Determination of pervious concrete mix by strength

Bo-Syun Huang¹, Yan-Fu Li¹, Chi-Hsing Wu² and Chi Tang*³

¹ Graduate Student, Department of Soil and Water Conservation, National Pingtung University of Science and Technology, Pingtung, Taiwan
² Associate Professor, Department of Civil Engineering, National Pingtung University of Science and Technology, Pingtung, Taiwan
³ Corresponding author: Associate Professor, Department of Soil and Water Conservation, National Pingtung University of Science and Technology, Pingtung, Taiwan

*E-mail: tangchi@mail.npust.edu.tw

Abstract. The paper first used a cement amount C=300 kg and a range of water-cement ratio W/C=0.36~0.44 to make pervious concrete specimens of different W/C to perform the compressive strength and the flexural strength tests, as well as the permeability coefficient and the porosity tests. These tests were to find the W/C of the maximum strength under meeting the requirements of permeability and water retention. The concrete mix corresponding to the W/C determined this way can be treated as the optimal mix since it gives the maximum strength for a cement amount C=300 kg. Then, similar tests were performed for C= 350 kg to determine its optimal mix. From which, the relationship of the strength of the optimal mix vs C is established.

1. Introduction

Traditional road pavements are paved by impervious material pavement, which will increase impervious area, add surface runoff and lead to flood problem. The water absorption and retention capability of soil is reduced due to lacking of seeping path of rainwater, and result in heat island effect in urban area. Additionally, the puddles on the road usually cause vehicles skid when raining. It also causes water mist and splashing when vehicles running, affects the safety of pedestrians and driving. If the traditional road pavements are replaced as pervious pavement, it can not only improve the urban flooding and heat island effect problems, but also enhance the safety of pedestrians and driving in raining days. However, roadbed of pervious pavement will become soft due to rain infiltration. If the bearing capacity of base and bottom courses is not enough, it often causes the road collapse to fail in high vehicle load. For this reason, US California Department of Transportation (Caltrans) in its pervious pavement design guidance [1] does not propose the pervious pavement used for road condition of Category D & E, which are categories of moderate are high heavy vehicular loads with high speed respectively.

Keda road pervious pavement in Neipu Township, Pingtung county, Taiwan was completed on July 29, 2018 (2018/7/29). It is four-lane road with total length 3,275 m. The lane width of north or south bounds is 8.8 m. The road was designed for high heavy and high speed vehicular load, and has been used for more than 14 months so far. The pavement offers very good traffic service and no pothole or collapse problems. The key to the success of Keda road pervious pavement is the pervious concrete in the base course is strong enough to resist vehicle load even the roadbed become soft by infiltrating rain. No wonder, pervious concrete has been recognized by US Environmental Protection Agency (EPA) as a Best Management Practices (BMP) for storm water management. Pervious concrete pavement may be an unique and effective means to address important environmental issues and support green, sustainable growth. Its technology creates more efficient land use by eliminating the
need for retention ponds, swales, and other storm water devices. Thus, pervious concrete has the ability to lower overall project on a first-cost basis.

Pervious concrete is a mixture of cement, water, and coarse aggregate, and little to no sand. It creates a very porous medium that allows water to drain to the underlying soils. Commonly, it may allow as much as 5000 mm/hr to pass through the body of the concrete. However, the pervious concrete usually gives a low strength due to inappropriate mix and improper construction.

The paper establishes the curves of strength vs water-cement ratio W/C to determine the concrete mix. The mix corresponding to the maximum strength for a given cement amount C can be treated as the optimal mix since it gives the possible largest strength effect for a cement amount without adding any chemical admixture. It is the most economical mix due to that the cement is the most expansive material in pervious concrete compositions. The strength tests include the compressive strength test and the flexural strength test. Normally, the former is used to determine the optimal mix. The permeability coefficient test and the porosity test were performed as well. The former is to investigate the permeability of pervious concrete, in which the permeability coefficient k is required larger than 10\(^{-3}\) cm/sec according to the Outline Specification for Public Construction [2] by Public Construction Commission, or more strictly required larger than 10\(^{-2}\) cm/sec according to the Evaluation Manual for Green Building Material [3] by Taiwan Architecture & Building Center. The latter is to investigate the water retention ability of pervious concrete, in which the porosity n is required larger than 15% according to the Evaluation Manual for Green Building Material [3].

The paper used cement amounts C=300 and 350 kg to perform mix design and tests respectively. The optimal mixes are then determined by the compressive strength test results for C=300 and 350 kg respectively. From which, the relationship of the strength of the optimal mix vs C is established.

2. Test plan
The tests are divided into three parts: coarse aggregate material property tests, fresh concrete tests, and pervious concrete specimen tests. They are described as follows.

2.1. Coarse aggregate material property tests
Coarse aggregate material property tests have the sieve test and the specific gravity and absorption test. They are described as follows.

(1) Sieve analysis test: According to CNS 486 “Method of test for sieve analysis of fine and coarse aggregates” [4], the aggregate sieve analysis test is performed to plot grain size distribution curve, and to gain the fine modulus and the grain size distribution.

