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Laboratory Study on Stormwater Runoff Treatment via Sand-Based Micron-scale Pore Pervious Paver

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Abstract: Stormwater runoff samples from a road in China were collected and analyzed for pH, TSS (total suspended solid), TDS (total dissolved solid), COD (chemical oxygen demand), TP (total phosphorus), TN (total nitrogen), Pb, Al, Zn, Fe, Cd, and Mn. Results showed that the pollutant concentrations from road runoff were relatively high. TSS and COD concentrations exceeded the Class B effluent requirement of the Chinese Standards of Pollutant Discharge from municipal WWTPs (wastewater treatment plants). COD, TP, and TN concentrations exceeded Class V of the Chinese Environmental Quality Standard for Surface Water. TSS, Zn, Fe, and Al concentrations exceeded the USEPA (U.S. Environmental Protection Agency) benchmark values. All these indicated proper runoff treatment to avoid negative impacts on the environment is needed. Metal partitioning analysis was conducted and it showed that Pb, Al, Zn, Fe, and Mn exist mostly in particulate forms in the runoff. Thus, gravitational settlement and filtration can still be cost-effective methods for removing most of these metals. Runoff samples were treated through two bench-scale laboratory set-ups, composed of micron-scale pore pervious paver systems and subsoil. The average removal rates of TSS, TP, and TN were 95.2%, 81.8%, 64.1%, and 64.4%, respectively. The removal rates of Pb, Al, Zn, Fe, and Cd also reached 50%-99.2%. The tested sand-based pervious paver has micron-scale pores with good filtration potential. The system can effectively reduce stormwater runoff pollution, thereby reducing the potential for groundwater pollution. In addition, residues and sediments collected from the surfaces of the pervious pavers were also tested. The metallic constituents in the residues and sediments were correlated to these in the runoff. Pb and Cr were low in the residues, but Zn exceeded the Class A limit of the Chinese Control Standard of Pollutants in Sludge for Agricultural Applications. Thus, proper disposal of the solid wastes generated from the pavers is also to be further investigated.

Key words: Pervious paver, stormwater runoff pollution, runoff treatment, sand-based pervious paver, sponge city.

1. Introduction

A few studies on road runoffs in China have shown that the SS (suspended solids) in many samples exceeded the Chinese Class B effluent requirements from municipal WWTP (wastewater treatment plants) [1, 2]. The concentrations of COD (chemical oxygen demand), TP (total phosphorus), TN (total nitrogen), and some heavy metals such as Pb, Zn, and Cd also exceeded the Chinese Class V Standard of Surface Water Quality [3, 4]. Numerical limits on stormwater runoff discharges are not very common. USEPA (U.S. Environmental Protection Agency) adopts a method of runoff benchmark values and publishes pollutant concentration thresholds as an index to evaluate the level of concern [5]. Pollutant concentrations above the benchmark values may directly or indirectly contribute to receiving water degradation or harm human health. Benchmark values can also be used as a reference for pollution control levels to determine whether a facility's stormwater

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pollution prevention measures are being successfully implemented.

Pervious pavers can effectively reduce pollutant concentrations in stormwater runoff through settling, filtration, and adsorption [6]. Due to the variances in the pore sizes, porosity, and wettability, the removal performances vary [6, 7]. The typical pore sizes of most pervious pavers, including pervious concrete and pervious asphalts, are in millimeter-scales. Fletcher et al. [8] summarized studies and estimated that the typical removal rates of TSS (total suspended solids), TN, TP, and metals (Pb, Cu, Cd, Zn, Ni) of these pavers were about 80%, 65%, 60%, and 75%, respectively. Qin [9] studied pollutant removal via pervious pavement structures, and the average removal rates of SS, COD, TP, and TN were 69.85%, 52.10%, 64.77%, and 36.39%, respectively. Pervious pavers with smaller pores can potentially remove more particulate pollutants than those with larger pores. Yao [7] concluded that a sand-based pervious paver with micropores can effectively reduce stormwater runoff pollution, and the removal performances were higher than those of pervious concrete, especially for SS with particle sizes of 100-600 μm.

