Finishing methods and compressive strength-void ratio relationships of in-situ porous concrete pavement

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Abstract.   In this paper, the effect of finishing methods on the relationships between compressive strength, permeability and void ratio of porous concrete (POC) or pervious concrete is discussed, using core specimens taken from actually constructed POC pavement. To attain reliable performance in the construction work, a newly designed finisher for POC is developed, and the performances as well as methods for controlling void ratio are examined. The POC pavements were finished with three finishing methods viz., no finishing, finishing with standard compactor and finishing with prototype compactor. The results show that the prototype POC finisher is efficient in controlling the void ratio and the quality of POC pavements. The relationships between compressive strength as well as permeability and void ratio of the in-situ POC pavements finished by the prototype machine were obtained. They are slightly different from the laboratory test results owing mainly to the mold effect and the differences in compaction modes.

Keywords: porous concrete; compaction; compressive strength; void ratio; pavement; finishing method.

1. Introduction

Porous concrete (POC) or pervious concrete is a special concrete consisting of coarse aggregate and cementing matrix (paste or mortar) with intentionally incorporated continuous voids (Japan Concrete Institute 2004). The POC provides high environmental performance in terms of water permeability/drainage, air permeability, sound absorbency, tolerance to the presence of plants and other organisms, weight reduction and usability of recycled materials. Furthermore, POC can be used in a wide range of applications. Thus, POC can be considered an environmentally friendly concrete that facilitates efforts in improvement of environment while promotes economic growth.

Fundamental information of various characteristics of POC has been studied and reported (Schaefer *et al.* 2006, Yang and Jiang 2003, Lian and Zhuge 2010, Meininger 1988, Ghafoori 1995, Yanagibashi and Yonezawa 1998, Fujiwara *et al.* 1998). Also, the authors have carried out a series of research work and proposed the relationships of void ratio and compressive strength of POC (Chindaprasirt *et al.* 2008, 2009). The advanced design framework on POC is usually limited to the laboratory data (Tran *et al.* 2009). There is limited information on the POC properties (Keven *et al.* 2006) including the void ratio and compressive strength relationships actually attained at construction

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sites.

Most of the fundamental properties of POC have been obtained from specimens cast in molds. There exist some differences between POC specimens cast in molds and those in the actual construction site. Causes of such difference are mainly as follows:

(1) Geometrically. There exists a boundary interference for POC due to the wall of the mold, which affects greatly the void ratio of POC especially when the aggregate size is large.

(2) Mechanically. There occurs some friction between the mold and POC when compacted. This reduces compaction efficiency to some extent.

Effects of such boundary due to molds are to be discussed, based on experimental data obtained by systematically designed compaction scheme.

In this study, a new type of POC finisher is developed to control compaction energy, and to find the most suitable compaction steps. This report presents measurements of the actual void ratio, water permeability and compressive strength of cored specimens from in-situ POC pavements compacted using the finisher. Also, the effect of the finishing methods on the quality of the in-situ POC is systematically discussed based on the magnitude of compaction energy.

2. Review of relationships of compressive strength with void ratio

The authors have already carried out a series of laboratory experiment by using cylindrical specimens, and reported numerical expressions of the relationships of compressive strength with void ratio of POC (Japan Concrete Institute 2004, Chindaprasirt *et al.* 2008, 2009). The results may be summarized as follows:

(1) Effect of binder strength and aggregate size on the strength-void ratio relationships are schematically shown in Figs. 1(a) and (b), respectively. The strength of POC increases with increasing binder strength and particle size of aggregate.

(2) Effect of compaction on the strength-void ratio relationships is illustrated in Fig. 1(c). The strength of POC increases with increasing compaction energy viz. no compaction, medium compaction (normally the designed void ratio is in this range of compaction) and full compaction.