(2) Specific gravity and absorption test: According to CNS 488 “Method of test for density, relative density (specific gravity), and absorption of coarse aggregate” [5], the specific gravity, absorption and water content of aggregate are determined. The oven-dry specific gravity will be used in the calculation of pervious concrete mix design, and the absorption and water content of aggregate will be used for adjusting the add water amount.

2.2. Fresh concrete tests
Fresh concrete tests include the drooping flow test and the unit weight and air content test. They are described as follows.

(1) Drooping flow test: Using the net cage method proposed by Hu [6] and Pan [7], the drooping flow amount of fresh concrete on is weighted to plot the drop flow curve of drooping flow amount vs W/C to estimate the possible W/C range of maximum strength, which will be used for selecting the W/C of specimens made for the pervious concrete test to save time and cost of the tests.

(2) Unit weight and air content test: According to CNS 11151 “Method of test for unit weight, yield, and air content (gravimetric) of concrete” [8], the fresh concrete is tested to find its unit weight and air content.
2.3. Pervious concrete specimen tests

Pervious concrete specimen tests include the compressive strength and the flexural strength tests, the permeability coefficient and the porosity tests. The former two tests are performed to evaluate the safety of pervious concrete. The latter two tests are performed to evaluate the permeability and water retentivity of pervious concrete respectively. They are described as follows.

(1) Compressive strength test: According to CNS 1232 “Method of test for compressive strength of cylindrical concrete specimen” [9], the compressive strength of concrete specimen is measured.

(2) Flexural strength test: According to CNS 1233 “Method of test for flexural strength of concrete (using simple beam with third-point loading)” [10], the modulus of rupture of concrete specimen is measured. The modulus of rupture is a measurement for the concrete tensile strength.

(3) Permeability coefficient test: According to CNS 14995 “Permeable concrete paving blocks” [11], the permeability coefficient of concrete specimen is measured.

(4) Porosity test: Referring to the test steps of CNS 488 [5], the porosity of concrete specimen can be evaluated by a proposed formula.

3. Methods of making specimens and samples

The size of specimen or sample for each test is listed in Table 1. The tool to impact the specimen or sample is steel impactor. The impactor has large impactor and small impactor. The detailed sizes of impactors are shown in Figure 1. The large impactor is designed for the \( \psi 15 \times 30 \) cm cylindrical specimen of the compressive strength test, but also can be used for making the specimen of the flexural strength test, for the samples of the drooping flow test and the unit weight and air content test of fresh concrete. The small impactor is designed for the \( \psi 10 \times 20 \) cm cylindrical specimen of the permeability coefficient test. The porosity test can use the same specimen as that of the permeability coefficient test. The design parameters of the impactors are listed in Table 2. The impactor has been obtained No. 1628335 invention patent by the Intellectual Property Office, Ministry of Economic Affair, ROC. Figure 2 shows the impacting operation using an impactor.

The fresh concrete is filled into the mold or container by several layers when making specimen or sample. Therefore, the number of layers and impact times is to produce equivalent compactness for all the specimens and samples, and these specimens and samples have the similar properties.

### Table 1. Size, number of layers and impact times of each specimen and sample

| Concrete Phase type | Test name                                      | Size of specimen or sample (cm) | Impact tool          | No of layer | Layer height (cm) | Impact times each layer |
|---------------------|-----------------------------------------------|---------------------------------|----------------------|-------------|------------------|-------------------------|
| Fresh Concrete      | Drooping flow test                             | \( 30 \times 16 \times 12 \)    | Large impactor       | 2           | 6                | 34                      |
|                     | Unit weight and air content test               | \( 20.3 \times 21.7 \)          | Large impactor       | 4           | 5.4              | 24                      |
|                     | Compressive strength test                     | \( 15 \times 30 \)              | Large impactor       | 6           | 5                | 12                      |
|                     | Flexural strength test                         | \( 53 \times 15 \times 15 \)    | Large impactor       | 3           | 5                | 54                      |
|                     | Permeability coefficient test                 | \( 10 \times 20 \)              | Small impactor       | 2           | 5                | 12                      |

| Harden Concrete     | Porosity test                                 |                                 |                      |             |                  |                         |

### Table 2. Parameters of impactors

| Parameters                              | Large impactor | Small impactor |
|-----------------------------------------|----------------|----------------|
| Specimen size (cm)                      | \( \psi 15 \times 30 \) | \( \psi 10 \times 20 \) |
| Hammer size (cm)                        | \( \psi 8 \times 13.0 \) | \( \psi 8 \times 6.0 \) |
| Hammer mass (kg)                        | 4.48           | 2.02           |
| Falling Distance (cm)                   | 54             | 54             |
| Unit momentum per impact (N \( \cdot \) sec/cm\(^2\)) | 0.0821        | 0.0825         |
compactness of the pervious concrete pavement in-situ. Thus test results using these specimens or samples can actually reflect and simulate the pervious concrete pavement in-situ. The number of layers and impact times for each specimen and sample is also listed in Table 1.

Figure 1. Sizes of impactors

Figure 2. Impacting operation

Figure 3. Coarse aggregate screen

Figure 4. Grain size distribution curve

4. Results and discussions
The test results are divided into three parts: coarse aggregate material property tests, fresh concrete tests, and pervious concrete specimen tests. They are described as follow:

4.1. Coarse aggregate material property test results and discussions
Coarse aggregate material property tests include the sieve test and the specific gravity and absorption test. The test results are discussed as follows.

