Emission Characteristic Analysis on Highway Rainwater Runoff Pollution of Asphalt Pavement

Tao Shuangcheng¹, Xiong Xinzhu¹, Li Lingyun², Chen Chengyong³, Li Hua⁴ and Kong Yaping¹

¹China Academy of Transportation Sciences, Beijing, China, 100029
²Qinghai Traffic Investment Company Limited, Xining, Qinghai Province, China, 810003
³Qilu Transportation Development Group, Jinan, Shandong Province, China, 250101
⁴China Highway and Transportation Society, Beijing, China, 100011
E-mail: tsc504@126.com

Abstract. In order to investigate the emission characteristics of rainwater runoff pollution from highway with asphalt pavement, simultaneous monitoring method of rainfall-runoff-pollutants was adopted. During 2006 to 2009, rainfall runoff samples from six asphalt pavement highways in 3 typical areas were collected and monitored, including Pearl River Delta Region in South China, Chongqing Province in South-west and Qingdao in East China. Results showed that average concentrations of SS, COD, TN and TP in runoff samples exceeded the Class V standard of surface water defined in Environmental Quality Standard for Surface Water (GB3838-2002). SS was the main pollutant of the highway asphalt pavement runoff, and was an important carrier of other major pollutants (such as heavy metals and chemical oxygen demand, COD) as well. The dust particle size of expressway road surface was generally small (more than 90 % less than 2mm). There was a big difference in concentrations of the same pollutant in particles with various sizes. Pollutant concentrations were increased with the reduction of particle size. Pavement runoff was less biodegradable and the ratio of BOD5/COD was 0.0188. Therefore, the ecological ditch combining percolation and drainage was proposed to purify the highway asphalt pavement runoff.

1. Introduction
Road runoff is a type of surface runoff with single function [1]. Frequent traffic activities have led to serious surface runoff pollution [2, 3]. The US Environmental Protection Agency has listed it as the third main source of contamination in rivers and lakes. With the rapid development of the expressway and the basic formation of road network in China, the environmental impact of road runoff on the surrounding sensitive water bodies has become increasingly prominent [4]. It is of great theoretical and practical significance to strengthen the research on the characteristics and rules of road runoff pollutants discharge in typical areas in China and provide a theoretical basis for the prevention and control measures for road runoff pollution projects [5].

Since the 1970s, lots of researches on road rainfall runoff have been carried out from different perspectives both domestic and overseas. The diachronic characteristics of runoff, initial erosion discipline, average pollutant concentration and sedimentation characteristics of event rainfall runoff have been studied [6, 7]. A number of characteristics analysis on the runoff pollution from different material pavement [8] especially the asphalt pavement [9] have been conducted. The research on
control technology of urban road runoff pollution mainly includes technologies such as ecological ditch [10], grass planting ditch [11] and pervious asphalt pavement purification technique [12, 13].

In recent years, monitoring and analysis on urban road runoff quality has also been carried out in Xi’an [14] and Chongqing [15]. Unfortunately, due to the limitation in bad weather and other sampling conditions, insufficient information has been published concerning asphalt pavement rainfall runoff pollutants emission and pollutant control. Most of the research is limited to a certain road. Little work has been done on highway runoff pollution in typical areas such as east, southwest and south China, where road network density is higher and water environment is more sensitive. In this paper, several typical highways were selected to conduct runoff tests of asphalt pavement in southwest, south China and eastern regions of China. Analysis had been carried out on the characteristics of pollutant discharge on expressway pavement rainwater runoff and the correlation between the indicators of pollutants. Measures suitable for highway pavement runoff purification were proposed, providing reference for the prevention and control of runoff pollution from asphalt pavement in expressway.

2. Materials and methods

2.1 Study Area Overview
The typical highways in areas with high density of road network, better road conditions, more developed economy and large traffic flow rate of trucks were studied, such as the Pearl River Delta in South China, Chongqing in the Southwest, and Qingdao in the East China. Figure 1 shows the study areas location. Considering the factors such as traffic flow rate, term of operation, sampling condition, six highways were selected to conduct highway runoff sampling and monitoring tests, including Guangzhou-Sanshui Expressway (Guangsan Expressway), Foshan-Kaiping Expressway (Fokai Expressway) and Foshan Ring Expressway in the Pearl River Delta, Chongqing-SichuanWusheng Expressway (Yuwu Expressway) and Chongqing Ring Expressway, and Qingdao-Yinchuan Expressway (Expressway) in Qinghai Province. The basic information of selected highways was listed in Table 1, including the traffic open time, the number of lanes, pavement materials and vehicles flow rate.

