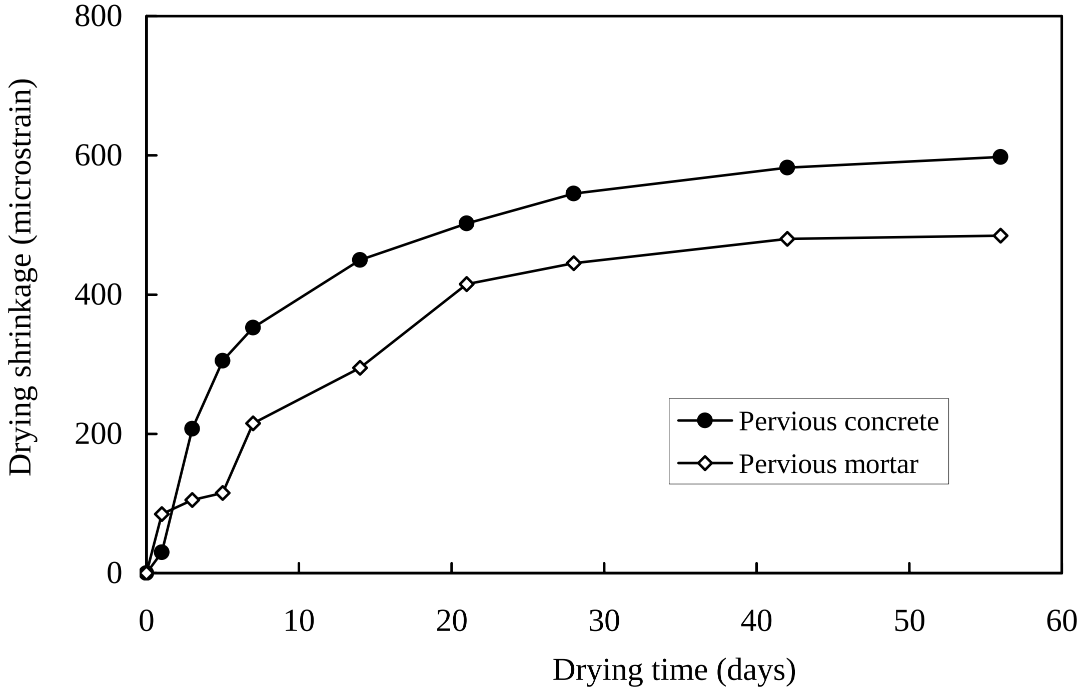


Figure 4.19 Development of drying shrinkage with time
for pervious concrete and pervious mortar

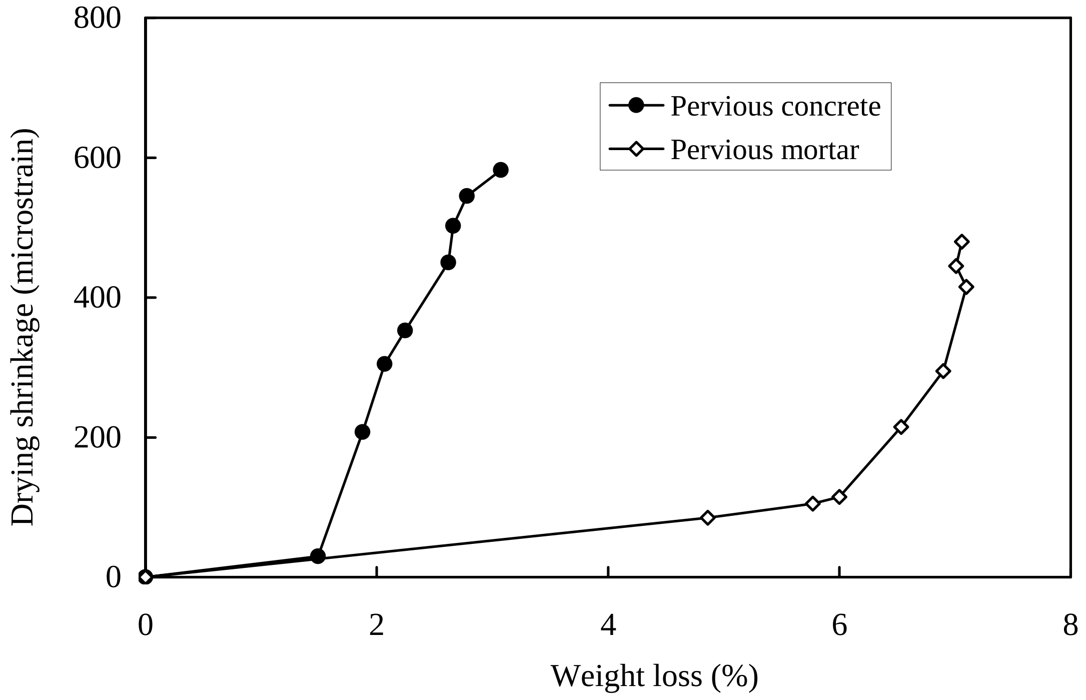


Figure 4.20 Relationship between drying shrinkage and weight loss
for pervious concrete and pervious mortar

4.7 Combination of pervious concrete and pervious mortar

Combination of pervious concrete and pervious mortar was developed. The pervious concrete with 20% fly ash and the pervious mortar with 0.35 water/cement ratio with compaction were used respectively. Two mixes were combined to produce mortar-concrete pervious system having two different thickness ratio; first is 60 mm pervious concrete with 20 mm pervious mortar and second is 40 mm pervious concrete with 40 mm pervious mortar. Both of them and pervious concrete and mortar specimens are tested for density and water permeability.

4.7.1 Density

Table 4.13 showed the 28 days density of pervious concrete with 20% fly ash replacement, pervious mortar, and two types of combination of pervious concrete and mortar.

The combination of pervious concrete and mortar showed similar density as pervious concrete and pervious mortar. The density of combination of 20 mm pervious mortar and 60 mm pervious concrete has 1780 kg/m^3, while the other combination of 40 mm each pervious concrete and mortar has slightly smaller than that of 1690 kg/m^3.

Table 4.13: Density of combination pervious concrete and pervious mortar in kg/m^3

Age (days)	**Pervious concrete**	**Pervious mortar**	**Combination**	
			20/60	**40/40**
28	1700	1690	1780	1690

4.7.2 Water permeability

Table 4.14 summarises the water permeability of pervious concrete, mortar and combination of pervious concrete and mortar under 100 mm and 150 mm water heads. The water permeability of combination of pervious concrete and mortar investigated having water flow in both sides; firstly it was tested when water flows from mortar to concrete and then it was investigated when flows from concrete to mortar. This was to find the effects of surface structure on water permeability.

The water permeability of combined structure was slightly higher than mortar, but significantly smaller than concrete. The average water permeability of combined concrete and mortar was 2.8 mm/s. The pervious mortar had water permeability 1.9 mm/s, while the pervious concrete had 16.9 mm/s. The combination structure was influenced by the mortar structure characteristic as expected.

The different water head affected water permeability only for combination of concrete and mortar. The water permeability under 150 mm water head was smaller than that under 100 mm water head, even though the pressure was higher. It did not influence to the pervious concrete and mortar system. This is caused by the ratio of specimen’s thickness and water head. The combined structure had 80 mm thickness hence the ratio of thickness and water head was quite high.

The thickness ratio of concrete and mortar lead to little difference for water permeability. 20 mm mortar and 60 mm concrete combination showed slight lower water permeability than 40 mm 40 mm. The small pore structure influenced to water permeability and caused to decrease water permeability.

The mortar surface showed the lower water permeability than concrete surface. The mean water permeability for 20 mm and 60 mm combination is 2.4 mm/s when the water entering surface is mortar, while that is 3.0 mm/s when the water entered from concrete surface. The same trend can be seen in case of 40 mm and 40 mm combination. The water permeability of 40 mm and 40 mm combination is 3.0 mm/s when the water entering surface is mortar, during that is 3.4 mm/s for concrete surface. The large pore structure surface leads to higher water permeability.

Table 4.14: Water permeability of combination pervious concrete and pervious mortar

Water head (mm)	**Water permeability coefficient (mm/s)**					
	Pervious concrete	**Pervious mortar**	**Combination**			
			20/60	**40/40**	**20/60**	**40/40**
			mortar to concrete		**concrete to mortar**	
100	16.4	1.8	2.4	3.2	3.0	3.4
150	16.3	1.9	2.3	2.8	2.7	3.0

In Figure 4.21 shows the relationship between H/t and Q/ATρw which are Darcy's First Law equation. The constant slope of this graph is equal to the permeability coefficient.

The coefficient of permeability for combination of concrete and mortar presents similar trend with pervious mortar. The coefficients for combination are between 2.8 mm/s and 2.9 mm/s, while pervious mortar is 1.9 mm/s and for pervious concrete is 15.9 mm/s. This is due to smaller pore structure in mortar.

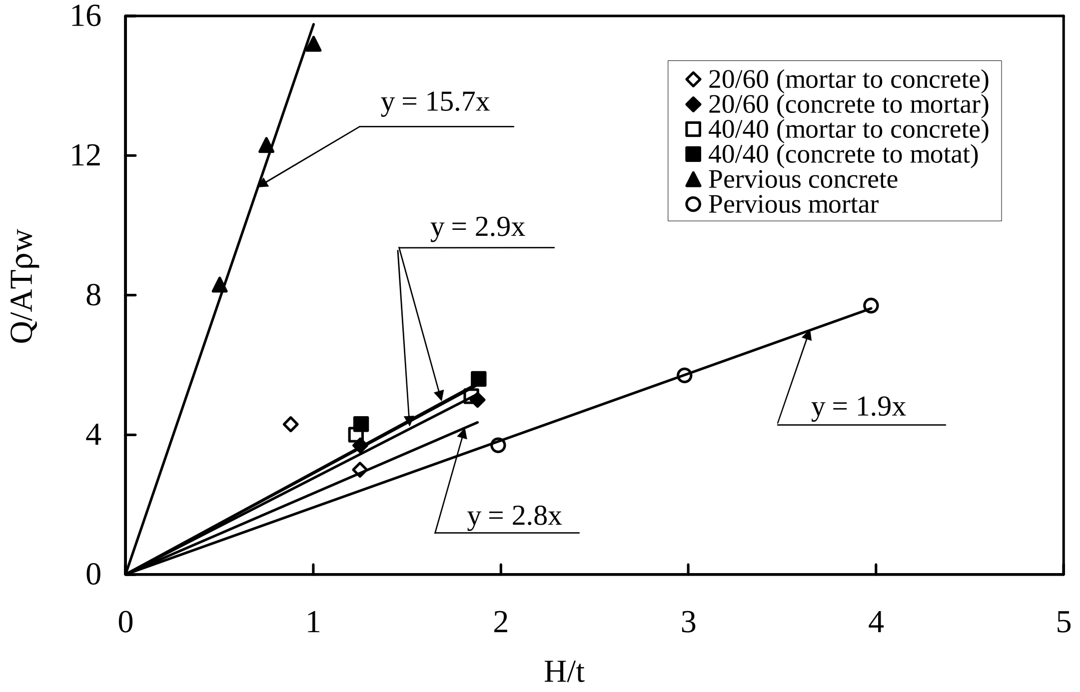


Figure 4.21 Determination of water permeability for pervious concrete, pervious mortar, combination of pervious concrete and pervious mortar

4.7.3 Relationship between density and water permeability

Figure 4.22 showed the relationship between density and water permeability under 100 mm water head for combination of pervious concrete and mortar.