(1) Sieve analysis test: According to CNS 486, 2000 g coarse aggregate was taken to perform the aggregate sieve analysis test. Figure 3 is the coarse aggregate screen for the sieve analysis test. The test results are listed in Table 3. The table shows that, the maximum size of the aggregate is 25.0 mm. The fineness modulus $FM$ is 6.76. Average grain size is 12.5 mm. Using the passing percentage in Table 3 to plot curve vs the aggregate size, a grain size distribution curve shown as Figure 4 is
obtained. The curve shows that, the aggregate for the test is basically uniform graded. The main grain size range is in #4~3/4” (4.75~19.0 mm).

Table 3. Sieve analysis test results of aggregate

| Sieve no (mm) | Sieve weight (g) | (Sieve+ Retained weight (g)) | Retained weight (g) | Retained percentage (%) | Cumulative retained percentage (%) | Passing percentage (%) |
|---------------|------------------|------------------------------|---------------------|-------------------------|-----------------------------------|------------------------|
| 1 1/2” (37.5) | -                | -                            | -                   | 0.0                     | 0.0                               | 100.0                  |
| 1” (25.0)*    | 4745             | 4745                         | 0                   | 0.0                     | 0.0*                              | 100.0                  |
| 3/4” (19.0)   | 5375             | 5407                         | 32                  | 1.6                     | 1.6                               | 98.4                   |
| 1/2” (12.5)*  | 4802             | 5796                         | 994                 | 50.2                    | 51.8*                             | 48.1                   |
| 3/8” (9.5)    | 4993             | 5451                         | 458                 | 23.2                    | 75.0                              | 25.0                   |
| #4 (4.75)     | 5227             | 5701                         | 474                 | 24.0                    | 99.0                              | 1.0                    |
| Chassis       | 4577             | 4597                         | 20                  | 1.0                     | 100.0*                            | 0.0                    |
| Total         | 1978             |                              | 100.0               | 175.6a                  |                                   |                        |
| $FM_1^a$      | 6.76             |                              |                     |                        | Average grain size                | 12.5$^b$               |

$FM_1=(\text{cumulative retained percentage}+500)/100$. Half-sieves and chassis are not counted in cumulative percentage. Sieve no 1” and 1/2” are half-sieves. Since #8~#100 have 5 sieves, $FM_1$ must add 500.

$^b$Average grain size $=0.016(\frac{25.0+19.5}{2})+0.502(\frac{19.0+12.5}{2})+0.232(\frac{12.5+9.5}{2})+0.240(\frac{9.5+4.75}{2})$

=0.36+7.91+2.55+1.71=12.5 mm

(2) Specific gravity and absorption test: According to CNS 488, 3000 g coarse aggregate was taken to perform the specific gravity and absorption test. Measure to average. Figure 5 shows the operation of aggregate weighting in water in the test. Table 4 is the test results. The table shows that, the oven-dry (OD), the saturated surface-dry (SSD) and the apparent specific gravities are 2.54, 2.58 and 2.65 respectively, the OD specific gravity will be used in the calculation of pervious concrete mix design. The absorption and water content are 0.84% and 1.56% respectively, which will be used for adjusting the add water amount.

The mix design procedure for pervious concrete follows those of Hu [6] and S-J Pan [7]. Using the OD specific gravity, absorption and water content of coarse aggregate obtained above, the concrete mix proportion can be calculated as in Table 5. The reason why the range of $W/C$ in the table is taken to be 0.36~0.44 for both $C=300$ kg and 350 kg will be explained in the drooping flow test in the next subsection.

4.2. Fresh concrete test results and discussions
Fresh concrete tests include the drooping flow test and the unit weight and air content test. The test results are discussed as follows.

(1) Drooping flow test: The drooping flow test results are listed in Table 6. Using the drooping flow amount vs $W/C$ in the table to plot curves, the droop flow curves shown as Figure 6 are obtained. The intersections of the horizontal and rising tangent lines are read at $W/C=0.38$ and 0.40 for $C=300$ kg.
and 350 kg respectively. The maximum strength would be near these W/C values. Therefore, the test range could be chosen in W/C=0.36~0.44 for both C=300 and 350 kg.

