



**HAL**  
open science

## Optimization of anti-clogging pervious pavement structure based on numerical evaluation

J. Zhang, S. Xia, N. Hu, W. Hao, R. Han, B. Meng, Z. Zhang

### ► To cite this version:

J. Zhang, S. Xia, N. Hu, W. Hao, R. Han, et al.. Optimization of anti-clogging pervious pavement structure based on numerical evaluation. *Construction and Building Materials*, 2021, 275, pp.122186. 10.1016/j.conbuildmat.2020.122186 . hal-03130519

**HAL Id: hal-03130519**

**<https://hal.science/hal-03130519v1>**

Submitted on 3 Feb 2023

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

1 **Amount of words: 7596**

2 **Optimization of anti-clogging pervious pavement structure**  
3 **based on numerical evaluation**

4 Jiong Zhang<sup>a, b, \*</sup>, Shuang Xia<sup>a</sup>, Nian Hu<sup>a</sup>, Wengang Hao<sup>c, \*</sup>, Ruonan  
5 Han<sup>a</sup>, Bowen Meng<sup>a</sup>, Zhongze Zhang<sup>a</sup>

6 <sup>a</sup>School of Civil Engineering, Shandong University, Jingshi Road, Jinan 250061, China

7 <sup>b</sup>Laboratoire LGCGM, INSA de Rennes, Université Européenne de Bretagne, France

8 <sup>c</sup>School of Energy and Power Engineering, Shandong University, Jingshi Road, Jinan 250061, China

9 **ABSTRACT:**

10 Based on numerical simulation methods, the anti-clogging performance of various pervious  
11 pavement structures were investigated. Different pavement structure models were built to analyze  
12 the effects of different pervious structures, top layer thicknesses and top aggregate gradations on  
13 the anti-clogging performance. The results shown that compared with single-layer structure, the  
14 double-layer pervious structure has better anti-clogging performance and maintenance efficiency.  
15 The most serious clogging of double-layer pervious structure can be hold within 3 mm of the  
16 superficial layer where the clogging particles can more easily be cleaned out. Smaller top layer  
17 thickness lead to a better anti-clogging performance and maintenance efficiency. And the top layer  
18 aggregate size should be selected only considering particle transport or shielding effect, based on  
19 the gradation of local clogging particles. In addition, based on the above findings, a new  
20 double-layer pervious structure with excellent anti-clogging performance has been developed,  
21 including a number of parallel vertical variable diameter tubular channels, the diameter of the  
22 upper layer is smaller than that of the lower layer.

23 **Keywords:** Pervious pavement; CFD-DEM simulation; Anti-clogging structure; Clogging depth;  
24 Clogging particles size distribution

25 **1. Introduction**

26 With the urbanization, impervious surfaces such as highways, streets and pavement have  
27 increased considerably, which increases the surface runoff and the risk of urban floods [1]. In  
28 order to adapt to the rapid development of urbanization, the concept of pervious pavement is  
29 proposed. It has a many number of connected pores within the aggregate skeleton. Generally, the  
30 pervious concrete is an environment friendly material with high porosity between 15% and 35%,  
31 and the initial permeability is typically about 2 - 6 mm/s even up to 10 mm/s [2, 3]. High  
32 permeable capacity guarantees good drainage capacity. Therefore, pervious pavement can  
33 effectively alleviate various problems existing in the city, such as ensure driving safety [4, 5], and  
34 reduce the concentration of pollutants in runoff [6], and alleviate the current situation of  
35 groundwater shortage [7, 8]. The maximum downward seepage velocity of pervious pavement  
36 structure was less than 1% of the average runoff velocity, so the flow was considered to be  
37 uniform [9].

38 The effective service life of pervious pavement is directly related to its permeability, and the

39 clogging of pores has a serious adverse effect on the permeability of pavement [10]. Porous  
40 pervious pavement can not only reduce the road surface runoff, but also allow the runoff to carry  
41 sediments into the connected pores of pavement structure, which greatly reduces its permeability  
42 until it becomes an impermeable pavement. Through previous research, it was found that the  
43 decrease of permeability of pervious concrete caused by initial sediments could reach 50% after 2  
44 or 3 year [11]. Kayhanian et al. [8] CT (Computed Tomography) scanned cores of pervious  
45 concrete pavements and measured the permeability to assess clogging. Walsh et al. [12] measured  
46 the effect of sediment accumulation on the hydraulic conductivity of pervious concrete in  
47 laboratory scale. Kandra et al. [13] focused on the effect of physical characteristics of filter media  
48 and flow-through rates on the clogging of stormwater filters. The clogging depth was usually  
49 concentrated in the upper layer of pervious pavement [14-16]. Other studies have observed that the  
50 clogging regions gradually occur and become stable, only the smallest clogging particles would  
51 continually transport into other places [17]. It was also found that for larger ratios, a single particle  
52 is generally not be stopped and clogging due to the arches formed when several grains attempt to  
53 go through smaller pores [17, 18]. Razzaghmanesh and Borst [19] investigated clogging dynamic  
54 of pervious pavement systems using embedded sensors and concluded that for every 6 mm of rain,  
55 clogging advanced 1 mm across the surface. The spalling of aggregate particles in porous  
56 pavement will also lead to pore clogging. Research shows that binder content and degree of  
57 compaction are the critical factors affect the raveling resistance of porous pavement structure [20].

58 Many numerical simulation methods were also developed to explore the hydraulic behavior and  
59 water quality performance of pervious pavement [21]. Pieralisi et al. [22] developed and validated  
60 an advanced computational fluid dynamics coupled with discrete element method (CFD-DEM)  
61 model to assess the permeability of pervious concrete. Ma et al. [23] based on virtual fatigue test,  
62 the influences by content, distribution, size and orientation of air voids on the fatigue life of  
63 asphalt mixture were evaluated by discrete element method. It was found that, higher air void  
64 content leads to lower fatigue life of asphalt mixture. Zhang et al. [24, 25] found that full-graded  
65 sands can percolate into depth of 30 mm in pervious pavement. Coarse sands can percolate in  
66 depth within 20 mm. Fine sands can percolate into the depth of 60 mm even 100 mm. Zhang et al.  
67 [25] studied the effect of the ration of the equivalent diameter of aggregate to the equivalent  
68 diameter of clogging particles on the pore clogging of pervious pavement, and found that when the  
69 ration was lower than 6.46, the clogging particles could be trapped inside the pores because they  
70 are too large to go through the smaller pores.

71 When the pervious pavement was clogged, the permeability can be restored to a certain extent  
72 by taking appropriate maintenance measures. Vantura et al. [26] studied the restoration of  
73 permeability of pervious pavement by vacuum hose, vacuum sweeper and regenerative air  
74 sweeper respectively. It shows that all these methods can clean clogging material in the void  
75 within the range of 3.18 mm on the surface of pervious concrete and the permeability of the  
76 pervious concrete was restored. Henderson and Tighe [27] found that in the common  
77 maintenance and cleaning measures, power spray cleaning can decrease permeability. It was also  
78 found that the combination of pressure wash and vacuum suction has the best maintenance effect,  
79 and periodic maintenance can extend the service life of pervious pavement [28].

80 In order to avoid the above problems, HEIJMANS road construction company in the  
81 Netherlands improves the pavement performance by using a two-layer pervious asphalt pavement  
82 consisting of fine-grained top layer and coarse-grained bottom layer [29]. The two-layer porous

83 asphalt concrete construction has a top layer grading 4-8 mm and bottom layer grading 11-16 mm.  
 84 The top layer is similar to a sieve and acts as a filter to prevent large-size clogging particles from  
 85 entering the bottom layer. At the same time, the pore diameter of the bottom layer is larger than  
 86 that of the top layer, which can make the incoming fine particles discharge smoothly. Therefore,  
 87 this pavement structure can maintain permeability for a longer time. In addition, the bottom  
 88 structure of macropores can also avoid the decrease of permeability caused by power spray  
 89 cleaning. The function of double-layer pervious structure is to improve the effectiveness and  
 90 durability and reduce the clogging problem [4, 30]. The selection of the aggregate size grading of  
 91 the top layer and bottom layer, especially the top layer, will directly affect the permeability of the  
 92 double-layer pervious pavement. Other studies have found that the thinner the top layer, the better  
 93 the cleaning effect [30]. Some studies show that the noise reduction performance of double porous  
 94 asphalt pavement was improved with the decrease of aggregate size distribution of the top layer  
 95 [31]. The double layer porous asphalt has a good hydrological performance, and it was able to  
 96 reduce the surface runoff from a precipitation of 100 mm/h, and the sand and soil used did not  
 97 significantly affect its infiltration capacity [32].

98 The anti-clogging effect of the double-layer pervious pavement structure has been proved by  
 99 many studies. However, there is no detailed research information on the anti-clogging mechanism  
 100 of the double-layer pavement, as well as the influence of specific aggregate size grading, layer  
 101 thickness and other parameters. In this study, CFD-DEM coupling numerical simulation method is  
 102 used to study the anti-clogging mechanism in rainfall environment. And a new tubular  
 103 double-layer pervious structure is also proposed based on the simulation results. The conclusions  
 104 derived from this study can contribute to the future research on construction of pervious pavement.