It should be noted that the void ratio of POC is designed basically with the value of bulk density of aggregate and the compaction effort. The relationship curve between void ratio and strength is unique for the same mixture of POC.
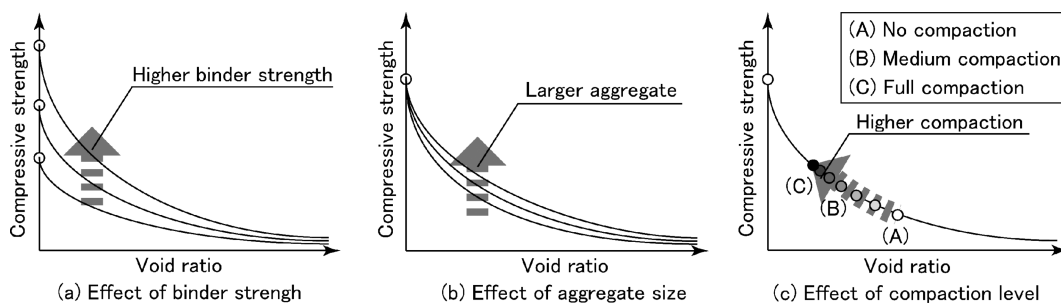

Fig. 1 Effect of various factors on compressive strength-void ratio relationships

3. Experimental details

3.1 Materials, mix proportion and mixing platform

Ordinary Portland cement (OPC), tap water and crushed limestone were the materials used. The specific gravity and Blaine fineness of OPC were 3.15 and 3150 cm^2/g. The crushed stone was 5.0-13.0 mm in diameter with fineness modulus (FM) of 6.2, specific gravity of 2.7 and void content of 41.4%. The mix proportions are given in Table 1. The designed void ratios were 20, 25 and 30%. The *W/C* ratio of 0.45 was used for all mixes.

The mixing was done on site in a large bucket with the aid of a backhoe as shown in Fig. 2. In the first step, cement and aggregate were thoroughly mixed. Water was then gradually added and mixed until uniform mixture was obtained. After mixing, the fresh POC was loaded into the POC leveler using the backhoe.

3.2 Paving and leveling

The leveling is usually performed manually with rakes and other leveling tools. This requires significant amount of manpower and time. In addition, there is still a high risk of obtaining the variable work quality. In order to resolve the above issues, the authors have designed and fabricated the prototype POC leveler shown in Fig. 3 to efficiently level POC pavements in an approximately continuous manner. Altogether 8 POC pavements of 2.0 m × 1.0 m section and 160 mm thick were constructed with the leveler.

3.3 Finishing

A normal compaction machine or vibrating roller is often used to compact the zero-slump concrete
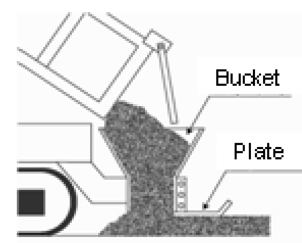
Table 1 POC mix proportions

Mix	Designed void ratio (%)	*W/C* (kg/m^3)	Water (kg/m^3)	Cement (kg/m^3)	Aggregate (kg/m^3)
No. 1	20	0.45	126	279	1559
No. 2	25	0.45	96	214	1559
No. 3	30	0.45	67	149	1559

Fig. 2 Mixing of POC in a bucket with backhoe

(a) Overview   (b) Section

Fig. 3 Prototype POC leveler

during the post-leveling or finishing process. While these conventional machines provide powerful compaction for normal concrete, they are not suitable for finishing POC pavement as they tend to leave irregularities in the POC surface. Furthermore, for reasons of operability and other performances; lower compaction intensity is needed to realize a required high void ratio.

To facilitate this, the authors have designed the prototype POC finisher as shown in Fig. 4. In addition to its normal features, the wider compacting plate than that of an standard plate compactor is installed. This allows suitable compaction effort and prevents over-compaction of the concrete. It also has the capability to stabilize compaction while producing high quality surface without irregularities.

The standard plate compactor has a vibrating frequency of 91.7Hz, vibrating force of 4.9 kN, engine power of 1.5 kW, compacting plate size of 0.11 m^2 (0.4 m × 0.28 m) and total weight of 33.0 kg. In use, it exerted a static pressure of 2.89 kN/m^2 on the POC. For normal finishing using the standard plate compactor, the problem of surface irregularities was encountered in a preliminary experiment. In order to have a good surface, several compaction passes were required.

