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Transformation impact of vertical revetment on the river water quality and its mechanism

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ABSTRACT

The vertical hard revetment can cause the disturbance in river flow with the results of destroyed features, degraded biodiversity, decreasing self-purification ability and deteriorated water quality. The current work is focused on the application of prefabricated porous concrete template covered on widespread vertical hard revetment for improving water purification, increasing biodiversity and decreased negative impact of hard concrete revetment to river quality. Six kinds of porous concrete with different void ratio, aggregate size and water cement ratio were prepared to investigate the compressive strength and water purification properties. A river simulator device was used to determine the water purification capacity of the porous concrete in flowing condition. Water quality purification mechanism of porous concrete was discussed thoroughly by the analysis of microbial community diversity. Results show that the compressive strength and water purification ability of porous concrete were higher when the void ratio, size of the aggregate material and water cement ratio were 30%, 10–20 mm and 0.3, respectively. Under the flow velocity of V = 0.03 m/s and hydraulic retention time of 6 d, the removal rates of M_2 biofilm for chemical oxygen demand (COD_{Mn}), ammonia nitrogen (NH_3–N), nitrate nitrogen (NO_3–N), total nitrogen (TN) and total phosphorus (TP) were 59.21%, 74.07%, 54.25%, 55.47% and 62.90%, respectively. Findings reveal that prefabricated porous concrete was efficient for river water purification. Porous concrete templates can be attached to a large number of microorganisms.

Keywords: Ecological slope; Porous concrete; Vertical hard revetment; Water quality; Biofilm

1. Introduction

Use of vertical hard revetment has brought many negative effects to river landscape and ecology [1,2]. Continuous vertical revetment structure changes the natural form of a meandering river to monotonous form [3]. Furthermore, hard revetment can also damages the coastal wetland structure, causing the river decrease in river flow velocity. It will also decrease biodiversity and results indicate a decrease of water self-purification ability [4]. An ecological revetment is a combination of civil engineering and ecological technology in order to ensure the flood control and bank stability performance and improve water self-purification capacity as well as ecological diversity. Chen et al. [5] illustrated two mitigation works for a debris flow torrent and a stream to introduce application ecological engineering methods in ecological revetment design and stream bank ecological restoration. Wu and Feng [6] established a theoretical analysis method on the basis of the set-valued iterative method and used Gray correlation analysis to a quantitative evaluation system for evaluating ecological restoration capability of the ecological revetment. Hartig et al. [7] investigated the ecological effectiveness of 38 soft shoreline engineering projects in the Detroit River-Western Lake Erie watershed to demonstrate the ecological effect of ecological revetment in enhancing aquatic and riparian diversity. Woo et al. [8] studied the situation and prospect of ecological engineering in Korea and illustrated the project process to removal dam, weir, revetment and many concrete

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works, and applied the ecological engineering technology to restore a stream that could also restore the stream ecosystem, enhance biodiversity and flood mitigation. Globally, most of the earlier studies were focused on regenerative ecological restoration methods that required breaking of vertical hard revetment and rebuilding ecological revetment. But, the hard revetment itself has a great advantage in flood control and drainage and its construction is also safe and stable. In addition, vertical hard revetment was used in large river remediation projects and replacing it by ecological revetment would need a large amount of time, but comprehensive removal of hard concrete revetment would need an investment of a huge amount of money and resources. It could be due to the contamination and river ecosystem. Therefore, the optimized ecological restoration based on the original hard bank revetment is more valuable.

The principle of modification and repairing of the hard revetment should reverse the current environmental condition to the initial state as possible [9]. Firstly, the main objective of the repair methods is to restore the biodiversity and its growing environment, usually with change or increase the medium suitable for biological survival and increase in the amount and type of animal, plants and microorganisms [10]. This can also improve the, self-purification ability of the river. At present, a suitable technology for the modification of vertical hard revetment can be divided into three categories, that is, plant rehabilitation technology, laying matrix modification and composite modification.

Porous concrete has continuous voids that can provide the inhabit space for microbes. The biofilm formed on the internal surfaces of voids provide a biopurification function there pore porous concrete is a good substrate for the hard revetment modification [11,12]. On the basis of performance that does not destroy original revetment, as well as not decreasing the water channel section, a modification technology using porous concrete plant was put forward. Six porous concrete samples with different void ratio, aggregate size and water cement ratio were prepared to investigate the compressive strength and water purification properties. A river simulator device was applied to determine the water purification capacity of the porous concrete in flowing condition. Water quality purification mechanism of porous concrete was discussed through the analysis of microbial community diversity.

2. Materials and methods

2.1. Materials

To reduce the weight of the porous concrete template, Tianjin 800 grade high-performance burn ceramics grain is selected as coarse aggregate. Burn ceramic mechanism characteristics were as follows: water absorption for 24 h as 6.1% and cylinder strength as 14.2 MPa, bulk density as 802 kg/m^3, apparent density as 1,340 kg/m^3 and porosity as 39.9%. In the current work, two types of material with the particle size of 10–20 and 16–25 mm were screened. In order to assure the strength of the porous concrete, P52.5 model of Portland cement was selected as the cementing material. Six kinds of porous concrete with different void ratio, aggregate size and water cement ratio were prepared. Each sample was made of six cubes with side length of 150 mm (Fig. 1), and mixture ratio of porous concrete as shown in Table 1.

2.2. Screening experiment of porous concrete

2.2.1. Measurement of total void ratio

Three polymer pipes (200 mm diameter) were used as the outer mold. Water was poured up to 200 mm and porous concrete was soaked in water for 24 h to check the water volume exchange to test void volume.

$$A = \frac{(V_1 - V_2) \times 100}{V_1} (\%) \quad (1)$$

where A is the total void ratio of the porous concrete (%); V_1 is the volume of porous concrete unit and V_2 is the volume of water increase when it entered in to the porous concrete unit.

2.2.2. Compressive strength tests

Six kinds of porous concrete with different void ratio, aggregate size and water cement ratio were prepared for the comprehensive strength tests. After a standard curing time of 28 d. The compressive strength of porous concrete was measured at the mechanical laboratory of Nanjing University of Aeronautics and Astronautics using a YES-1000 digital pressure tester (Fig. 2). Each block subjected to three compressive strength tests and obtained average values. Compressive strength of the porous concrete experimental blocks was calculated as follows:

$$f = \frac{F}{A} \times 1000 \quad (2)$$

where f is the compressive strength of porous concrete experimental block (MPa); F is the experimental block failure load (KN) and A is the experimental block pressure area (cm^2).

2.2.3. Static experiment for water quality improvement

Static experimental devices were made by plastic sheets which used to measure the water purification effect of six

Fig. 1. Porous concrete experiment cubes.