## 105 2. Mathematical modeling

106 In the CFD-DEM model, the flow in the whole flow region is calculated based on the continuity  
 107 and the Navier-Stokes equations, with a porosity term and an additional body force term used to  
 108 explain the presence of particles in the fluid. The formula is as follows:

$$109 \quad \frac{\partial \Phi}{\partial t} + \nabla \cdot (\Phi \vec{u}) = 0 \quad (1)$$

$$110 \quad \frac{\partial(\rho\Phi\vec{u})}{\partial t} + (\nabla \cdot \vec{u})(\rho\Phi\vec{u}) = -\nabla p + \mu\nabla^2(\Phi\vec{u}) - \sum_{i=1}^{n_p} \vec{f}_{fluid,i} + \rho\Phi\vec{g} \quad (2)$$

111 where  $\rho$  is the density of the fluid,  $\Phi$  is the porosity,  $\vec{u}$  is the fluid velocity,  $p$  is the fluid  
 112 pressure,  $\mu$  is the dynamic viscosity of the fluid,  $\vec{g}$  is the gravitational acceleration,  $\vec{f}_{fluid,i}$  is the  
 113 total force applied by the fluid on particle  $i$ ,  $n_p$  is the number of particles per unit volume.

114 The porosity and body force of the fluid mesh elements are determined through DEM. The  
 115 equations of motion for the particles have an additional force term to account for interaction with  
 116 the fluid. The equations are given as follow:

$$117 \quad m \frac{\partial \vec{u}_p}{\partial t} = \vec{f}_{mech,i} + \vec{f}_{fluid,i} + m\vec{g} \quad (3)$$

$$118 \quad \frac{\partial \vec{\omega}}{\partial t} = \frac{\vec{M}}{I} \quad (4)$$

119 where  $\vec{u}_p$  is the particle velocity,  $m$  is the particle mass,  $\vec{f}_{mech,i}$  is the sum of additional forces

120 acting on the particle,  $\vec{\omega}$  is the particle angular velocity,  $I$  is the moment of inertia,  $\vec{M}$  is the  
 121 torque acting on the particle.

122 The total force applied by the fluid on particle  $I$ ,  $\vec{f}_{fluid,i}$  consists of two parts: drag force and a  
 123 force resulting from the fluid pressure gradient. Other particle-fluid forces, such as the lift force is  
 124 ignored in this study. The resulting relationship could be expressed as:

$$125 \quad \vec{f}_{fluid,i} = \vec{f}_{drag,i} + \frac{4}{3}\pi r^3 \nabla p \quad (5)$$

$$126 \quad \vec{f}_{drag,i} = \left(0.63 + \frac{4.8}{\sqrt{Re_{p,i}}}\right)^2 \left(\frac{1}{2}\rho\pi r_i^2 |\vec{u} - \vec{u}_{p,i}| (\vec{u} - \vec{u}_{p,i})\right) \Phi^{-\chi} \quad (6)$$

127 where the  $\Phi^{-\chi}$  term is an empirical factor accounts for the local porosity,  $Re_p$  is the particle  
 128 Reynolds number.

129 DEM and CFD two-way coupling is numerically achieved as follows: Eqs. (1) – (2) are solved  
 130 with the CFD code, while Eqs. (3) – (6) are solved with DEM code. Porosity and body force are  
 131 determined by DEM and divided by the volume from CFD. The fluid velocity and fluid pressure  
 132 for every element are determined by the CFD and then sent to the DEM in each coupling data  
 133 exchange. The coupling of CFD with DEM is realized with commercial software of Fluent and  
 134 EDEM(the software for bulk material simulation) [25] in this study.

### 135 3. The setup of simulation study

#### 136 3.1 The setup of DEM simulation

137 Both clogging particles and aggregates are generated in EDEM. During the simulation process,  
 138 the fully graded clogging material designed artificially is used. The clogging particle size  
 139 distribution is shown in Table 1. Fine particles account for a large proportion in the composition of  
 140 the material. The clogging material can make the pervious structure completely and quickly  
 141 clogged by experiment verification [28].

142 **Table 1**  
 143 Grading distribution of clogging particles.

Particle size (mm)	1.18-2.36	0.6-1.18	0.3-0.6	0.15-0.3	0.1
Particle proportion (%)	15%	20%	20%	20%	25%
Color	Pink	Blue	Green	Red	Yellow

##### 144 3.1.1 Selection of aggregate size

145 In the double-layer pervious pavement structure, the choice of aggregate gradation has a great  
 146 influence on the anti-clogging performance. There are two possibilities for the selection of  
 147 aggregate size. One of which is based on the theory of Terzaghi filter layer, which needs sufficient  
 148 permeability and can reduce the possibility of arching. When fine particles enter the structure, and  
 149 they will drain away from the previous pavement, so they will not cause clogging. Another  
 150 possibility is that the aggregate particles in the top layer can act as a shield against the clogging  
 151 particles, that enhance the trapping effect of the top layer to prevent entering of clogging particles  
 152 to the maximum extent. Both of considerations can minimize the occurrence of pore clogging.

153 In order to ensure sufficient particle transport ability, equation (7) is used to calculate the range  
 154 of aggregate particle size proposed by Terzaghi.  $D_{15}$  is the particle size with cumulative

155 distribution of 15% in aggregate particles, and  $d_{15}$  is the particle size with cumulative distribution  
 156 of 15% in clogging particles.

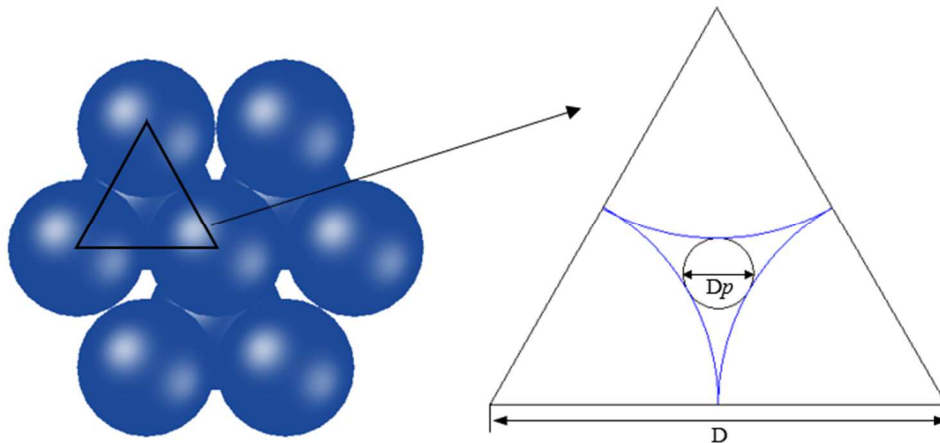
$$157 \quad \frac{D_{15}}{d_{15}} \geq 4 \quad (7)$$

158 In order to maximize the shielding effect of the top layer, that most of the clogging particles can  
 159 be trapped on the surface of the pavement. The pore formed by the aggregate particles is shown in  
 160 Fig. 1, and the pore diameter can be calculated as follows:

$$161 \quad D_p \approx \left(\frac{2\sqrt{3}}{3} - 1\right)D \quad (8)$$

162 where  $D$  is the aggregate diameter,  $D_p$  is the pore diameter. If  $D_p$  is smaller than the moving  
 163 particles, then all the particles can be trapped on the surface. As the aggregate particles are  
 164 irregular in arrangement, the calculated result is a rough estimate.

165 Therefore, the design size of aggregate particles can be determined by the size of clogging  
 166 particles, different clogging particle gradations will induce different aggregate gradations. For  
 167 example, in this study, as Table 1 shows  $d_{15}=0.1$  mm, the calculated  $D_{15}\geq 0.4$  mm by equation (7).  
 168 So, in order to ensure sufficient particle transport ability, the range of top aggregate particle size is  
 169  $D\geq 0.4$  mm. While in order to keep all the clogging particles can be trapped on the surface,  $D_p$   
 170 should be smaller than 0.1 mm, then the range of top aggregate particle size should be  $D < 0.65$   
 171 mm, if the aggregate is composed by single size particles.



172  
 173 **Fig.1 Pores between aggregates**

174 Based on the above calculation, if the clogging particles is allowed to be discharged from the  
 175 bottom of the pervious layer, the range of the top aggregate particle size should be  $D\geq 0.4$  mm.  
 176 Thus, 1 mm and 0.6 mm were taken as the top aggregate particles to meet this requirement. If all  
 177 the clogging particles can be trapped by the top layer, the range of the top aggregate should be  $D <$   
 178 0.65 mm. Therefore, 0.6 mm and 0.3 mm were chosen as the top aggregate particles to meet this  
 179 requirement. The size of the bottom aggregate particles is 3 mm for all cases, which can ensure  
 180 that the bottom pore is large enough and the clogging particles entering the bottom can be  
 181 discharged smoothly.

### 182 **3.1.2 Selection of layer thickness**

183 It is found that the top 0-10 mm of the pavement is the most serious clogged region by  
 184 experimental and numerical simulation [24, 25]. Therefore, the thickness of top layer is chosen as  
 185 10 mm, 8 mm and 5 mm for comparison and analysis. The total thickness of the pervious

186 pavement structure is 55 mm.

