Research Article

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Relationship between percolation mechanism and pore characteristics of recycled permeable bricks based on X-ray computed tomography

<https://doi.org/10.1515/rams-2021-0022>

Received Dec 29, 2020; accepted Jan 28, 2021

Abstract: The relationship between percolation mechanism and pore characteristics for recycled permeable bricks with different porosities is investigated in this study based on X-ray computed tomography (X-CT). Permeability coefficients are measured and some characteristics including size, amount, and distribution of the pore are analysed. The results show that the effective porosity and permeability coefficient of the recycled permeable bricks exhibit a linear relationship first and then a quadratic curve relationship, where the critical effective porosity is 12%. Meanwhile, we discovered that nonlinear channels in permeable bricks are larger and fewer compared with linear percolation channels, regardless of whether the percolation stage is linear or nonlinear. Additionally, when the area and number ratios of the linear and nonlinear percolation channels reached 80% and 10%, respectively, the overall percolation state of the permeable bricks changed from linear to nonlinear percolation. This research is helpful to improve the mechanical and percolation properties of recycled concrete bricks and promote the application of porous permeable material.

Keywords: X-ray computed tomography, percolation mechanism, pore characteristics

1 Introduction

Rapid urbanisation greatly meets the needs of people's lives while leading to several problems such as environmental pollution, urban waterlogging, and the urban heat island effect. The use of construction waste to prepare permeable bricks not only enables the recycling of construction waste, but also helps alleviate urban waterlogging. Owing to the effective mitigation of urban problems, studies regarding recycled permeable bricks have received widespread attention.

Currently, some engineering applications of recycled permeable concrete exist; however, research related to them is still in the initial stage, and pertains primarily to the mix ratio and basic properties, such as flexural strength, compressive strength, porosity, and permeability coefficient [1–8]. Some scholars studied the relationship between the pore structure and permeability coefficient of permeable concrete and provided some interesting researching results. Kuang *et al.* studied permeable pavement pore-structure parameters using a modified Kozeny–Carman model and discovered that the relationship between permeability coefficient (k) and porosity exhibited a power law model [9]; Sumanasooriya *et al.* [10], Sumanasooriya and Neithalath [11], Neithalath *et al.* [12] employed a computational procedure to predict the permeability of 12 different pervious concrete mixtures. Zhong *et al.* [13] used the linear path function proposed by Lu *et al.* [14] to calculate the pore size distribution of permeable concrete and verified it through image analysis. These studies mainly analysed the relationship between the internal pore structure and permeability, but did not reveal the internal percolation mechanism of permeable concrete and the key parameters governing the percolation state.

Hence, to reveal the percolation mechanism, an in-depth investigation regarding the relationship between the permeability and pore characteristics of recycled permeable bricks based on the existing porous media percolation theory was performed in this study. Regarding porous medium percolation theory, Darcy's law is the most extensively used

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empirical formula for calculating flow in porous media. Subsequently, Reynolds identified two different fluid morphologies, *i.e.* laminar and turbulent, and reported that a critical velocity (v) existed between the two, which was related to the equivalent diameter (d), viscosity (μ), and density (ρ) of the fluid, hence, the Reynolds number

$$Re = \frac{vd\rho}{\mu}. \quad (1)$$

In addition, Bachmat *et al.* discovered that Darcy's law in porous media percolation is applicable only at low Reynolds numbers ($Re < 1 \sim 10$) [15]. Many scholars studied the deviation from Darcy's law. For example, Hubbert [16] and Scheidegger [17], reported that the deviation from Darcy's law was caused by inertial forces, and that the fluid was in a nonlinear laminar flow stage.

The characterisation of internal pore structure is critical to study the percolation problem in porous media. Currently, the main methods for characterising pores include image analysis as well as intrusive and nonintrusive methods. Among them, the intrusive method mainly includes the mercury injection method and nitrogen adsorption methods [18], whereas the nonintrusive method mainly include nuclear magnetic resonance, sound absorption coefficient [19], small-angle scattering, and X-ray computed tomography (X-CT). X-CT offers outstanding advantages in the analysis of pore structure in porous media owing to its nondestructive and high accuracy. In recent years, many re-

searchers have applied X-CT to concrete materials. Results show that X-CT is not only used to identify the internal components of concrete based on image grayscale [20], but also used to characterise changes in pores and cracks in concrete and the interface between aggregates and cement at different time periods [21–25]. At the same time, X-CT is often used to characterize the dynamic changes of the internal structure of concrete under external loads [26–28].

