Asian Journal of Chemistry; Vol. 26, No. 6 (2014), 1811-1815

ASIAN JOURNAL OF CHEMISTRY

http://dx.doi.org/10.14233/ajchem.2014.17363

# Orthogonal Analysis of Water Permeability of Pervious Concrete†

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*Published online*: 10 March 2014; AJC-14904

The development application of pervious concrete is reviewed in this article. The study state of pervious concrete on working performance, mechanical performance, drainage and sound absorption performance is summarized, especially the drainage performance. The paper use orthogonal test and analyze four factors, the types of aggregate, sand rock volume ratio, cement amount and molding pressure to specify the impacts on permeability coefficient of pervious concrete. The experimental results are valued by maximum range and standard deviation to judge the influential degree of each factor. Regression equation and its functional image are imitated to reaffirm the accuracy of the previous judgment.

**Keywords: Pervious concrete, Permeability coefficient, Orthogonal experiment design.**

## INTRODUCTION

Pervious concrete (porous concrete), a kind of porous concrete with continuous pores as the important species of ecological concrete, is made by specifically graded aggregate, cement, water, additives and admixtures through a certain proportion and special processes.

Its apparent density is generally 1600-2100 Kg/m$^3$, 28d compressive strength is 10-40 MPa, flexural strength is 2-7 MPa, permeability coefficient is 1-20 mm/s and the effective target porosity is 18-22 %. From the technical performance point of view, in addition to reducing the surface water, the performances of the permeable concrete on purifying water, reducing road traffic noise, regulating the humidity and temperature of urban space and other aspects are equally obvious, compared with the impervious concrete pavement.

Therefore, under the guidance of thinking of the maintenance of ecological balance and sustainable development, America, Europe, Japan, Korea and some other developed countries began the research and application of pervious concrete over 50 years ago. The porous concrete has been extensively applied road works, landscaping works, environmental engineering and other fields achieving good social, environmental and ecological effects. In China, the theoretical analysis has made some achievements but still it its infancy. In view of this, the study uses orthogonal experimental design method and bases on the experimental data using regression analysis and range analysis to analyze the factors which affect the permeability of concrete and offer valuable reference for the design of the best mix ratio test of the pervious concrete.

**Pervious concrete research overview:** Pervious concrete application began 100 years ago. According to the documentation of Malhortra, in 1852, the born of the pervious concrete was due to the lack to fine aggregate concrete during the British construction[1].

United States in the 1960s began the research of the proportioning ratio of porous concrete comparing with the ordinary concrete. In 1995, Southern Illinois University, Nader Ghafoori proposed a summary discussing the possibility of the non-fine-aggregate concrete, introduced the skills of using porous concrete as the paving materials and set up plenty of researches of its physical mechanical characters and states, especially the impacting reinforced law when produce the concrete. In the summary, he discussed during the process of reinforcement the energy, effect, deployment, manufacturing technology and some other factors which affect the physical mechanical characters after the hardening of the concrete. Plus, he also mentioned the abrasion resistance and frost abilities of porous concrete[2].

†Presented at The 7th International Conference on Multi-functional Materials and Applications, held on 22-24 November 2013, Anhui University of Science & Technology, Huainan, Anhui Province, P.R. China

In Japan, in order to solve the ground subsidence and other issues caused by groundwater pumping, in the late 1970s, 'underground rainwater reduction policy' was proposed; permeable concrete paving was developed and applied into practical engineering. Professor Tamai Motoharu, in 1987, in department of civil engineering, University of Osaka Kini, added polymer resin and super-fine aggregate into cementation material to create pervious concrete and successfully applied for a patent. Nowadays, Japan in the area of proportional design, construction, maintenance and management has formed comprehensive nation-state standards which vigorously give promotions of the application of pervious concrete[3].

Pervious concrete, although started late in China, there are still some ground breaking researches. In 1995, China Building Materials Academy took the lead in successfully developing the pervious concrete in the country. Then, Tsinghua University, Yang Jing *et al.* in the trial also joined by 6 % silica fume, enhancers and other mineral fine materials and additives in order to improve the microstructure and improve the adhesive bond strength of cement. Consequently the pervious concrete 28d compressive strength reached 50 MPa, flexural strength reach 6 MPa with fine qualities of permeability, abrasion resistance and durability. In addition, Chen Yu in the Central South University and Zheng Mu-Lian in Chang an University from the effective ratio of mineral admixture and additives, relations of the strength development, methods of elastic modulus test, optimal production conditions and other aspects commit a large number of in-depth researches, which played an important role in the amelioration of the mechanical property of pervious concrete[4].