Table 4. Specific gravity and absorption test results of aggregate

| Items | Test values |
|-------|-------------|
| 1     | 2           | 3    | Average |
| (1) Sample weight W_1 (g) | 3000 | 3000 | 3000 | 3000 |
| (2) Plate weight (g) | 88 | 87 | 86 | 87 |
| (3) Oven-dry (OD) (sample+plate) weight (g) | 3066 | 3065 | 3055 | 3062 |
| (4) OD sample weight W_2 (g) | 2978 | 2978 | 2969 | 2975 |
| (5) Water content W_6 = W_1 - W_2 (g) | 22 | 22 | 31 | 25 |
| (6) Water content ratio M = \frac{W_w}{W_2} \times 100\% | 0.74 | 0.74 | 1.04 | 0.84 |
| (7) Saturate surface-dry (SSD) weight W_3 (g) | 3003 | 2999 | 3020 | 3007 |
| (8) Cage weight in water W_4 (g) | 493 | 493 | 493 | 493 |
| (9) Cage+sample weight in water W_5 (g) | 2341 | 2324 | 2341 | 2335 |
| (10) Apparent mass of sample in water immersion E = W_5 - W_4 (g) | 1848 | 1831 | 1848 | 1842 |
| (11) Water weight of the same volume as SSD sample = W_3 - E (g) | 1155 | 1168 | 1172 | 1165 |
| (12) OD weight in water immersion W_6 (g) | 2960 | 2958 | 2965 | 2961 |
| (13) Water absorption ratio M_S = \frac{W_3 - W_6}{W_6} \times 100\% | 1.45 | 1.39 | 1.85 | 1.56 |
| (14) OD specific S_d = \frac{W_6}{W_6} | 2.56 | 2.53 | 2.53 | 2.54 |
| (15) SSD specific S_s = \frac{W_3}{W_6} | 2.60 | 2.57 | 2.58 | 2.58 |
| (16) Apparent specific S_a = \frac{W_6}{W_6 - E} | 2.66 | 2.62 | 2.65 | 2.65 |

(2) Unit weight and air content test: The unit weight and air content test results are listed in Table 7. Using the unit weight U and the air content Air vs W/C in the table to plot line graphs, the results are shown as Figure 7 and 8 respectively. The figures show that, the U of C=350 kg is larger than that of C=300 kg, while the Air is smaller at the same W/C. That means that, more cement amount C will produce more slurry in fresh concrete such that its U is larger and Air is smaller for a same W/C. Larger U of larger C implies that, it will give a more compact density of pervious concrete after concrete become harden. Thus its strength will be higher and permeability and porosity be lower. Other thing to be mention is that, both air content curves in Figure 8 show an obvious drop at W/C=0.40. It may be that, the slurry become obvious increase after W/C=0.40 such that the Air begin to obvious drop down. The results are very coincident with those of the drooping flow test, where the slurry begin obviously getting more at W/C=0.38 for C=300 kg and at W/C=0.40 for C=350 kg respectively.
**Figure 5.** Specific gravity test of coarse aggregate

**Table 5.** Pervious concrete mix

| Cement amount C (kg) | Water-cement ratio W/C | Assumed air content | Water Amount (kg) | Aggregate amount a (kg) | Total material mass (kg) |
|----------------------|------------------------|---------------------|-------------------|------------------------|-------------------------|
| 0.36                 | 21.0                   | Trial mix 108       | 119               | 1490                   | 1503                    | 1922                    |
| 0.38                 | 20.5                   | Trial mix 114       | 125               | 1488                   | 1500                    | 1925                    |
| 0.40                 | 20.0                   | Field mix 120       | 131               | 1485                   | 1498                    | 1928                    |
| 0.42                 | 19.5                   | Field mix 126       | 137               | 1483                   | 1495                    | 1932                    |
| 0.44                 | 19.0                   | Field mix 132       | 143               | 1480                   | 1493                    | 1935                    |
| 0.36                 | 21.0                   | Field mix 126       | 136               | 1404                   | 1416                    | 1902                    |
| 0.38                 | 20.5                   | Field mix 133       | 143               | 1399                   | 1411                    | 1904                    |
| 0.40                 | 20.0                   | Field mix 140       | 150               | 1394                   | 1406                    | 1906                    |
| 0.42                 | 19.5                   | Field mix 147       | 157               | 1389                   | 1401                    | 1908                    |
| 0.44                 | 19.0                   | Field mix 154       | 164               | 1384                   | 1396                    | 1910                    |

aAggregate: OD specific gravity = 2.54, SSD specific gravity = 2.58, water content ratio = 0.84%, absorption = 1.56%.

**Table 6.** Drooping flow test results

| Cement amount C (kg) | Water-cement ratio W/C | Drooping slurry weight (g) | Drooping flow amount (g) |
|----------------------|------------------------|---------------------------|-------------------------|
| 0.36                 | 21.0                   | 395                       | 14                      |
| 0.38                 | 20.5                   | 404                       | 23                      |
| 0.40                 | 20.0                   | 585                       | 204                     |
| 0.42                 | 19.5                   | 599                       | 218                     |
| 0.44                 | 19.0                   | 602                       | 221                     |
| 0.36                 | 21.0                   | 408                       | 27                      |
| 0.38                 | 20.5                   | 523                       | 142                     |
| 0.40                 | 20.0                   | 528                       | 147                     |
| 0.42                 | 19.5                   | 731                       | 350                     |
| 0.44                 | 19.0                   | 957                       | 576                     |