Table 1
Mixture ratio of porous concrete

Serial number	Aggregate size/mm	Water/cement ratio (w/c)	Void ratio (%)	Unit volume material consumption/(kg/m^3)		
				Ceramsite	Cement	Water
A	10–20	0.29	25	366	472	137
B	10–20	0.30	30	366	369	111
C	10–20	0.31	35	366	268	83
D	16–25	0.30	25	352	502	151
E	16–25	0.31	30	352	400	124
F	16–25	0.32	35	352	300	96

Fig. 2. Compressive strength experimental.

different porous concretes. Each of the experiment devices has capacity of holding 25 L water. Six porous concrete blocks were placed within these devices. To promote microorganisms breeding in the porous concrete, the existed water was replaced with fresh river water in devices every day where each device was poured 18 L river water. The conversion of water quality indicators was detected after 2 months. The hydraulic retention time (HRT) in the experimental work was set to 6 d [13]. Static experimental devices are shown in Fig. 3.

2.3. Simulation test for water quality improvement

A river simulator device was installed to determine the water purification capacity of the porous concrete in flowing condition. Porous concrete templates were placed in device in July 2015. The porous concrete modular were produced with the volume of 60 × 30 × 8 (cm^3) of template. Water was

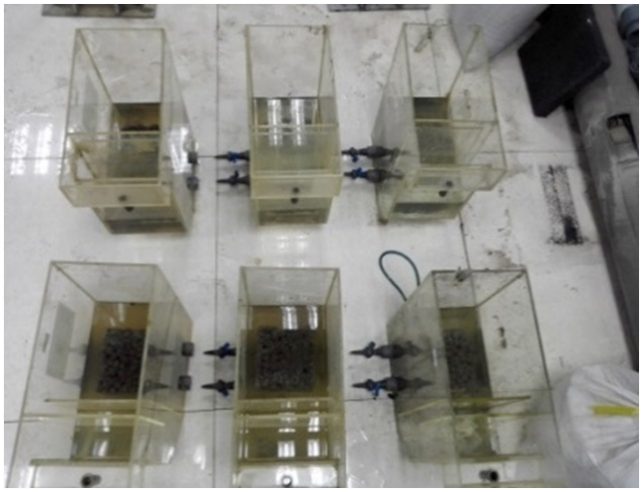


Fig. 3. Static experimental devices.

changed in device in every 2 weeks started from February 2016. During each experimental period, the HRT was 6 d and the river water was circulating in the device through the submersible pump. About 300 mL of microbial liquid was added once a day to the simulated river device for continuous curvature. Nutrients such as 30 g $C_6H_{12}O_6$, 10 g NH_4Cl, 15 g KNO_3, 6 g KH_2PO_4 and 3 g beef powder were added into the device to enhance the biofilm culture. The height of prefabricated porous concrete plate was 0.6 m, while the effective water depth was 0.5 m and the total water volume was 6 m^3. Two submersible pumps were installed to discharge the water for 45 and 60 m^3/h to control the flow velocity from 0.006 to 0.093 m/s. The simulated river device is present in Fig. 4. After 2 weeks duration, four different biofilms were noticed from different flow velocity curvature. This forming biofilm was collected from the porous concrete surface to determine the thickness and distribution of dissolved oxygen (DO) concentration in biofilm using DO microelectrode device.

2.4. Determination of DO concentration distribution in biofilm

2.4.1. DO distribution and reaction in biofilm

Ning et al. [14] indicated that the DO distribution of inside the biofilm could be achieved. The DO concentration distribution in biofilm was determined by Eqs. (3) and (4). The distribution entering flux ($-D\,\partial C/\partial z\,dxdy$) of DO is equal

to the distribution loss in flux –D ∂/∂z (C + ∂C/∂z dz) dxdy plus the consumption (–OURdxdydz).

$$-D\frac{\partial C}{\partial z}\,\mathrm{dxdy} = -D\frac{\partial}{\partial z}\left(C+\frac{\partial C}{\partial z}\mathrm{dz}\right)\mathrm{dxdy} - \mathrm{OUR}\,\mathrm{dxdydz} \quad (3)$$

By Eq. (3), we can get the following short cut formula as:

$$D\frac{\mathrm{d}^2C}{\mathrm{dz}^2} = -\mathrm{OUR} \quad (4)$$

where D is the effective distribution coefficient of DO (m^2/d); C is the DO concentration (g/m^3) and OUR (oxygen uptake rate) is the DO consumption rate ($g/m^3\,d$).

2.4.2. Distribution of DO in biofilm

Experimental work was carried out at the Jiangsu Zhongyi Jinda Analytical Testing Co., Ltd., Yixing, Jiangsu, China. A DO microelectrode (DO 50-type) manufactured by OX-N Universe, Denmark, was used to determine the DO concentration and thickness of the biofilm. The biofilm structure was observed by using a scanning electron microscope of JEOL 6380LV. Biofilm collected from concrete surface that distant from outlet pipe was 1.5–1.8 m thick. Biofilms collected during experiment were persevered on the plate and soaked with distilled water to keep it wet. Samples were transported to the laboratory within 1 h to determine the DO concentration distribution (Fig. 5).

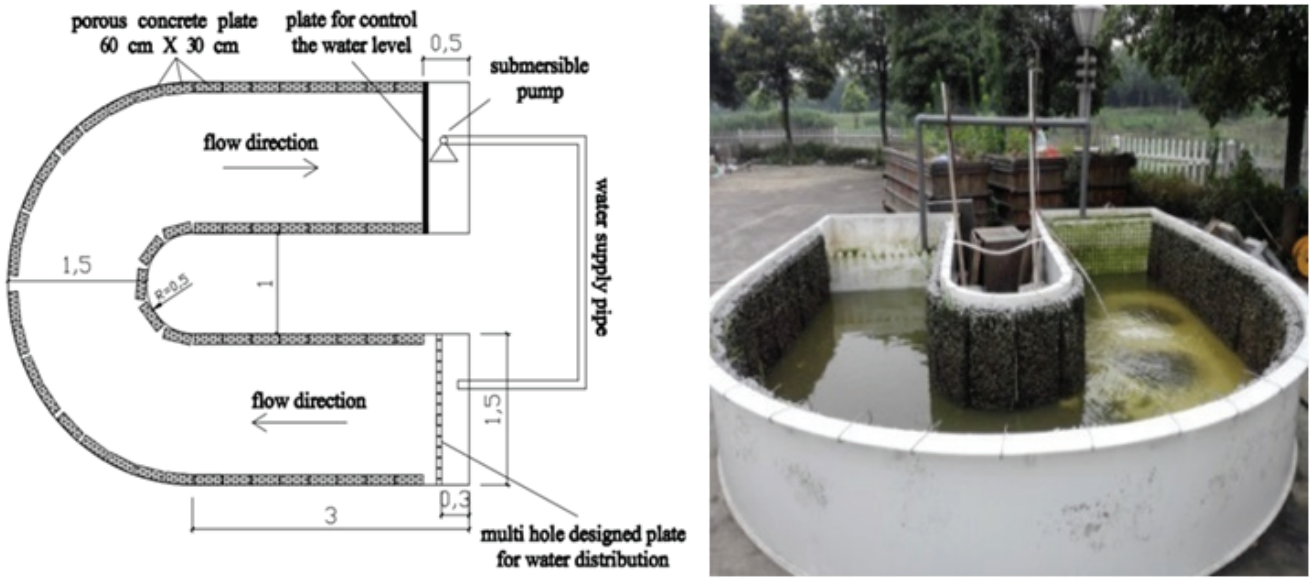


Fig. 4. Simulated river device.