In its application, in the United States, pervious concrete generally does not contain fine aggregate, known as non-sand concrete. The application about pervious concrete began in 1956. Gl Washa used lightweight aggregate pervious concrete, effectively exploiting its insulation resistance and permeability. Afterwards, in Florida, New Mexico and Utah, non-fine aggregate concrete was used as the road surface material in constructing the parking area roads. In Florida's Sa Rasota church parking lot, the road used the concrete mixed by Type I Portland cement, aggregate sized from 6-21.5 mm and entraining agent. Consequently, 53 'non-sand' parking lots were built in Florida coastal areas. In China, pervious concrete has been used in the construction of the Beijing Olympic Park and the Shanghai World Exposit and many other practical engineering applications. The application of the porous concrete became bright spots due to its excellent water permeability and pristine beautiful visual effects[5], giving promotions to the enthusiasm of pervious concrete researches in China. Furthermore, pervious concrete also gives extent to the environment, ecology project. Zou[6] investigated the functions of the membrane biofilm characters and working states on the removal of organic matter and total nitrogen content in municipal wastewater. The investigation identified in the diaphragm reactor the biomass, the biological activity, the distribution of microorganisms and analyzed the biofilm characters and denitrification performances[6].

**Research of drainage performance:** Drainage function is an important feature of pervious concrete when the concrete is used as pavement materials. The rain falling on the permeable surface layer can penetrate inside the pavement structure and flow away through the internal connective pore without forming harmful film of water or runoff on the road surface, which would undermine the hydrodynamic pressure. It therefore enables the maintenance the serious contact of vehicle tires and road surface, so as to avoid hydroplaning phenomenon generated from high speed driving and improve the safety of vehicles.

Zheng and Wang[7] in Chang an University, use porosity and permeability coefficient as the index and the experimental method of setting water level to study permeable concrete drainage performance. The results showed that the effective porosity increased with the increase of the whole porosity and the ratio between the effective porosity and whole porosity increased also, which confirmed that the two factors had good correlation of quadratic relationship. However, as the porosity increases, the compressive strength decreases and the correlation between compressive strength and total porosity is superior to the correlation between compressive strength and effective porosity. See the formulae (1-4).

$$n_e = -0.1661n_0^2 + 12.745n_0 - 209.61(R = 0.9848) \quad (1)$$

$$\frac{n_e}{n_0} = -0.0591n_0^2 + 5.0122n_3 - 6.6846(r = 0.9748) \quad (2)$$

In the formula $n_0$-porosity; $n_e$-effective porosity.

$$f_{c,7} = -0.3806n_e + 17.058(R = 0.8631) \quad (3)$$

$$f_{c,7} = -0.7545n_0 + 30.873(R = 0.8928) \quad (4)$$

In the formula $f_{c,7}$-7d flexural strength of pervious concrete; $n_0$-porosity; $n_e$- effective porosity. R-Relative coefficient experiment group: 16 groups.

On this basis, Liu[8] used efficiency coefficient analysis methods to analyze the comprehensive relationships and appraisal between the compressive strength and permeability coefficient. The results are obtained to ensure the best proportioning design method: water-cement ratio 0.30; sets cement ratio 3.5; aggregate size of 2.36-4.75 mm with the proportion of 100 %; adding appropriate mineral admixtures and additives[8]. The mix ratio enables the favourable correlation relationships between compressive strength and permeability coefficient.

$$f_{c28} = 27.499 - 32.402x + 10.293x^2 (R = 0.717) \quad (5)$$

In the formula: $f_{c28}$-28d compressive strength MPa; X-permeability coefficient (mm/s); R- experiment group: 45 groups.

Haselbach *et al.*[9] through the establishment of sand covering the surface of the pervious concrete system model simulating the runoff under the condition of contamination with pollution and blocked pores to analyze the permeability impact from active runoff and passive runoff. The formula:

$$k_{eff} = \left(\frac{p_{top}}{100}\right)k_{sand} \quad (6)$$

In the formula: $K_{eff}$-effective permeability with covering layer; $p_{top}$-test piece 1/4 upper average porosity; $K_{sand}$-sand permeability.

In Japan, in order to solve the clogging of dust and sediment, resulting in decreased permeable pavement permeable functional problems, the general pressure of 4-7 MPa pressure washer is used for the road surface or high pressure cleaning with the vacuum suction and recovery method, which enable the recovery to the initial 80 % of the permeable restore function.