The combination of pervious concrete and mortar showed similar density and water permeability with pervious mortar. This is quite acceptable results. It is expected that the combination of pervious concrete and pervious mortar is more likely affected by pervious mortar due to smaller pore structure.

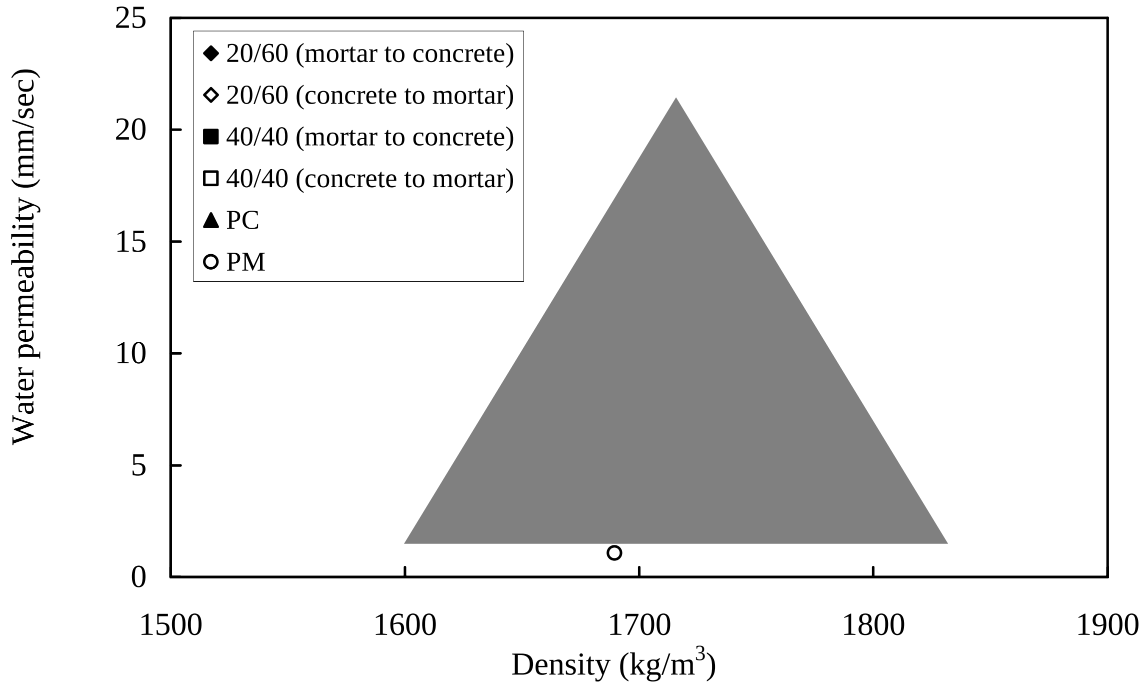


Figure 4.22 Effect of density on water permeability
for combination of pervious concrete and pervious mortar

4.8 Summary

The experimental results of pervious concrete, pervious mortar and combination of pervious concrete and mortar were shown in this section. The experimental results were including the density, porosity, compressive strength, water permeability coefficient, drying shrinkage and weight loss. The results showed the particular pervious concrete and pervious mortar were within the value of the materials using for the pavement. Further research is needed to determine the permeability of combination of pervious concrete and pervious mortar pavement system to increase the water permeability.

Chapter 5

Conclusions and Recommendations for Further Research

5.1 Summary

Pervious concrete has high water permeability due the presence of interconnected air voids. The presence of high porosity relative to conventional concrete makes the pervious concrete to become light weight concrete with limited compressive strength. However, pervious concrete has been significantly popular for a few decades due to its potential to reduce the incidence of flooding, and to assist in recharging the ground water level.

Portland cement production is known to deliver significant amount of carbon dioxide and causing global warming. In order to minimise the environmental impact of using concrete it becomes necessary to reduce the amount of Portland cement used in concrete mixes. This research investigated the characteristics of pervious concrete containing up to 50% reduction in the amount of Portland cement. Low calcium fly ash was used to replace the Portland cement and environmentally friendly pervious concrete was produced.

In addition, investigation was carried out on the effects of incorporating fine aggregate, up to 10% by weight of the total aggregate, on the properties of pervious concretes. The pervious concrete properties were compared with those of conventional concrete. Pervious mortar was also produced and tested for its properties. Finally, a combination of pervious concrete and pervious mortar pavement system was investigated for its water permeability performance.

5.2 Conclusions

5.2.1 No-fines pervious concrete and conventional concrete

- The porosity of the pervious concrete was 0.33, compared to 0.08 for conventional concrete and the density of pervious concrete was about 1800 kg/m^3, which was 25% lower than that of conventional concrete

- The porosity of conventional concrete decreased by 60% from the age of 7 days to 28 days. On the other hand, the porosity of pervious concrete was not significantly influenced by age.
- The compressive strength of the pervious concrete was around 10 MPa, which was 20% of that for the conventional concrete.
- The total drying shrinkage of pervious concrete was around 600 microstrain, while those for conventional concrete was approximately 700 microstrain. The shrinkage of pervious concrete was developed at a faster rate.
- The weight loss for pervious concrete on air drying was twice larger than that for conventional concrete.

5.2.2 Pervious concrete containing fly ash

- The density of pervious concrete decreased marginally when the cement is partially replaced with fly ash. The density values were 1800, 1800 and 1750 kg/m^3 when 0%, 20% and 50% of cement was replaced with fly ash, respectively.
- The porosity of pervious concrete was not significantly influenced by cement replacement with fly ash.
- The compressive strength of pervious concrete decreased when the cement was partially replaced with fly ash. At 50% cement replacement levels, the compressive strength of pervious concrete was reduced to 5.66 MPa compared to 10.1 MPa with 100% cement.
- Pervious concrete showed a relatively high water permeability of 13 mm/s and was not affected by cement replacement with fly ash.
- The water permeability of pervious concrete could be determined under water head of 100 mm.
- The drying shrinkage of pervious concrete decreased by cement replacement with fly ash.
- The weight loss of pervious concrete on drying was increased when the cement was partially replaced with fly ash.

5.2.3 Effect of aggregate grading for pervious concrete

- The density of no-fines pervious concrete was marginally increased by adding fine aggregate.
- The porosity and drying shrinkage of pervious concrete were marginally reduced when the fine aggregate content was increased from 0% to 10% total weight of aggregate.
- The compressive strength of pervious concrete was not influenced when increasing the fine aggregate content. However, the water permeability of pervious concrete was marginally affected.

5.2.4 Pervious mortar

- In terms of porosity, density and compressive strength, pervious mortar having water/cement ratio 0.35 with compaction were similar to those for pervious concrete, while water permeability is smaller than that of pervious concrete.
- Density of pervious mortar ranges form 1290 kg/m^3 to 1690 kg/m^3.
- Porosity of pervious mortar shows around 0.31 while some of them show relatively high porosity of 0.55.
- Compressive strength of pervious mortar is smaller than that of pervious concrete, namely 2.66 MPa to 5.81 MPa.
- The water permeability of pervious mortar was around 2 mm/s.
- Drying shrinkage of pervious mortar was lower than that for pervious concrete.
- Weight loss of pervious mortar on drying was around 6%, which is significantly high

5.2.5 Combination of pervious concrete and pervious mortar

- The density of the combination of pervious concrete and pervious mortar ranged from 1690 to 1780 kg/m^3.
- The water permeability of the combination of pervious concrete and pervious mortar was 3 mm/s, which is smaller than that of pervious concrete but similar to pervious mortar.

- In terms of water permeability and surface structure, combination of pervious concrete and mortar can be used for the pavement structure, with proper selection of the component materials.

5.3 Recommendations for further work

Suggestions for future research work can be summarised as follows:

1) The effect of time on the properties of pervious concrete should be investigated.
2) The pore structure should be investigated because of its effect on the water permeability of pervious concrete.
3) A clogging test for a combination of pervious concrete and pervious mortar should be carried out to evaluate the long-term performance of pervious concrete under severe conditions.
4) A detailed study is needed to develop combined pervious concrete and pervious mortar for pavement application having adequate water permeability, strength, volume stability and durability.
5) A durability of pervious concrete, pervious mortar and combination of pervious concrete and mortar should be investigated to use the pavement structure.

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10. ASTMC260, *Standard Specification for Air-Entraining Admixtures for Concrete*, ASTM, Editor. 2006.
11. ASTMC494, *Standard Specification for Chemical Admixtures for Concrete*, ASTM, Editor. 2005.
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Appendix

List of Published Papers

Environmentally friendly sustainable pervious concrete

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ABSTRACT**:** Portland cement is considered as one of the environmentally unfriendly materials due to its contribution to the increased liberation of carbon dioxide to the environment during production. In addition to its impervious nature, when it is used for pavement application, it contributes to increased stormwater runoff to drainage systems, over-burdening the infrastructure and causing excessive flooding in built-up areas. This paper presents the results of an experimental investigation associated with quantifying the properties of pervious concrete containing fly ash, up to 50% as partial replacement for cement. The main goal of this research is to promote the utilisation of fly ash for developing durable and sustainable pervious concrete, which creates less negative environmental impacts.

1. INTRODUCTION

Impervious nature of normal weight pavement concrete contributes to the increased stormwater runoff into drainage systems, over-burdening the infrastructure and causing excessive flooding in built-up areas. Pervious concrete, having high water permeability, has mainly been developed in the USA in order to meet the US Environmental Protection Agency stormwater regulation requirements (Tennis et. al., 2004). It is mainly is used for parking lots, footpaths, bus terminals, low traffic pathways and so on. The pervious concrete is becoming popular, particularly in USA, because of its potential for solving environmental issues. In addition, pervious concrete is suitable for sound absorption (Neithalath et al., 2005) and vegetation growth (Kitsutaka, et al., 2006).

Fly ash is an industrial by-product generated from the combustion of coal in power generating plant. Due to the presence of reactive silica and alumina, it is a pozzolanic material and accepted as a supplementary cementitious material in producing structural concrete mixes. Utilisation of fly ash in concrete reduces the Portland cement consumption by the concrete industry. Since one tonne of cement production releases 0.94 tonnes of carbon dioxide into the atmosphere, cement production contributes significantly to global warming and climate change. Hence, fly ash is a suitable environmentally friendly supplementary cementitious material to partially replace Portland cement in all types of concrete including in making pervious concrete.

In this paper, the properties of pervious concrete containing fly ash as a cement replacement material up to 50% by weight are presented. Standard and non-standard tests were conducted to determine water permeability, compressive strength, void content and drying shrinkage of pervious concrete.

2. RESEARCH SIGNIFICANCE

The pervious concrete is routinely produced using conventional concrete making materials with or without fine aggregate to retain a void content ranged from 15% to 25%. The connected large-sized void structure leads to a high water permeability coefficient. The mean water permeability of pervious concrete is generally between 1 and 10mm/s. The compressive strength of pervious concrete is between 5 and 20MPa. Drying shrinkage of pervious concrete occurs sooner but it is lower than conventional concrete (Tennis et al., 2004; Aoki and Sri Ravindrarajah, 2008). A proper understanding of the effects of cement replacement with fly ash on the properties of pervious concrete is needed to produce environmentally friendly sustainable pervious concrete.

3. EXPERIMENTAL PROGRAM

General purpose Portland cement (AS 3972, 1997) and New South Wales low calcium fly ash (AS3582, 1998) were used as binder materials in the production of pervious concrete mixes. Single sized (10mm) crushed river gravel (specific gravity of 2.70) was used as coarse aggregate (AS1141.4, 2000).