Therefore, the pore structure in permeable bricks was studied based on X-CT images, and the percolation state of recycled permeable bricks was analysed based on porous media percolation theory in this study. Furthermore, the effects of the distribution, number, and pore size of linear and nonlinear channels on the permeability of recycled permeable bricks were studied to ascertain the relationship between the percolation mechanism and pore characteristics of recycled permeable bricks.

2 Materials and test methods

2.1 Materials

P.O 42.5 cement in accordance with the requirements of the GB175-2007 Chinese standard [29] produced by Zhejiang Qianchao Co., Ltd. and fly ash in accordance with the requirements of the GB/T 1596-2017 Chinese standard [30]

Table 1: Properties and composition of cement

Density (kg/m ³)	Chemical composition (%)						
	SiO ₂	Al ₂ O ₃	Fe ₃ O ₄	CaO	MgO	SO ₃	Na ₂ O
3090	22.37	4.36	3.38	61.08	2.43	2.45	0.506

Table 2: Properties and composition of fly ash

Density (kg/m ³)	Chemical composition (%)						
	CaO	SiO ₂	Al ₂ O ₃	MgO	Fe ₂ O ₃	K ₂ O	Loss
2400	3.41	49.83	27.58	0.81	4.26	1.31	9.87

Table 3: Properties of HSC polycarboxylic superplasticiser

Water reduce ratio (%)	PH	Specific gravity	Solid content (%)
28–35	6.8	1.08	40%

Table 4: Properties of recycled aggregates

Particle size (mm)	Apparent density (kg/m ³)	Bulk density (kg/m ³)	Water ratio (%)	Water absorption (%)
4.75–9.5	2485	1362	10.1	11.3

Table 5: Properties of PVA fibre

Length (mm)	Diameter (um)	Tensile strength (MPa)	Elasticity modulus (GPa)	Elongation at break (%)
6	5–20	1200–1500	32–40	5–15

were used, and their properties are listed in Table 1 and Table 2 respectively. The superplasticiser used in the test was polycarboxylic superplasticiser produced by Qingdao Hongxia Company, and its properties are listed in Table 3. The recycled aggregates produced by Haining Hongxiang Building Materials Co., Ltd. were used, and its basic properties are listed in Table 4. PVA fibre with a bulk density of 0.45 g/cm^3 and hydroxypropyl methyl cellulose (HPMC) were used as admixtures in the test. The properties of PVA fibre are presented in Table 5.

2.2 Test methods

2.2.1 Preparation of recycled permeable bricks

After being stirred in an LHB-III asphalt mixer, cement mixture with recycled aggregate was poured into a steel mould measuring $40 \text{ mm} \times 120 \text{ mm} \times 160 \text{ mm}$ and subjected to a certain pressure (3.0 MPa) using a pressure testing machine. A photograph of the experimental setup is shown in Figure 1. Moulded samples were cured indoors at 20°C for 24 h and then cured at the standard curing temperature of 20°C and a humidity above 95%.

The mix ratio design of the recycled permeable brick was based on the volume method of the target porosity. Specifically, the amount of each material was calculated

Figure 1: Forming test of recycled permeable bricks

according to the volume formula after determining the empirical water–cement ratio and setting the target porosity. The amount of fly ash was 10% of the binding materials, and the amount of superplasticiser was adjusted to ensure that the same fluidity for each test group. The mix proportions of the specimens are shown in Table 6. Groups C are recycled permeable bricks with different target porosities, whereas groups M are recycled permeable bricks modified with PVA fibre and HPMC.