## EXPERIMENTAL

Pervious concrete is mainly constituted by cement, coarse aggregate, fine aggregate and water. This test uses "stone shield" brand PO·42.5 class ordinary class Portland cement; sand as an ordinary river sand, fineness modulus was 2.95; natural coarse aggregate for a single graded gravel and pebbles; recycled coarse aggregate crushing by the waste processing is made of reinforced concrete beams, the compressive strength resulted from the drill core sampling of waste concrete as 35-45 MPa in between; Hefei drink tap water for concrete mixing and curing. The basic properties of coarse aggregate are presented in Table-1.

**Experiment design:** In order to analyze the relationships between properties of pervious concrete and each influential factor to find out the optimal mixture ratio for production to meet the requirement of permeability coefficient. We use orthogonal design principles based upon four main factors, the aggregate kinds, the volume ration of sand, the molding pressure and cement content to know the influential extent to the permeability index from each factor mentioned above. Plus, each correlation could be quantized through standard differential analysis method[10,11]. Pervious concrete mix design test, select $L_{16}(3^4)$ orthogonal arrangements, factor-level shown in Table-2, pervious concrete mix shown in Table-3.

**Experiment results:** In the test, the permeability coefficient of pervious concrete was tested, the test results shown in Table-4. It can be visually seen from the table that when the molding pressure is 0 MPa, the permeability coefficient is maximum and the permeability coefficient increases with the increase of molding pressure.

According to the orthogonal theory, maximum ranges and standard deviation of the quantized influence from coarse aggregate types (A), volume ratio of sand (B) and molding pressure (C) are calculated, shown in the Table-5. The factor with a big maximum range means comparatively more impact on permeability coefficient between the deviations of three levels and usually is considered as an important factor. Standard deviation as a secondary factor for auxiliary judgment determines the accuracy of data. Plus, the smaller the standard deviation is, the more accurate the data becomes.

In Table-5, Qi means the sum of each level result and qi is the average value of Qi. S means maximum range and R means standard deviation. Table-5 showed the random of the permeability coefficient factors reflecting the influential degree of each factor is C → D → B → A, namely molding pressure → cement amount → sand volume ratio → aggregate kinds. The result of the maximum range analysis is similar to the result standard deviation analysis, which proves the accuracy and assurance of the consequences.

## RESULTS AND DISCUSSION

**Numerical analysis of test results:** Firstly analyze the permeability coefficient and then use single factorial regression method to, respectively analyze the influence of molding pressure, the amount of cement and sand rock volume ratio

TABLE-1
COARSE AGGREGATE PROPERTY

| Class | Grading (mm) | Apparent density (kg/m³) | Determination density (kg/m³) | Porosity (%) | Water absorption (%) | Crush value (%) |
|---|---|---|---|---|---|---|
| Cobble | 5.0-10.0 | 2600 | 1501 | 42 | 1.75 | 12.9 |
| Stone | 5.0-10.0 | 2700 | 1458 | 46 | 1 | 10.9 |
| Regenerating aggregate | 5.0-10.0 | 2480 | 1298 | 48 | 4.25 | 17.9 |
| Fine gravel aggregate | 5.0-10.0 | 2650 | 1454 | – | – | – |

TABLE-2
FACTOR-LEVEL OF ORTHOGONAL DESIGNING METHOD

| Level | Factors | | | |
|---|---|---|---|---|
| | A (Aggregate kinds) | B (Sand volume ratio) (%) | C (Crush strength) (MPa) | D (Cement quantity) (kg/m³) |
| 1 | Cobble (L) | 0 | 0 | 150 |
| 2 | Stone (S) | 10 | 1.0 | 200 |
| 3 | Regenerating aggregate (Z) | 20 | 1.5 | 250 |

TABLE-3
ORTHOGONAL EXPERIMENT GROUP AND CONTENT

| Number | Aggregate | Sand-stone | Crush | Cement | Material | | | |
|---|---|---|---|---|---|---|---|---|
| | Kinds | Volume ratio (%) | Strength (MPa) | Quantity (kg/m³) | Cement | Water | Coarse aggregate | Fine aggregate |
| 1 | L(A1) | 0(B1) | 0(C1) | 150(D1) | 150 | 60 | 1501 | 0 |
| 2 | L(A1) | 10(B2) | 1.0(C2) | 200(D2) | 200 | 80 | 1351 | 150 |
| 3 | L(A1) | 20(B3) | 1.5(C3) | 250(D3) | 250 | 100 | 1201 | 300 |
| 4 | S(A2) | 0(B1) | 1.0(C2) | 250(D3) | 250 | 100 | 1458 | 0 |
| 5 | S(A2) | 10(B2) | 1.5(C3) | 150(D1) | 150 | 60 | 1312 | 146 |
| 6 | S(A2) | 20(B3) | 0(C1) | 200(D2) | 200 | 80 | 1166 | 292 |
| 7 | Z(A3) | 0(B1) | 1.5(C3) | 200(D2) | 200 | 80 | 1298 | 0 |
| 8 | Z(A3) | 10(B2) | 0(C1) | 250(D3) | 250 | 100 | 1168 | 130 |
| 9 | Z(A3) | 20(B3) | 1.0(C2) | 150(D1) | 150 | 60 | 1038 | 260 |