**Figure 6.** Drooping flow curves
Table 7. Unit weight and air content test results

| Cement amount C (kg) | Water-cement ratio W/C | Assumed air content Air (%) | Total material mass W (kg) | (Barrel a + mixed concrete weight) W1 (kg) | Mixed concrete weight (%) Air (%) | Measured unit weight U b (kg/m³) | Measured concrete volume V c (m³) | Total material volume V 1 d (m³) | Measured air content Air e (%) | △Air (%) |
|----------------------|----------------------|---------------------------|--------------------------|-------------------------------------------|----------------------------------|----------------------------------|----------------------------------|---------------------------------|---------------------------------|---------|
| 300                  | 0.36                 | 21.0                      | 1922                     | 16.417                                    | 13.825                           | 1982                             | 0.969                           | 0.790                           | 18.5                             | -2.5    |
|                      | 0.38                 | 20.5                      | 1925                     | 16.373                                    | 13.781                           | 1976                             | 0.974                           | 0.795                           | 18.4                             | -2.1    |
| 350                  | 0.40                 | 20.0                      | 1928                     | 16.351                                    | 13.759                           | 1973                             | 0.977                           | 0.800                           | 18.2                             | -1.8    |
|                      | 0.42                 | 19.5                      | 1932                     | 16.419                                    | 13.827                           | 1983                             | 0.974                           | 0.805                           | 17.4                             | -2.1    |
|                      | 0.44                 | 19.0                      | 1935                     | 16.571                                    | 13.979                           | 2004                             | 0.966                           | 0.810                           | 16.1                             | -2.9    |
|                      | 0.36                 | 21.0                      | 1902                     | 16.597                                    | 14.005                           | 2008                             | 0.947                           | 0.790                           | 16.6                             | -4.4    |
|                      | 0.38                 | 20.5                      | 1904                     | 16.421                                    | 13.829                           | 1983                             | 0.960                           | 0.975                           | 17.2                             | -3.3    |
|                      | 0.40                 | 20.0                      | 1906                     | 16.372                                    | 13.780                           | 1976                             | 0.965                           | 0.800                           | 17.1                             | -2.9    |
|                      | 0.42                 | 19.5                      | 1908                     | 16.525                                    | 13.933                           | 1998                             | 0.955                           | 0.805                           | 15.7                             | -3.8    |
|                      | 0.44                 | 19.0                      | 1910                     | 16.666                                    | 13.974                           | 2004                             | 0.953                           | 0.810                           | 15.0                             | -4.0    |

a barrel inner size: ψ20.3×21.7; barrel weight=2.592 kg; content volume of barrel=6.974 L= 0.06974 m³

b measured \( U = \text{mixed concrete weight (kg)}/0.06974 \text{ m}^3 \)

c measured \( V = W_1/U \)

d total material volume \( V_1 = (1-\text{assumed \( \text{Air} \)(1m}^3) \)

e measured \( \text{Air} (\%) = (V-V_1)/V \times 100\% \)

Figure 7. Line graphs of measured \( U \) vs water-cement ratio \( W/C \)

Figure 8. Line graphs of measured \( \text{Air} \) vs water-cement ratio \( W/C \)

4.3. Pervious concrete specimen test results and discussions

Pervious concrete specimen tests include the compressive strength and the flexural strength tests, the permeability coefficient and the porosity tests. The test results are discussed as follows.
(1) Compressive strength test: The compressive strength test results are listed in Table 8. The table shows that, the ratio of the 7th day to 28th day compressive strength \(f_c/f_{28}\) in the range of 0.70–0.87, average 0.79 for C=300 kg. The range of \(f_c/f_{28}\) is 0.80–0.87, average 0.84 for C=350 kg. Using the compressive strength \(f_c\) in the table vs W/C to plot line graphs, the results are shown as Figure 9. The figure shows that, both the maximum \(f_c\) of the 7th and 28th days are at W/C=0.38 for C=300 kg. The values are 159 and 194 kgf/cm² (15.6 and 19.0 MPa) respectively. Thus, the ratio \(f_c/f_{28}=0.82\) at W/C=0.38. Both the maximum \(f_c\) of the 7th and 28th days are at W/C=0.40 for C=350 kg. The values are 212 and 251 kgf/cm² (20.8 and 24.6 MPa) respectively. Thus, the ratio \(f_c/f_{28}=0.84\) at W/C=0.40.

(2) Flexural strength test: The flexural strength test results are also listed in Table 8. The table shows that, the ratio of the 7th day to 28th day modulus of rupture \(R_7/R_{28}\) is in the range of 0.67–0.79, average 0.74 for C=300 kg. The ratio of the 28th day modulus of rupture to 28th day compressive strength \(R_{28}/f_{28}\) is in the range of 0.16–0.22, average 0.19 for C=300 kg. The ranges of \(R_7/R_{28}\) and \(R_{28}/f_{28}\) are 0.74–0.89 and 0.13–0.20, average 0.83 and 0.16 respectively for C=350 kg. Using the modulus of rupture \(R\) in the table vs W/C to plot line graphs, the results are shown as Figure 10. The figure shows that, both the maximum \(R\) of the 7th day and 28th day are at W/C=0.38 for C=300 kg. The values are 22.6 and 31.4 kgf/cm² (2.2 and 3.1 MPa) respectively. Thus, the ratio \(R_7/R_{28}=0.67\) and \(R_{28}/f_{28}=0.16\). Both the maximum \(R\) of 7th day and 28th day are at W/C=0.40 for C=350 kg. The values are 27.5 and 32.7 kgf/cm² (2.7 and 3.2 MPa) respectively. Thus, the ratio \(R_7/R_{28}=0.84\) and \(R_{28}/f_{28}=0.13\). The W/C values of the maximum strength in the flexural strength test is exactly the same as those of the compressive strength test for C=300 and 350 kg.