The prototype POC finisher was developed from the standard plate compactor described above. The compacting plate was enlarged to 0.23 m^2 (0.4 m × 0.58 m) and the machine weight was increased to 46.2 kg with a static pressure of 1.95 kN/m^2 on the POC. The design of the POC finisher allowed the addition of extra weights on the two side of the compacting plate as shown in Fig. 4. Three weight levels of 46.2, 55.2 and 65.3 kg with static pressures of 1.95, 2.33 and 2.76 kN/m^2 were used. For the three weights, the finishing was done with a single pass. Additional four passes were made with one pavement in order to compare the results. Various types of pavement surface finishing viz., no finishing, finishing with standard compactor and finishing with prototype compactor were tested. The details of the POC pavement are shown in Table 2.

3.4 Curing and sampling methods

The pavements were cured by leaving them exposed in an outdoor environment in order to replicate actual paving conditions. The average temperature and humidity were between 10-20°C

Table 2 Details of the tested pavements

Pavement No.	Designed void ratio (%)	Finishing methods		
		Types	Weight of finisher (kg)	Number of pass
1	20	A	46.2	1
2	25	A	46.2	1
3	30	A	46.2	1
4	30	A	55.2	1
5	30	A	65.3	1
6	30	A	46.2	4
7	30	B	33.0	4
8	30	C	0	0

Note: (1) All pavements were paved and leveled with the prototype POC leveler,
(2) A = prototype POC finisher, B = standard finisher and C = without finishing.

Fig. 4 Prototype POC finisher

Fig. 5 Core sampling

and 60-80% R.H.. Cores of 100 mm in diameter were taken from the middle parts of the POC pavements at 14 days after casting as shown in Fig. 5. Both ends of the cores were polished, and void ratio and water permeability were measured at the age of 19 days. The compressive strength test were carried out at the age of 28 days.

3.5 Test methods

Total void ratio and water permeability were measured using test methods for porous concrete as suggested by the Technical Committee on Establishment of Design and Practical Method of Porous Concrete (Japan Concrete Institute 2004). The compressive strength was measured according to ASTM *C*39/*C*39*M* (2510). The obtained results were then compared with the previous published results obtained from the laboratory condition.

4. Results and discussion

4.1 Void ratio

4.1.1 Finishing method and void ratio

The results of the measured void ratio and finishing methods are shown in Fig. 6. The specimens of POC without finishing had void ratio of 39.5% which was almost 10% higher than the designed level. The void ratios were 30.3, 30.2 and 29.4% for the samples using the prototype POC leveler and finisher with weight of 46.2, 55.2 and 65.3 kg, respectively. The variation in the void ratios here was very small with the change of weight of the designed finisher.

For the basic prototype POC finisher of 46.2 kg with four passes, the void ratio of the sample reduced to 21.8% which was about 8% lower than the designed level. For the standard finisher, after four passes the void ratio was 19.5% which was slightly more than 10% lower than the designed value.

It is as expected that void ratio of the POC could be controlled by setting the number of finisher passes. It is also clear that changing the weight of the designed POC finisher with large plate had a
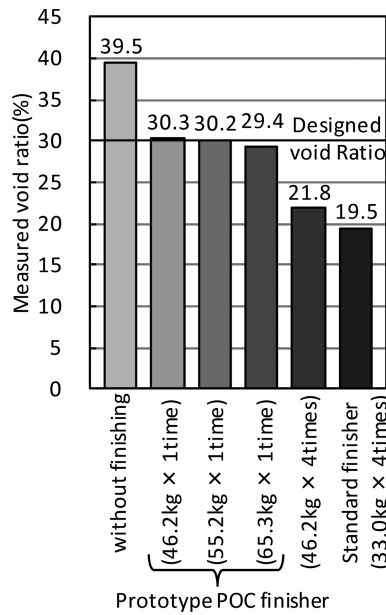
Fig. 6 Measured void ratio and finishing methods

slight effect on the void ratio.