Table 1: Mix proportions for pervious and non-pervious concrete mixes, by weight

Mix	C (%)	F (%)	W/B Ratio	CA/B Ratio	FA/B Ratio
Mix C1	100	0	0.35	2.80	1.40
Mix C2	80	20	0.35	2.80	1.40
Mix P1	100	0	0.35	4.00	-
Mix P2	80	20	0.35	4.00	-
Mix P3	50	50	0.35	4.00	-

C: cement; F: fly ash; B: Binder (cement plus fly ash); W: water: CA: coarse aggregate; and FA: fine aggregate

Table 1 summarises the mix proportions of the pervious concrete (P1 to P3) and control (non-pervious) concrete (C1 and C2). Three different pervious concrete mixes has been prepared in this research: the first mix was made with 100% Portland cement (Mix P1), the second mix was with 80% cement and 20% fly ash (Mix P2), and the final mix was with of 50% cement and 50% fly ash (Mix P3). The water to binder materials (cement plus fly ash) ratio for all three mixes was maintained at 0.35, to satisfy the workability requirement of pervious concrete as discussed by Sri Ravindrarajah and Aoki (2008).

Fresh concrete mixes were produced in a pan-type of concrete mixer. For each concrete mix, a number of 100mm diameter by 200mm high cylinders and two 75mm by 75mm by 285mm prisms were cast in the corresponding steel moulds. The cast test specimens were demoulded after 24 hours and stored in water at 20°C until the age of testing. The compressive strength, void content and permeability of hardened concrete were determined using the cylindrical specimens, whereas the prisms were used to determine the free drying shrinkage.

The compressive strength was carried out in accordance with the test procedures given in AS 1012, and the mean of three results obtained with three identical specimens are reported. The void content of hardened concrete was calculated from the oven dried and saturated weights using the equation produced by Park and Tia (2004). The water permeability was determined by using the procedure developed by Sri Ravindrarajah and Aoki (2008) is used. Figure 1 shows the experimental test set-up for the water permeability test. The water permeability was calculated based on Darcy's Law, given below:

$$\frac{Q}{AT\rho_w} = k\frac{\Delta H}{t} \tag{1}$$

Where, A is the cross-sectional area of the cylinder, Q is the quantity of water collected over 30s, ρ_w is the density of water, T is the time (30s), k is the water permeability coefficient, ΔH is the water head, and t is length of specimen.

In this study, three different water heads (100mm, 150mm and 200mm) were used.

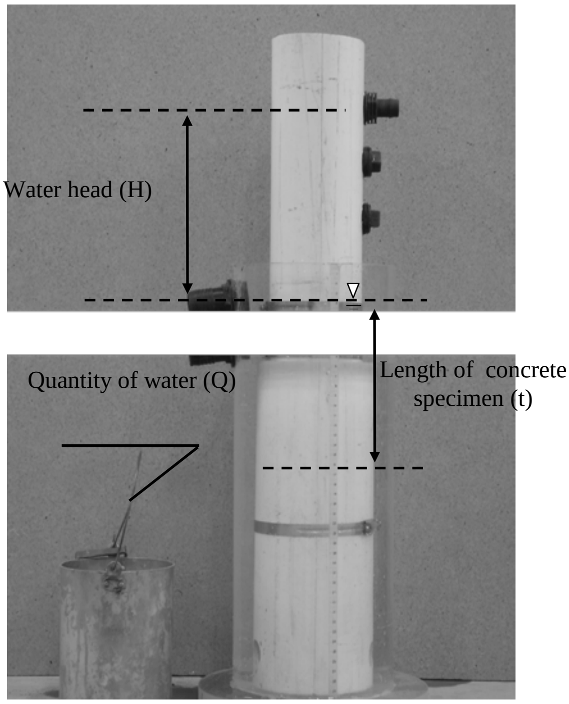

Figure 1: Water permeability experimental test set-up for pervious concrete

The drying shrinkage of concrete was monitored on the prisms, over a 200mm gauge length, using a demountable mechanical strain gauge on the opposite longitudinal sides. The prisms were allowed to dry in the unsaturated laboratory environment (mean temperature and relative humidity of 20°C and 65% R.H.) for 56 days. The reported results are the average of 2 readings taken on both sides of a shrinkage prism. Weights of the prisms were also taken at the time of shrinkage measurement.

4. RESULTS AND DISCUSSION

Table 2 summarises the compressive strengths for pervious and non-pervious mixes at the ages of 7 and 28 days. The strengths of pervious concrete show to a certain extent lower than conventional concrete. Both of them developed strength with age increasing. Especially, higher amount fly ash concrete demonstrated a dramatic increase with time. However, adding fly ash leads to a reduction in strength in both pervious and non pervious concrete.

Table 2: Compressive strength of pervious and non-pervious concretes

Age (days)	Non-pervious Concrete	
	Mix C1: 100%C	Mix C2: 80%C & 20%F
7	45.3 MPa	28.7 MPa
28	50.6 MPa	41.2 MPa

Age (days)	Pervious concrete		
	Mix P1: 100% C	Mix P2: 80%C & 20%F	Mix P3: 50%C & 50%F
7	7.6 MPa	6.9 MPa	2.7 MPa
28	10.1 MPa	8.8 MPa	5.7 MPa

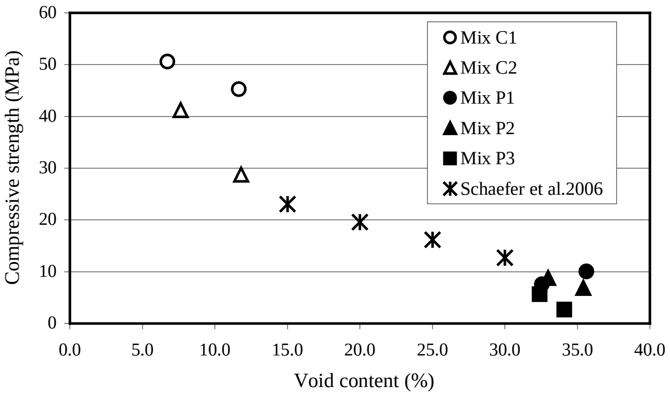

Figure 2: Effect of void content on compressive strength of concrete

Figure 2 shows the effect of increasing void content on the compressive strength for pervious and non-pervious concrete mixes. Schaefer et. al. (2006) results are also included in this plot. The results clearly show the non-linear relationship between compressive strength and void content. The compressive strength decreased at an increasing rate with the increase in the void content. The pervious concrete mixes, having over 30% void content, had the compressive strength below 10MPa. The results also showed that there is no significant difference on void content for pervious concrete mixes as the results of partial cement replacement with fly ash.

Figure 3 shows the exponential relationship between water permeability coefficient (k) and void content for pervious concrete, based on Schaefer's results (2006). The results obtained in this study with three pervious concrete mixes under 100mm water head are also included in the plot. The results show that for pervious concrete with 35% void content the water permeability coefficient is approximately 12mm/s. Although marginal increase in the void content was noted for pervious concrete mixes with cement replacement with fly ash, the water permeability coefficient of 15mm/s was recorded with the Mix P3 with 50% cement replacement with fly ash, by weight.

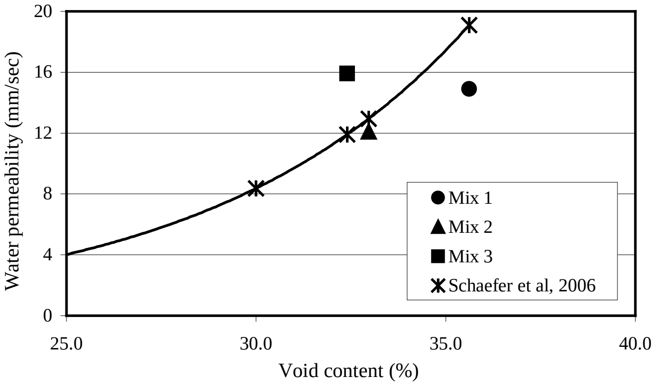

Figure 3: Relationship between water permeability and void content for pervious concrete (100mm water head)

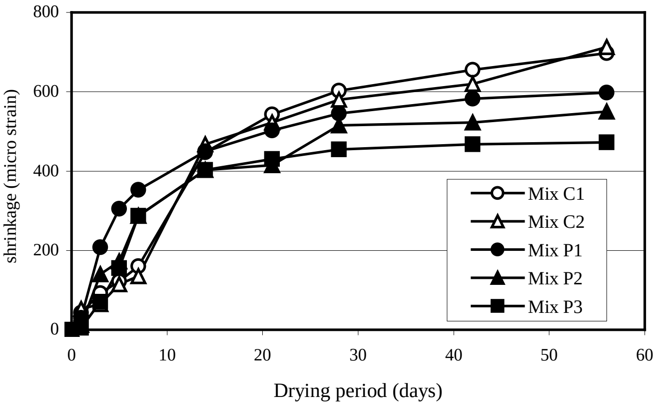

Figure 4: Development of free drying shrinkage with time for pervious and non-pervious concretes

Figure 4 shows the development of free drying shrinkage with drying time for both pervious and non-pervious concretes. The results show that the shrinkage for both concretes increased with drying time at a decreasing rate. The pervious concrete showed significantly lower 56-days shrinkage compared to non-pervious concrete. In addition, the 56-day shrinkage for pervious concrete is found to decrease with the increase in the level of cement replacement with fly ash. The pervious concrete with 100% cement (Mix P1) showed the 56-day shrinkage of 600 microstrain compared to 450 microstrain for the pervious concrete with 50% cement and 50% fly ash (Mix P3) after the same period of drying.

The results showed that the total weight loss was around 3% for pervious concrete, while the water loss for non-pervious concrete was less than 2%. Since the pervious concrete has an open-structured interconnected pores, the previous concrete is capable of readily losing the unbound free water compared to non-pervious concrete with closed pores. For pervious concrete, cement replacement with fly ash has marginally affected the water loss.

Figure 5 shows the relationship between drying shrinkage and weight loss for both pervious and non-pervious concretes. Since most of the water lost

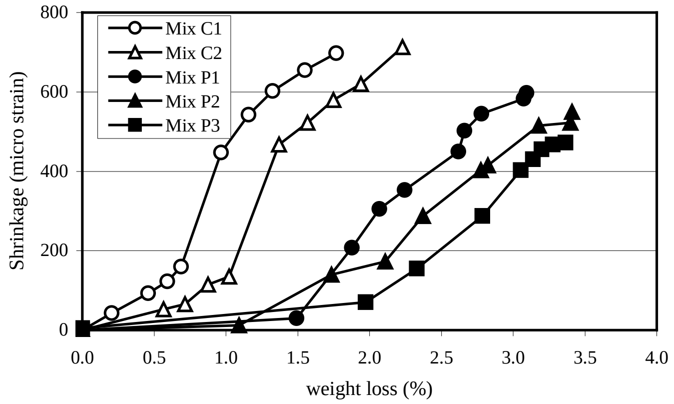

Figure 5. Relationship between free drying shrinkage and weight loss for pervious and non-pervious concretes

from the pervious concrete is free non-bonded water from large-sized open voids, the water loss has significantly reduced effect on the development of drying shrinkage. Since modification in the pores structure of the hardened binder paste is expected with the cement replacement with fly ash, it is not surprising to note its impact on the relationship between shrinkage and water loss with the increased level of cement replacement with fly ash. The drying shrinkage results indicate that pervious concrete having an improved moisture induced dimensional stability, could be achieved by partially replacing cement with fly ash in the pervious concrete mixes.