![Figure 1. Study Area location](image)

Table 1. Basic situation of expressway for road runoff experiment

| No. | Highway     | Lane number | Traffic flow rate | Open year | Pavement material         |
|-----|-------------|-------------|-------------------|-----------|---------------------------|
| 1   | Guangsan    | 4-lane      | 45000 veh/d       | 1994      | asphalt pavement          |
| 2   | Fokai       | 4-lane      | 70000 veh/d       | 1996      | asphalt pavement          |
| 3   | Foshan Ring | 8-lane      | 20000 veh/d       | 2006      | asphalt pavement          |
| 4   | Yuwu        | 4-lane      | 32000 veh/d       | 2002      | asphalt pavement          |
2.2 Sampling and analysis methods
According to the regional weather forecast conditions on the highway, runoff samples were immediately collected when it was rainy. Each sample was collected at intervals of 5 min within 60 min since the initial runoff formed. And then each sample was collected at intervals of every 15 min, until the end of the rainfall event. Three parallel samples with 1000 ml volume were synchronously acquired in each time period. In addition, rainfall characteristics were recorded with a JDZ-1 digital rain gauge at a distance of 150 m from the sampling point. Road dust samples were collected in hand sweeping way during a period more than 3 days with no precipitation in April 5 to April 7, 2009.

Water samples were frozen in cold storage immediately after collection. In addition, 1ml potassium iodide and 2ml potassium permanganate were dropped in water samples for BOD5 test. Water quality analysis items included pH, SS, COD, BOD5, TN, TP, Cu, Zn, lead (Pb) and petroleum. Guided by Determination methods for examination of water and wastewater, pH was determined by the glass electrode method, SS by gravimetric method, TN by UV spectrophotometry, TP by ammonium molybdate spectrophotometry, BOD5 by dilution inoculation method, COD by dichromate method, Cu, Zn, Pb by atomic absorption spectrophotometry, and petroleum by infrared spectrophotometry.

After the road surface dust sample collection, it is naturally dried in a cool and ventilated place and sieved evenly to remove impurities such as stones, leaves and melon seeds with a standard sieve of 2.0 mm, 1.0 mm, 0.25 mm and 0.15 mm, and to determine the contamination of various particle sizes. Guided by Principles and Applications of Agricultural Environmental Monitoring, the dust samples were monitored and analyzed, in which pH was determined by potentiometric method, TN by semitrace Kjeldahl method, TP by molybdenum-antimony colorimetric method, Cu, Zn and Pb by aqua regia-perchloric acid complete digestion atomic absorption spectrophotometry. In order to ensure that the analysis results were reliable, all of the above tests were carried out simultaneously in parallel experiments, blank experiments and standard control.

3. Results and discussion

3.1 Runoff pollutant concentration characteristics
Main pollutant concentration monitoring results were shown in Figure 2, which included six highway asphalt pavement rainfall runoff, that is, highways in the Pearl River Delta region of Guangdong (1 # Guansan Expressway, 2 # Fokai Expressway and 3 # Foshan Ring), Chongqing (4 # Yuwu Expressway and 5 # Ring Expressway) and Shandong Qingdao (6 #).

Concentration of pollutants in the asphalt pavement of the expressway in different regions varies widely, even though the pollutant concentrations of runoff on different highways in the same area are quite different. Guansan Expressway, Fokai Expressway and Chongqing Yuwu Expressway have much higher pollutant concentrations than other expressways. The pollutant concentrations at Qingying Expressway are much lower than those in other areas. The reason is believed to be related to the road traffic flow rate, that is, the traffic flow rates of Yu Wu Expressway, Guansan Expressway and Fokai Expressway were more than 30,000 vehicles per day while that of Qingying Expressway was only 1,440 vehicles per day. Regional differences in road runoff pollutant concentration are not significant, but traffic flow rate is one of the main factors affecting the pollutant concentration [16].