Two sets of experimental boxes were fabricated to study the performances of a sand-based pervious paver with micron-scale pores. Stormwater runoff samples were collected from a heavily trafficked road in Beijing and were used for the simulated treatment under laboratory conditions. Water quality at both the inlet and outlet was analyzed, and the system's removal rates were calculated. In addition, the filter residue and sediment retained on the surface of the pavers were also analyzed to determine appropriate land disposal methods.

2. Laboratory Setups and Materials

2.1 Laboratory Setups

Experiments were conducted in two open-top glass boxes measuring 912 mm × 462 mm × 1,190 mm. Runoff samples were poured on top of the pervious pavers and the outfall samples were collected at the bottom of the boxes via tubes at the bottom of the subsoil layer. See Fig. 1 for a sketch and a photo of the laboratory setups.

2.2 Materials

Pervious paver systems were installed in layers in the experimental boxes, as same as typical field installations [10], which is shown in Fig. 2. Setups of Layers 1 to 5, from top to bottom, are described below.

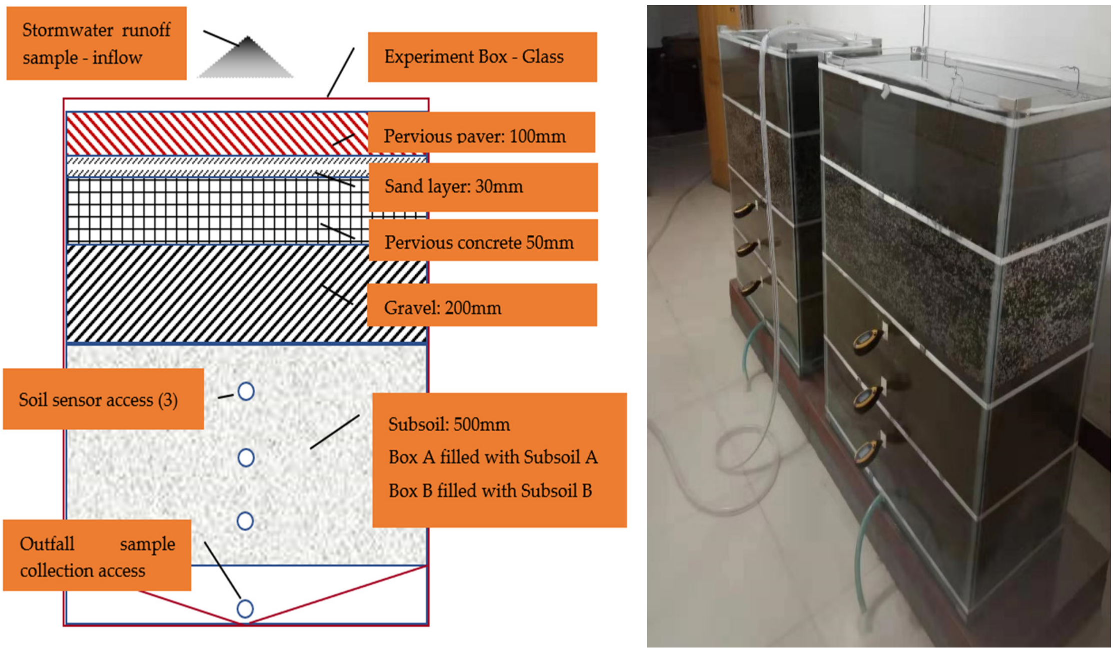

Fig. 1 Experimental set-ups: conceptual illustrations (left) and photo (right).

Fig. 2 Sand-based paver—typical field installation.

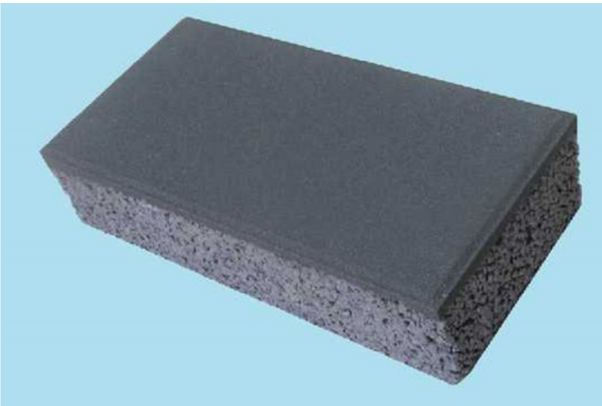

Fig. 3 Sand-based paver used in the experiment

2.1.1 Layer 1: Sand-Based Pervious Paver with Micropore Features

The top layer is the pervious brick which is manufactured by Rechsand Science and Technology Group [11], as shown in Fig. 3. The material is made from coated silica sands, with special resins to form bricks without sintering processes. The typical D_{50} pore size is 75 μm, which is much smaller than most conventional pervious pavers.