Table 3: Effect of water head on water permeability coefficient for pervious concrete

Water head (mm)	Water permeability coefficient (mm/s)		
	Mix P1	Mix P2	Mix P3
100	14.90	12.11	15.90
150	17.33	11.13	17.20
200	13.63	9.25	12.99

Table 3 shows the water permeability coefficient for pervious concrete under of the water heads of 100, 150 and 200mm. The water permeability coefficient with 200mm water head showed the lowest value for all pervious concrete mixes. Moreover, pervious concrete with no fly ash (Mix P1) and 50% fly ash pervious concrete (Mix P3) showed the highest water permeability coefficient under the water head of 150mm. If the Darcy’s law is fully applicable, the water flow should be laminar and then the water permeability coefficient should be independent of the water head. The probably reason for the variability for the water permeability coefficient with increased water head could be related to the change in the flow pattern of water through the pervious concrete from laminar to turbulence flow due to variation in pore sizes and structure. Further investigation is needed to establish the flow pattern under varying water head for pervious concrete.

5. CONCLUSIONS

Based on the experimental results, the following conclusion could be made:

1. No-fine pervious concrete showed a lower compressive strength, while its water permeability and void content was relatively high.
2. High volume fly ash pervious concrete showed similar properties compare to no fly ash pervious concrete.
3. Drying shrinkage of pervious concrete are lower compared to that for non-pervious concrete.
4. Pervious concrete with 50% cement and 50% fly ash presented the lowest drying shrinkage and the highest weight loss.
5. Water permeability coefficient for pervious concrete is affected by the water head possibly due to the change in the nature of flow through porous concrete.
6. Environmentally friendly pervious concrete could be produced with 50% cement and 50% fly ash.

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Environmentally Friendly Pervious Concrete

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Abstract

One of the reasons for flooding in urban areas is the increased water runoff associated with the increase in the paved areas. The existing drainage system becomes over-burdened and efforts have to be made to minimise the water runoff in order to prevent flooding. In many developed countries, the use of pervious concrete for the construction of car parks, pathways and driveways is becoming popular. In order to develop materials specification it is necessary to highlight on the testing and performance of this type of new concrete. This paper presents the preliminary results from an experimental investigation into the properties of pervious concrete containing fly ash. The main aim of the research is to develop a sustainable pervious concrete, having environmentally friendly component materials.

INTRODUCTION

In 2003, the world cement production has reached 1.9 billion tonnes. The most populous countries on earth namely China and India had produced 41.9% and 6.2%, respectively of the world cement output. As the demand for concrete increases with time, the current cement production could be substantially higher than those reported in 2003. Since the 1 tonne of cement production releases 0.94 tonne of CO_2 into the atmosphere, the cement production contributes significantly to the global warming and climate change. Hence, it is essential for the concrete industry to be aware with the consequence of utilising environmentally unfriendly cement. Every effort should be taken to minimise the use of cement in concrete construction. In concrete mixes, cement should be partially replaced with a variety of proven supplementary cementitious materials such as natural pozzolans, fly ash and ground granulated blast furnace slag.

Normal weight concrete is known for its strength and durability. However, when it is used for pavement applications, impervious nature of this type of concrete increases the water runoff to the drainage system, thus over-burdening the infrastructure and causing excessive flooding in built-up areas. If the concrete is able to allow water to flow through, then the water runoff could be reduced. Pervious concrete of porous nature is becoming a popular material in many countries for the construction of paved areas, car parks, driveways and pathways. This type of concrete has its potential in minimising the runoff and recharging the groundwater level.

The pervious concrete has been developed in USA to meet the Environmental Protection Agency stormwater regulation (Tennis et. al. (2004)). In order to develop specification, ASTM Concrete Committee (C09) has formed a new sub-committee on pervious concrete. European countries have developed the pervious concrete not only for water permeability but also for sounds absorption. In Japan, the pervious concrete has been researched for using road surface and river bank, although the Japanese researchers focused on high porosity which can lead to vegetation growth (Zouaghi and Kumagai (2000)).

The pervious concrete is quite a new type of concrete in many countries. So far there is no standard specification for producing and testing of this type of concrete. The main aim of this research is to develop a sustainable pervious concrete, having environmentally friendly component materials. This paper reviews the main characteristics of pervious concrete and discusses the properties of pervious concrete containing fly ash.

GENERAL BACKGROUND OF PERVIOUS CONCRETE

Materials for Pervious Concrete Production

Ordinary Portland cement is mainly used for the pervious concrete, however the use of blended cement, eco-cement and cement supplementary materials (fly ash, pozzolan, ground-granulated blast furnace slag and silica fume) are reported (Matsuo et. al. (2005); Schaefer et. al. (2006); Yang and Jiang (2003)). Gravel and crushed aggregate are used as coarse aggregate in single size or narrow gradation size. The amount of fine aggregate is critical in the production of pervious concrete mix since the fine aggregate can reduces the porosity and hence permeability of concrete due to the reduced in interconnectivity of the pores. All types of chemical admixtures could be used to achieve modification of the concrete properties.

Mix Proportion of Pervious Concrete

The water to cementitious materials ratio for pervious concrete is from 0.30 to 0.40. Tennis et. al. (2004) recommended that water to cement ratio should be determined based on the ability of the pervious concrete to shape into a ball with one’s hands. Since the pervious concrete workability is sensitive for amount of water, so that it should be controlled strictly. Aggregate to cementitious materials ratio is 4:1 to 4.5:1 by mass, as indicated by Ghafoori and Dutta (1995).

Specification of Pervious Concrete

A pervious concrete mix basically consists of conventional concrete making materials with a high void content between 15% and 30%. The open and interconnected pore structure contributes to the high permeability property of pervious concrete. The mean water permeability of pervious concrete is normally between 1mm/s and 10mm/s compared to 10^{-9}mm/s for the conventional concretes. The high void content in pervious concrete contributes to a low compressive strength and the strength varies between 5MPa and 20MPa. The main applications of pervious concrete are for parking lots, pathways, driveways, pavement, bus terminals, a low traffic roads and so on. Due to lack of strength, pervious concrete is not suitable for the construction of highways or heavy traffic concrete roads.

Properties and Specification of Pervious Concrete

Similar to the conventional concrete, strength and permeability of pervious concrete are influenced by factors such as, mix compositions, types of component materials and void content. Workability of pervious concrete is quite low (Ghafoori and Dutta (1995); Tennis et. al. (2004)). During construction with pervious concrete, a roller compaction is much appropriate to achieve uniformity. The density of pervious concrete is approximately 1900kg/m^3.

The void content required in pervious concrete for high permeability is between 15% and 25%. The mean compressive strength of this concrete ranges from 3.5 MPa to 35.5 MPa (Ghafoori and Dutta (1995); Tennis et al. (2004); Yang and Jiang (2003)). An increase in the aggregate content reduces the compressive strength (Ghafoori and Dutta 1995). Drying shrinkage of pervious concrete occurs sooner but it is lower than that for the conventional concrete as reported by Tennis et. al. (2004). The average permeability of pervious concrete is from 5mm/s to 20mm/s, although there is no standard value is recommended. ACI (2006) adopted the falling head method (Fig. 1) developed by Neithalath et. al. (2006). The permeability is calculated using Darcy Law. However, Neithalathe et. al. (2006) pointed out that there is no definitive relationship between void content and permeability, even though a relationship is expected.

Durability of Pervious Concrete

There is no published research on the durability of pervious concrete as pointed out by report of pervious concrete ACI (2006). According to Tennis et. al. (2004), acid and sulphate resistance for pervious concrete is similar to conventional concrete. Nevertheless, pervious concrete can be more influenced than conventional concrete because of its high volume and low strength characteristics. So far, deterioration of pervious concrete under service conditions was not reported.

The most significant problem of pervious concrete is clogging of the permeable pores which lead to a dramatic decrease of permeability. To solve this, maintenance and surface sweeping are required (Haselbach et. al. 2006). The surface ravelling of pervious concrete might be happened very early stage mainly caused by heavy load, so that if there is optimum compaction and curing techniques, surface ravelling could be reduced (Tennis et. al. 2004). However, ACI (2006) claimed that there is limited information of long-performance of pervious concrete.

EXPERIMENTAL INVESTIGATION

Materials

Type GP cement and low calcium fly ash were used as cementitious materials in this study. 10mm single sized crushed river gravel was used as coarse aggregate. Coarse river sand was used as fine aggregate.

Mix Proportions of Pervious and Conventional Concretes

The mix proportion for pervious concrete of 1.0 : 4.0 : 0.35 (cementitious materials : coarse aggregate : water) was based on the properties of trial mixes. Four trials mixes with the water cement ratios of 0.25, 0.30, 0.35, and 0.40 indicated that the water to cement of ratio of 0.35 was suitable for the forming ball with the fresh pervious concrete. Conventional structural grade concrete mixes were also produced and tested for properties comparison with pervious concrete. The mix proportion of conventional concrete was

1.0: 2.8: 1.4:0.5 (cementitious materials, coarse aggregate, fine aggregate, and water); respectively. Both types of concretes were produced having 100% Portland cement (Mix 1) and 80% Portland cement and had 20% of fly ash (Mix 2), as cementitious materials in the concrete.

Mixing of Concrete, Casting and Curing of Test

Specimens

Concrete batches were mixed in a pan-type of mixer. Immediately after mixing, wet density of concrete was determined. A number of standard 100mm diameter by 200mm high cylinders were cast in steel moulds for compressive strength testing and water permeability tests on hardened concrete at appropriate ages. All the specimens were demoulded after 24 hours and stored in water at 20$_o$C.

Testing of Hardened Concrete

Cylinder strength and drying shrinkage testing on hardened concrete test specimens were carried out in accordance with the test procedures given in AS 1012. The void content of hardened concrete was calculated from the oven dry and saturated weights using the following equation.

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

where,

V_r = void content

W_1 = weight under water

W_2 = oven dry weight,

Vol = volume of sample,

and ρ_w = density of water.

Water Permeability Test

Constant head method was used to measure the water permeability of pervious concrete. Fig. 3 shows the schematic diagram of the permeability test. The water heads adopted were 100, 150, or 200mm. The test cylinders were covered with sponge rubber to stop water leakage is the transverse direction. The cylinders were placed in the chloride vinyl pipe and tightened by buckles. Under a given water head, the permeability testing was carried out when steady state of flow was reached. The amount of water flowing through the specimens over 30 seconds was measured and the permeability coefficient was determined using Darcy's Law equation, given below:

$$\frac{Q}{AT\rho_w} = k\frac{H}{t} \qquad (2)$$

where,

A = cross-sectional area of cylinder
Q = quantity of water collected over 30s
ρ_w = density of water ($1000 kg/m^3$)
T = time (30s)
k = water permeability coefficient
H = difference of water head
and t = length of specimen

RESULTS AND DISCUSSION

Table 1 summarises the compressive strength for conventional concrete and pervious concrete, with and without cement replacement, after 7 and 28 days of water curing. Both types of concrete improved in strength with the increase in the age of concrete. The pervious concrete showed significantly lower strength than those for the conventional concrete due to very high void content of about 30%. The results also show that cement replacement by fly ash reduced the 7-day strength by 51% after 7 days and by 18% after 28 days for the conventional concrete. The pervious concrete showed 18% strength reduction after 28-days.