### Table 8. Compressive strength test and flexural strength test results

| Water-cement ratio | Compressive strength \(f_c\) (kgf/cm²) | Modulus of rupture \(R\) (kgf/cm²) |
|-------------------|-----------------------------------|-------------------------------|
| Cement amount C (kg) | \(7^{th}\) day \(f_c\) | \(28^{th}\) day \(f_{28}\) | \(7^{th}\) day \(R_7\) | \(28^{th}\) day \(R_{28}\) | \(R_7/R_{28}\) |
| 300 | W/C | 1 | 2 | 3 | Avg | 1 | 2 | 3 | Avg | 1 | 2 | 3 | Avg | 1 | 2 | 3 | Avg |
| 0.36 | 128 | 133 | 133 | 132 | 170 | 169 | 154 | 165 | 0.80 | 21.0 | 30.8 | 0.68 | 0.16 |
| 0.38 | 157 | 158 | 161 | 159 | 221 | 176 | 185 | 194 | 0.82 | 22.6 | 31.4 | 0.67 | 0.16 |
| 0.40 | 124 | 100 | 103 | 109 | 151 | 168 | 150 | 156 | 0.70 | 22.3 | 28.1 | 0.79 | 0.18 |
| 0.42 | 118 | 108 | 119 | 115 | 136 | 125 | 137 | 132 | 0.87 | 22.0 | 28.5 | 0.77 | 0.22 |
| 0.44 | 102 | 107 | 90 | 99 | 123 | 132 | 134 | 129 | 0.77 | 22.6 | 28.6 | 0.79 | 0.22 |
| Avg | 0.79 | 0.79 | 0.79 | 0.79 | 0.79 | 0.79 | 0.79 | 0.79 | 0.79 | 0.79 | 0.79 | 0.79 | 0.79 |
| 350 | W/C | 1 | 2 | 3 | Avg | 1 | 2 | 3 | Avg | 1 | 2 | 3 | Avg | 1 | 2 | 3 | Avg |
| 0.36 | 122 | 137 | 130 | 130 | 119 | 155 | 171 | 148 | 0.87 | 24.5 | 29.1 | 0.84 | 0.20 |
| 0.38 | 135 | 131 | 156 | 141 | 167 | 191 | 150 | 169 | 0.83 | 24.9 | 29.0 | 0.86 | 0.17 |
| 0.40 | 224 | 197 | 215 | 212 | 247 | 260 | 247 | 251 | 0.84 | 27.5 | 32.7 | 0.84 | 0.13 |
| 0.42 | 177 | 156 | 187 | 173 | 207 | 201 | 211 | 206 | 0.84 | 23.5 | 31.9 | 0.74 | 0.15 |
| 0.44 | 136 | 171 | 127 | 144 | 178 | 180 | 185 | 181 | 0.80 | 24.5 | 27.5 | 0.89 | 0.15 |
| Avg | 0.84 | 0.84 | 0.84 | 0.84 | 0.84 | 0.84 | 0.84 | 0.84 | 0.84 | 0.84 | 0.84 | 0.84 | 0.84 |

(3) Permeability coefficient test: The permeability coefficient test results are listed in Table 9. The table shows that, the permeability coefficient \(k\) is in the range of 0.070–0.185 cm/sec. All the \(k\) values are much larger than the requirement 10⁻² cm/sec. Using the \(k\) in the table vs W/C to plot line graphs, the results are shown as Figure 11. The figure shows that, the minimum \(k\) values are at W/C=0.38 and 0.42 for C=300 and 350 kg respectively. The values are 0.083 and 0.070 cm/sec respectively. The
result is exactly the same as the \( W/C = 0.38 \) of the maximum compressive strength for \( C = 300 \text{ kg} \), and very close to the \( W/C = 0.40 \) of the maximum compressive strength for \( C = 350 \text{ kg} \). The high compactness of pervious concrete would give high strength, but low permeability. Therefore, the results of the permeability coefficient test are quite coincident with those of the compressive strength test.

(4) Porosity test: The porosity test results are also listed in Table 9. The table shows that, the porosity \( n \) is in the range of 36.3\%~40.8\%. All the \( n \) values are much larger than the requirement 15\%. Using the \( n \) in the table vs \( W/C \) to plot line graphs, the results are shown as Figure 12. The figure shows that, the minimum \( n \) values are at \( W/C = 0.38 \) and 0.42 for \( C = 300 \) and 350 kg respectively. The values are 36.7\% and 36.3\% respectively. The results are exactly the same as the \( W/C = 0.38 \) of the maximum compressive strength for \( C = 300 \text{ kg} \), and very close to the \( W/C = 0.40 \) of the maximum compressive strength for \( C = 350 \text{ kg} \). The high compactness of pervious concrete would give high strength, but low porosity. Therefore, the results of the porosity test are quite coincident with that of the compressive strength test.