TABLE-4
EXPERIMENTAL RESULTS OF PERMEABILITY COEFFICIENT

| Number | Aggregate kinds | Permeability coefficient (mm/s) |
|---|---|---|
| 1 | L(A1) | 28.9 |
| 2 | L(A1) | 15 |
| 3 | L(A1) | 6.8 |
| 4 | S(A2) | 9.5 |
| 5 | S(A2) | 11.5 |
| 6 | S(A2) | 14.5 |
| 7 | Z(A3) | 13.2 |
| 8 | Z(A3) | 16.5 |
| 9 | Z(A3) | 12.5 |

TABLE-5
STANDARD DEVIATION AND MAXIMUM RANGE OF EXPERIMENT RESULTS

| Code | 28d permeability coefficient (mm/s) | | | |
|---|---|---|---|---|
| | A | B | C | D |
| Q1 | 50.7 | 51.6 | 59.9 | 52.9 |
| Q2 | 35.5 | 43 | 37 | 42.7 |
| Q3 | 42.2 | 33.8 | 31.5 | 32.8 |
| q1 | 16.9 | 17.2 | 19.9 | 17.6 |
| q2 | 11.8 | 14.3 | 12.3 | 14.2 |
| q3 | 14.1 | 11.2 | 10.5 | 10.9 |
| S | 4.3 | 4.6 | 3.8 | 4.3 |
| R | 2.8 | 6.0 | 9.4 | 6.7 |

on permeability. The aggregate has roughly the same size of each other, thus we did no regression test on it. MATLAB software was used to draw the table of unified dimensions seen in the Table-6, draw the functional image and make compare between data and functional image.

TABLE-6
UNIFIED DIMENSION ANALYSIS FROM MATLAB

| Sand volume ratio | Molding pressure | Cement amount | Permeability coefficient |
|---|---|---|---|
| 0 | 0 | 0.08 | 28.9 |
| 0.1333 | 2.2857 | 0.1067 | 15 |
| 0.2667 | 3.4286 | 0.1333 | 6.8 |
| 0 | 2.2857 | 0.1333 | 9.5 |
| 0.1333 | 3.4286 | 0.08 | 11.5 |
| 0.2667 | 0 | 0.1067 | 14.5 |
| 0 | 3.4286 | 0.1067 | 13.2 |
| 0.1333 | 0 | 0.1333 | 16.5 |
| 0.2667 | 2.2857 | 0.08 | 12.5 |

**Single factorial regression analysis of impact on permeability coefficient:** Based on a unified dimension, we set P (B) as the polynomial fitting function of factor sand volume ratio to the permeability coefficient, P (C) as the function of factor molding pressure and P (D) as the function of factor cement amount. The function of P (B):

$$P(B) = \sum_{i=o}^{2} a_i (X_1)^i$$

In the same way:

$$P(D) = \sum_{i=o}^{2} a_i (X_2)^i$$

$$P(B) = \sum_{i=o}^{2} a_i (X_3)^i$$

In the formula: $a_0$, $a_1$, $a_2$ mean fitting coefficient.

From the Table-6, we get the linear regression equation: $P(B) = 201.693X_1^2 - 65.345X_1 + 16.9$, presented as Fig. 1. In the same way: $P(C) = 0.506X_2^2 - 4.497X_2 + 19.9667$, presented as Fig. 2. $P(D) = 61.510X_3^3 - 138.860X_3 + 28.348$, presented as Fig. 3.