The conventional concrete had the void content below 12% compared to over 30% void content for the pervious concrete. Fig. 4 shows the relationship between strength and void content for concrete. As expected, significant drop in strength was noted with the increase in the void content.

Fig. 5 shows the exponential relationship between water permeability and void content for pervious concrete with and without fly ash. Shaefer et. al. (2006) relationship is also included in this plot. Further analysis of the results indicated that pervious concrete with 20% fly ash showed a decrease in the water permeability and more tests are undertaken to confirm this trend.

CONCLUDING REMARKS

Based on the experimental investigation into the properties of pervious concrete, the following conclusions are made: Pervious concrete could be made with conventional concrete making materials to have 30% void content and eater permeability between 6mm/s and 17 mm/s. Cement replacement with fly ash contributed to the reduction in long term strength of pervious concrete similar to that noted with the conventional concrete. Since the water permeability as the main criterion for the pervious concrete, fly ash can be used in the production of pervious concrete to achieve an environmentally friendly concrete.

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Table 1: Compressive Strength of Conventional and Pervious Concretes

Age (days)	**100% Cement (Mix 1)**		**80% Cement and 20% Fly Ash (Mix 2)**	
	Conventional	**Pervious**	**Conventional**	**Pervious**
7	**45.3**	**6.9**	**22.2**	**7.6**
28	**50.0**	**10.0**	**41.2**	**8.8**

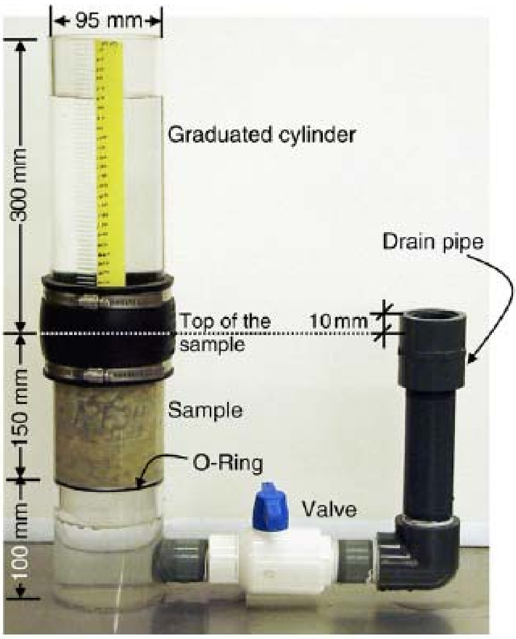

Fig.1 Falling Head Water Permeability Test (Neithalath, N. et. al. (2006)

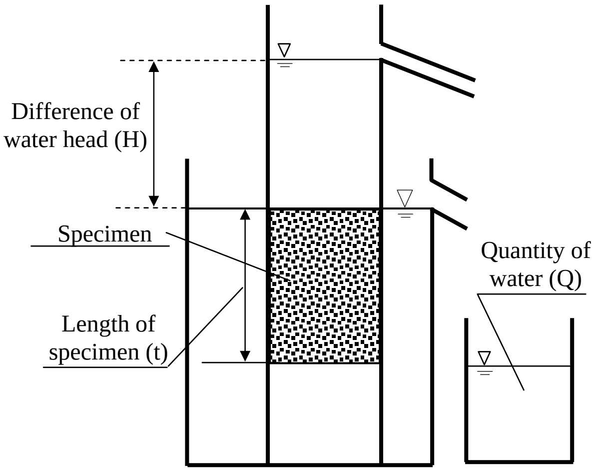

Fig.3 Constant Head Water Ppermeability Test

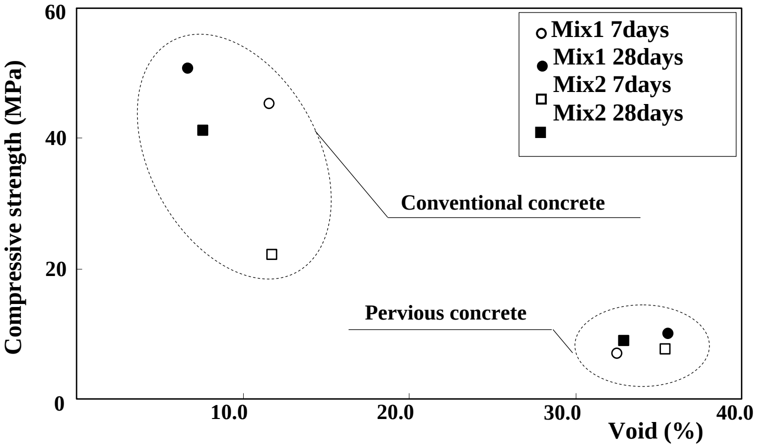

Fig. 4 Relationship between Strength and Void Ccontent

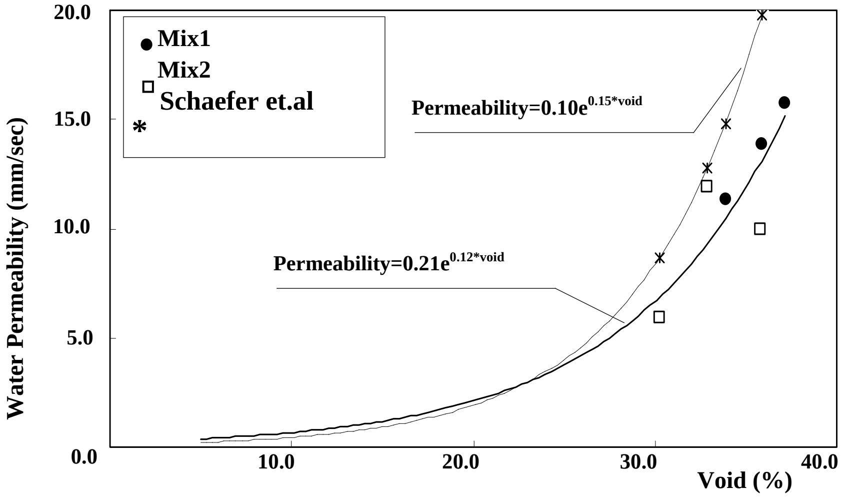

Fig. 5 Relationship between Water Permeability and Void Content

EFFECT OF FLY ASH PERFORMANCE OF PERVIOUS CONCRETE

Y. Aoki, R. Sri Ravindrarajah and H. Khabbaz

Synopsis: Production of good quality pervious concrete is necessary to meet specification requirements for the construction of durable concrete pervious pavements. This paper reports and discusses the results of an experimental investigation into the physical and engineering properties of pervious concrete having varying amounts of fly ash as the cement replacement material. The following properties were studied: porosity, density, compressive strength, weight loss on drying, free drying shrinkage and water permeability under constant head. The results showed that porosity has significant effect on compressive strength and permeability of pervious concrete. Replacement of cement with fly ash up to 50%, by mass of binder, had no significant effect on the water permeability and shrinkage of the pervious concrete, although marginal effect on strength was noticed.

Keywords: Drying shrinkage, Fly ash, Pervious concrete, Porosity, Strength, Water permeability

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INTRODUCTION

Impervious nature of normal weight concrete used for pavement applications contributes to the increased stormwater water runoff into drainage systems and causing excessive flooding in built-up urban areas. Pervious concrete, an open-graded material has significantly high permeability due to the presence of interconnected pores, ranging from 2 to 8 mm [1]. By capturing stormwater and allowing it to seep into the ground, the pervious concrete is instrumental in recharging groundwater and reducing stormwater runoff. In addition, pervious concrete is applied as a sound absorbing material for highway applications in Europe [2] and river banks in Japan [3].

The pervious concrete is produced by using conventional concrete making materials, with or without fine aggregate to have a porosity ranging from 15% to 35%. The connected large-sized pores in the concrete system lead to produce a high water permeability lightweight concrete compared to normal-weight concrete. Typical water permeability coefficient for pervious concrete is about 10 mm/s compared to 10^{-9} mm/s for normal-weight concrete. Typical compressive strength for pervious concrete is ranging from 5 to 10 MPa, and used mainly for the construction of parking lots, footpaths, bus terminals and low traffic pathways.

World’s cement production in 2003 reached 1.9 billion tonnes and the most populous countries, namely China and India, produced 41.9% and 5.2%, respectively, of the world’s cement output [4]. Since 1 tonne of portland cement production releases 0.94 tonne of carbon dioxide gas into the atmosphere, cement production contributes significantly to global warming and climate change. In Australia, 9 million tonnes of cement was produced in 2006 and due to the use of secondary materials, such as fly ash and slag, carbon dioxide emission is reduced to 0.72 tonne per tonne of cement produced [5].

Considering the environmental effects of using portland cement, it is essential for the concrete industry to minimise the use of cement in the production of both structural and non-structural concrete. One way to reduce cement consumption is to use fly ash, a waste product from the combustion of coal for thermal power generation, as a cement replacement material because of the pozzolanic reactivity of fly ash. This paper reports the results of an experimental investigation into the production and properties of pervious concrete with reduced amount of portland cement using high volume additions of fly ash.

RESEARCH SIGNIFICANCE

For the past few years, pioneering research on pervious concrete is being carried out at the University of Technology, Sydney, Australia. Preliminary results on the production and properties of pervious concrete were reported elsewhere [6-8]. The research is aimed to produce sustainable environmentally friendly pervious concrete, having significant water permeability with moderate strength of around 10 MPa. Portland cement replacements of up to 50% by mass with low-calcium fly ash are investigated. The influence of cement replacement with fly ash on porosity, density, compressive strength, drying shrinkage and water permeability were determined. The significance of this research is to evaluate the feasibility of the production of environmentally friendly pervious concrete to meet the specification requirements for pavement application.

EXPERIMENTAL PROGRAM

General purpose (GP) portland cement, conforming to AS3972 [9] and New South Wales low-calcium fly ash, conforming to AS3582 [10] were used as binder materials in the production of pervious concrete mixtures. Typical chemical compositions for NSW fly ash indicate the lime, silica and alumina contents of 1.59%, 65.9% and 24.0%, respectively. Single size (10 mm) crushed river gravel (specific gravity of 2.70) was used for the coarse aggregate. Fine aggregate was not used the pervious concrete.

Three pervious concrete mixtures were produced having three cement replacement levels of 0, 20% and 50% with fly ash, by mass of binder. The aggregate-to-cementitious materials ratio for the investigated mixtures was fixed at 4.0, by mass. The free water-to-cementitious materials ratio for these mixtures was maintained at 0.35 to maintain suitable workability assessed by test described elsewhere [6, 8].

Fresh pervious concrete mixtures were produced in a pan-type mixer. For each mixture, a sufficient number of 100 mm diameter by 200 mm high cylinders and two 75 × 75 × 285 mm prisms were cast in standard steel moulds. Minimum compaction effort was used to cast the test specimens. The concrete was removed from the moulds after 24 hours and stored in water at 20°C until the age of testing. The cylindrical specimens were used to determine the compressive strength and permeability of concrete, whereas the prismatic specimens were used for free drying shrinkage testing. The shrinkage specimens were water-cured for 7 days followed by drying in an unsaturated uncontrolled laboratory environment, having a mean temperature and relative humidity of 20°C and 65%, respectively, for 56 days. The compressive strength was carried out in accordance with the test procedures given in AS1012 [11]. At each age, identical three cylinders were tested, and the average of three results is reported. Porosity of pervious concrete mixtures was calculated using Eq. (1)

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

where, V_r = porosity (%), W_1 = weight under water (g), W_2 = oven dry weight (g), Vol = volume of sample (m^3), and ρ_w = density of water (g/m^3).