2.2.2 Determination of water permeability coefficient

At the age of 28 days, a 75-mm-diameter cylinder was removed from the recycled permeable brick using a coring

Table 6: Mix proportions of specimens

NO.	Target porosity (%)	Composition of materials (kg/m^3)						
		Fly ash	Cement	Water	Superplasticiser	Aggregates	HPMC	PVA
C1	10	58	526	164	4.09	1330	/	/
C2	15	50	451	140	4.01	1341	/	/
C3	20	42	376	117	3.76	1343	/	/
C4	25	34	302	94	3.35	1346	/	/
C5	30	25	227	71	2.52	1349	/	/
C6	35	17	152	47	1.69	1355	/	/
M2	15	50	451	140	4.01	1341	/	/
M2H	15	50	451	140	6.01	1341	0.5	/
M2F	15	50	451	140	6.52	1341	/	0.9
M2HF	15	50	451	140	10.02	1341	0.5	0.9
M3F	20	42	376	117	7.11	1343	/	0.9
M3HF	20	42	376	117	10.46	1343	0.5	0.9

machine, and the water permeability coefficient was measured in accordance with the requirements of the GB / T 25993-2010 Chinese standard [31]. The formula to calculate the water permeability coefficient is shown in (2).

$$K_{\tau} = \frac{QL}{AHt} \quad (2)$$

Where Q is the seepage flow (cm^3); L is the thickness of the permeable brick (cm); A is the cross-sectional area of the permeable brick (cm^2); H is the head difference (cm); t is the seepage time (s); K_{τ} is the water permeability coefficient (cm/s).

2.2.3 Determination of effective porosity by Archimedes

The effective porosities of recycled permeable bricks by Archimedes were measured in accordance with the requirements of the DB11/T775-2010 Chinese standard [32]. After the specimen was dried to a constant weight in an oven at $(105 \pm 5)^{\circ}\text{C}$, the size of the specimen was measured, and the volume V (cm^3) was calculated. Subsequently, the specimen was immersed in water and the weight, m_1 (g) of the specimen in water was measured. The weight m_2 (g) of the specimen was measured after the specimen was removed from the water and dried in an oven at 60°C for 24 h. The formula to calculate the effective porosity P by Archimedes is shown in (3).

$$P = 1 - \frac{m_2 - m_1}{\rho_w V} \quad (3)$$

2.2.4 X-CT

An XHT320 X-ray computed tomography scanner with a resolution less than $10 \mu\text{m}$ from Zhejiang University was used. The permeable brick was dried in an oven at 60°C for 48 h, and then a computed tomography scan was performed to obtain a three-dimensional (3D) image of the permeable brick, as shown in Figure 2.

Figure 2: 3D image of recycled permeable brick

The 3D image of the permeable brick was cut horizontally into 200 layers, and the porosity was calculated using a Matlab program. First, the pixel threshold was determined for binarisation; then, the 'bwareaopen' function was used to denoise and the 'bwlabel' function to obtain the pore area; finally, the 'tabulate' function was used to count the distribution frequency of the pores. The binary process is shown in Figure 3, from which we can count the effective porosity of each sample as well as the area and number of pores of different sizes.

Figure 3: Binary process of recycled permeable bricks

3 Results and discussion

3.1 Percolation mechanism of recycled permeable brick

3.1.1 Effective porosity of recycled permeable bricks by X-CT and Archimedes

The effective porosity of the recycled permeable bricks obtained from Archimedes and X-CT are shown in Figure 4. As shown, the effective porosities obtained by the two test methods were close, and the overall trend was consistent. When the effective porosity was small, the effective porosity by Archimedes was smaller than the effective porosity by X-CT. As the effective porosity increased, the effective porosity by Archimedes increased faster and exceeded the effective porosity by X-CT. This occurred because Archimedes' method could not incorporate closed pores, whereas X-CT

Figure 4: Effective porosity of permeable bricks under different test methods

could not incorporate the pores of the surface error layer. When the effective porosity was small, more closed pores appeared inside the permeable brick, rendering the porosity by Archimedes smaller than the porosity by X-CT; when the effective porosity increased, the decrease in cement slurry reduced the proportion of closed pores and the effect of closed pores was less prominent than that of the pores on the surface error layer, rendering the porosity by Archimedes greater than that by X-CT.

3.1.2 Relationship between effective porosity and permeability coefficient of recycled permeable bricks

Figure 5 shows the relationship between the effective porosity and permeability coefficient by Archimedes and X-CT. The fitting function is shown in the figure, where K_A is the permeability coefficient obtained by Archimedes, K_C is the permeability coefficient obtained by X-CT, and P_e is the effective porosity.