4.1.2 Void ratio and compaction energy

The compaction energy can be calculated using the following equation (Japan Concrete Institute 1995)

$$E = 2a(W + F/2)n \cdot t \cdot 1/S \tag{1}$$

Where E : Compaction energy ($N \cdot$ m/m^2)
  a : Vibratory amplitude (m)
  n : Vibration frequency (Hz)
  W : Load from compactor (N)
  S : Pressure area (m^2)
  F : Vibratory force (N)
  t : Compacting time (s)

The relationship between total void ratio and vibrating energy of the compactor and finisher as shown in Fig. 7 showed a strong correlation between void ratio and compaction energy. These data fit an exponential function. The *y*-intercept corresponds to the void ratio achieved with no finishing. Additionally, it can be seen that void ratios only slightly reduced with the increase in POC finisher weight mainly because the compaction energy did not significantly increase with the increase in the weight.

4.2 Water permeability

The water permeability of the materials is related to the continuous voids. The relationship
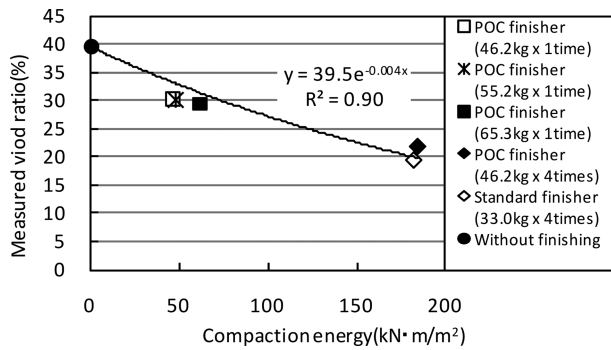
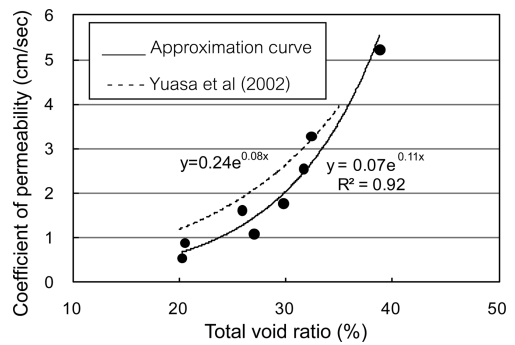Fig. 7 Relationship between total void ratio and vibrating energy

Fig. 8 Relationship between water permeability and total void ratio

between water permeability and total void ratio of POC pavement is shown in Fig. 8. As expected, there existed a strong correlation between the two quantities. The obtained void ratios were between approximately 20-40%. The corresponding coefficients of permeability varied between 0.6-5.2 cm/sec. Similar trend of results obtained from the laboratory testing was reported previously (Yuasa *et al.* 2002). The graph obtained from field compaction using the prototype leveler and finisher was slightly lower than that obtained from the laboratory compaction. This indicated that the coefficients of permeability of the POC obtained from field compaction were slightly lower than those obtained from laboratory compaction. This is as expected since the laboratory samples are made using a small standard molds. The wall or mold effect of the laboratory samples and the field samples are thus different. Furthermore, the compaction modes are also different.

4.3 Compressive strength and void ratio

The height to diameter ratio (*H/D*) of the cored specimens taken from the pavement was different from 2.0. The obtained strengths of POC samples were adjusted to the strengths of those of *H/D* of 2.0 using the expression as follows, the relationship being illustrated in Fig. 9 (Nakagawa *et al.* 2004)
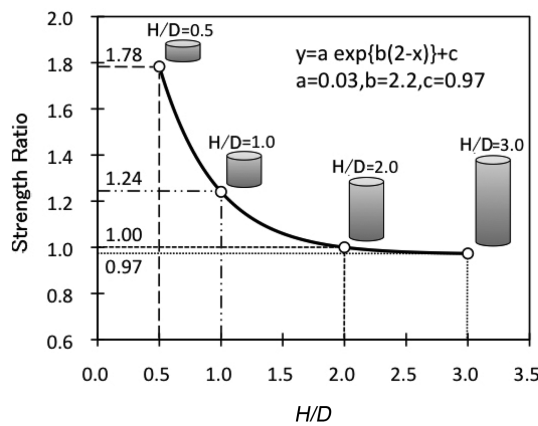

Fig. 9 Relationship between strength ratio to that of *H/D* = 2 and *H/D* of specimen

$$\sigma = n \ \sigma c \tag{2}$$

$$n = 1/[a \ \exp\{b(2 - x)\} + c] \tag{3}$$

Where, σ is compressive strength of porous concrete of $H/D = 2$
σc is compressive strength of core specimen
n is modification coefficient of compressive strength,
x: H/D ratio of specimen,
a,b,c: experimental constant ($a = 0.03$, $b = 2.2$, $c = 0.97$)