The water permeability of pervious concrete was determined using a procedure described elsewhere [6]. Figure 1 shows the experimental test set-up for the determination of water permeability of pervious concrete under constant head. Permeability of pervious concrete was determined over a period of 30 seconds under a water head of 100 mm. The water permeability coefficient was calculated using Darcy's Law, as shown in Eq. (2)

$$\frac{Q}{At\rho_w} = k\frac{\Delta H}{L} \tag{2}$$

where, A = cross-sectional area of the cylinder (mm^2), Q = quantity of water collected (g) over time (t), ρ_w = density of water (1×10^{-3} g/m^3), k = water permeability coefficient (mm/s), ΔH = water head (mm), and L = length of specimen (mm).

Free drying shrinkage of pervious concrete was determined during 56 days of drying period over a 200 mm gauge length using a demountable mechanical strain gauge on two identical prismatic specimens. The reported results were the average of four readings taken on two opposite sides of each specimen. The shrinkage specimens were weighed, at the time of the shrinkage measurements.

RESULTS AND DISCUSSION

Density of pervious concrete

Figure 2 shows the density of the hardened pervious concrete as a function cement replacement with fly ash at 7 and 28 days. The mean density of the pervious concrete mixtures is about 1770 kg/m^3. Mixes 1 and 2 had approximate density of 1800 kg/m^3 compared to 1750 kg/m^3 for Mix 3. The density variations in pervious concrete mixtures are the combined effects of varying degree of compaction and presence of low density fly ash compared to portland cement.

Porosity of pervious concrete

Porosity of the three pervious concrete mixtures is shown in Figure 3. The results show that the porosity is not significantly affected by the partial replacement of cement by fly ash. These finding are not surprising since the porosity of pervious concrete is mainly affected by the grading of the aggregate. The mean porosity for the pervious concrete mixtures is 0.33.

Water permeability of pervious concrete

Figure 4 shows the water permeability coefficient of the pervious concrete mixtures under the water head of 100 mm. The pervious concrete had a water permeability coefficient of 12 to 16 mm/s. The lower water permeability was observed for the pervious concrete with 20% cement replacement with fly ash (Mix 2). The control pervious concrete (Mix 1) and the mix with 50% fly ash (Mix 3) showed nearly the same water permeability coefficient of 16 mm/s. Independent of the cement replacement with fly ash, the pervious concrete showed high water permeability to be accepted for pervious pavement applications.

Relationship between porosity and permeability for pervious concrete

Figure 5 shows the relationship between porosity and permeability for pervious concrete, plotted with published data [12] and the results reported in this study. For pervious concrete having the porosity between 15% and 40%, a linear relationship could be derived between porosity and permeability and given by Eq. (3)

$$k = 0.41\ V + 0.51 \tag{3}$$

where, k = permeability coefficient in mm/s; and V = porosity in percent

Compressive strength of pervious concrete

Figure 6 shows the compressive strength of the pervious concrete mix at the ages of 7 and 28 days. Each result showed the mean of three identical cylinders tested at the same age for each concrete mixture. Noticeable strength variations were noted among the three specimens due to the variation in the degree of compaction. As expected, the compressive strength of the pervious concrete increased with the increase in age. This is due the progress of cement hydration and pozzolanic reaction of the fly ash with lime liberated from cement hydration. The control pervious concrete mix with 100% cement (Mix 1) and that mix with 20% fly ash (Mix 2) showed 30% increase in the compressive strength from the age of 7 to 28 days. The pervious concrete with 50% fly ash (Mix 3) showed an increase of 50% in strength during the same period.

At the age of 28 days, the highest compressive strength of about 10 MPa was recorded for the control pervious concrete (Mix 1), and the lowest strength of about 6 MPa for Mix 3 (50% fly ash). Since there is no strength requirement in the specification for pervious concrete, cement replacement with 50% fly ash will not affect the acceptance of pervious concrete as a material for pavement application.

Relationship between porosity and compressive strength for pervious concrete

Figure 7 shows the relationship between porosity and compressive strength at 28 days for pervious concrete based on the published results [12]. The results of this investigation support this trend. Within the porosity between 15% and 30%, the compressive strength dropped linearly with the increase in porosity as shown in Eq. (4)

$$f = -\ 0.71\ V + 26.6 \tag{4}$$

where, f = compressive strength at 28 days in MPa; and V = porosity in percent.

Drying shrinkage of pervious concrete

Figure 8 shows the development of drying shrinkage with time for the pervious concrete. Figure 9 shows the relationship between drying shrinkage and mass loss for pervious concrete. Drying shrinkage for pervious concrete increased with time at a decreasing rate. The 56-day drying shrinkage ranged from 480 to 600 microstrain. The pervious concrete having 50% cement and 50% fly ash (Mix 3), showed the lowest shrinkage of 480 microstrain compared to the control pervious concrete (Mix 1) of 600 microstrain. The results imply that the cement replacement with fly ash increased the dimensional stability of pervious concrete.

The mean mass loss for the pervious concrete mixtures after 56 days of drying in the uncontrolled laboratory environment was about 3.2%. Pervious concrete having 50% cement replacement with fly ash (Mix 3) showed the highest mass loss of about 3.5%, whereas the pervious concrete without cement replacement (Mix 1) showed the lowest mass loss of around 3%. For a given mass loss, the control pervious concrete showed maximum shrinkage compared to other pervious concrete mixtures having cement replacement with fly ash.

Relative effects of partial cement replacement with fly ash on properties of pervious concrete

Table 1 summarises the engineering properties of pervious concrete mix made using low calcium fly ash relative to the control pervious concrete. In comparison with the properties of pervious concrete with no cement replacement, the results showed that 50% of Portland cement with fly ash, by mass, can reduce 28-day compressive strength of pervious concrete by 4%. However, water permeability was insignificantly reduced and the drying shrinkage after 56 days was reduced by 21%.

CONCLUSIONS

Three pervious concrete mixtures made with 0, 20% and 50% fly ash substitutions to cement were investigated. The pervious concrete with high porosity showed low compressive strength and high water permeability. Based on the results presented, linear relationships between porosity and compressive strength, and porosity and permeability are established for pervious concrete within the porosity range of 15% to 30%.

The results showed that the water permeability of pervious concrete was not significantly affected when 50% of the cement was replaced by fly ash. However, the dimensional stability due to drying shrinkage was increased significantly with fly ash use. It can be concluded that environmentally friendly sustainable pervious concrete could be produced with significantly reduced amount of Portland cement with fly ash.

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Table 1: Effects of cement replacement with fly ash on the properties of pervious concrete mixtures

Cement (%)	**Fly Ash (%)**	**Porosity**	**Strength**	**Water permeability**	**Drying shrinkage**	**Mass loss**
100	0	100	100	100	100	100
80	20	92	87	81	92	110
50	50	89	56	107	79	109

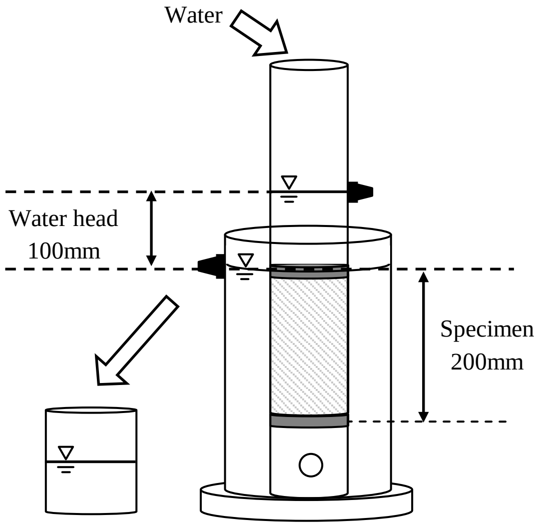

Figure 1-- Water permeability test set-up for pervious concrete

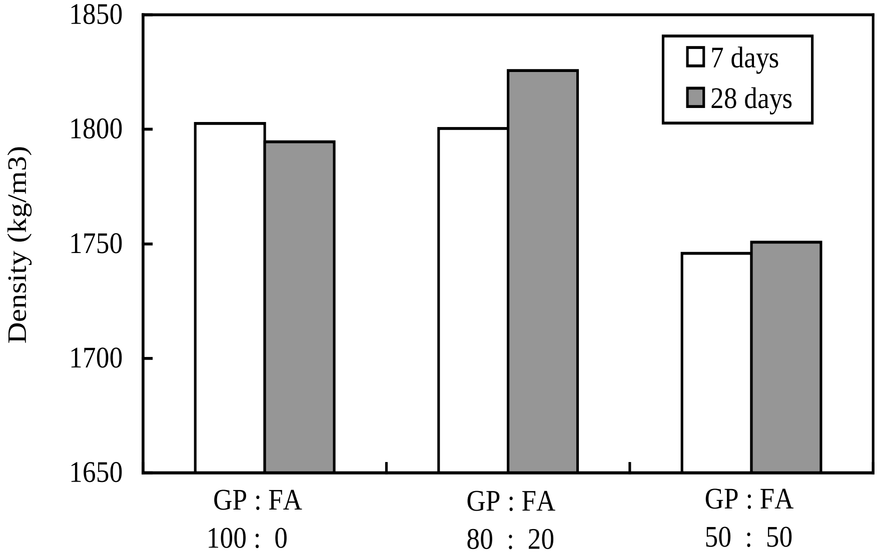

Figure 2-- Effect of age and fly ash content on density of pervious concrete

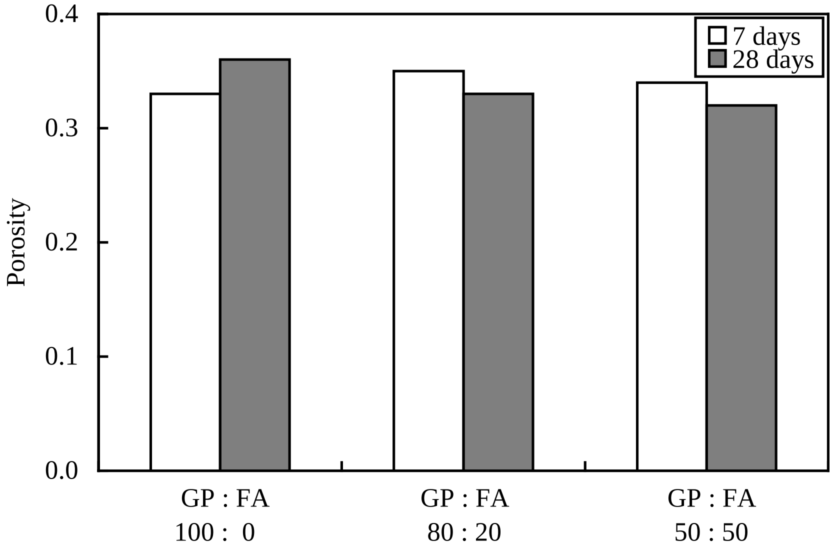

Figure 3-- Effect of age and fly ash content on porosity of pervious concrete

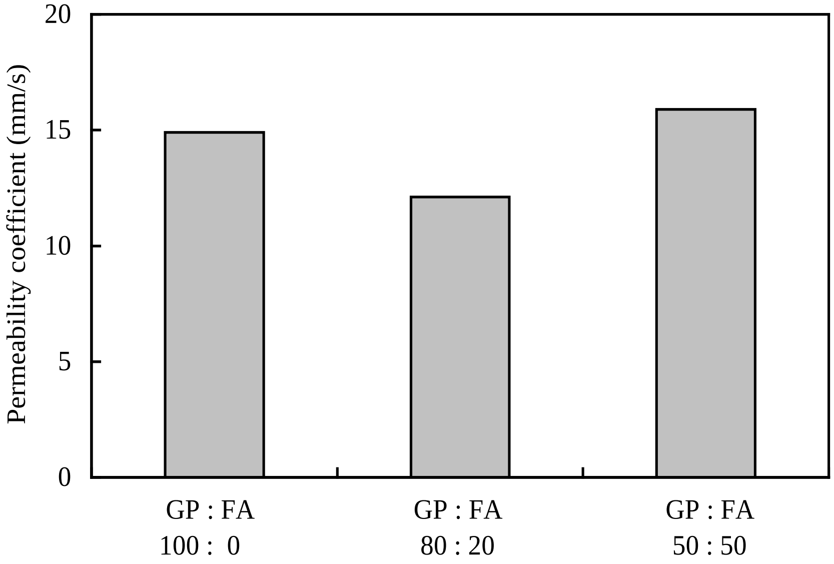

Figure 4-- Effect of fly ash on the permeability coefficient of pervious concrete