### 187 3.1.3 Model design

188 In order to reduce the time and costs required in the numerical simulation, the volume of  
 189 pervious pavement model is fixed and its length, width, and thickness is  $20 \times 20 \times 55$  mm. Particle  
 190 accumulation theory indicates that when a single particle size is randomly filled, the average  
 191 porosity is 0.359-0.375. Due to the influence of wall effect, the porosity is uniformly 0.39 in this  
 192 study. Total volume of aggregates and cement paste used in pervious pavement model is calculated  
 193 by the equation  $V_{ac} = V \times (1 - P)$ , where  $V_{ac}$  is the total volume of aggregates and cement paste,  $V$   
 194 is the volume of pervious pavement,  $P$  is the porosity of pervious pavement. In order to simplify  
 195 this model, the cement paste volume is directly incorporated into the aggregate volume, using only  
 196 single-phase aggregate particles in pervious pavement model.

197 According to the above discussion of aggregate size and top layer thickness, 6 models were  
 198 established according to the structure type, top layer thickness and aggregate gradation (Table 2).  
 199 The control group was single-layer structure and the other five models were double-layer  
 200 structure.

201 **Table 2**  
 202 Pervious pavement structure model

Model		Control group	U1-10	U1-8	U1-5	U0.6-5	U0.3-5
Aggregate size (mm)	Top layer	3	1	1	1	0.6	0.3
	Bottom layer		3	3	3	3	3
Thickness (mm)	Top layer	55	10	8	5	5	5
	Bottom layer		45	47	50	50	50

203 As shown in Table 3, the basic parameter settings of each type of particle. The Poisson's ratio of  
 204 aggregate particles is 0.3, the shear modulus is  $1.85e + 06$  Pa, and the density is  $2450 \text{ kg/m}^3$ ; the  
 205 Poisson's ratio of clogging particles is 0.3, the shear modulus is  $1.85e + 06$  Pa, and the density is  
 206  $2650 \text{ kg/m}^3$ . The restitution coefficient between particles is 0.001, the static friction coefficient is  
 207 0.5, and the rolling friction coefficient is 0.2. In particular, the shear modulus of the simulated  
 208 material is usually much smaller than the actual value to increase the time step used for  
 209 simulations. This leads to larger overlaps between particles but does not change the overall  
 210 behavior of clogging in pervious pavement model.

211 **Table 3**  
 212 Basic parameter setting of particles

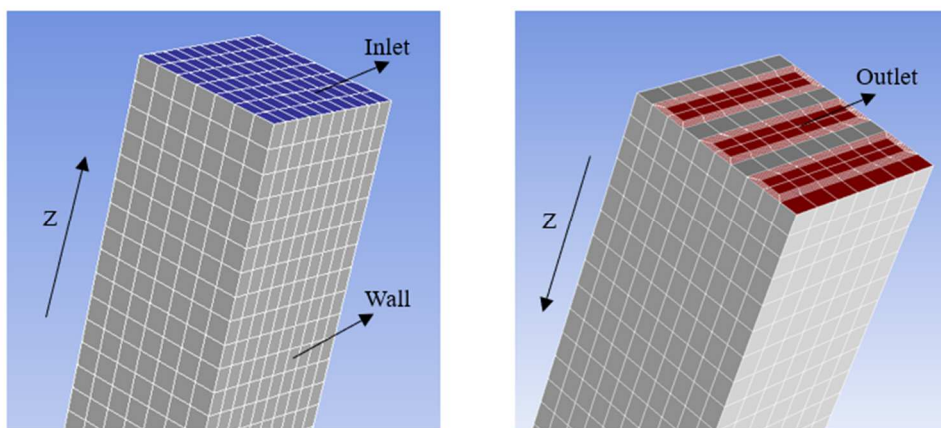
Particles	Poisson's ratio	Shear modulus	Density
Aggregate particles	0.3	$1.85E+06$ Pa	$2450 \text{ kg/m}^3$
Clogging particles	0.3	$1.85E+06$ Pa	$2650 \text{ kg/m}^3$
Contact parameters	Coefficient of restitution	Coefficient of static friction	Coefficient of rolling friction

Particle-Particle	0.001	0.5	0.2
-------------------	-------	-----	-----

213 When establishing the model in EDEM software, aggregate particles are randomly generated by  
 214 the Particle-factory and compacted with plates to closely fill them to achieve the required porosity.  
 215 The BPM (bonded particle model) model is applied to remedy the drawback that lacks cement  
 216 paste. It is added to aggregate particles to bond them as a whole pervious pavement model under  
 217 the cohesive force. When bonding particles with BPM model, the normal stress and shear stress  
 218 are set at  $2e+07$  N/m, and the critical normal stress and the critical shear stress are set at  $5e+30$  Pa.  
 219 Both the critical normal stress and the critical shear stress are much larger than the actual critical  
 220 value in order to prevent the structure from being destroyed, as the clogging behavior is the  
 221 primary goal of this study rather than the mechanical behavior. When bonding aggregate particles,  
 222 the time step should be about 10% of Rayleigh time step.

### 223 3.2 The setup of CFD-DEM coupling model

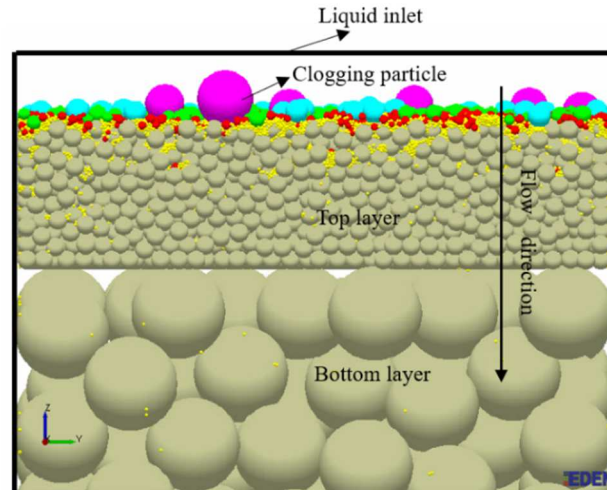
224 After the DEM model is established, the coupling setup with CFD is performed. During the  
 225 coupling process, the grid size in Fluent should be greater than or equal to the largest particle size  
 226 in EDEM. It has been pointed out that when the size of the mesh is slightly smaller than the fixed  
 227 particle size and larger than the movable particle size, it has little influence on the analysis of the  
 228 movement and position of the clogging particles [33]. Therefore, the mesh size used in this  
 229 simulation is 3 mm, and the outlet position has been encrypted to some extent. This meets the size  
 230 requirements of the CFD-DEM coupling to the grid. Fig.2 shows the grid used in the coupling  
 231 process, gray represents the wall, blue represents the inlet, and red represents the outlet.



232  
 233 **Fig.2** CFD grid model

234 As shown in Fig.3, the CFD-DEM coupling model simulates the rapid clogging process of  
 235 pervious pavement under rainfall conditions. The standard  $k-\varepsilon$  turbulence model and PISO  
 236 (Pressure Implicit with Splitting of Operator) method are used to simulate rainfall in Fluent. In the  
 237 setting of boundary conditions, the inlet is set as the velocity inlet, the flow rate is set as 0.03 m/s  
 238 and the outlet is set as the pressure outlet. Water flows from the inlet to the outlet in the -Z  
 239 direction.





240  
241 **Fig.3** CFD-DEM coupling model

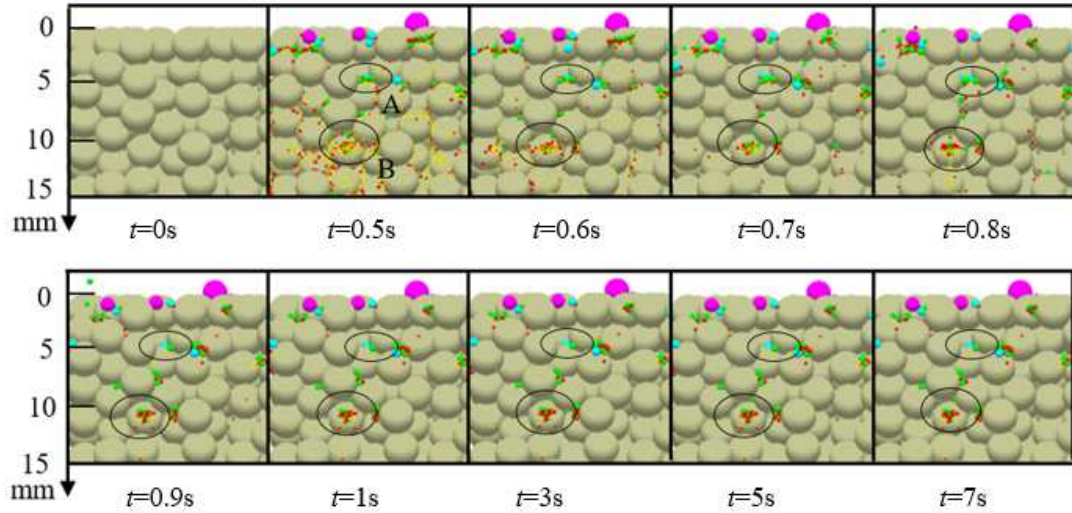
242 During the coupling calculation, the whole process is carried out for 7s. 0-0.5s is the process of  
243 adding clogging particles. Some fine-sized clogging particles directly enter the pore structure  
244 under the action of gravity. After 0.5s, rapid clogged under the condition of rainfall begins. The  
245 calculation time step of CFD is  $5 \times 10^{-4}$ s and that of DEM is  $2 \times 10^{-6}$ s (31% Rayleigh time step).  
246 During the coupling process, the structure of the pervious pavement remains stationary, and the  
247 clogging particles move under the action of gravity and water flow. Some of the clogging particles  
248 are trapped on the surface of the structure. Some of the clogging particles eventually pass through  
249 the structure model of the pervious pavement and are carried away by water flow. Otherwise,  
250 some of the clogging particles are trapped in the pores, which reduces the permeability of the  
251 pervious pavement.