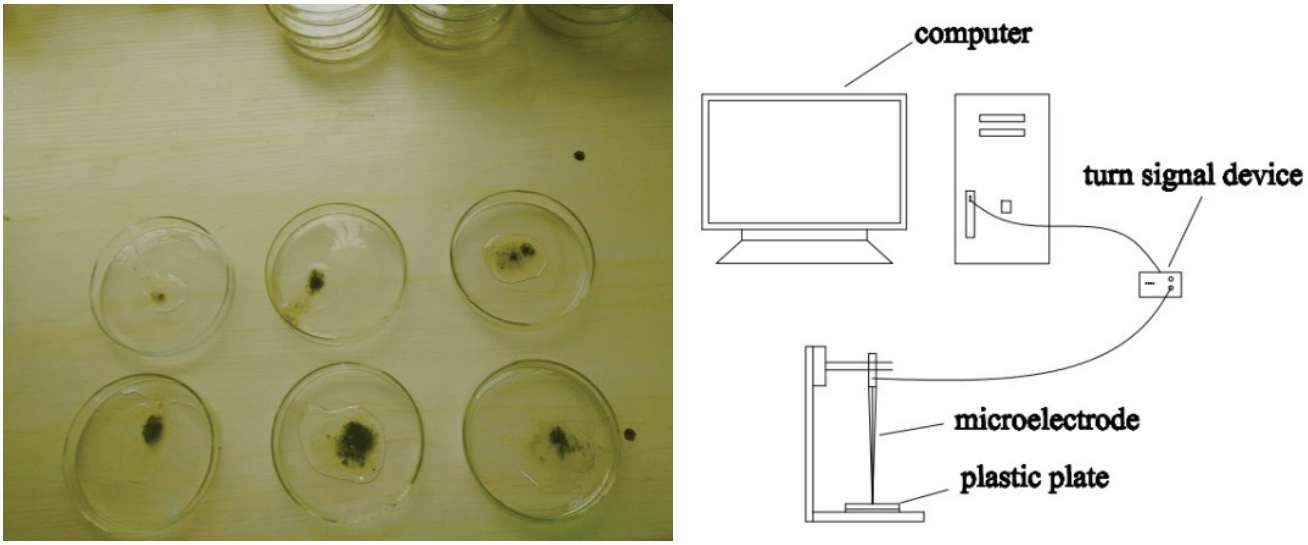


Fig. 5. Biofilm dissolved oxygen concentration distribution determined.

2.5. Analysis of microbial community diversity

The high-throughput DNA sequencing polymer chain reaction (PCR) technology was adopted to explore the influence of porous concrete plant to suspended microorganisms in water and adherent microbes. Eight samples were collected to analyze the microbial community diversity (Fig. 6). All these samples were as follows: sample 1#, freshwater; sample 2#, water from the side area of device; sample 3#, water from intermediate device; sample 4#, mud above the 5 cm of water line; sample 5#, mud near the water line; sample 6#, mud below the 25 cm of water line; sample 7#, mud below the 45 cm of water line and sample 8#, mud inside the porous concrete plant. MiSeq high-throughput sequencing technique was used in the current experiment for microbial species identification. The process was as follows: (1) The extracted genomic DNA was detected by 1% agarose gel electrophoresis. (2) Specific primers with "5" Barcode "3" were synthesized according to the designated sequencing region. (3) All samples were tested according to the official conditions and each sample was repeated for three times. The PCR products of the same sample were purified, mixed and detected by 2% agarose gel electrophoresis. (4) The PCR products were quantified by Qubit according to the preliminary quantitative result electrophoresis. (5) MiSeq sequencing. Key analysis process in the current study was a valid sequence statistics, optimization of sequence statistics, diversity index and species classification.

3. Results and discussion

3.1. Compressive strength and static water purification effect of porous concrete

The compressive strength and static characteristics of porous concrete are shown in Table 2. The difference between design and actual void ratio of the porous concrete unit was 0.3%–0.6%. Therefore, this can be utilized for further experimental work. Space per aggregate was increased along with the void ratio. The comprehensive strength was low because it can damage easily when the bonding point gets increased. Chindaprasirt et al. [15] uses the product of porous concrete with four binder strengths between 30 and 135 MPa, five void ratio between 15% and 30% and three single aggregate size of 5, 13 and 20 mm to study the effect of binder strength and aggregate size on the compressive strength and void ratio of porous concrete and revealed that the compressive strength of porous concrete reduces with an increase void ratio. When the aggregate size increases, the contact point between the aggregate becomes less even when the porosity was uniform.

Fig. 6. Microbial community diversity sample.

Table 2
Compressive strength and static water purification effect of porous concrete

Serial number	Compressive strength (MPa; 28 d)	Actual void ratio (%)	COD_{Mn} removal (%)		NH_3–N removal (%)		TN removal (%)		TP removal (%)	
			HRT, 2 d	HRT, 6 d	HRT, 2 d	HRT, 6 d	HRT, 2 d	HRT, 6 d	HRT, 2 d	HRT, 6 d
A	11.35	24.38	37.6	45.4	21.1	54.4	9.1	32.4	12.5	9.4
B	8.23	29.52	44.0	54.8	40.4	65.5	17.7	42.2	3.1	12.5
C	5.89	34.73	43.2	53.4	36.3	64.3	22.4	40.0	9.4	3.1
D	8.47	24.61	42.5	50.4	44.4	63.2	2.1	38.6	6.3	12.5
E	5.54	30.39	45.3	55.1	49.1	68.4	1.5	45.4	12.5	15.6
F	4.47	34.24	44.9	55.0	45.6	66.7	10.9	43.7	–3.1	12.5

Under pressure, porous concrete is more vulnerable to damage. Park and Tia [12] studied the compressive strength of porous concrete made by crushed stone and confirmed that the concretes with 5–10 mm aggregate size exhibited 1.8–2.0 times greater strength than those with 10–20 mm aggregate size. The sorting strength of six kinds of concrete was as follows: A > D > B > C > E > F. Water quality purification ability of six kinds of porous concrete is different. Four measures of water quality variation are basically identical. Water purification effect of sorting is E > F > B > C > D > A. The water purification effect was best when the aggregate particle size ranged between 16 and 25 mm and the void ratio of 30%.