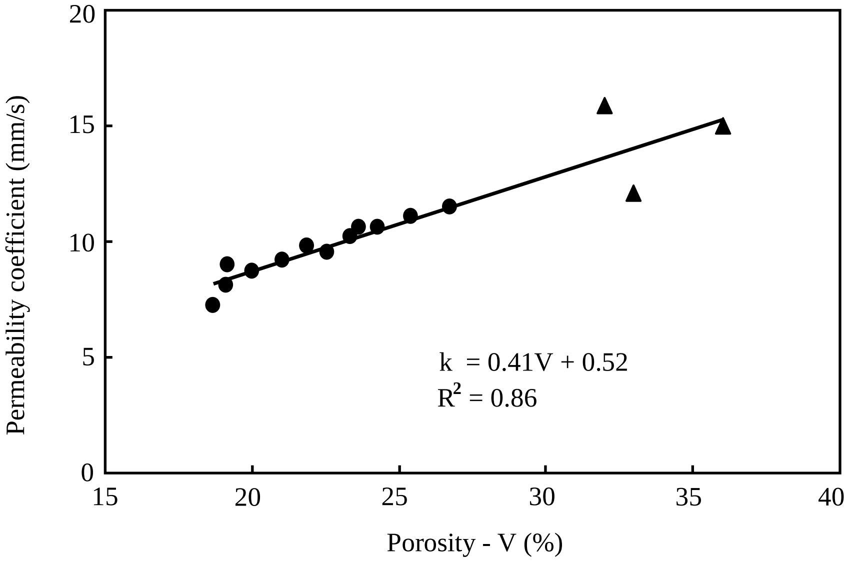

Figure 5-- Relationship between porosity and permeability for pervious concrete

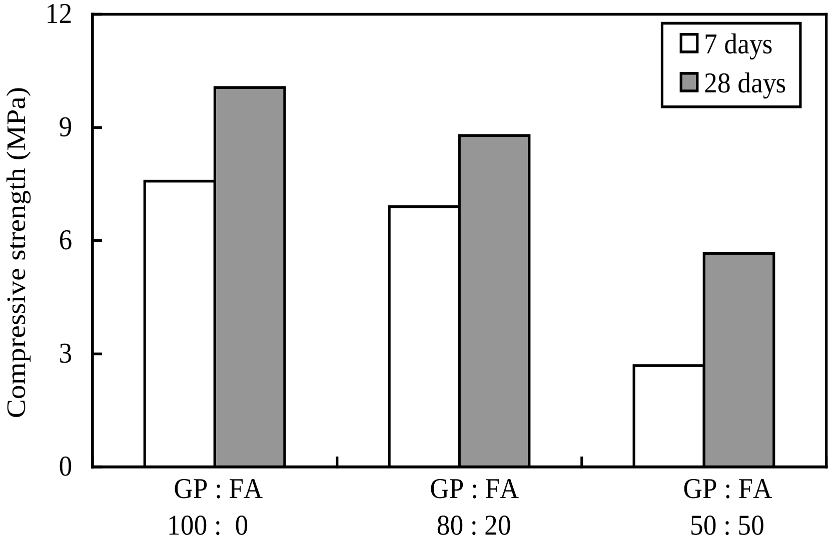

Figure 6-- Effect of age and fly ash content on compressive strength of pervious concrete

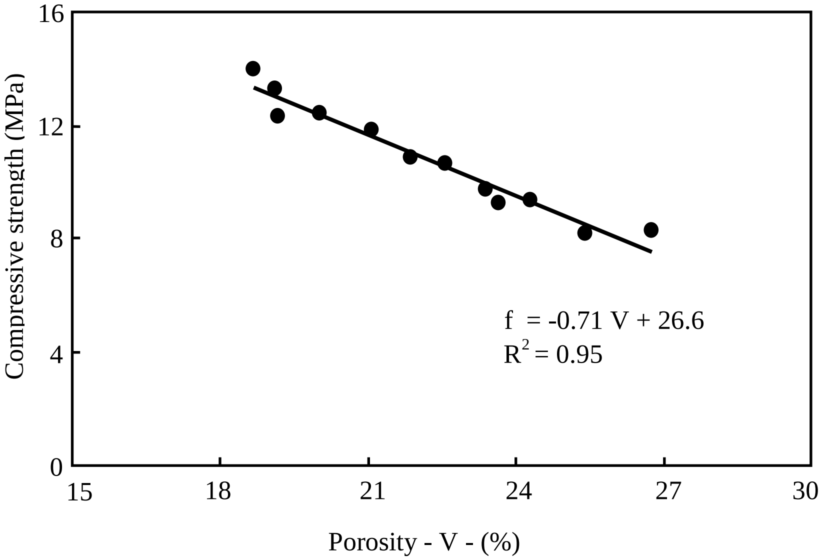

Figure 7-- Relationship between porosity and compressive strength for pervious concrete

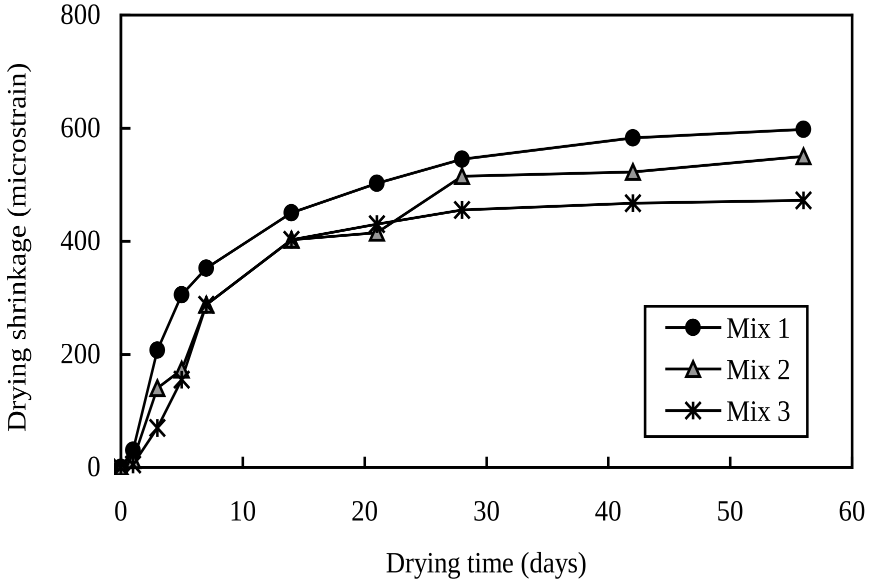

Figure 8-- Development of shrinkage with time for pervious concrete

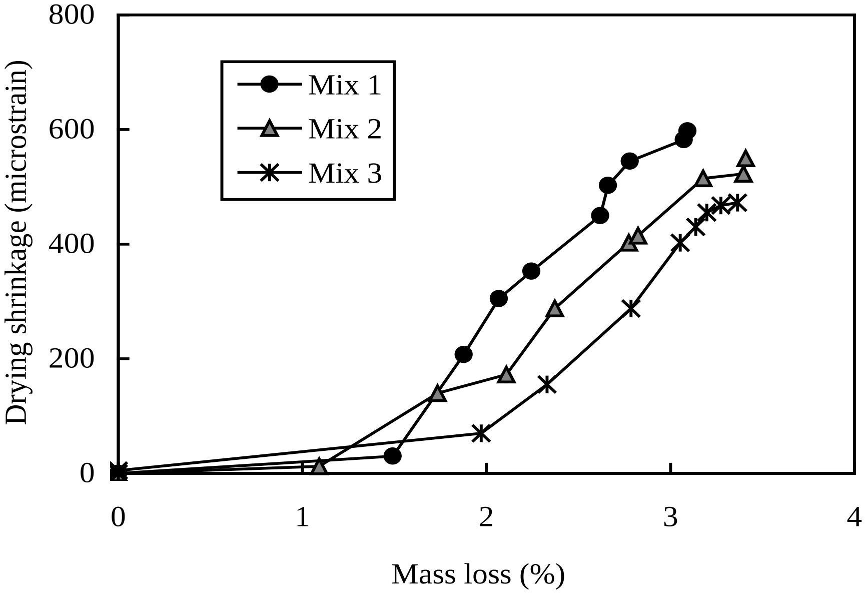

Figure 9-- Relationship between shrinkage and mass loss for pervious concrete

SHRINKAGE OF ENVIRONMENTALLY FRIENDLY SUSTAINABLE PERVIOUS CONCRETE

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Abstract : Pervious concrete, a special type of concrete having a high void content of about 30%, is becoming popular in USA and other countries due to its potential to reduce water runoff to the drainage systems. The pervious concrete containing supplementary cementitious materials could be considered as an environmentally friendly sustainable concrete. This paper reports the results of an experimental investigation into the production and properties of pervious concrete. The compressive strength and drying shrinkage for pervious concrete mixes containing cement and fly ash as binding materials are reported. The results showed that the drying shrinkage of pervious concrete is lower than that for non-pervious concrete due to the loss of free non-bound water from open void structure in the pervious concrete. The shrinkage of pervious concrete is marginally affected by the increase in fine aggregate content and partial cement replacement with fly ash.

Key words : pervious concrete, drying shrinkage, fly ash, environmentally friendly concrete

1. INTRODUCTION

Impervious nature of normal weight concrete used for pavement construction increases the water runoff and contributes to over-burdening to the existing drainage system. Pervious concrete is a special type of concrete having high water permeability (ACI (2006)) due to the presence of open void structure. The type of concrete has been developed in USA to meet the Environmental Protection Agency (EPA) stormwater regulation (Tennis et. al. 2004). In Europe, the pervious concrete is used to produce concrete panels for sound absorption whereas in Japan it is used for road surface and river banks construction (Kitsutaka et. al. 2006; Zouaghi and Kumagai 2000)..

It is known that one tonne of Portland cement production releases 0.94 tonne of CO_2 into the atmosphere. Therefore, any amount of cement replacement in concrete mixes with fly ash, a waste material from coal-fired power stations, will be help in producing environmentally friendly sustainable concrete.