As shown in the figure, the relationships between effective porosity and permeability coefficient obtained using the two methods were similar. As the effective porosity increased, both K_A and K_C increased linearly first and then increased in a curve. The critical effective porosities obtained by Archimedes and X-CT were both approximately 12%. When the effective porosity was less than 12%, a linear relationship was exhibited between the effective porosity and permeability coefficient; however, when the effective porosity was greater than 12%, a quadratic function relationship was exhibited between the effective porosity and permeability coefficient, indicating that the larger the effective porosity, the faster the permeability coefficient increased. Meanwhile, at the linear stage, the fitting slopes obtained by X-CT and Archimedes were similar, *i.e.* approximately 0.4; at the quadratic function stage, the increase

Figure 5: Relationship between effective porosity and permeability coefficient by Archimedes and X-CT

rate of the permeability coefficient obtained by X-CT was greater.

3.1.3 Percolation mechanism of recycled permeable bricks based on porous medium percolation theory

According to porous media percolation theory [33–36], a functional relationship is exhibited between the effective porosity and permeability coefficient because as the effective porosity increased, the number and size of pores inside the permeable brick increased, causing the Reynolds number to increase gradually; hence, the laminar flow transformed into a turbulent flow.

Therefore, we propose to divide the percolation channels inside the recycled permeable brick into linear and nonlinear channels. A linear channel refers to a type of percolation channel where the Reynolds number is small and the viscous force of the channel is dominant, thereby presenting a linear laminar flow. A nonlinear channel is a type of percolation channel where the dominance of channel percolation changes from viscous force to inertial force as the Reynolds number increases, thereby presenting a nonlinear laminar flow. The effective porosity increased gradually with the Reynolds number of the channels. When the Reynolds number was less than the critical Reynolds number, the percolation of the linear channel was dominant such that the overall percolation state inside the permeable bricks was reflected as a linear laminar flow; when the Reynolds number exceeded the critical Reynolds number, the nonlinear laminar flow percolation was dominant such that the overall percolation state inside the permeable brick was reflected as a nonlinear laminar flow.

According to the relationship between effective porosity and permeability coefficient, the critical effective porosity of the percolation state inside the recycled permeable brick was 12%. When the effective porosity was less than 12%, the linear channels dominated, and the overall percolation state of the permeable bricks was reflected as a linear laminar flow; when the effective porosity was greater than 12%, the nonlinear channels dominated, and the overall percolation state inside the permeable bricks was reflected as a nonlinear laminar flow.

3.2 Pore structure characteristics of recycled permeable bricks by X-CT

3.2.1 Distribution of pores inside recycled permeable bricks

The 3D image of the recycled permeable bricks obtained by X-CT were sliced horizontally into 200 layers to obtain the pore structure of each layer of the recycled permeable bricks, as shown in Figure 6. The effective porosity of each slice of the recycled permeable bricks can be calculated using Matlab. The distribution of effective porosity with different layers is shown in Figure 7.

Figure 6: Images of different slice layers in group C3

Figure 6 shows that the effective porosity of different layers of Group C3 differed. Figure 7 shows the distribution characteristics of pores with the depth of permeable bricks with different target porosities. The result shows that the effective porosities of the 0–10 and 190–200 layers of the

Figure 7: Effective porosity with different layers of recycled permeable bricks

permeable bricks were relatively large, indicating that the pressure formed caused the porosity of the surface and bottom to increase, and that the effect of the pressing passive surface was greater than that of the pressing active surface. By contrast, the effective porosities of the middle layers were relatively small.

It is clear that the deviation in the effective porosity distribution should be monitored when preparing permeable bricks. If moulding methods such as double-sided or double pressing can be adopted, then the longitudinal distribution of pores in the permeable bricks will be more uniform and the overall permeability will improve.

3.2.2 Linear channels and nonlinear channels of recycled permeable bricks

Based on the relationship between effective porosity and permeability coefficient, the critical effective porosity was approximately 12%. The C4 group was closest to this critical state; therefore, it was regarded as the critical point for the change in the percolation state, where the effective porosity was 12.3%, and the permeability coefficient was 4.3×10^{-2} cm/s. Meanwhile, the kinematic viscosity of water was 1.006×10^{-6} m²/s at 20°C, and $Re = 1$ was defined as the boundary between linear laminar and nonlinear laminar. Therefore, the critical pore diameter (d_{cr}) was 0.233 cm according to Reynolds formula (1). As such, channels with equivalent pore diameters larger than 0.233 cm were considered as nonlinear channels in this study.