The biofilm was formed on the porous concrete blocks after 2 weeks due to microbial attachment. Biofilm structure was similar in six blocks and the thickness of A, B, C, D, E and F biofilms was 417, 428, 425, 427, 431 and 429 μm, respectively. Due to the development of biofilm in a static hydraulic condition with low DO concentration that cannot satisfy microbial oxygen requirement, the growth and reproduction of biofilm were reduced. In addition, low DO condition provided the good development environment for anaerobic microbial activities. Therefore, the development of anaerobic bacteria was better than aerobic bacteria. Fig. 7 shows the cluster structure state of biofilm in six porous concrete blocks.

Analysis shows that the void ratio decides the number of porous concrete gaps. Increase in void ratio was synonyms to the increase in space for microbial development which can increase the amount of microbial adhesion. But, when the void ratio was greater than 30%, the microbial membrane number may have limited effect. Furthermore, because of the influence of hydraulic condition, pollutant removal efficiency was even lower than the porous concrete (void ratio 30%). In addition, the cement which was used as a main glue aggregate of porous concrete block could release alkaline substances could have caused the death of microbes. Xiao et al. [16] revealed through investigations that the damages of microbial cell structure indicated the most damage of bound extracellular polymeric substances (EPS), cell walls, cell membranes and cell nuclei occurred at pH 11.5–12.0 (46.2%), pH 11.0–11.5 (27.3%), pH 9.0–10.0 (34.2%) and pH 11.5–12.0 (44.4%), respectively. Therefore, increasing void ratio not only enhance habitat space of microbes, but also reduced the amount of cement used to produce porous concrete which enhance and increase the microbial biomass and nutrient removal effect.

The size of the gap is decided by aggregate size. If the aggregated particle size is large, the void size and connection space increases, which in turn favors the adhesion of the microbial survival. In addition, water can bring nutrient and DO flow into voids to satisfy microbial development, a requirement that can improve biomass and nutrient absorption capability of microbes. The pollutants removal effect was better in increasing aggregate size. In addition, more void ratio would lead the more water to flow in the void space that can dilute and reduce the alkaline that slowed the cresis death of microbes.

The results from comprehensive comparison of the compressive strength and water purification effect revealed that although the water purification effect of E block (void ratio of 30% and aggregate size of 16–25 mm) was best, but its compressive strength was only 5.54 MPa. The block B has relatively high compressive strength (8.23 MPa) and good water purification effect so it (void ratio of 30% and aggregate size of 10–20 mm) was therefore selected to product concrete template.

3.2. Forming biofilm structure analysis

3.2.1. Biofilm structure in microbial culture

Biofilm was formed on porous concrete surface due to microbial attachment after 2 weeks curvature. Biofilm was formed in difference flow velocities V_1 = 0.01 m/s, V_2 = 0.03 m/s, V_3 = 0.06 m/s and V_4 = 0.09 m/s with culture conditions and has different structural shapes which are termed as M_1, M_2, M_3 and M_4 (Figs. 8 and 9). With the water flow rate of 0.01 m/s for M_1 in curvature condition, the

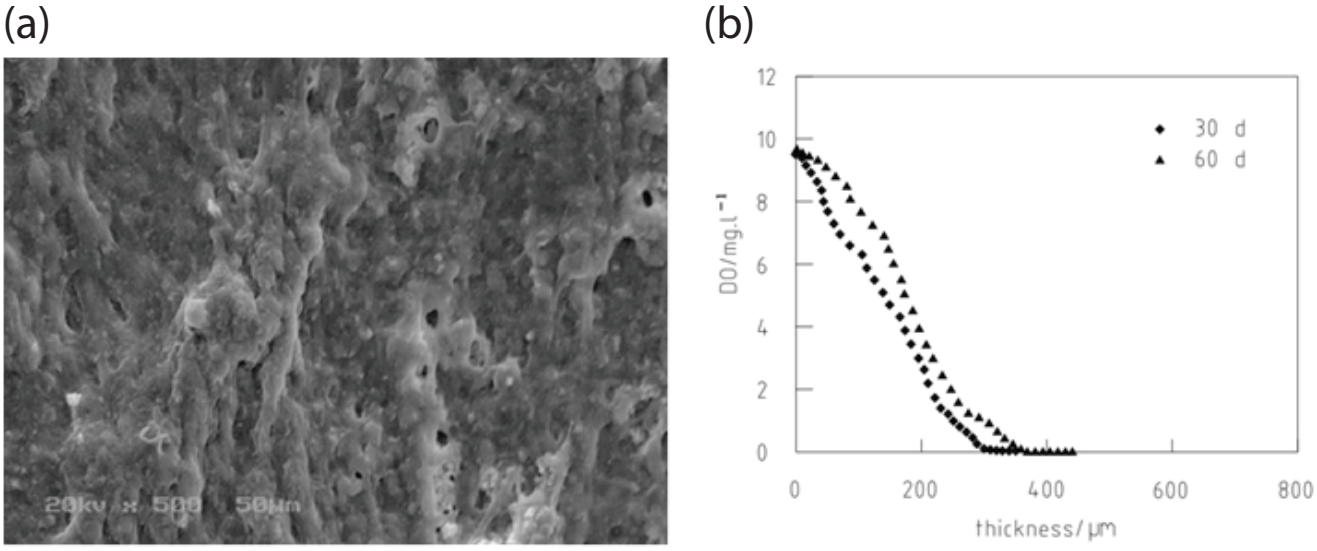


Fig. 7. (a) The molding structure of concrete block E; and (b) thickness vs. DO distribution curve.