2.1.2 Layer 2: Base Sand Layer

Base sand of 30 mm was applied under the sand-based paver with a minimum infiltration rate greater than 0.02 cm/s.

2.1.3 Layer 3: Pervious Concrete Subbase Layer

A 150 mm pervious concrete layer was installed under the base sand layer, with an infiltration rate greater than 0.02 cm/s.

2.1.4 Layer 4: Gravel Subbase Layer

Under the previous concrete layer was a 200 mm of gravel sub-base layer.

2.1.5 Layer 5: Subsoil Layer

Subsoils of 500 mm were installed at the bottom below the gravel. Two types of subsoils were obtained from the Miyun District in Beijing. No. 16 sieve was used when samples were collected, to remove stones and debris before the installation. The soil properties are listed in Table 1.

Gravels and perforated tubes were used to collect outfall samples at the bottom of the boxes.

3. Methodology

3.1 Stormwater Runoff Sample Collection

Grab samples were collected during two storm events from a local road surface in Miyun Economic Development Zone in Beijing (GPS coordinates: 40°21′31″ N, 116°48′28″ E), as summarized in Table 2.

Table 1 Soil properties.

Subsoil	Sampling depth	Infiltration rate (cm/s)	% of mass 0.05-2 mm	% of mass 0.002-0.05 mm	% of mass < 0.002 mm	D_{50} (mm)	D_{10} (mm)
A	0.5-1 m below surface	2.1×10^{-4}	94.77	5.01	0.22	0.14	0.068
B	At surface	4.7×10^{-3}	92.66	7.05	0.29	0.50	0.057

Table 2 Rainfall events.

	Date of the event	Event precipitation (mm)	Antecedent dry days (day) 错误!未找到引用源。
Event #1	2019/10/24	4.8	5
Event #2	2020/4/19	2.5	4

Table 3 Tested flow conditions.

	Runoff sample used	Inflow duration (min)	Equivalent rainfall intensity (mm/h)	Equivalent rainfall depth (mm)	Equivalent rainfall intensity in Beijing [12]
Experiment #1	Event #1	40	253	190	Peak 100a, 10 min intensity (240 mm/h）
Experiment #2	Event #2	135	105	237	Peak 100a, 60 min intensity (120 mm/h)

The collected stormwater runoff samples were well stirred in large containers and then spread onto the top of the pervious pavers in the boxes. Table 3 summarized the inflow and the equivalent rainfall intensity in the experiments.

Stormwater runoff samples were infiltrated through the system in the boxes, and effluent samples were collected at the outfalls.

3.2 Water Sample Analysis

Composite inflow and outflow samples were sent to a certified laboratory and tested for turbidity, pH, TSS, TDS, COD, TP, TN, and metals (Pb, Al, Zn, Fe, Cd, Mn). Turbidity was determined by spectrophotometric method; pH was determined by glass electrode method; suspended solids were determined by 0.45 μm paper filtration followed by dry weighing method; COD was determined by dichromate method; TP was determined by ammonium molybdate spectrophotometric method; TN was determined by alkaline potassium persulfate ablation UV (ultraviolet) spectrophotometric method; metals in water were determined by inductively coupled plasma emission spectrometry, for both total metals and dissolved metals (filtrate through the 0.45 μm standard filter paper).

3.3 Sediment Sample Analysis

Since the surface of the pervious bricks tested is smooth, collection of the filter residue and sediment on the surface of the brick was possible. After each experiment, the filter residue and sediment were carefully brushed into metal containers and dried at 105 °C before being sent to a certified laboratory. Metallic elements (Pb, Al, Zn, Fe, Cd, Mn) and organic material composition were determined using Standard JY/T 015-1996 for General Guidelines for Inductively Coupled Plasma Atomic Emission Spectrometry Methods and NY/T 1121.6-2006 for Soil Testing-Determination of Organic Matter, respectively.