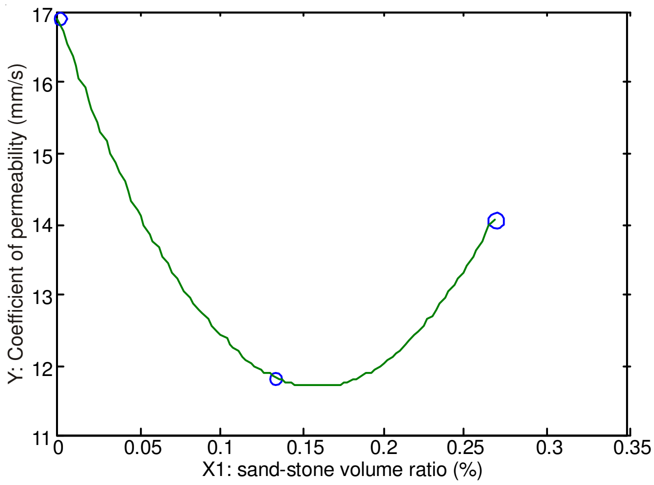


Fig. 1. Functional image of P (B)

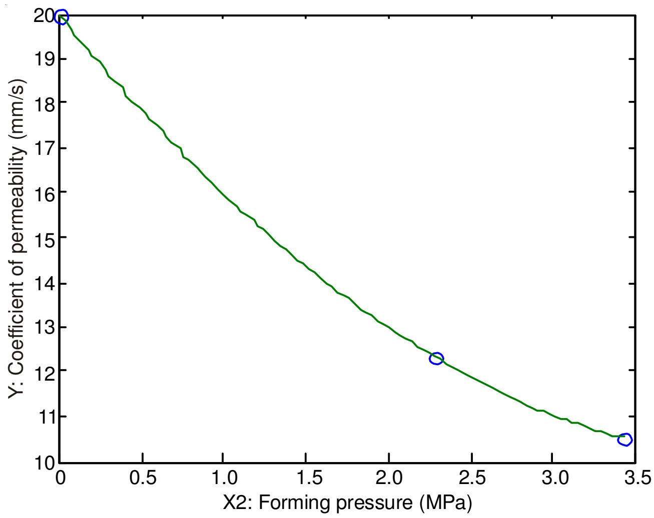


Fig. 2. Functional image of P (C)

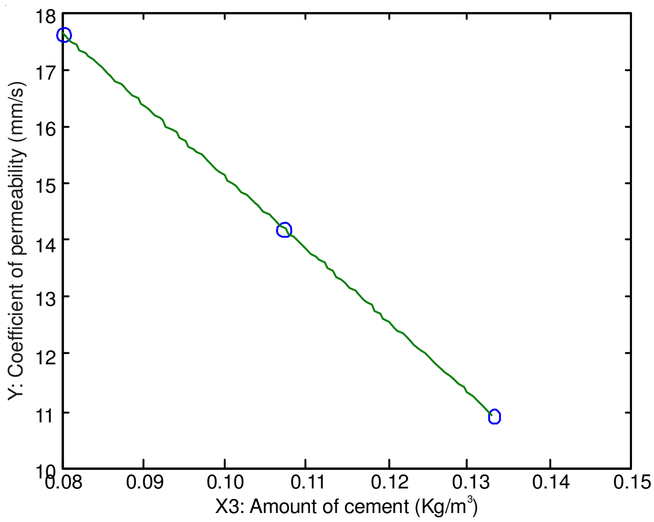


Fig. 3. Functional image of P (D)

To draw conclusions from the regression equation, the priority of impact factors of the pervious concrete permeability coefficient is C → D → B, which shows the unanimous result of standard deviation analysis. It is observed from the functional image that the influential value of factor B, the cement amount, exist extreme points and the influential value of factor C and factor D, the molding pressure and sand volume ratio, are negatively correlated with permeability coefficient.

**Conclusion**

• The randomness of the permeability coefficient factors reflecting the influential degree of each factor is C (molding pressure) → D (cement amount) → B (sand volume ratio) → A (aggregate kinds). Molding pressure has the most significant impact on permeability coefficient; the amount of cement has a comparatively significant impact while the sand volume ratio is less affected. As the molding pressure increases, the permeability has a large decline; with the increase of sand volume ratio, the permeability coefficient reduces; with the increase of the cement amount, the permeability firstly decreases then increases in the later.

• In engineering practice, the factors giving impaction on the pervious concrete properties are much more than the factor mentioned in the experiment above. One can use the analytical method described in this paper to examine the impact of other factors, such as ashes ratio, aggregate size and water-cement ratio which can impact the permeability and 28d compressive strength of pervious concrete, for the design optimal mixture ratio.

## ACKNOWLEDGEMENTS

This work was supported by the Natural Science Research Fundation of Hefei University (12KY03ZR),and the College Students' Innovation and Entrepreneurship Training Program of China (No. 201311059013, 201311059014, 201311059015, 201311059016, 201311059039, 201311059040, 201311059041, 201311059144).

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