The relationship between compressive strength and total void ratio was then plotted as shown in Fig. 10. It has been shown that the relationship between compressive strength and void ratio of a porous brittle material suggested by Ryshkewitch (1953) and Duckworth (1953) shown in Eq. (4) can be used to describe porous concrete (Chindaprasirt *et al.* 2009).

$$\sigma = \sigma_0 \ \exp \ (-BV) \tag{4}$$

Where, σ : Compressive strength (MPa)
σ_0 : Compressive strength at zero void (MPa)
B : Strength reduction parameter
V : Air void (%)

The relationship between compressive strength and void ratio of the POC compacted using the prototype leveler and finisher was

$$\sigma = \sigma_0 \ \exp \ (-0.075V) \tag{5}$$

The equation for the relationship between compressive strength and void ratio of the POC compacted in laboratory was shown to be (Chindaprasirt *et al.* 2009)

$$\sigma = \sigma_0 \ \exp \ -(0.196 - 0.0174 \ \text{FM})V \tag{6}$$

where FM is fineness modulus of the aggregate

The fineness modulus of the aggregate is 6.2 and the relationship between compressive strength and void ratio thus becomes
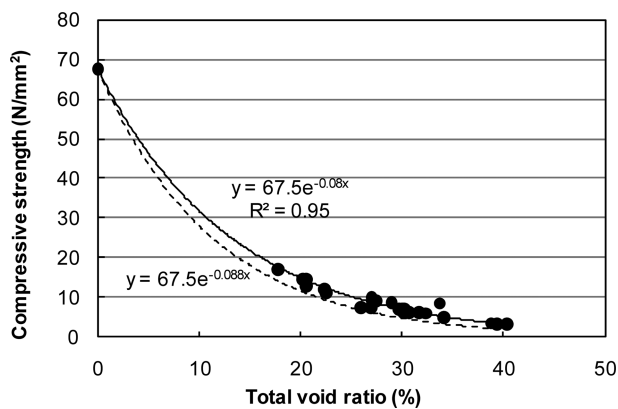

Fig. 10 Relationship between compressive strength and total void ratio

$$\sigma = \sigma_0 \exp(-0.088)V \qquad (7)$$

Comparing Eqs. (5) and (7) showed that the obtained results of relationships between compressive strength and void ratio of the POC compacted in laboratory and compacted using the designed leveler and finisher were slightly different as shown in Fig. 10. Again, the wall effect or the mold effect and the different compaction modes are mainly responsible for the difference.

It is shown here that the relationship between the strength and void ratio of the in-situ POC lies slightly above that obtained from laboratory cylindrical compacted samples. At the same void ratio, the laboratory results, therefore, slightly underestimate the strength value due to the mould effect.

5. Conclusions

The prototype leveler and finisher were developed with the objective of easing the process of POC paving. Without the finisher, the void ratio obtained was almost 10% higher than the designed level. When the 33 kg standard finisher was used to compact the POC pavement, however, four passes were required to produce quality surface without irregularities owing to the small compaction plate (0.11 m^2). The 46.2 kg prototype finisher with larger compaction plate (0.23 m^2) could be used to compact the POC pavement and to control the void ratio using the number of finishing passes. Changing the weights of the prototype finisher (46.2, 55.2 and 65.3 kg) has a limited effect on void ratio as the increase in compaction energy was not significant owing to the comparatively large compaction plate. Only one pass is required with the prototype POC finisher to obtain the target design level specified for the mixture in this experiment.

The normal relationship between permeability and void ratio; and strength and void ratio were obtained. The in-situ test compressive strength equation gave slightly higher strength values than the laboratory test compressive strength at the same void ratio. The in-situ test permeability equation gave slightly higher permeability values than the laboratory permeability at the same void ratio. The mold effect and the different compaction modes are mainly responsible for the differences. The general trend of the results, however, confirmed that once the targeted void ratio is attained, the expected compressive strength and permeability could be obtained.

Acknowledgements

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