252 **4. Results and discussion**

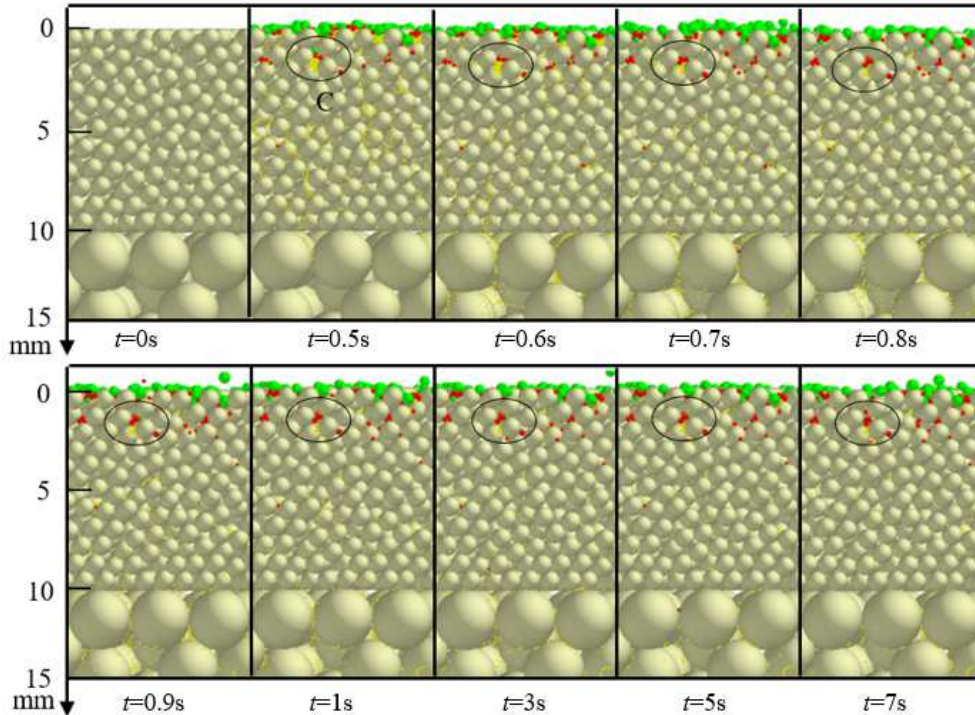
253 Surface sediments can be easily cleaned up when conducting pervious structure clogging  
254 experiments indoors. However, it is difficult to achieve the clearing operation in the process of  
255 EDEM simulation. Therefore, in the process of analyzing the clogging particle volume data, the  
256 clogging particle volume remaining in the depth of structure surface (the depth of half aggregate  
257 particle size) is not considered, and the clogging particle in this thickness can be easily removed.  
258 Thus, the volume of clogging particles in the effective thickness of each model (total thickness  
259 minus half aggregate particle size at the top of the model) is selected for analysis.

260 **4.1 Development of clogging in pervious structure**

261 Fig. 4 shows the movement of clogging particles of different particle sizes over time within the  
262 depth of 0-15 mm on the pervious structure surface. Fig. 4 (a) represents a single-layer pervious  
263 structure, and Fig. 4 (b) represents a double-layered pervious structure.



(a) Single-layer structure: control group



(b) Double-layer structure: U1-10

**Fig. 4** Movement of clogging particles in pervious structure

Fig. 4 (a), shows that in addition to the largest particle (i.e. pink,  $d_s=1.18-2.36$  mm), the rest particles enter into the structure. In region A (the depth of 5 mm in pervious pavement), the blue clogging particles ( $d_s=0.6-1.18$  mm) are involved. They are mainly settled on shallow surface within depth of 5 mm, and a few blue particles could percolate down to the depth of 10 mm. This blue particles deposit into the pores and becomes new skeleton particles. This causes some pore channels of pervious pavement suddenly get narrow. Over time, it is easy to accumulate other small size of clogging particles around it and clog the pore.

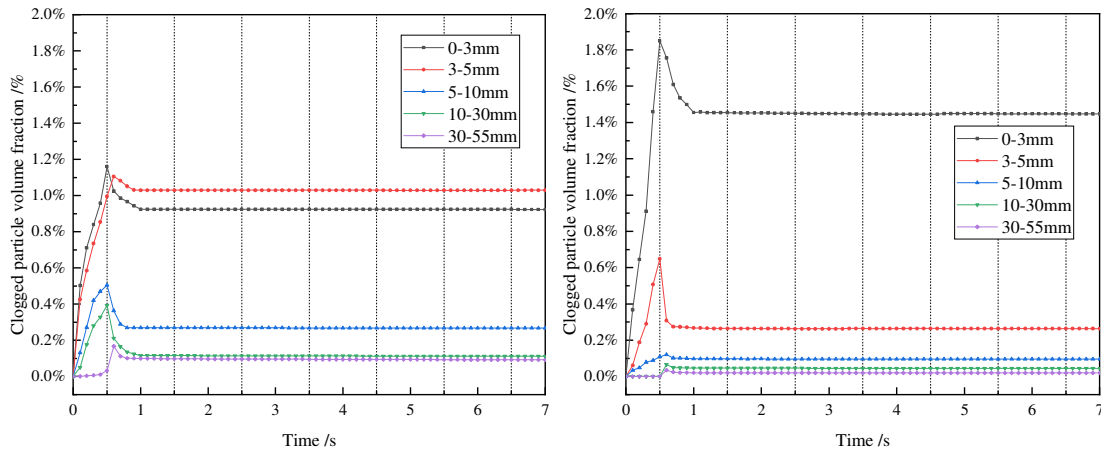
There is no large diameter clogging particles in region B (the depth of 10 mm in pervious pavement). Green ( $d_s=0.3-0.6$  mm), red ( $d_s=0.15-0.3$  mm) and yellow ( $d_s=0.1$  mm) clogging particles transport deeply under the effect of seepage flow. Yellow particles basically do not

279 deposit in the pore, some red and green particles can gather to clog the pore.

280 In Fig. 4 (b), as shown in regional C (the depth of 2 mm in pervious pavement). It can be found  
281 that only red and yellow two small sizes of sediments can enter the pores in the top layer of the  
282 double-layer pervious structure, while the others are left outside the structure. The red particles are  
283 mainly settle on shallow surface of 3 mm depth. This red particles remaining in the pore become  
284 new skeleton particles. Over time, the small yellow particles will gather around and slowly block  
285 the pore.

286 Thus, in the single-layer pervious structure, it is found that there are many kinds of clogging  
287 particles which can enter the pore, and the percolate depth is deeper. In the double-layer pervious  
288 structure, due to the shielding effect of the top structure, the types of clogging particles that can  
289 enter the pore and the depth of entry are reduced, and the possibility of forming complex particle  
290 groups between clogging particles is greatly reduced.

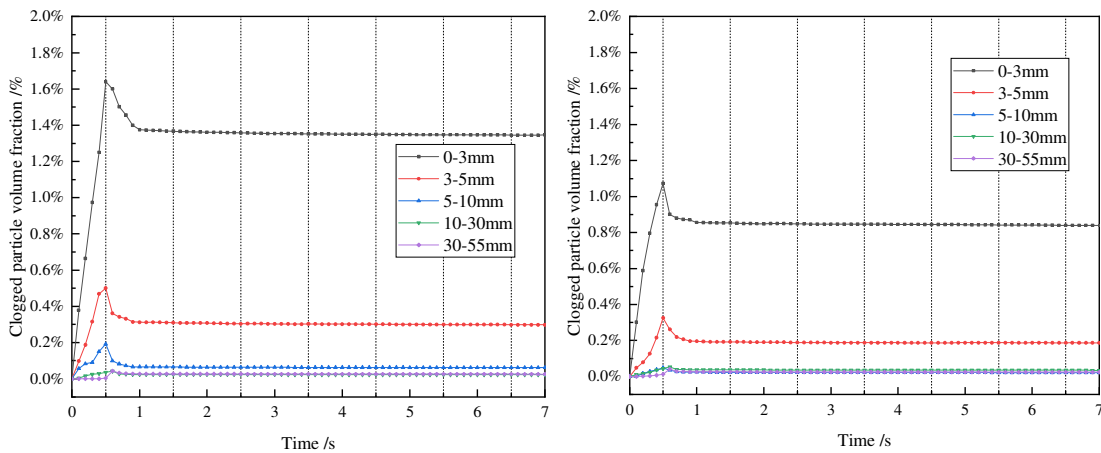
291 Furthermore, in order to study the development of clogging at different depth region of each  
292 pervious structure, the models are divided into five layers by the depth, which are layer I (0-3 mm),  
293 II (3-5 mm), III (5-10 mm), IV (10-30 mm), and V (30-55 mm) respectively. The variation  
294 processes of the volume of clogged particles in each layer compared to the total volume of the  
295 layer, i.e. clogged particle volume fraction, are shown in Fig. 5.