4. Results and Discussion

4.1 Stormwater Runoff Quality

Constituent concentrations in the stormwater runoff are summarized in Table 4. The results were compared with some local standards and USEPA benchmark values.

The concentrations of COD and TN in both runoff samples were higher than the Chinese Class V Standard of Surface Water Quality, and TP in one of the two runoff samples was higher. The TSS and COD concentrations were also higher than the Chinese Class B effluent requirements from municipal WWTPs, and the TP and Zn in one of the two runoff samples were higher. These exceedances indicated that the runoff water quality could be worse than some seriously degraded surface water and higher than some WWTP effluents, which is similar to some findings by other studies [1-4]. Compared with the USEPA benchmark values, Cd and Mn in both runoff samples were relatively low. However, TSS, Zn, Fe, and Al were all higher than the benchmark values. These exceedances indicated the potential runoff pollution to the degradation of receiving water quality may be harmful to human health.

In summary, pollution concentrations and potential impacts from stormwater runoff collected are substantial. To reduce environmental impacts, proper management and treatment are needed to reduce pollutant concentration before it is discharged to surface water or recharged to groundwater.

Table 4 Characteristics of stormwater runoff quality.

Constituents	Event #1	Event #2	Surface water quality Class V [13]	WWTP effluent requirements Class A [14]	WWTP effluent requirements Class B [14]	USEPA benchmark values [5]
TSS (mg/L)	173	1,255	-	10	20	100
COD (mg/L)	76	272	40	50	60	120
TP (mg/L)	0.2	1.1	0.4	0.5	1	2
TN (mg/L)	12.7	2.4	2.0	15	20	-*
pH	7.39	7.21	6-9	6-9	6-9	6-9
Pb (mg/L)	0.042	0.1	0.1	0.1	0.1	0.0816
Zn (mg/L)	0.664	1.23	2.0	1.0	1.0	0.117
Fe (mg/L)	7.74	39.8	-	-	-	1
Cd (mg/L)	0.0012	Not detected	0.01	0.01	0.01	0.0021
Mn (mg/L)	0.19	0.87	-	2.0	2.0	1
Al (mg/L)	6.06	29.4	-	-	-	0.75

* USEPA has published a benchmark value of nitrate & nitrite nitrogen based on NURP EMC. There is no benchmark value for total nitrogen.

4.2 Metal Partitioning

Metal partitioning in the stormwater runoff samples is shown in Fig. 4. Particulate metals (Pb, Zn, Fe, Mn, and Al) are relatively high, averaging 50% to 99.7% of the total. Therefore, treatment processes such as gravitational separation and filtration will be effective practices to reduce metal concentrations in such stormwater runoff.

4.3 Removal Rates via the Pervious Paver System

The removal rates by the pervious paver systems are summarized in Table 5.

The results showed that the average removal rates for TSS, TP, and TN, were 81.8%, 64.1%, and 64.4%, respectively. Good removal rates for metals other than Mn were also achieved. The overall pollutant removal performances are higher than many reports using conventional large pore pavers. Experimental Box A (with subsoil A, longer residence time), in general, performed better in removal than Experimental Box B (with subsoil B, shorter residence time). For TDS, COD, and Mn, the effluent concentrations were higher than those in the influent, due to the possible precipitation from the freshly installed materials. The pH readings were slightly elevated, which is possible because of the