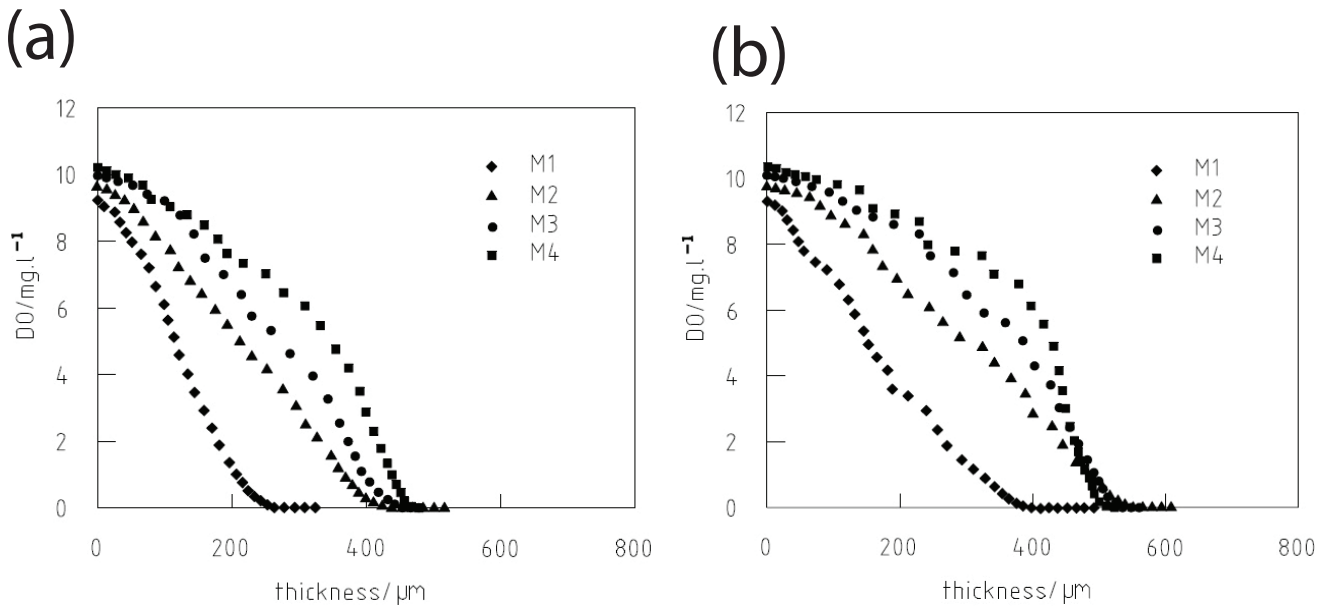


Fig. 8. Biofilm structure (a) after 8 d; and (b) after 15 d of culture.

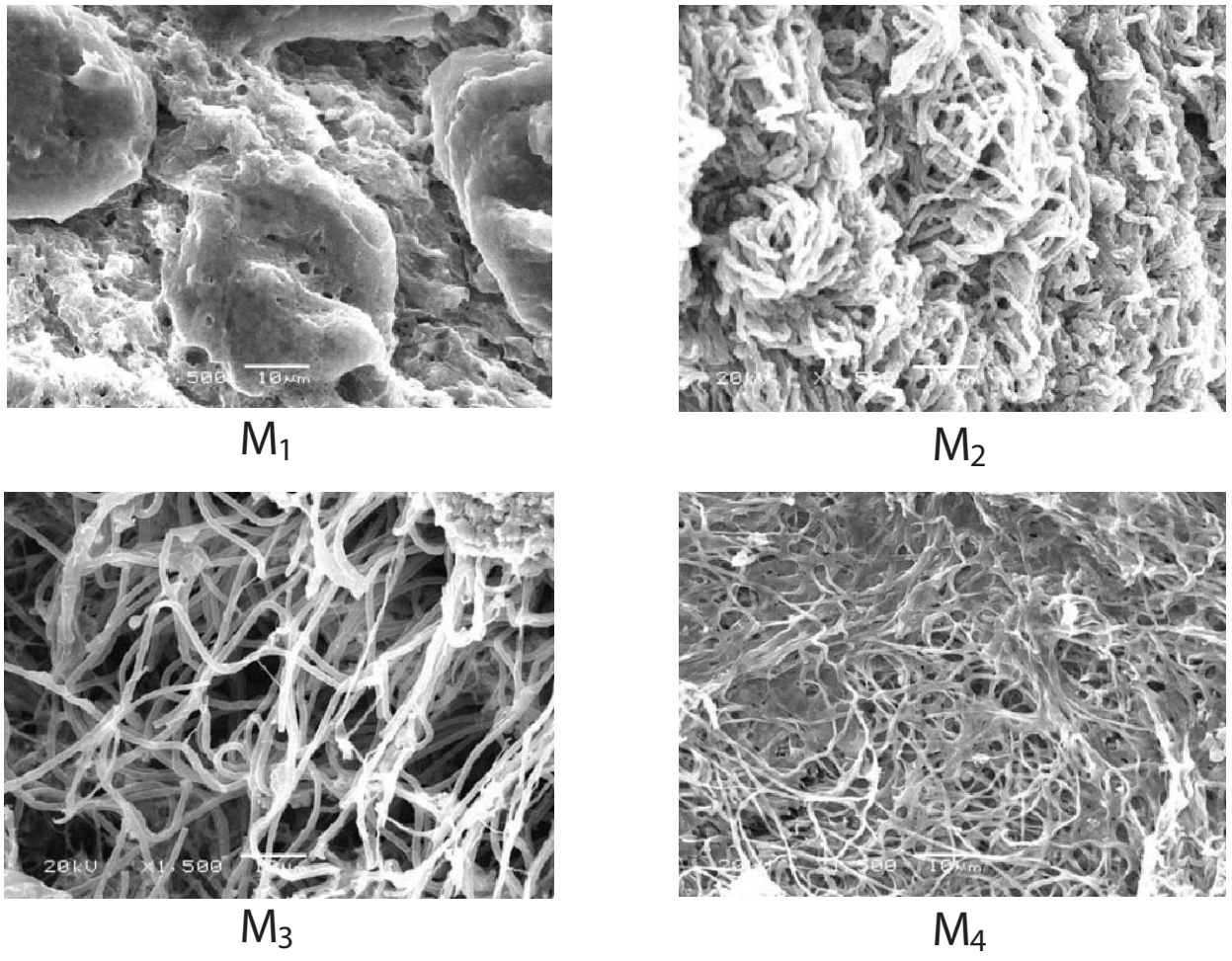


Fig. 9. Biofilm in different hydraulic culture condition of the molding structure.

thickness of the formed biofilm was 494 μm. Due to slow velocity condition, the hydraulic flow could only transport low diameter organic matter and microbial guide to porous concrete surface, another number of organic matter could be deposited at bottom of the device, therefore, it was difficult to form the rich nutrient base or microbial attachment on porous concrete surface [17,18]. In addition, the slow water flow caused by low DO that cannot satisfy the microbial oxygen requirement, causes difficulty in the growth and reproduction of microbes. But, lack of DO condition provided the platform for development of anaerobic and modest bacterial species. Microbial observation results revealed that the M_1 biofilm has a cluster structure state. According to the distribution of DO and the biofilm structure, the development of anaerobic bacteria was better than aerobic bacteria [14,19].

Results reveal that the biofilm with 612 μm thickness was formed in M_2 under the water flow rate of 0.03 m/s culture condition. Milisa and Habdija [20] studied the role of flow velocity in vertical distribution of particulate organic matter on mostly covered travertine barrier dictated that fine organic matter and ultrafine organic matter is negatively correlated with flow velocity along vertical profile. When hydraulic flow velocity increased from 0.01 to 0.03 m/s, it transported more organic matter and microbial guide to porous concrete surface, and as a result of increase in water velocity the transport of organic matter of water capacity gets improved and the organic accumulated on porous concrete surface gets increased [17,21]. The roughness of porous concrete surface can create the water flow resistance force. This condition can enhance the interception and accumulation of microbes and organic matter on surface and pores of the porous concrete, which is a favorable condition for biofilm formation. Increased flow velocity also improved water of dissolved oxygen that provided good conditions for growth and propagation for aerobic bacterial in biofilm, causing the biofilm thickness to increase quickly [22–24]. The aerobic and anaerobic layer of biofilm reached a better development degree and M_2 biofilm had filamentous structure. According to the distribution of DO, this biofilm structure indicated that the development of anaerobic and aerobic bacteria is very good.