296  
297

(a) Control group

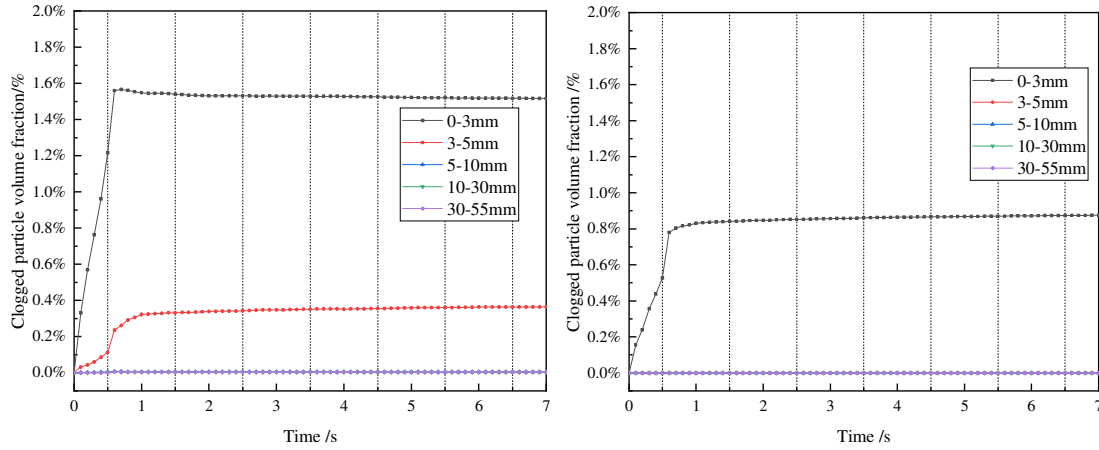
(b) U1-10



298  
299

(c) U1-8

(d) U1-5



(e) U0.6-5

(f) U0.3-5

**Fig. 5** Clogging development process in different layers

#### 4.1.1 The influence of single- and double-layer structure

As shown in Fig. 5 (a) and (b), we can find that the trend of the volume fractions of clogged particles in most layer is upward within 0-0.5s and downward after 0.5s, then tends to be stable. The main reason is that before the rainfall, some small size clogged particles enter the pore structure under the action of gravity, and the volume fractions increases. Afterwards, due to the effect of seepage flow, these small particles continue to move downwards and the volume fractions decreases, finally gradually becoming stable.

In Fig. 5 (a) and (b), comparing the layers I and II of the control group, it can be found that after 0.55s, the volume fraction of clogged particles in layer II is larger than layer I. This is due to the early rainfall, layer I of clogged particles are transported to the layer II quickly under the effect of seepage flow. In the layer II the clogged particles quickly gathered, the seepage flow effect gradually decreased, clogging particles transported speed becomes slower. Finally, the volume fractions of clogged particles in layer II is larger than layer I. The volume fractions of clogged particle in layer I of U1-10 structure is much larger than that in other layers of U1-10 and also larger than that in the layers I and II of control group. In addition, the volume fractions of clogged particles in the layers II and III of U1-10 is one-fourth of control group. This indicates that the most of clogged particles can be hold within 3 mm of the superficial layer of the double-layer structure.

Through comparative analysis, it is shown that the shielding effect of the double-layer structure is obvious, and the clogged particles can be hold within 3 mm of the superficial layer, which cannot cause serious clogging problems in deep layers, and reduce the difficulty of maintenance.

#### 4.1.2 The influence of top thickness of double-layer pervious structure

In Fig. 5 (b), (c) and (d), the clogging development process of the double-layer pervious structure with a top layer thickness of 10, 8 and 5 mm is shown respectively. It can be found that the layers with the largest volume fractions of clogged particles in the three structures is the layer I, and followed by layer II. And the volume fractions are very small in the other three layers. However, the volume fractions of clogged particles in the layers I and II of U1-5 are only half of those in U1-10 and U1-8, and particles clogged in the other layers also reduce. Therefore, with the decrease of the top layer thickness, the volume fractions of the clogged particles in each layer

332 decreases, and the anti-clogging performance of the structure improves.

### 333 4.1.3 The influence of aggregate gradation on top layer

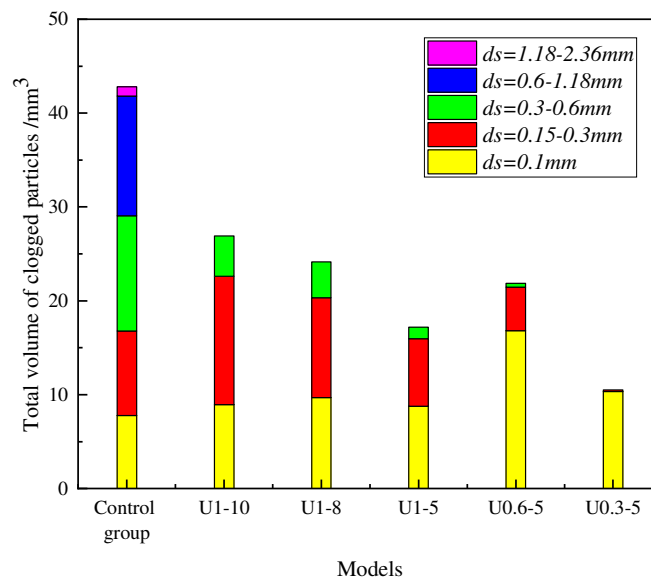
334 In Fig. 5 (d), (e) and (f), the clogged development processes of the double-layer pervious  
335 structures with 1, 0.6, and 0.3 mm particle size of the top aggregate are respectively represented. It  
336 can be found that in the U0.6-5 and U0.3-5 structures, there are no obvious decrease trend of the  
337 volume fractions of clogged particles, but only rises and finally tends to stabilize. This is because  
338 with the decrease of the top aggregate size, the pore diameter of the structure decreases, and the  
339 shielding effect increases. The clogged particles can only move slowly and are difficult to enter  
340 deeper layers, even under the action of seepage flow.

341 By comparing the layers where clogged particles exist in each structure, it is found that clogged  
342 particles exist in all layers in the U1-5 structure, while only two layers in the U0.6-5, which are  
343 layers I and II, and only one layer in the U0.3-5, which is layer I. This means that as the top  
344 aggregate size decreases, the accessible depth of the clogged particles decrease.

345 In the layers I and II of U0.6-5, the volume fractions of clogged particles increase compared  
346 with that in the same layers of U1-5. The reason is that with the decrease of top aggregate size,  
347 shielding effect increases very slightly, which results in the gradual accumulation clogged particles.  
348 While for U0.3-5, when the top aggregate size is further decreases, the shielding effect is greatly  
349 enhanced and plays a major role. Therefore, the volume fractions of clogged particles in the layer I  
350 decreases. More detailed analysis can be found in section 4.2.3.

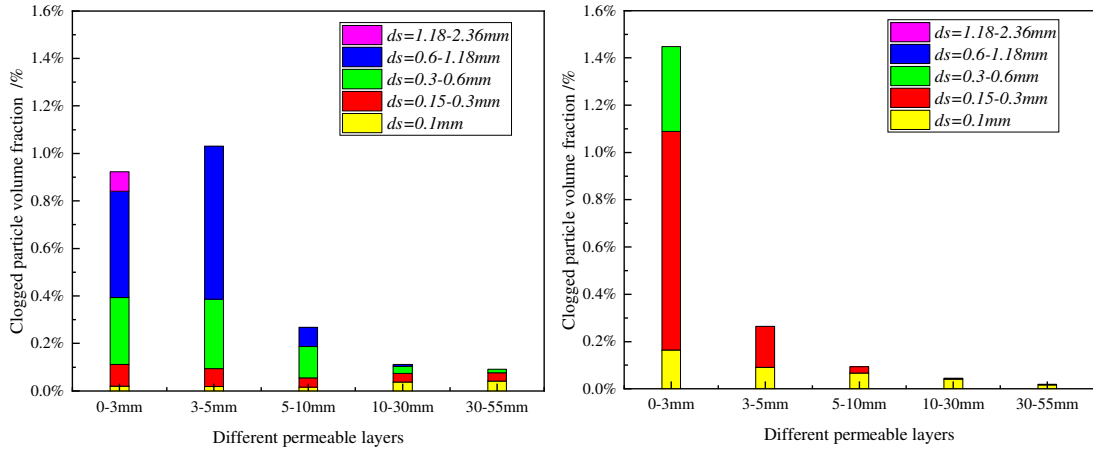
## 351 4.2 Analysis on final clogged state of pervious pavement structure

352 After clogging becomes stable, the total volume of clogged particles trapped inside the pore  
353 structure of each model is shown in Fig. 6 to compare the anti-clogging performance of each  
354 model. Fig.7 demonstrates the distribution of clogged particles in different layers of each models.