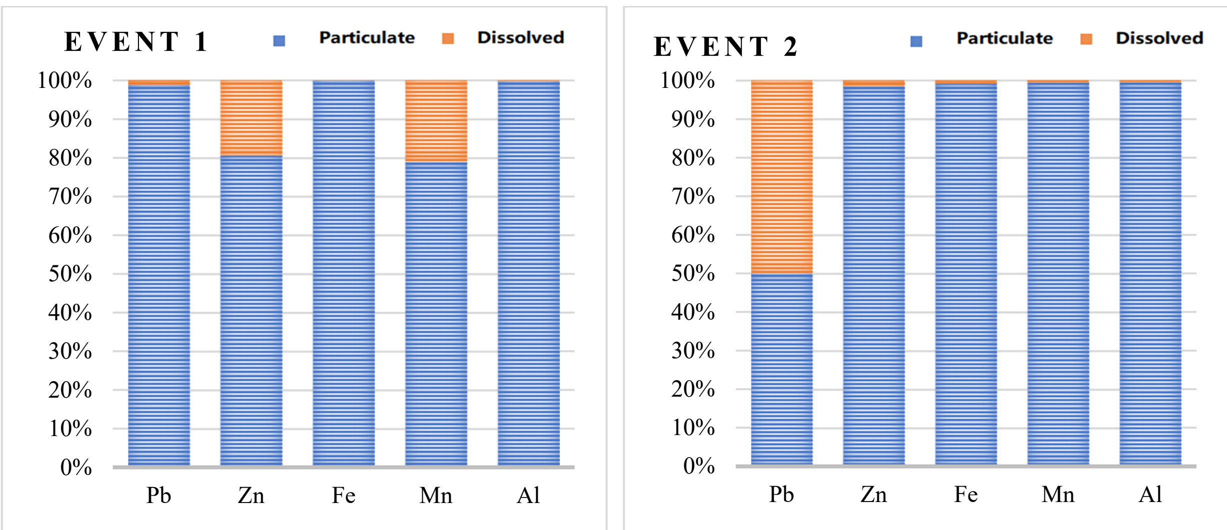

Fig. 4 Metal partitioning in the stormwater runoff—Storm Event #1 (left) and Storm Event #2 (right).

Table 5 Removal rates of constituents.

Constituents	Experiment #1[a]		Experiment #2[a]	
	Box A Subsoil A	Box B Subsoil B	Box A Subsoil A	Box B Subsoil B
pH	7.39 to 7.97	7.39 to 8.39	7.21 to 7.51	7.21 to 8.02
TSS	80.9%	77.5%	92.0%	76.8%
TDS	-15031%[b]	-10755%[b]	-236%[b]	-515%[b]
COD	-17%[b]	-25%[b]	76.3%	-25%[c]
TP	80.0%	20.0%	77.3%	79.1%
TN	60.7%	42.5%	66.3%	87.9%
Pb	83.3%	73.8%	50%[c]	50%[c]
Zn	97.9%	97.7%	96.7%	96.2%
Fe	98.3%	95.3%	99.0%	63.8%
Cd	91.7%	50.0%	-[d]	-[d]
Mn	89.5%	0%[b]	14.9%	-2107%[b]
Al	99.2%	98.9%	93.9%	93.5%

[a] pH shown are readings at the inflow and the outflow. Other values are the removal rates calculated: (inlet concentration - outlet concentration)/(inlet concentration)×100%

[b] Negative removals: the constituent concentration in the outflow was higher than that in the inflow, possibly because of released constituents from the previous paver system and/or subsoil.

[c] Constituents were not detected in the outflow samples. One-half of the detection limit was used in the calculation.

[d] Constituents were not detected in the outflow or the inflow samples.

Table 6 Organic and metal composition in the sediments.

Composition	Event #1 Sediment (mg/kg)	Event #2 Sediment (mg/kg)	Typical Sludge from WWTP [15]	GB 4284 Sludge Standard for Agricultural Applications [16]	
				Class A[a]	Class B[b]
Organic residues	214,000	187,000	-	-	-
Al	33,100	24,300	-	-	-
Fe	20,100	26,300	-	-	-
Zn	1,340	821	729.6	1,200	3,000
Mn	470	530	-	-	-
Pb	154	62.3	65.3	300	1,000
Cd	Not detected	1.9	2.1	3	15

[a] Class A requirements refer to cultivated lands and farmlands for food production.

[b] Class B requirements refer to cultivated lands that can be used for gardening and landscapes only where lands are not allowed for food production.

release of alkalis from the pavers and concretes. This 0.5-1.5 pH increase was also gradually observed by the soil sensors (Fig. 1) during the experiment.

4.4 Sediment Properties and discussion on Sediment Disposal

The composition of the filter residue and sediment is summarized in Table 6.

The filter residue and sediment sample analysis showed that the organic component is 18.7% to 21.4% by weight. The metal compositions in these sediments, from high to low, are Al, Fe, Zn, Mn, Pb, and Cd. The average concentrations of Zn, Pb, and Cd in the runoff sediment are close to these in the typical sludge from a WWTP. Compared to GB 4284—Sludge Standard for Agricultural Applications [16], Zn exceeded the Class A requirement in one of the two samples, preventing it from disposal in cultivated lands and farmlands for food production.