Expressway asphalt pavement rainfall runoff was in a complex pollutants composition and in a high degree of pollution. The average concentrations of SS and COD in runoff of Guansan Expressway, Fokai Expressway and Yuwu Expressway were 2.21 times and 5.62 times, 2.55 times and 11.81 times, 2.14 times and 8.71 times higher than the concentration limits of Class V surface water (SS 200 mg/m3, COD 40 mg/m3) required in Environmental Quality Standard for Surface Water (GB3838-2002), respectively. And they were around 62.89 times and 2.25 times, 7.28 times and 4.72 times, 6.11 times and 3.79 times higher than the first grade limitation in Integrated Wastewater Discharge Standard (GB8978-1996) (SS 70 mg/m3, COD 100 mg/m3) respectively, which even exceed the limitation of Water Quality Standard of Farmland Irrigation (SS 150 mg/m3, COD 200
mg/m³). It can be considered that the major pollutants in runoff of expressway asphalt pavement are SS and CODCr. Surface runoff with high concentrations of SS and COD directly discharged into surface water bodies along the road will inevitably have a bad impact on the quality of surface water environment.

Concentrations of Cu and Zn in the runoff on expressway asphalt pavement are all far lower than the threshold value of Class V (Cu 1.0 mg/m³ and Zn 2.0 mg/m³) in Surface Water Environmental Quality Standard. This study also found that Pb average concentration in rainwater runoff of Yuwu Expressway and Chongqing Ring Expressway asphalt pavement are 6.3 times and 2.8 times, even 20.6 times higher than the threshold value in the Standard (Pb = 0.1 mg/m³) respectively. It is consistent with the conclusion that Pb concentration exceeded the standard in Xi’an-Lintong Expressway [17]. However, Pb concentrations in surface runoff in the Pearl River Delta and Qingdao areas are generally low, which is slightly different from the results in other studies. The reason for this may be that unleaded gasoline had been promoted in recent years, and Pb in road surface runoff is mainly related to vehicle emissions after the fuel combustion.

![Graphs showing pollutant concentrations](image)

Fig. 2. Pollutant concentration characteristics of pavement runoff on typical Expressway in Pearl River Delta, Chongqing and Qingdao

The maximum values of average concentrations of nutrients such as BOD5, TN and TP in road surface runoff were 1.49 times, 2.92 times and 0.8 times than the threshold value of Class V in surface water standard (BOD5 10.0 mg/m³, TN 2.0 mg/m³, TP 0.4 mg/m³). But those values were far lower
than the threshold value of Class I in Integrated Wastewater Discharge Standard (BOD$_5$ 20.0 mg/m$^3$, TN 15.0 mg/m$^3$, TP 0.5 mg/m$^3$). Therefore, it is unreasonable to simply equate the surface runoff with the discharged sewage to manage it. However, in road sections along sensitive water bodies and high traffic flow rate, emissions of organic pollutants such as TN and TP and heavy metal pollutants such as copper, zinc and lead were supposed to be considered promptly.

3.2 Correlation analysis of runoff pollutants

Some studies showed that there was a correlation between various pollutants in road surface runoff [18]. The correlation between pollutants can be characterized by calculating the correlation coefficient $R$ between pollutants.

$$ R_{X,Y} = \frac{\text{Cov}(X,Y)}{\sigma_X \cdot \sigma_Y} $$

(1)

In which, $R_{X,Y}$ is the correlation coefficients of the two pollutants X and Y; Cov(X, Y) is the covariance of the two pollutant concentrations; $X$ and $Y$ are the standard deviations of this two pollutants.