5. Further discussions on the test results
Comparison among the \( W/C \) values of the intersections of tangent lines on drooping flow curves, the obvious dropping points of air content line graphs, the maximum compressive strength, the maximum modulus of rupture, the minimum permeability coefficient, and the minimum porosity can give a table as Table 10. The table shows that, the \( W/C \) values of the maximum strength are totally coincident either for \( C = 300 \text{ kg} \) or 350 kg, for the compressive strength or the modulus of rupture, for the 7\textsuperscript{th} or 28\textsuperscript{th} day strengths. All maximum strengths are at \( W/C = 0.38 \) for \( C = 300 \text{ kg} \), at \( W/C = 0.40 \) for \( C = 350 \text{ kg} \). It can be sure of that, the optimal mix is at \( W/C = 0.38 \) for \( C = 300 \text{ kg} \), and at \( W/C = 0.40 \) for \( C = 350 \text{ kg} \) from these results. Table 10 also shows that, the \( W/C \) values of drooping flow amount are totally coincident with those of the strength for \( C = 300 \text{ kg} \) and 350 kg. This result confirms that, the drooping flow test is able to estimate the possible \( W/C \) range of the maximum strength of pervious concrete.

### Table 9. Permeability coefficient test and porosity test results

| Cement amount C (kg) | Water-cement ratio W/C | Permeability coefficient \( k \) (cm/sec) | Porosity \( n \) (%) |
|----------------------|------------------------|---------------------------------|-----------------|
| 300                  | 0.36                   | 0.106                           | 39.8            |
|                      | 0.38                   | 0.083                           | 36.7            |
|                      | 0.40                   | 0.179                           | 37.1            |
|                      | 0.42                   | 0.118                           | 39.4            |
|                      | 0.44                   | 0.176                           | 39.9            |
| 350                  | 0.36                   | 0.185                           | 40.8            |
|                      | 0.38                   | 0.164                           | 38.5            |
|                      | 0.40                   | 0.110                           | 36.5            |
|                      | 0.42                   | 0.070                           | 36.3            |
|                      | 0.44                   | 0.108                           | 36.5            |

### Table 10. Comparison of water-cement ratio \( W/C \) of test results

| Test name                     | Cement amount C (kg) | 300 | 350 |
|-------------------------------|----------------------|-----|-----|
| Drooping flow test            |                      | 0.38| 0.40|
| Unit weight and air content test |                    | 0.40| 0.40|
| Compressive strength test 7\textsuperscript{th} day | | 0.38| 0.40|
| Compressive strength test 28\textsuperscript{th} day | | 0.38| 0.40|
| Flexural strength test 7\textsuperscript{th} day | | 0.38| 0.40|
| Flexural strength test 28\textsuperscript{th} day | | 0.38| 0.40|
| Permeability coefficient test | | 0.38| 0.42|
| Porosity test                 | | 0.38| 0.42|
For $C=300$ kg, only the $W/C=0.40$ of the air content is not coincident with $W/C=0.38$, but still very close to it. For $C=350$ kg, only the $W/C=0.42$ of the permeability coefficient and the porosity is not coincident with $W/C=0.40$, but also very close to it. Therefore, these test results provide evidences for the optimal mix determined above.

6. Revising the optimal mixes
A concrete mix proportion is defined as that the material amount of it will produce 1 m³ volume of concrete after mixed. It is learned that from Table 7, for $C=300$ kg, the measured air content of
$W/C=0.38$ is 18.4%, smaller than the assumed air content 20.5%. Thus, the optimal mix in Table 5 will produce a volume of concrete smaller than 1 m$^3$. Therefore, the optimal mixes in Table 5 should be properly revised.

Assuming that the actual volume of the mix in Table 5 is $V$ after mixed, $V$ can be obtained by the equation

$$(1\text{-measured Air})V=1\text{-assumed Air} \tag{1}$$

From Table 7, it is read that measured $Air=18.4\%$ and assumed $Air=20.5\%$ at $W/C=0.38$ for $C=300$ kg. Substituting them into Equation (1), then

$$(1-0.184)V=1-0.205$$

gives $V=0.974$ m$^3$. From Table 7, it is read that measured $Air=17.1\%$ and assumed $Air=20.0\%$ at $W/C=0.40$ for $C=350$ kg. Substituting them into Equation (1), then

$$(1-0.171)V=1-0.200$$

gives $V=0.965$ m$^3$. Dividing the mixes of $W/C=0.38$ for $C=300$ kg and $W/C=0.40$ for $C=350$ kg by 0.974 and 0.965 respectively, the revised mixes are obtained. The results are listed in Table 11, which are the optimal mixes finally determined for pervious concrete of $C=300$ and 350 kg.

From Table 11, the relationship between cement amount $C$ and the 28th day compressive strength may be established by interpolating as

$$f_c=1.04C-125 \text{ kgf/cm}^2 \text{ for } C=300\text{~}370 \text{ kg} \tag{2}$$

This formula can be used to estimate the optimal compressive strength for a pervious concrete mix of cement amount $C$.

| Table 11. Revised optimal pervious concrete mixes and test values |
|---------------------------------------------------------------|
| Mix | $W/C$ | $C$ (kg) | $W$ (kg) | $G$ (kg) | $U$ (kg/m$^3$) | $f_c$ (kgf/cm$^2$) | $R$ (kgf/cm$^2$) | $k$ (cm/sec) | $n$ (%) |
|------|-------|--------|---------|---------|---------------|-----------------|----------------|-------------|---------|
| Original | 0.38 | 300 | 114 125 1488 1500 | 1976 18.4 194 0.82 31.4 0.67 0.16 0.083 36.7 |
| Revised | 0.38 | 308 | 117 128 1528 1540 |
| Original | 0.40 | 350 | 140 150 1394 1406 | 1976 17.1 251 0.84 32.7 0.84 0.13 0.110 36.5 |
| Revised | 0.40 | 363 | 145 155 1445 1457 |