Metals in the filter residue and sediment were compared with the constituents' concentration in the runoff. Fig. 5 shows that these two sets of data are correlated in liner formation. This could be because of similar metal

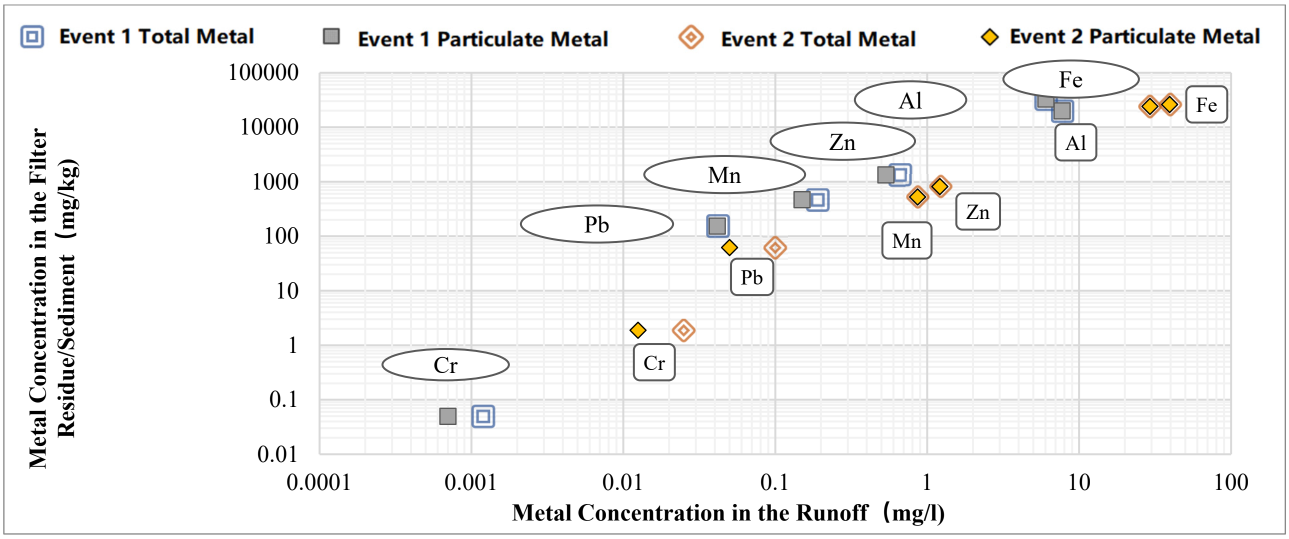

Fig. 5 Metals in the residue and sediment vs. these in the stormwater runoff.

partitioning and removal. Since the collection of sediment is not easy in many pervious paver applications, knowing the runoff quality may provide some useful information about the sediment properties.

5. Conclusions

Some pollutant concentrations in the stormwater runoff collected were found to be high, especially TSS, Zn, Fe, and Al, which exceeded the USEPA benchmark values. Some pollutants also exceeded Chinese Class V surface water standards and WWTP effluent requirements. Stormwater runoff contamination is significant, highlighting the need for appropriate management and treatment. Metal partitioning studies showed that particulate matter is the predominant form of metal present.

The sand-based pervious paver system with micron-scale pores has proven to be efficient in removing pollutants from stormwater runoff. The removal rates of TSS, TP, and TN were 81.8%, 64.1%, and 64.4%, respectively, which are higher than many conventional pavers. Removal rates of metals, other than Mn, were 50% to 99.2%. More comprehensive studies in the future are recommended to further explore the advantages of using the finer-pored pavers.

The metal contents in the filter residue and sediment of the paver included Al, Fe, Zn, Mn, Pb, and Cd, in order from high to low. They also showed a good correlation with the metal concentrations in the runoff. Since Zn exceeds the Class A threshold for agricultural land applications, the sludge cannot be used on lands for food production. Thus, safe disposal of solid wastes generated from pavers, such as street sweeping, is crucial to mitigate the risks of secondary pollution.

Acknowledgements

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