The pollutant concentrations in runoff in the Pearl River Delta and Chongqing areas were selected to analyze the correlations among the pollutants such as SS, CODcr, BOD$_5$, TP, TN, petroleum, Cu, Zn and Pb. The mean of the coefficients were shown in Table 2 and Table 3.

| SS     | CODcr | BOD$_5$ | TN    | TP    | Petroleum |
|--------|-------|---------|-------|-------|-----------|
| SS     | 1     |         |       |       |           |
| CODcr  | 0.486 | 1       |       |       |           |
| BOD$_5$| 0.762 | 0.751   | 1     |       |           |
| TN     | 0.453 | 0.945   | 0.616 | 1     |           |
| TP     | 0.370 | 0.723   | 0.459 | 0.578 | 1         |
| Petroleum | 0.487 | 0.729   | 0.358 | 0.854 | 0.538     | 1         |

Table 3. Correlation coefficients of different pollutants in Chongqing area (n=55)

| SS     | COD | BOD$_5$ | TN | TP | Cu  | Zn  | Pb  | Petroleum |
|--------|-----|---------|----|----|-----|-----|-----|-----------|
| SS     | 1   |         |    |    |     |     |     |           |
| CODcr  | 0.506| 1       |    |    |     |     |     |           |
| BOD$_5$| 0.193| 0.559   | 1  | 1  |     |     |     |           |
| TN     | 0.712| 0.763   | 0.586| 1  |     |     |     |           |
| TP     | 0.603| 0.346   | 0.490| 0.609| 1  |     |     |           |
| Cu     | 0.458| 0.200   | -0.065| 0.282| 0.242| 1  |     |           |
| Zn     | 0.619| 0.621   | 0.516| 0.750| 0.697| 0.344| 1  |           |
| Pb     | 0.366| 0.691   | 0.583| 0.634| 0.516| 0.256| 0.800| 1         |
| Petroleum | 0.545| 0.760   | 0.492| 0.727| 0.404| 0.195| 0.505| 0.575     | 1         |

It can be seen from Table 2 and Table 3 that the correlation between various pollutants was significant at the level of $R = 0.1$ or above. The correlation coefficient between SS and COD was between 0.486 and 0.505, and that between SS and pesticide was between 0.487 and 0.545. The correlation coefficients between SS and heavy metals (Cu, Zn and Pb) were 0.458 (<0.5), 0.619 (>0.5) and 0.366 (<0.5) respectively, which indicated that the correlation between SS and Cu, Zn was significant and the correlation between SS and Pb was statistically non-significant. In addition, the correlation coefficients between SS and TN, TP showed some differences in various regions. The correlation coefficient between SS and TN, TP in the runoff in the Pearl River Delta were relatively small at 0.453 (<0.5) and 0.37 (<0.5), respectively. And those values in Chongqing area were 0.712
and 0.603 (> 0.5). Therefore, in the control of runoff pollution, it can be considered to effectively remove COD, TN, TP, petroleum and heavy metal pollutants in runoff by controlling SS.

Several indicators showed a slight difference between the Pearl River Delta and Chongqing area. The removal of SS in the Pearl River Delta showed a significant effect on the synergistic control of BOD5 (R = 0.762), but worse in Chongqing (R = 0.193) and need further removal by other means. It can be considered that the effective removal of suspended solids (SS) from road surface runoff along sensitive water bodies was a good way to remove other pollutants (such as COD, TN, TP, petroleum and heavy metals).

3.3 Road surface dust particle size distribution and pollution characteristics

The pollutants in road surface runoff mainly come from the erosion of rainfall. The dust of road surface is the main source of SS and other pollutants in runoff. The composition of road dust has obvious influence on the pollutants composition of road runoff. During the study period, road surface dust samples in Yuwu Expressway and Chongqing Ring Expressway were collected and the mass proportion of different particle size particles was measured, as shown in Figure 3. It can be seen from Figure 3 that the mass fraction of the dust particles with diameter less than 1mm in the road Yuwu Expressway and the Ring Expressway reached 62.84 % and 80.0 % respectively. And the mass fraction of the dust particles with diameter less than 2mm was more than 90 %. It can be seen that the diameter of dusts on the highway was relatively small, and it was highly vulnerable to rainwater erosion into the runoff leading to the un-attainment of SS and other pollutants.

Fig.3. Distribution map of road dust particle size in Chongqing area

Fig.4. Pollutant content in the dust particles of expressways in Chongqing

TN, TP, heavy metals and other pollutants contained in Chongqing area road dust particles in different sizes have been shown in Figure 4. It can be seen from Figure 4 that the TN content of the pollutants contained in the particles in different particle diameters was the highest at 54.39 ~ 534.85 mg/kg and the lowest was Cu at 11.6 ~ 68.88 mg/kg. There was a big difference in concentration of the same pollutant in different particle size, the smaller the particle size, the higher the concentration.
of pollutants. It has been shown that more than 80% of the pollutants accumulate in dusts under 2.0 mm [19], thus enhancing the efficient removal of small particles (<2 mm) from suspended solids (SS) in road surface runoff was the key to the removal of other pollutants.