To study the distribution of nonlinear and linear channels in recycled permeable bricks and ascertain its relationship with the overall percolation state of permeable bricks, the total area, total number, and average area of the linear

and nonlinear channels of the recycled permeable bricks in 200 layers were calculated in a Matlab program. Their relationships with effective porosity are shown in Figure 8–10.

As shown in Figures 8–10, the total areas of the nonlinear channels are always larger than those of the linear channels, and the total numbers of nonlinear channels are always smaller than that of linear channels. For the nonlinear channels, the total and average areas increased linearly, and the total numbers increased slightly between 13 and 30 with the increase in effective porosity. Meanwhile, the total areas, total numbers, and average areas of the linear channels did not change significantly with the increase in effective porosity. For the linear channels, the total area declined slightly between 0.7 and 1.1 cm^2 , the total numbers

Figure 8: Relationship between total areas of linear and nonlinear channels and effective porosity of recycled permeable bricks

Figure 9: Relationship between total numbers of linear and nonlinear channels and effective porosity of recycled permeable bricks

Figure 10: Relationship between average areas of linear and nonlinear channels and effective porosity of recycled permeable bricks

decreased slightly between 150 and 300, and the average areas remained between 0.003 and 0.005 cm^2 .

Therefore, both linear and nonlinear channels existed inside the permeable bricks regardless of whether the linear percolation stage was linear or nonlinear. In addition, the areas of the linear channels were always smaller than those of the nonlinear channels, and the numbers of linear channels were always greater than those of the nonlinear channels. We believe that the change in the overall percolation state of the permeable bricks was due to the different development laws of the area and the numbers of linear and nonlinear channels. The decisive factor for the overall percolation state of the permeable brick may be the proportion of the area and the number of linear and nonlinear channels, rather than their specific values. Hence, the areas and numbers of nonlinear channels were calculated based on those parameters, and the results are shown in Figure 11.

Figure 11 shows that the proportion of the area and the number of nonlinear channels of the permeable bricks increased linearly with the effective porosity. In addition, the threshold of the percolation state requires the proportion of area of the nonlinear channel to be approximately 80% and the proportion of number of nonlinear channels to be approximately 10%. When the two proportions reached the threshold, the percolation state of the permeable bricks changed from linear to nonlinear percolation with a network-like nonlinear laminar flow system forming inside the permeable brick.

Figure 11: Proportion of areas and numbers of nonlinear channels in recycled permeable bricks

4 Conclusion

In this study, pore structure characteristics including pore size, number, and distribution inside a permeable brick was investigated through X-CT and a Matlab program, and the relationship between percolation mechanism and pore characteristics of recycled permeable bricks was ascertained. The main conclusions are as follows:

1. With the increase in the effective porosity obtained by Archimedes and X-CT, the permeability coefficients of recycled permeable bricks increased linearly first and then increased in a quadratic function. In the linear stage, the fitting slopes of the graphics obtained by X-CT and Archimedes were similar, *i.e.* approximately 0.4. In the quadratic stage, the increase rate of the permeability coefficient obtained by X-CT was greater with the increase in the effective porosity.
2. The critical effective porosity of the percolation state inside the recycled permeable bricks was 12%. When the effective porosity was less than 12%, the linear channels dominated the percolation flow, and the overall percolation state of the permeable brick presented a linear laminar flow; when the effective porosity was greater than 12%, the nonlinear channels dominated the percolation flow, and the overall percolation state of the permeable brick presented a nonlinear laminar flow.
3. Regardless of whether the percolation stage was linear or nonlinear, the total areas of the nonlinear channels were always larger than those of the linear channels, and the total numbers of nonlinear channels were always smaller than those of the linear channels. With the increase in the effective porosity,

the total and average areas of the nonlinear channels increased linearly and the number of nonlinear channels increased slightly; however, the total area, number, and average area of the linear channels did not change significantly. Additionally, when the area and number of nonlinear channels reached approximately 80% and 10%, respectively, the overall percolation state of the permeable bricks changed from a linear percolation flow to a nonlinear percolation flow.

This research is helpful to improve the mechanical and percolation properties of recycled concrete bricks and promote the application of porous permeable material.