The formed biofilm thickness was 518 μm for M_4 under the water flow rate of 0.09 m/s culture condition. Flow velocity value of 0.06 m/s could transport high diameter matter, but with high velocity condition, microbial and organic matter finds it is difficult to attach on the surface of porous concrete. Besides, in high speed flow condition, shear force occur and scour the biofilm and nutrient of material surface, causing the biofilm thickness to become thinner like M_2, M_3 kind. M_4 biofilm structure has filamentous structure. DO distribution results revealed that the development of aerobic bacteria was better than aerobic bacteria. The formed biofilm thickness was 518 μm for M_4 under the water flow rate of 0.09 m/s culture condition. Flow velocity value of 0.09 m/s could transport high diameter matter, but with high velocity condition, microbes and organic matter find it difficult to attach to material surface [17,24]. Besides, in high speed flow conditions, shear force occurs and scours the biofilm and nutrient of material surface, causing the biofilm thickness to become thinner than M_2 and M_3. Li et al. [25] studied the effect of hydrodynamic regime on microbial communities within fluvial biofilm and indicated that at flow velocity <0.041 m/s, roughness Reynolds number was <1,750, and bacterial abundance began to increase with the increasing flow velocity. The bacterial abundance reached highest diversity level in the flow velocity from 0.041 to 0.061 m/s with roughness Reynolds number from 1,750 to 2,400. But, in flow velocity >0.061 m/s and roughness Reynolds number >2,400, the bacterial abundance started to decrease with the increase of flow velocity due to the detachment of biofilm. M_4 biofilm structure has filamentous structure. According to the distribution of DO, it indicated that the development of oxic layer was better than anoxic layer. In addition, high velocity can decrease the community diversity of microbes that could cause a reduction in the removal of nutrient capability of the biofilm, therefore, M_4 biofilm can have low efficiency in the removal of water nutrients. Wang et al. [26] investigated the effect of flow velocity on the distribution and composition of EPS in biofilm demonstrated that the thick biofilm which was formed in intermediate velocity as 0.1 m/s, was high growth rate and thickness but less EPS content. However, thin biofilm which was formed in high velocity (0.28 m/s) has lower growth and thickness but high EPS content. The result proved that high flow can simulate biofilm of microbial secrete more EPS to respond to the high strength hydraulic condition and stable biofilm structure.

Microbial cultured in flow rate of 0.01 m/s condition showed worst formation of biofilm and that cultured in flow rate of 0.03 m/s condition showed the best formation of a biofilm. Jalil et al. [27] studied about upflow velocity on performance and biofilm characteristics in treating high-strength wastewater indicated that the average biomass concentration gets highest value as 15.5 g Vss/L and biofilm thickness as 352 μm after 48 h in upflow velocity as 0.05 m/min (=0.008 m/s) of condition, the biomass and biofilm thickness decreased when upflow velocity gets increased. Rodrigues et al. [28] investigated the effects of flow velocity and humic substances (Hss) concentration on biofilm which showed that the velocity was increased from 0.04 to 0.1 m/s without Hss, volatile suspended solids (Vss) of biofilm varied from 34.3 ± 1.7 to 89.7 ± 5.1 g/m^2, and in velocity 0.1 m/s, volatile suspended solids and total countable cells were highest.

In this study, it is confirmed that the biofilm thickness and water treatment effect would improve if flow velocity increases and the flow velocity rate of 0.03 m/s is best for biofilm culture and formation. At the flow velocity with 0.03 m/s, the thickness of M_1, M_2, M_3 and M_4 biofilms was 511, 694, 603 and 549 μm, respectively. Results show that M_1, M_2, M_3 and M_4 biofilm thickness gets increased with flow velocity of 0.03 m/s. It proves that at hydraulic condition with velocity as 0.03 m/s is best for growing of biofilm. At the similar hydraulic conditions, the DO concentration distribution and biofilm structure tends to be similar (Fig. 10).

3.3. Water quality improvement experiment in simulated river device

At a water flow velocity rate of 0.03 m/s, the effect of biofilm structure was tested on the improvement of water quality. Water purification effect became better with the

change of four kinds of biofilm structure as shown in Table 3 and Fig. 11. After 6 d HRT, the COD removal ratio of four different biofilm structures was 46.36%, 59.21%, 52.17% and 49.47%, respectively. Because M_2, M_3 and M_4 biofilm structure were thicker, large of microbial existed and exerted the role of organic master of decomposition and transformation. However, M_1 biofilm was thin in which less of microbial existed, therefore, its organic matter of decomposition and transformation was relatively weak.

The NH_3–N removal ratio of four different biofilm structures was 51.56%, 74.07%, 66.67% and 62.18%, respectively. As M_2, M_3 and M_4 biofilm had filamentous structure, thus aerobic bacterial colonies accounted for a higher ratio. Aerobic bacteria can play the role of absorption or oxidation of NH_3–N to convert it to NO_3–N for decreasing ammonia nitrogen concentration.

The NO_3–N removal ratio of four biofilm structure devices was 51.42%, 54.25%, 36.54% and 33.49%, respectively. M_1 and M_2 biofilms have deep anoxic layer that exist large number of anaerobic bacteria and reduced NO_3–N concentration, which can be achieved through the bacterial absorption or denitrification of NO_3–N to N_2.

TN removal ratio in four devices with different biofilm structures was 46.18%, 55.47%, 46.01% and 42.80%, respectively. M_2 biofilm structure has a greater thickness and development of aerobic and anoxic layer was better, that could play a greater role in nitrification, denitrification and decomposition to decrease nitrogen concentration.

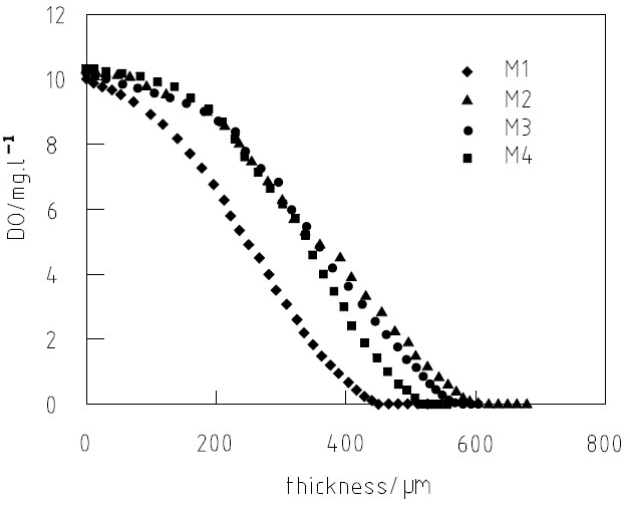


Fig. 10. DO concentration and biofilm structure after 6 d in natural water condition with 0.03 m/s.