7. Concluding remarks

The main grain size range of aggregate used in the tests is in #4~3/4” (4.75~19.0 mm). The water-cement ratio $W/C=0.36$~0.44 of pervious concrete mixes of cement amount $C=300$ and 350 kg was used to make fresh concrete samples to perform the drooping flow test and the unit weight and air content test. Then the specimens of pervious concrete were made to perform the compressive strength test, the flexural strength test, the permeability coefficient test and the porosity test in order to find the $W/C$ of the maximum strength, which satisfies the requirements of permeability and retention. The mix of this $W/C$ determined is the optimal economic effect mix.

The strength test results show that, the $W/C$ values of the maximum strength are totally coincident either for $C=300$ kg or $350$ kg, for the compressive strength $f_c$, the modulus of rupture $R$, for the 7th day or 28th day strengths. All maximum strengths are at $W/C=0.38$ for $C=300$ kg and at $W/C=0.40$ for $C=350$ kg. These results can be sure of that, the optimal mix is at $W/C=0.38$ for $C=300$ kg and at $W/C=0.40$ for $C=350$ kg. The optimal mix of $C=300$ kg gives strengths $f_{c7}=159$ kgf/cm$^2$ (15.6 MPa), $f_{c28}=194$ kgf/cm$^2$ (19.0 MPa), $R_7=22.6$ kgf/cm$^2$ (2.2 MPa), $R_28=31.4$ kgf/cm$^2$ (3.1 MPa). Thus, it gives the strength ratios $f_{c7}/f_{c28}=0.82$, $R_7/R_28=0.67$ and $R_{28}/f_{c28}=0.16$. The optimal mix of $C=350$ kg
gives strengths $f_{c7} = 212 \text{ kgf/cm}^2$ (20.8 MPa), $f_{c28} = 251 \text{ kgf/cm}^2$ (24.6 MPa), $R_1 = 27.5 \text{ kgf/cm}^2$ (2.7 MPa), $R_2 = 32.7 \text{ kgf/cm}^2$ (3.2 MPa). Thus, it gives the strength ratios $f_{c7}/f_{c28} = 0.85$, $R_1/R_2 = 0.84$ and $R_2/f_{c28} = 0.13$.

The W/C values of the rising points at the drooping flow curves are totally coincident with those of the maximum strengths for C=300 kg and 350 kg. These results strengthen that, the drooping flow test is able to estimate the possible W/C range of the maximum strength of pervious concrete.

For C=300 kg, only the W/C=0.40 of obvious drop point at the air content line graph is not coincident with W/C=0.38, but still very close to it. For C=350 kg, only the W/C=0.42 of the permeability coefficient and the porosity tests is not totally coincident with W/C=0.40, but also very close to it. All the other test results are totally coincident with each other. Therefore, these test results provide evidences for the optimal mix determined above.

Only the W/C=0.40 of the air content test for C=300 kg is not totally coincident with W/C=0.38, but still very close to it. Only the W/C=0.42 of the permeability coefficient and the porosity tests for C=350 kg is not totally coincident with W/C=0.40, but also very close to it. Therefore, these test results provide evidences for the optimal mix determined above.

Since the measured air content is not the same with the assumed air content 20.5%, the original mix must be properly revised to produce 1 m$^3$ of concrete volume. The revised mixes are listed in the following table, and are the optimal mixes finally determined. From this table, it can be said that, the pervious concrete mixes of C=308 and 363 kg can optimally produce 194 kgf/cm$^2$ (19.0 MPa) and 251 kgf/cm$^2$ (24.6 MPa) of the 28th day compressive strength respectively. The mixes would give permeability coefficient $k = 0.083$ and 0.110 cm/sec and porosity $n = 36.7\%$ and 36.5\% respectively. These $k$ values are much larger than the permeability coefficient requirement 10$^2$ cm/sec and the $n$ values are much larger than the porosity requirement 15%. The results shown in a table 12 as below,

| $C$ (kg) | $W$ (kg) | $W/C$ | $G$ (kg) | $U$ (kg/m$^3$) | $f_c$ (kgf/cm$^2$) | $R$ (kgf/cm$^2$) | $k$ (cm/sec) | $n$ (%) |
|---------|---------|-------|---------|--------------|-----------------|----------------|-------------|--------|
| 308     | 0.38    | 117   | 128     | 1528         | 1540            | 1976          | 18.4        | 0.82   | 31.4 | 0.67 | 0.16 | 0.083 | 36.7 |
| 363     | 0.40    | 145   | 155     | 1445         | 1457            | 1976          | 17.1        | 0.84   | 32.7 | 0.84 | 0.13 | 0.110 | 36.5 |

From the above table, the relationship between cement amount $C$ and the 28th day compressive strength may be established by interpolating as $f_c = 1.04C - 125 \text{ kgf/cm}^2$ for $C=300-370$ kg. This formula can be used to estimate the compressive strength for a pervious concrete optimal mix of cement amount $C$.

8. References
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