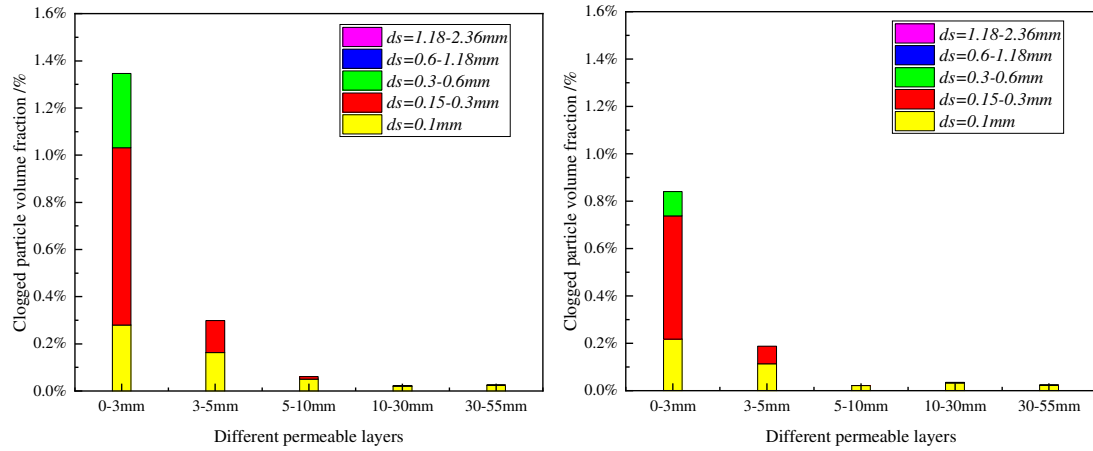


355  
356

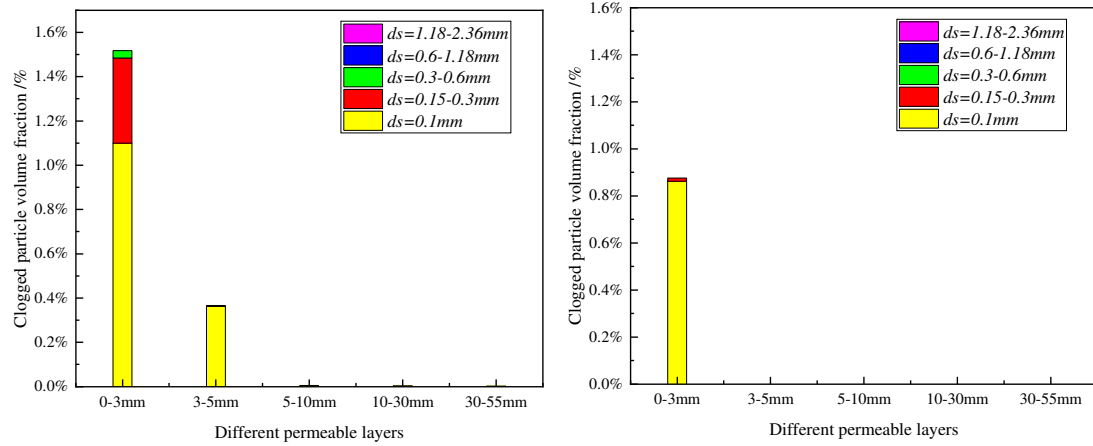
Fig.6 Volume of clogged particles with different sizes in each model



357  
358



359  
360



361

362

363

(a) U0.6-5 (b) U0.3-5

**Fig. 7** Distribution of clogging particles in different layers

364 **4.2.1 The influence of single- and double-layer structure**

365 As shown in Fig. 6, the total volume of clogged particles in the control group is the largest  
 366 compared with all other structures, and all kinds of particles exist. Besides the largest particles (i.e.  
 367 pink,  $ds=1.18-2.36$  mm), the volume of other clogged particles whose size range from 0.1 to 1.18  
 368 mm are roughly the same. It indicates that in the control group, the kind of clogged particles is

369 complex, and the clogged volume is large. Meanwhile, it can be found that the volume of clogged  
370 particles in U1-10 is reduced by 37.08%, U1-8 by 43.59%, U1-5 by 59.81%, U0.6-5 by 48.92%  
371 and U0.3-5 by 75.45% compared with the control group. Therefore, single-layer structure has the  
372 worst anti-clogging performance.

373 As shown in Fig. 7 (a). It is found that in the layers I and II of the control group, the largest  
374 clogged volume fraction is caused by blue ( $d_s=0.6-1.18$  mm) particles, followed by green  
375 ( $d_s=0.3-0.6$  mm); The other three layers have 3-4 kinds of clogging particles but the total clogged  
376 volume fraction is small. The pink ( $d_s=1.18-2.36$  mm) particles could be transported down to the  
377 depth of 3 mm (Layer I), and blue ( $d_s=0.6-1.18$  mm) particles could be transported down to the  
378 depth of 30 mm (Layers I - IV). The particles size range from 0.1 mm to 0.6 mm could be  
379 transported to the depth of 55 mm (Layers I - V). However, as shown in Fig. 7 (b), the large  
380 particles such as pink ( $d_s=1.18-2.36$  mm) and blue ( $d_s=0.6-1.18$  mm) are not able to enter the pore  
381 of double-layer pervious structure. In the layer I of U1-10, the largest clogged volume fraction is  
382 caused by red ( $d_s=0.15-0.3$  mm) particles, followed by green ( $d_s=0.3-0.6$  mm). The other four  
383 layers only have 1-2 kinds of clogging particles and the total volume fraction is small. The green  
384 ( $d_s=0.3-0.6$  mm) particles could enter the depth of 3 mm (Layers I - IV), and red ( $d_s=0.15-0.3$  mm)  
385 particles could enter the depth of 10 mm (Layers I - III). Only the yellow ( $d_s=0.1$  mm) particles  
386 could enter the depth of 55 mm (Layers I - V). The clogged volume fraction in the layer I of the  
387 U1-10 is larger than that of the control group, but the other four layers are smaller than that of the  
388 control group.

389 Therefore, compared with the single-layer pervious structure, the total clogged volume fraction  
390 of the double-layer pervious structure is smaller, and the size of the clogged particles in each layer  
391 becomes smaller. Therefore double-layer pervious structure has better anti-clogging performance.

#### 392 **4.2.2 The influence of top thickness of double-layer pervious structure**

393 As shown in Fig. 6 and Fig. 7 (b), (c) and (d), it is found that the size distribution of clogged  
394 particles are roughly the same in each layer of the U1-10, U1-8, U1-5 structures, and the size  
395 distributions get narrower with the increase of the depth. The green ( $d_s=0.3-0.6$  mm) particles are  
396 not able to move deeper, they stop in the layer I. The red ( $d_s=0.15-0.3$  mm) particles could be  
397 transported to the depth of 10 mm (Layers I - III) in the U1-10 and U1-8, but they are stopped at  
398 depth of 5 mm (Layers I - II) in the U1-5. It indicates that as the thickness of the top layer  
399 decreases, the volume fraction of green and red clogged particles decreases and the total volume  
400 fraction decreases in the each layer. Therefore, the anti-clogging performance of the double-layer  
401 permeable structure improves with the decrease of the top layer thickness.

#### 402 **4.2.3 The influence of aggregate gradation on top layer**

403 As shown in Fig. 7 (d), (e) and (f), it is found that the green ( $d_s=0.3-0.6$  mm) particles could  
404 enter the depth of 3 mm (Layer I) in the U1-5 and U0.6-5. The red ( $d_s=0.15-0.3$  mm) particles  
405 could enter the depth of 5 mm (Layers I - II) in the U1-5, but it could enter the depth of 3 mm  
406 (Layer I) in the U0.6-5, the green ( $d_s=0.3-0.6$  mm) and red ( $d_s=0.15-0.3$  mm) particles are not  
407 able to enter the pores of U0.3-5. The yellow ( $d_s=0.1$  mm) particles could enter the depth of 55  
408 mm (Layers I - V) in the U1-5, but they are stopped at the depth of 5 mm (Layers I - II) in the  
409 U0.6-5, and they are stopped at the depth of 3 mm (Layer I) in the U0.3-5. It shows that with the  
410 decrease of the top aggregate size, the shielding effect of the double-layer structure increases.