The TP removal ratio of four biofilm structure was 44.58%, 62.90%, 48.19% and 45.75%. Microbial of biofilm can go through metabolic process to absorb phosphorus to satisfy microbial cell growth and reproduction. Besides, microbes can play a role in adsorption of phosphorus in cell. At last, biofilm has high glue performance that can intercept and fix floating phosphate organic and mineral. However, M_2 biofilm structure has deeper thickness that has large amount of microbial species. Therefore, it could play a role in phosphorus adsorption and accumulation to remove phosphorus.

3.4. Water purification mechanism of porous concrete

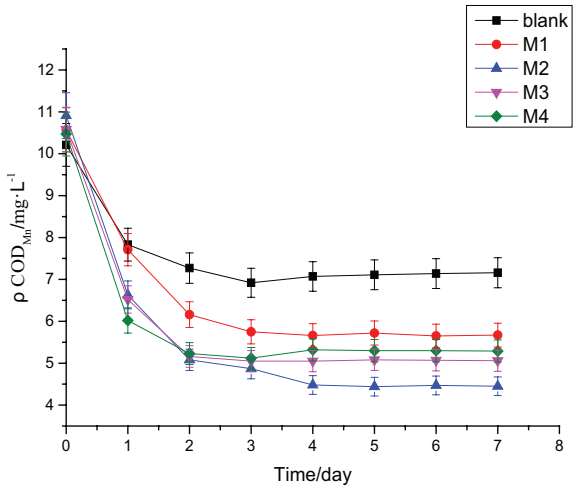
3.4.1. Sequence information and the diversity index

Sequence information and the diversity index are shown in Table 4. Chao index is often used to estimate the total number of species in ecology. Abundance-based coverage estimators index (ACE index) is also used to estimate the number of operational taxonomic units (OTUs). The total number of species was high based on Chao and ACE index. Total number of species in order from high to low is 8# > 7# > 5# > 4# > 1# > 3# > 6# > 2#. Shannon index and Simpson index were used to estimate the microbial community diversity in the sample. Higher Shannon index result represents the higher community diversity, whereas higher Simpson index also suggest the lower community diversity. Microbial community diversity from high to low order is 5# > 8# > 4# > 7# > 6# > 1# > 2# > 3# [29–31].

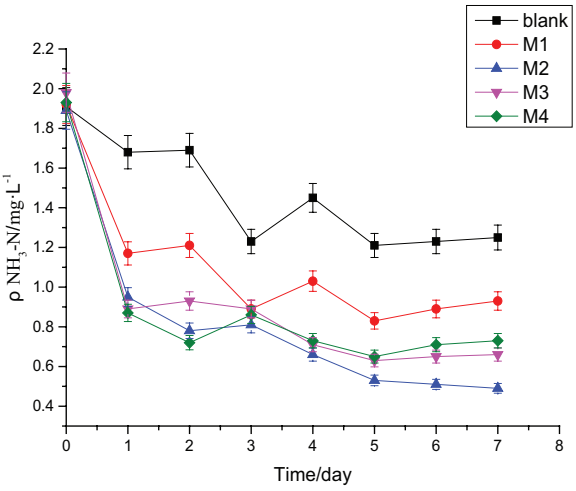
The total number of species and community diversity of suspended microbes in an experiment device are generally lower than the freshwater. The total number of species and community diversity of attached microbes in the surface and interior of porous concrete is higher than the suspended microbes present in freshwater. Sample 8# was taken from the interior of porous concrete plant, and sample 7# was taken from the bottom of the plant. Because of the scouring strength of water flow on sample 7# and sample 8# location, was relatively weak; in addition, the high nutrient concentration content in sediment that deposit at device bottom or accumulate in void of porous concrete, caused total number of microbial species of sample 8# were higher than sample 7#. Sample 5# was taken near the water, where the water level

Table 3
Water purification effect in different flow velocities

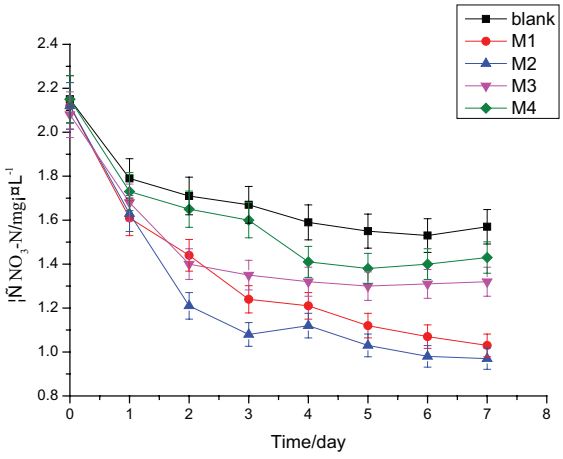
Biofilm structures	Water purification effect							
	M_1		M_2		M_3		M_4	
	0 d	7 d	0 d	7 d	0 d	7 d	0 d	7 d
COD_{Mn} (mg/L)	10.57	5.47 ± 1.82	10.91	3.65 ± 2.51	10.58	5.56 ± 1.83	10.47	5.69 ± 1.76
NH_3–N (mg/L)	1.92	0.93 ± 0.35	1.89	0.62 ± 0.43	1.98	0.86 ± 0.41	1.93	0.73 ± 0.47
NO_3–N (mg/L)	2.13	1.13 ± 0.35	2.12	0.83 ± 0.46	2.08	1.24 ± 0.29	2.15	1.33 ± 0.30
TN (mg/L)	5.37	2.94 ± 0.83	5.34	2.07 ± 1.13	5.23	2.74 ± 0.85	5.21	2.92 ± 0.81
TP (mg/L)	0.249	0.13 ± 0.040	0.248	0.102 ± 0.050	0.247	0.109 ± 0.050	0.247	0.094 ± 0.050
Biofilm thickness (μm)	494	511	612	694	566	603	518	549