Funding information: This work was supported by the Bilateral Zhejiang-West Flanders Industrial R&D Project of Zhejiang Key Research & Development Program (2020C04013).

Author contributions: *Songsong Lian:* Methodology, Formal analysis, Writing – Original Draft. *Tao Meng:* Conceptualization, Writing – Review & Editing, Supervision, Project administration, Funding acquisition. *Hongqi Song:* Validation. *Zhongjia Wang:* Investigation. *Jiabin Li:* Validation.

Conflict of interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement: The data that support the findings of this study are available on request from the corresponding author.

References

- [1] Yang, J., and G. Jiang. Experimental study on properties of pervious concrete pavement materials. *Cement and Concrete Research*, Vol. 33, No. 3, 2003, pp. 381–386.
- [2] Nguyen, D. H., N. Sebaibi, M. Boutouil, L. Leleyter, and F. Baraud. A modified method for the design of pervious concrete mix. *Construction & Building Materials*, Vol. 73, No. 73, 2014, pp. 271–282.
- [3] Meng, T., J. L. Zhang, H. D. Wei, and J. Shen. Effect of nano-strengthening on the properties and microstructure of recycled concrete. *Nanotechnology Reviews*, Vol. 9, No. 1, 2020, pp. 79–92.
- [4] Yahia, A. and K. D. Kabagire. New approach to proportion pervious concrete. *Construction and Building Materials*, Vol. 62, 2014, pp. 38–46.
- [5] Park, S. B., D. S. Seo, and J. Lee. Studies on the sound absorption characteristics of porous concrete based on the content of