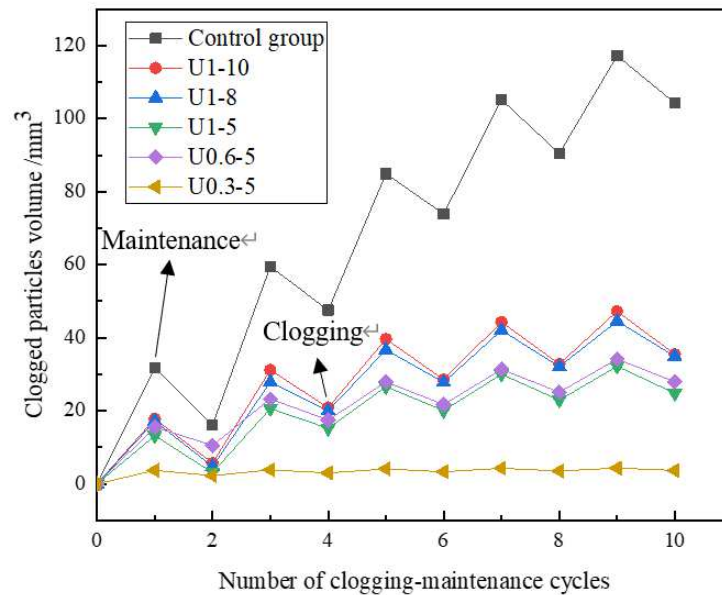
411 Meanwhile, the size distribution of clogged particles narrows in the same layer.

412 In Fig. 6 and Fig. 7, it can be found that there are three kinds of clogging particles in U0.6-5,  
413 which are green ( $ds=0.3-0.6$  mm), red ( $ds=0.15-0.3$  mm), and yellow ( $ds=0.1$  mm), and there is  
414 only one kind of particles in U0.3-5, which is yellow ( $ds=0.1$  mm). The total volume of clogged  
415 particles in U0.6-5 is more than that of U1-5 and U0.3-5, because of the accumulation of yellow  
416 ( $ds=0.1$  mm) particles in the pores of U0.6-5. The aggregate size of U0.6-5 structure is greater  
417 than 0.4 mm and less than 0.65 mm, as analyzed in section 3.1.1, which achieves both goals at the  
418 same time, e.g. shielding effect and ensuring particle transport ability. But the results show that  
419 while the shielding effect on green ( $ds=0.3-0.6$  mm) and red ( $ds=0.15-0.3$  mm) particles is  
420 enhanced, the yellow ( $ds=0.1$  mm) particles are not shielded, and meanwhile their transport in  
421 pore is greatly restricted, which finally leads to large accumulation of yellow particles in the pores  
422 of the U0.6-5. Compared with U1-5 and U0.3-5 structures, U0.6-5 has either particle transport or  
423 shielding capabilities for yellow ( $ds=0.1$  mm) particles.

424 Therefore, in order to enhance the anti-clogging performance of the double-layer permeable  
425 structure, the top aggregate size should be selected only considering one of the factors, either  
426 particle transport or shielding effect, based on the gradation of local clogging particles.

### 427 4.3 The maintenance efficiency of different pervious structures

428 In order to study the maintenance efficiency of different pervious pavement structures, the  
429 clogging-maintenance cycle is carried out with the numerical simulation. The maintenance  
430 measure adopted is vacuum suction. The vacuum suction pressure is 0.05 MPa and the suction  
431 time is 1s. The comparison of multi cycle maintenance efficiency of different models are shown  
432 in Fig. 8.



433

434

**Fig. 8** Clogging of different pervious pavement structures after clogging-maintenance cycles

435

436

437

438

439

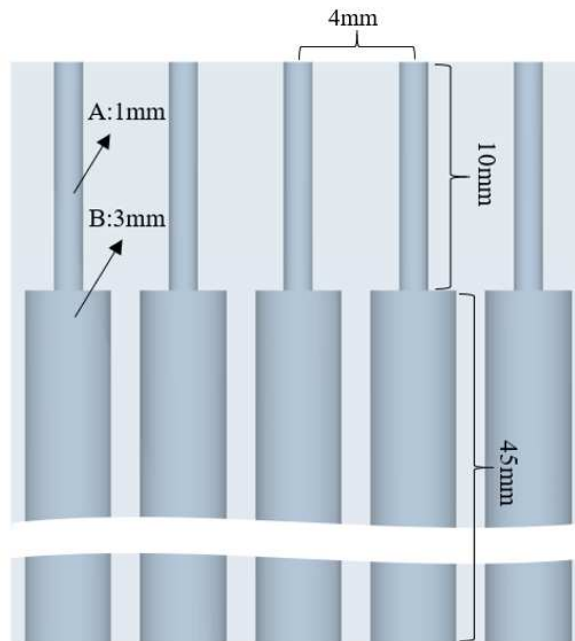
As shown in Fig. 8, it can be found that the clogged of each structure has been restored to a certain extent after each maintenance, but the recovery result is different. The clogged particles volume finally presents an upward trend in the structures. With the increase of the number of cycles, the upward trend of the control group is the most obvious, and the volume of clogged particles increases sharply, the maintenance effect is not good. Therefore, under the same



440 conditions, the single-layer pervious structure will first reach a completely clogged state, and the  
 441 effective service life will be short. In the double-layer pervious structure, with the increase of the  
 442 number of cycles, the volume of clogged particles increases very gently, and the maintenance  
 443 effect is very good. Compared with U1-10 and U1-8, the U1-5, as the thickness of the top layer  
 444 decreases, the maintenance efficiency and effective life increase. It is consistent with the  
 445 conclusion of Hamzah et al. [30]. U0.3-5 structure has no obvious upward trend in the volume of  
 446 clogged particles after several clogging cycles due to its strong shielding effect, and has good  
 447 anti-clogging ability.

#### 448 **4.4 A new double-layer pervious structure**

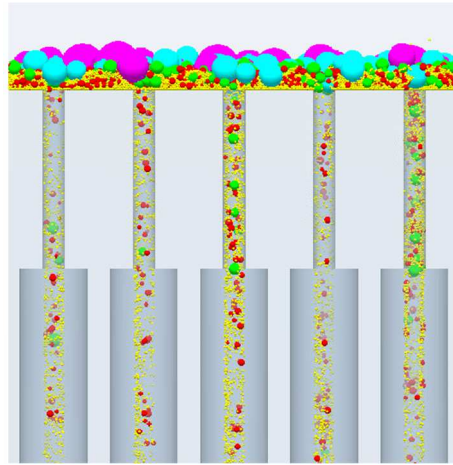
449 Pore structure of common pervious pavement is characterized by high tortuosity, variable  
 450 diameter section and pore throat, which are the main reasons for clogging of pervious pavement.  
 451 Therefore, a new tubular double-layer pervious structure with no curved channels has been  
 452 developed, based on the above investigation on the anti-clogging ability of the double-layer  
 453 pervious pavement structure. As shown in Fig. 9, A and B represent interconnected tubular pore  
 454 with different diameters, which concentrate the pores together, giving them low tortuosity, uniform  
 455 cross-section and no pore throat. According to the above aggregate size analysis, in order to ensure  
 456 its permeability and shielding effect, the pore diameter of the top layer is 1 mm, the bottom layer  
 457 is 3 mm, the thickness of the top layer is 10 mm and the bottom layer is 45 mm. In addition, the  
 458 spacing of the top tubular pore is 4 mm to ensure that its porosity is similar to the above structures  
 459 ( $P=0.39$ ).



460  
 461 **Fig.9** New tubular double-layer pervious structure

462 The clogging experiment to the new developed structure has also been carried out. Fig.10 (a)  
 463 shows the movement of the clogging particles in the simulation process, and Fig.10 (b) and (c) are  
 464 the cross-sectional and top views of the structure after clogging is stable. It is found that the new  
 465 tubular double-layer pervious structure will not trap the clogging particles in the pore due to its  
 466 own structural characteristics (the clogging particle model used in the simulation is regular  
 467 spherical), which ensures the anti-clogging property of the structure to the maximum extent and

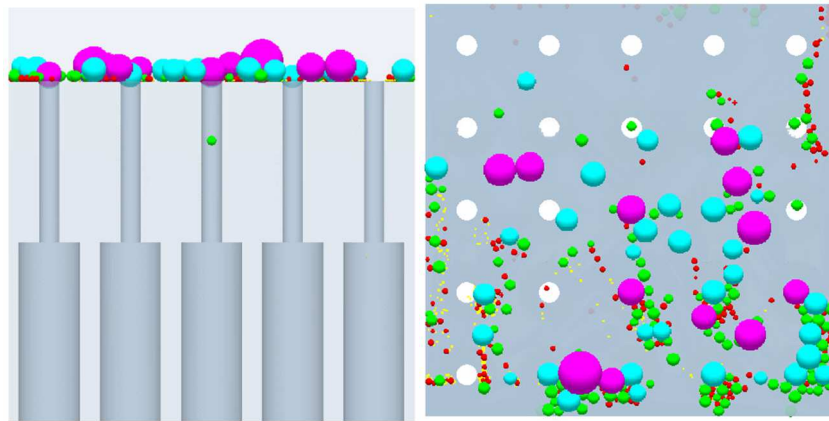
468 extends the effective service life greatly. In actual construction, the new developed pervious  
469 structure can be prefabricated in factories (Fig. 11 is a resin model), and paved on site. More  
470 investigation of the performance of this new developed pervious structure, such as the relationship  
471 of the porosity and strength will be carried out in the further study.