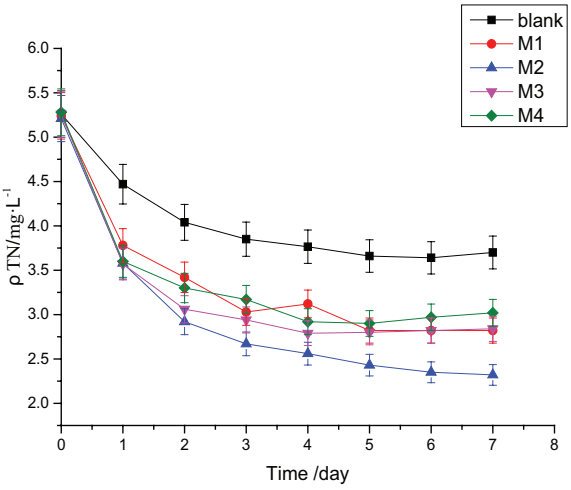
(a) COD_{Mn}



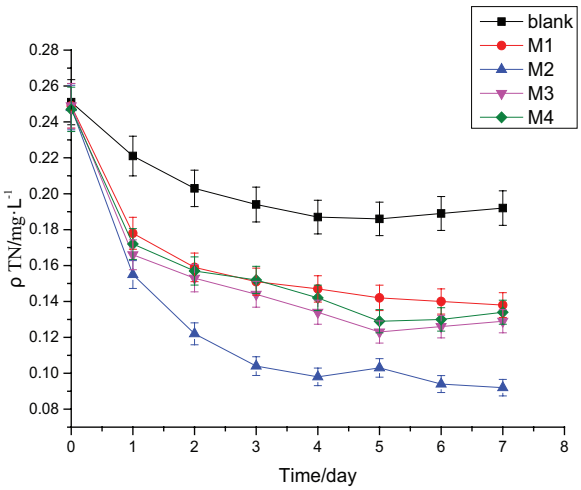
(b) NH_3-N



(c) NO_3-N



(d) TN



(e) TP

Fig. 11. Changes of the water quality indicators in simulated river device.

Table 4
Sequence information and the diversity index

Number of samples	Reads		Diversity index (3% cutoff)				
	After trim	Unified sequencing depth	OTUs	Chao	Shannon	ACE	Simpson
Sample 1#	44,750	30,905	6,763	15,889.085	6.783135	29,037.458	0.008712
Sample 2#	36,075	30,905	5,986	12,434.575	6.371754	20,805.174	0.013939
Sample 3#	36,187	30,905	5,963	14,190.431	6.244056	25,849.694	0.015417
Sample 4#	30,994	30,905	8,973	17,814.774	7.853358	30,215.282	0.001684
Sample 5#	33,923	30,905	9,275	18,310.133	7.973866	28,604.250	0.001434
Sample 6#	30,905	30,905	7,336	14,185.051	7.183864	22,398.087	0.00647
Sample 7#	35,023	30,905	8,785	18,525.985	7.653868	30,783.832	0.002929
Sample 8#	61,578	30,905	9,298	23,381.157	7.855577	44,097.948	0.001637

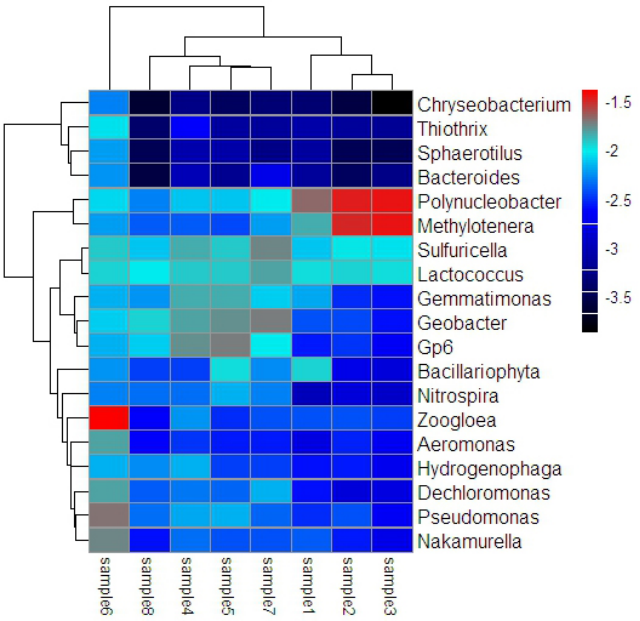


Fig. 12. The classification of microbial species up to the genus level.

usually has exchange. It is easy for various microorganisms to breed as the dry and wet alternate environment. Microbial community diversity of sample 5# was highest whereas it was second highest in sample 8#.

3.4.2. Species classification

Through high sequencing technology, bacterial amount of 337, 344, 311, 292, 379, 383, 393 and 369 were detected, respectively, in eight samples. Species were classified according to the genus. At least 0.5% of the sample content was used to draw the classification of the microbes at genus level (Fig. 12). Results reveal that the species composition of sample 2# and sample 3# is basically the same, but different from the freshwater of sample 1#. Relative to the freshwater, *Polynucleobacter* and *Methylotenera* contents were significantly high. Wu and Hahn [32] found that *Polynucleobacter* widely exists in freshwater lake and rivers, and the bacteria are mainly affected by pH and temperature by the research of Mondsee lake, Taihu lake and Kleine lake. As the porous concrete will slowly release alkaline and the water in device was less, the water temperature of device was higher than the river during the day. Therefore, the *Polynucleobacter* in sample 2# and sample 3# were higher than the sample 1# having freshwater. Kalyuzhnaya et al. [33] found that *Methylotenera* belongs to methyl nutritional bacteria. The bacteria mainly decompose carbon compounds and ammonium (NH_4^+) simple compounds.

The amount and diversity of microorganisms attached to the porous concrete were significantly higher than the water suspended microbes. Among them, *Sulfuricella*, *Gemmatimonas*, *Geobacter*, *Gp6*, *Nitrospira*, *Zoogloea*, *Hydrogenophaga*, *Dechloromonas* and *Pseudomonas* contents were significantly higher. *Zoogloea* bacteria belong to the aerobic *heterotrophic* bacteria, with a variety of metabolic pathways. Its main role is to combine many bacteria together to form a crumb. *Hydrogenophaga* and *Pseudomonas* are aerobic denitrifying bacteria, whereas *Dechloromonas* and *Nitrospira* belong to the anaerobic denitrifying bacteria and the nitrifying bacteria [34].

4. Conclusions

The compressive strength and water purification ability of porous concrete was highest when the void ratio, size of the aggregate material and water cement ratio were 30%, 10–20 mm and 0.3, respectively. Compressive strength of porous concrete was 8.23 MPa after curing for 28 d. Under the HRT of 6 d, the removal rates of COD_{Mn}, NH_3–N, TN and TP were 54.8%, 65.5%, 42.2% and 12.5%, respectively. After 2 weeks, the microbial culture with different flow velocity conditions (V_1 = 0.01 m/s, V_2 = 0.03 m/s, V_3 = 0.06 m/s and V_4 = 0.09 m/s) resulted in different structural shapes in M_1, M_2, M_3 and M_4 biofilms. In low velocity microbial curvature, forming bacterial have cluster structure state, however, in high velocity microbial culture, forming bacteria have filamentous structure state. Biofilm formed with velocity rate of 0.03 (m/s) has the best structure. In the same velocity V = 0.03 m/s and HRT of 6 d, M_2 biofilm removal rates of COD_{Mn}, NH_3–N, NO_3–N, TN and TP were 59.21%, 74.07%, 54.25%, 55.47% and 62.90%, respectively. Diversity index showed that the sample taken from inside the porous concrete plant had the highest total number of microbial species. Species identification results showed that the microbial community had

both aerobic and anaerobic bacteria. The water contaminants of nitrogen and organic matter can be removed through microbial nitrification and denitrification.

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