- recycled aggregate and target void ratio. *Cement and Concrete Research*, Vol. 35, No. 9, 2005, pp. 1846–1854.
- [6] Wang, H., A. Zhang, F. Shi, J. Liu, P. Cao, T. Du, et al. Development of relationships between permeability coefficient and electrical and thermal conductivity of recycled aggregates permeable cement concrete. *Construction & Building Materials*, Vol. 254, 2020, p. 119247.
- [7] Aliabdo, A. A., A. E. M. Abd Elmoaty, and A. M. Fawzy. Experimental investigation on permeability indices and strength of modified pervious concrete with recycled concrete aggregate. *Construction & Building Materials*, Vol. 193, 2018, pp. 105–127.
- [8] Liu, T., Z. Wang, D. Zou, A. Zhou, and J. Du. Strength enhancement of recycled aggregate pervious concrete using a cement paste redistribution method. *Cement and Concrete Research*, Vol. 122, 2019, pp. 72–82.
- [9] Kuang, X., J. Sansalone, G. Ying, and V. Ranieri. Pore-structure models of hydraulic conductivity for permeable pavement. *Journal of Hydrology*, Vol. 399, No. 3–4, 2011, pp. 148–157.
- [10] Sumanasooriya, M. S., D. P. Bentz, and N. Neithalath. Planar image-based reconstruction of pervious concrete pore structure and permeability prediction. *ACI Materials Journal*, Vol. 107, No. 4, 2010, pp. 413–421.
- [11] Sumanasooriya, M. S., and N. Neithalath. Stereology-and morphology-based pore structure descriptors of enhanced porosity (pervious) concretes. *ACI Materials Journal*, Vol. 106, No. 5, 2009, pp. 429–438.
- [12] Neithalath, N., M. S. Sumanasooriya, and O. Deo. Characterizing pore volume, sizes, and connectivity in pervious concretes for permeability prediction. *Materials Characterization*, Vol. 61, No. 8, 2010, pp. 802–813.
- [13] Rui, Z. and W. Kay. Linking pore system characteristics to the compressive behavior of pervious concrete. *Cement and Concrete Composites*, Vol. 70, 2016, pp. 130–138.
- [14] Lu, B., and S. Torquato. Lineal-path function for random heterogeneous materials. *Physical Review A*, Vol. 45, No. 2, 1992, pp. 922–929.
- [15] Bachmat, Y. On the similitude of dispersion phenomena in homogeneous and isotropic porous mediums. *Water Resources Research*, Vol. 3, No. 4, 1967, pp. 1079–1083.
- [16] King Hubbert, M. Darcy's law and the field equations of the flow of underground fluids. *International Association of Scientific Hydrology. Bulletin*, Vol. 2, No. 1, 1957, pp. 23–59.
- [17] Scheidegger, A. E. *The Physics of Flow Through Porous Media*. New York: Macmillan, 1957, pp. 236.
- [18] Yu, W. M., and H. M. Tang. Experimental study on the existence of nano-scale pores and the evolution of organic matter in organic-rich shale. *Nanotechnology Reviews*, Vol. 8, No. 1, 2019, pp. 156–167.
- [19] Lapcik, L., M. Vasina, B. Lapcikova, D. Hui, E. Otyepková, R. W. Greenwood, et al. Materials characterization of advanced fillers for composites engineering applications. *Nanotechnology Reviews*, Vol. 8, No. 1, 2019, pp. 503–512.
- [20] Zhang, J., G. Ma, R. Ming, X. Cui, L. Li, and H. Xu. Numerical study on seepage flow in pervious concrete based on 3D CT imaging. *Construction & Building Materials*, Vol. 161, 2018, pp. 468–478.
- [21] Ren, W., Z. Yang, R. Sharma, C. Zhang, and P. J. Withers. Two-dimensional X-ray CT image based meso-scale fracture modelling of concrete. *Engineering Fracture Mechanics*, Vol. 133, 2014, pp. 24–39.
- [22] Huang, Y., Z. Yang, W. Ren, G. Liu, and C. Zhang. 3D meso-scale fracture modelling and validation of concrete based on in-situ X-ray Computed Tomography images using damage plasticity model. *International Journal of Solids and Structures*, Vol. 67–68, 2015, pp. 340–352.
- [23] Nguyen, T. T., H. H. Bui, T. D. Ngo, and G. D. Nguyen. Experimental and numerical investigation of influence of air-voids on the compressive behaviour of foamed concrete. *Materials & Design*, Vol. 130, 2017, pp. 103–119.
- [24] Yu, F., D. Sun, M. Hu, and J. Wang. Study on the pores characteristics and permeability simulation of pervious concrete based on 2D/3D CT images. *Construction & Building Materials*, Vol. 200, 2019, pp. 687–702.
- [25] Tekin, I., R. Birgul, I. Ozgur Yaman, O. Gencel, and H. Yilmaz Aruntas. Monitoring macro voids in mortars by computerized tomography method. *Measurement*, Vol. 63, 2015, pp. 299–308.
- [26] Mao, L. T., Z. X. Yuan, M. Yang, H. Liu, and F. Chiang. 3D strain evolution in concrete using in situ X-ray computed tomography testing and digital volumetric speckle photography. *Measurement*, Vol. 133, 2018, pp. 456–467.
- [27] Tian, W., and N. Han. Analysis on meso-damage processes in concrete by X-ray computed tomographic scanning techniques based on divisional zones. *Measurement*, Vol. 140, 2019, pp. 382–387.
- [28] Zhang, L., F. N. Dang, W. H. Ding, and L. Zhu. Quantitative study of meso-damage process on concrete by CT technology and improved differential box counting method. *Measurement*, Vol. 160, 2020, id. 107832.
- [29] China National Standards. Common portland cement, 2007, GB175 (in Chinese).
- [30] China National Standards. Fly ash used for cement and concrete, 2017, GB/T 1596 (in Chinese).
- [31] China National Standards. Permeable paving bricks & permeable paving flags, 2010, GB / T 25993 (in Chinese).
- [32] China National Standards. Technical specification for pervious concrete pavement. 2010, DB11/T775 (in Chinese).
- [33] Blick, E. F. Capillary-orifice model for high-speed flow through porous media. *Industrial & Engineering Chemistry Process Design and Development*, Vol. 5, No. 1, 1966, pp. 90–94.
- [34] Richards, L. A. Capillary conduction of liquids through porous mediums. *Physics*, Vol. 1, No. 5, 1931, pp. 318–333.
- [35] Rumer, R. R., Jr., and P. A. Drinker. Resistance to laminar flow through porous media. *Journal of the Hydraulics Division*, Vol. 92, No. 5, 1966, pp. 155–163.
- [36] Dudgeon, C. R. An experimental study of the flow of water through coarse granular media. *Houille Blanche*, Vol. 21, No. 7, 1966, pp. 785–801.