472

473

(a) Clogging particles movement



474

475

476

(b) Cross-section View

(c) Top view

**Fig.10** Clogging process of new developed pervious structure



477

478

**Fig.11** A resin model of the new developed pervious structure

## 479 **5. Conclusion**

480 Through CFD-DEM coupling method, 7 different models were established to analyze the  
481 effects of different structure types, top layer thicknesses and top aggregate sizes on the  
482 anti-clogging performance of the pervious pavement structure. The conclusions are as follows:

- 483 1. Compared with the single-layer pervious pavement structure, the total clogged volume  
484 fraction of the double-layer pervious structure is smaller, and the size distribution of  
485 clogged particles narrows in each layer. Therefore, the double-layer pervious pavement has  
486 better anti-clogging performance. Meanwhile the maintenance efficiency and effective  
487 service life of double-layer pervious pavement are greater than that of single-layer.
- 488 2. For the double-layer pervious pavement structure, due to the shielding effect of the top  
489 layer, the most serious clogged of the double-layer pervious structure were 0-3 mm below  
490 the pavement surface, followed by 3-5 mm. Therefore, the double-layer pervious pavement  
491 structure reduces the depth of clogging.
- 492 3. For the double-layer pervious pavement structure, with the decrease of top layer thickness,  
493 the volume fractions of the clogged particles in each layer decreases, the anti-clogging  
494 performance improves. Meanwhile with the decrease of top layer thickness, the  
495 maintenance efficiency is improved and effective life is prolonged. The results show that  
496 the top layer thickness of 5 mm has the best the anti-clogging performance in this study.
- 497 4. For the double-layer pervious pavement structure, as the top aggregate size decreases, the  
498 shielding effect increases, and the accessible depth of the clogged particles decrease. The  
499 results show that the top layer aggregate size of 0.3 mm has the best the anti-clogging  
500 performance in this study.
- 501 5. In addition, the design size of top aggregate particles can be determined by the size of  
502 clogging particles, different clogging particle gradations will induce different aggregate  
503 gradations. The results showed that the top aggregate size should be selected only  
504 considering particle transport or shielding effect, based on the gradation of local clogging  
505 particles.
- 506 6. A new tubular double-layer pervious structure has been invented and studied, which has  
507 excellent anti-clogging performance due to its unique pore structure. The new developed  
508 pervious structure can be prefabricated and paved on site in real application cases.  
509

## 510 **6. Acknowledgements**

511 The authors would like to thank the National Key Research and Development  
512 Project(2018YFB1600100), Natural Science Foundations of Shandong Province, China (Nos.  
513 2017GSF22101, and ZR2018MEE046) and the Fundamental Research Funds for the Central  
514 Universities (No.2018JC040).  
515

## 516 **7. References:**

- 517 [1]. Zhu, H., et al., Simulation Study on Effect of Permeable Pavement on Reducing Flood Risk of  
518 Urban Runoff. *International Journal of Transportation Science & Technology*, 2019.
- 519 [2]. Montes, F. and L. Haselbach, Measuring hydraulic conductivity in pervious concrete.  
520 *Environmental Engineering Science*, 2006. 23(6): p. 960-969.
- 521 [3]. Paul D. Tennis, M.L.L.A., *Pervious Concrete Pavements*. 2004.
- 522 [4]. Liu, M., X. Huang and G. Xue, Effects of double layer porous asphalt pavement of urban streets  
523 on noise reduction. *International journal of sustainable built environment*, 2016. 5(1): p. 183-196.
- 524 [5].Mullaney, J. and T. Lucke, Practical Review of Pervious Pavement Designs. *Clean-soil Air Water*,

2014. 42(2): p. 111-124.

[6]. Pagotto, C., M. Legret and P.L. Cloirec, Comparison of the hydraulic behaviour and the quality of highway runoff water according to the type of pavement. *Water Research*, 2000. 34(18): p. 4446-4454.

[7]. Sansalone, J.J., et al., Filtration and clogging of permeable pavement loaded by urban drainage. *Water Research*, 2012. 46(20): p. 6763-6774.

[8]. Kayhanian, M., et al., Permeability measurement and scan imaging to assess clogging of pervious concrete pavements in parking lots. *Journal of Environmental Management*, 2012. 95(1): p. 114-123.

[9]. Zhang, J., et al., Sediment transport and pore clogging of a porous pavement under surface runoff. *Road Materials and Pavement Design*, 2017. 18(sup3): p. 240-248.

[10]. Lu, G., et al., Development of a sustainable pervious pavement material using recycled ceramic aggregate and bio-based polyurethane binder. *Journal of Cleaner Production*, 2019. 220: p. 1052-1060.

[11]. Balades, J., M. Legret and H. Madiec, Permeable pavements: pollution management tools. *Water Science and Technology*, 1995. 32(1): p. 49-56.

[12]. Walsh, S.P., A.A. Rowe and Q. Guo, Laboratory Scale Study to Quantify the Effect of Sediment Accumulation on the Hydraulic Conductivity of Pervious Concrete. *Journal of Irrigation and Drainage Engineering-asce*, 2014. 140(6): p. 04014014.

[13]. Kandra, H.S., et al., Assessment of clogging phenomena in granular filter media used for stormwater treatment. *Journal of Hydrology*, 2014. 512: p. 518-527.

[14]. Bean, E.Z., W.F. Hunt and D. Bidelspach, Field Survey of Permeable Pavement Surface Infiltration Rates. *Journal of Irrigation and Drainage Engineering-asce*, 2007. 133(3): p. 249-255.

[15]. Haselbach, L., S. Valavala and F. Montes, Permeability predictions for sand-clogged Portland cement pervious concrete pavement systems. *Journal of Environmental Management*, 2006. 81(1): p. 42-49.

[16]. Yong, C.F., D.T. Mccarthy and A. Deletic, Predicting physical clogging of porous and permeable pavements. *Journal of Hydrology*, 2013. 481: p. 48-55.

[17]. Remond, S., DEM simulation of small particles clogging in the packing of large beads. *Physica A-statistical Mechanics and Its Applications*, 2010. 389(21): p. 4485-4496.

[18]. Li, H. and A.P. Davis, Urban Particle Capture in Bioretention Media. II: Theory and Model Development. *Journal of Environmental Engineering*, 2008. 134(6): p. 419-432.

[19]. Razzaghmanesh, M. and M. Borst, Investigation clogging dynamic of permeable pavement systems using embedded sensors. *Journal of Hydrology*, 2018. 557: p. 887-896.

[20]. Wang, D., et al., Effects of Material Composition on Mechanical and Acoustic Performance of PoroElastic Road Surface (PERS). *construction and building materials*, 2017. 135: p. 352-360.

[21]. Pieralisi, R., S.H.P. Cavalaro and A. Aguado, Discrete element modelling of the fresh state behavior of pervious concrete. *Cement and Concrete Research*, 2016. 90: p. 6-18.

[22]. Pieralisi, R., S.H.P. Cavalaro and A. Aguado, Advanced numerical assessment of the permeability of pervious concrete. *Cement and Concrete Research*, 2017. 102: p. 149-160.

[23]. Ma, T., et al., Influences by air voids on fatigue life of asphalt mixture based on discrete element method. *construction and building materials*, 2016. 126: p. 785-799.

[24]. Zhang, J., et al., Experimental simulation study on pore clogging mechanism of porous pavement. *Construction and Building Materials*, 2018. 187: p. 803-818.

[25]. Zhang, J., et al., Numerical study on pore clogging mechanism in pervious pavements. *Journal of Hydrology*, 2018. 565: p. 589-598.

[26]. Vancura, M.E., K. MacDonald and L. Khazanovich, Location and Depth of Pervious Concrete

569 Clogging Material before and after Void Maintenance with Common Municipal Utility Vehicles.  
570 journal of transportation engineering asce, 2012. 138(3): p. 332-338.  
571 [27]. HendersonVimy and L. TigheSusan, Evaluation of pervious concrete pavement permeability  
572 renewal maintenance methods at field sites in Canada. canadian journal of civil engineering, 2011.  
573 [28]. Hu, N., et al., A field performance evaluation of the periodic maintenance for pervious concrete  
574 pavement. journal of cleaner production, 2020. 263.  
575 [29]. Bochove, V. and G. G, TWINLAY, A NEW CONCEPT OF DRAINAGE ASPHALT  
576 CONCRETE. 1996.  
577 [30]. Hamzah, M.O., et al., Laboratory simulation of the clogging behaviour of single-layer and  
578 two-layer porous asphalt. Road Materials and Pavement Design, 2013. 14(1): p. 107-125.  
579 [31]. Kuijpers, A. and G. Blokland, Modeling and optimization of two-layer porous asphalt roads.  
580 2000.  
581 [32]. Afonso, M.L., C. Fael and M. Dinisalmeida, Influence of clogging on the hydrologic performance  
582 of a double layer porous asphalt. International Journal of Pavement Engineering, 2018: p. 1-10.  
583 [33]. Ma, G., et al., Reply to the Comment on “Numerical study on pore clogging mechanism in  
584 pervious pavements”. Journal of Hydrology, 2019. 578: p. 124050.