Since compressive strength and permeability are the most important properties of pervious concrete, published research mainly focused on these properties. However, the dimensional stability of pervious concrete due to the changes in the moisture content is also equally important in developing pervious concrete specification. Hence, the main purpose of this paper is to report the results of an experimental investigation into the development of free drying shrinkage for pervious concrete and compared with that for non-pervious concrete. The effects of having varying fine aggregate content and partial cement replacement with fly ash on the shrinkage characteristics of pervious concrete are studied.

2. RESEARCH SIGNIFICANCE

The pervious concrete is produced using conventional concrete making materials with or without fine aggregate to have a void content ranged from. 15% to 25%. The connected large-sized void structure leads to high water permeability. The mean water permeability of pervious concrete is generally 1 to 10mm/s compared to 10^{-9}mm/s for conventional non-pervious concretes. The compressive strength of pervious concrete is around 5MPa and mainly used for parking lots, pavement, bus terminal, low traffic and so on. Drying shrinkage of pervious concrete occurs sooner but it is lower than conventional concrete (Tennis et. al. 2004) due to the availability of large surface area (Ghafoori and Dutta 1995).

Fig. 1: Too Dry Pervious Concrete
(Water/Binder ratio of 0.25)

Fig. 2: Pervious Concrete shaped to a ball with hand
(Water/Binder ratio of 0.35)

3. EXPERIMENTAL DETAILS

3.1 Materials

Type GP Portland cement (AS3972 1997) and NSW low calcium fly ash (AS3582 1998) were used as binder materials in the concrete mixes. Single sized (10mm maximum size) crushed river gravel (specific gravity of 2.70) was used as coarse aggregate (AS1141.4 2000). Equal weight proportions of fine and coarse sands (AS1141.5 2000) were used as fine aggregate. The specific gravity of sand was 2.60.

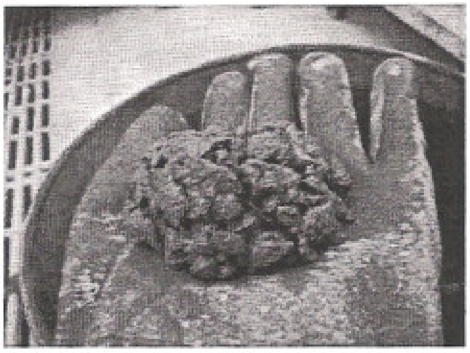

Fig. 3: Too Wet Pervious Concrete
(Water/Binder ratio of 0.40)

3.2 Mixture properties

Mix proportion by weight for pervious concrete was 1:4:0.35 (binder material, coarse aggregate and water), respectively. The binder material in Mix 1 is Type GP cement whereas it in Mix 2 was a combination of Type GP cement and fly ash in the ratio of 4:1. Water to binder ratio is important in the production of pervious concrete since it has an influence of the workability of pervious concrete. Figs. 1 and 3 show the dry and wet pervious concrete mixes, respectively. At the water to binder ratio of 0.35, the pervious concrete mixes were able to be shaped with hand into a small ball as shown in Fig. 2 and used in all pervious concrete mixes.

The mix proportion for non-pervious concrete is binder materials, coarse aggregate, fine aggregate, and water; 1.0: 2.8: 1.4:0.5 respectively.

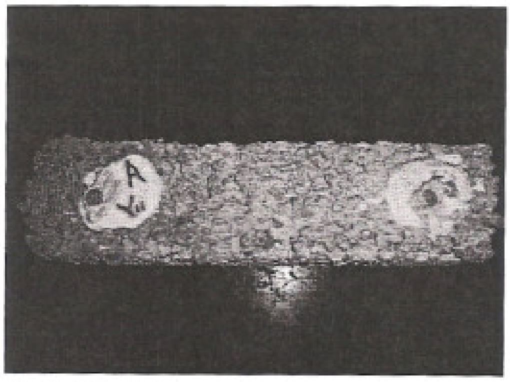

Fig. 4: Drying shrinkage pervious concrete specimen

3.3 Casting, Curing and Testing of Concrete

Fresh concrete mixes (pervious and non-pervious) were produced in a pan-type of mixer. For each concrete mix, a number of 100mm diameter by 200mm high cylinders and two 75mm by 75mm by 285mm prism specimens were cast in steel moulds. All the test specimens were demoulded after 24 hours and stored in water at 20°C until the ages of testing. The compressive strength and permeability of hardened concrete were determined using the cylindrical specimens whereas the prismatic specimens were used to determine the free shrinkage. The shrinkage specimens were water cured for 7 days followed by drying in an unsaturated uncontrolled laboratory environment having the mean temperature and humidity of 20°C and 65% R.H.

The shrinkage of each specimen was monitored over a 200mm gauge length using a demountable mechanical strain gauge on the opposite longitudinal sides over 56 days of drying. The reported results are the average of 2 readings taken on both sides of a shrinkage specimen as shown in Fig. 4. Weight of the shrinkage specimens were also taken at the time of shrinkage measurements.

Table 1: Compressive Strength (MPa) of Concretes

Age (days)	100% Cement (Mix 1)		80% Cement and 20% Fly Ash (Mix 2)	
	Non-Pervious	Pervious	Non-Pervious	Pervious
7	45.3	6.9	22.2	7.6
28	50.0	10.0	41.2	8.8

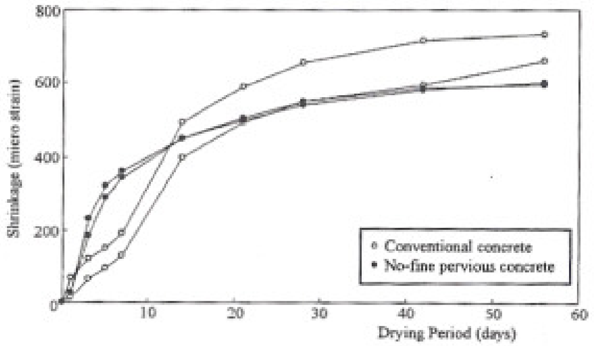

Fig.5: Development of shrinkage with time (100% Cement)

4. `RESULTS AND DISCUSSION

4.1 Strength of non-pervious and pervious concrete

Table 1 summarises the compressive cylindrical strengths for pervious and non-pervious concrete mixes with and without cement replacement with fly ash after 7 and 28 days. The void content for hardened concrete was determined using oven-dry and saturated weights, as described by Sriravindrarajah and Aoki (2008). The void content was about 12% and about 30%, respectively for non-pervious and pervious concretes, respectively.

The 28-day compressive strength for pervious concrete was 10.0MPa compared to 50MPa for the non-pervious concrete. As expected the increased void content had reduced the compressive strength for pervious concrete. When 20% of cement was replaced with fly ash 28-day strength was reduced for both non-pervious and pervious concretes. The non-pervious concrete strength was dropped from 50.0MPa to 41.2MPa whereas the pervious concrete strength was dropped from 10.0MPa to 8.8MPa.

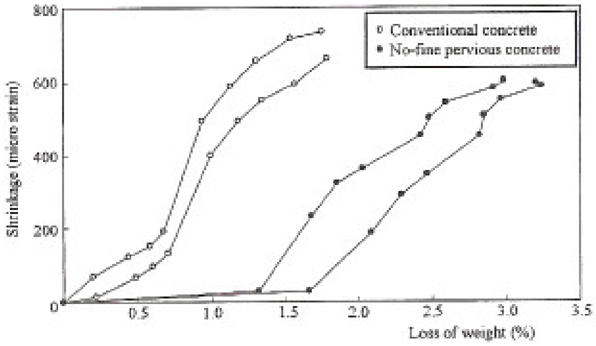

Fig. 6: Relationship between shrinkage and weight loss

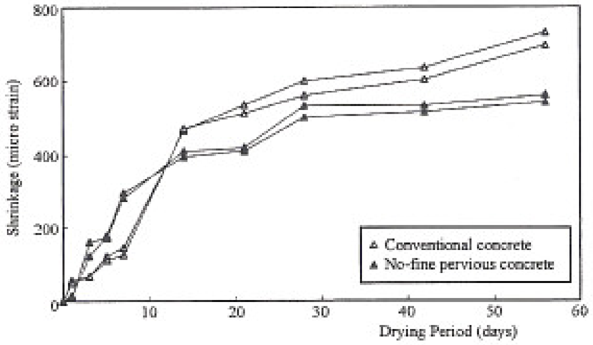

Fig.7: Development of shrinkage with time (80% Cement and 20% Fly Ash)

4.2 Shrinkage of non-pervious and pervious concretes with 100% cement

Fig. 5 shows the development of drying shrinkage with time for pervious concrete and non-pervious concretes. Fig. 6 shows the relationship between the drying shrinkage and weight loss for these two concrete types having the cement as the binder material.

Drying shrinkage for both concrete types increased with time at a decreasing rate. The 56-day shrinkage was lower for the pervious concrete compared to that for the non-pervious concrete. The mean 56-day shrinkage for pervious concrete with non-fines was about 600 microstrain.

The pervious concrete showed significant weight loss, expressed as the percentage of concrete weight, compared to that for the non-pervious concrete. Total weight losses for pervious and non-pervious concretes were 3.3% and 1.5%, respectively. The loss of water equal to 1.5% of weight of the corresponding concrete specimens produced shrinkage of about 50 and 700 microstrain with pervious and conventional concretes, respectively.

4.2 Shrinkage of non-pervious and pervious concretes with 80% cement and 20% fly ash as binders

Fig. 7 shows the development of shrinkage with drying time for non-pervious and pervious concretes with 80% cement and 20% fly ash. Both concretes showed gradual increase in shrinkage with drying time at a decreasing rate. Once again, the pervious concrete showed lower shrinkage compared to non-pervious concrete. The pervious concrete showed significant shrinkage for a given percentage of weight loss on drying. The water loss corresponds to 2% weight of concrete specimen produced shrinkage of about 600 microstrain with non-pervious concrete compared to about 200 microstrain for pervious concrete. Most of the water loss from pervious concrete is free non-bonded water from large void structure and hence its effect is low in the development of shrinkage.

4.3 Shrinkage of pervious concretes with varying fine aggregate content

Pervious concrete mixes containing fine aggregate contents of 0, 7.5% and 10% by weight of total aggregate were studied for its drying shrinkage. The results showed that 56-day shrinkage for all these three pervious concrete mixes was around 550 microstrain.

5. CONCLUDING REMARKS

Pervious concrete is produced with conventional concrete making materials with no-fines and fine aggregate contents of 7.5% and 10% of the total aggregate content. Based on the preliminary trial mixes for the balling ability the water to binder ratio of 0.35 by weight was found to be the ideal to produce workable pervious concrete. In order to reduce the cement content in pervious concrete, 20% of the cement was replaced with fly ash.

The results showed that the no-fines pervious concrete had the void content of about 30% compared to 12% for the conventional concrete. 20% cement replacement with fly ash reduced the 28-day compressive strength of pervious concrete by about 12%.

Drying shrinkage of pervious concrete is lower that that for the non-pervious concrete due to the reduced effect of water loss in developing shrinkage. The loss of free and non-bound water from the open void structure from pervious concrete has a minimum effect on drying shrinkage of concrete. In addition, drying shrinkage for pervious concrete developed more rapidly compared to that for non-pervious concrete.

The drying shrinkage for pervious concrete is smaller than non-pervious concrete, namely the average total shrinkage of pervious concrete was about 600, while its non-pervious concrete was about 800.

Drying shrinkage of pervious concrete with 7.5% and 10% fine aggregate content was similar to that for non-fines pervious concrete.

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