### 3.4 Biodegradability of runoff pollution

Correlation analysis of BOD$_5$ and COD in rainwater runoff pollutants of expressway asphalt pavement has been shown in Figure 5. The linear correlation between BOD$_5$ and COD concentration in road runoff was not significant, which is $R^2 = 0.4434$. The ratio BOD$_5$/COD of runoff was 0.0188, which was far less than 0.3, indicating the poor biodegradability of runoff contaminants. Therefore, in the process of pavement surface runoff pollutant purification and treatment, the physical and chemical treatment methods (such as filtration, infiltration, precipitation, etc.) were better to be considered in order to achieve better results.

![Fig. 5. Correlation between BOD and COD in pavement run-off](image)

### 3.5 Treatment of Asphalt Pavement Rainwater Runoff with Percolation and Drainage Combined Ecological Ditch

Based on the analysis of the characteristics of runoff pollution, combined with the construction requirements of the drainage ditch of expressway, a kind of freeway drainage ditch based on the combination of percolation and drainage is proposed. The schematic diagram of the ditch cross section is shown in Figure 6. The traditional freeway side ditches (ecological grass ditches or concrete ditches) were reformed, and the seepage drainage pipes were arranged laying along the bottom of the drainage ditches in the length direction. The percolation layers composed of artificial soil or gravel were filled around the seepage drainage pipes. Soil was used to sow seeds or sod the turf above the percolation layer. The indoor test results showed that using fly ash as the matrix of the percolation layer was good to its purification effect. The removal rate of ammonium nitrogen, total nitrogen, total phosphorus, soluble phosphate can reach 30% ~ 45%, 25% ~ 30%, 90% ~ 95%, and 60% ~ 90% respectively. Meanwhile, increasing the vegetation condition would be helpful to improve the removal rate of total nitrogen by 5% ~ 30% [20].

![Fig. 6. Cross section of the percolation and drainage combined Ecological Ditch](image)
coefficient were both increased with the higher coverage of the herbaceous plant [21], which can effectively improve the sedimentation effect of suspended matter, especially small particle size particles (<2 mm) in road runoff. At the same time, the initial rainfall water volume was not that great, but the pollutant concentration was high and can be slowly drained out after it was fully filtered and purified. This process can effectively remove the small size particles and most of the dissolved pollutants from the initial rainfall runoff. With the prolongation of rainfall duration, the amount of runoff water became larger while the pollution level lower. It can ensure the timely discharge of rainwater through the surface drainage of the ditches and the integrated drainage of the seepage pipes, keeping the stability of subgrade and traffic safety.

4. Conclusion
1) Concentration of pollutants in the pavement rainwater runoff of expressway in different areas varies widely, and even that in the same area various relatively large. SS and COD concentrations were higher than the threshold value of Class V in *Surface Water Environmental Quality Standard* and Class I in *Integrated Wastewater Discharge Standard*. However, the average concentration of nutrients such as BOD$_5$, TN and TP were far below the threshold of Class I in *Integrated Wastewater Discharge Standard*. Therefore, it cannot be regarded simply as sewage discharge. The discharge of pollutants from road runoff should be timely considered especially in road sections along the sensitive water bodies and large traffic flow rate.

2) Correlation between SS and COD in road runoff was significant, ranging from 0.486 to 0.505. Correlation coefficient between SS and TN, TP varied in different regions, with 0.453 and 0.37 (< 0.5) in the Pearl River Delta, while 0.712 and 0.603 (> 0.5) respectively in Chongqing area. And the correlation of SS between Petroleum, Cu, and Zn was relatively significant, and that for Pb was non-significant. In the runoff pollution control, it can be considered to control the SS to effectively remove COD, TN, TP, petroleum and heavy metal from the runoff.

3) Dust particle size of expressway pavement was generally small. Mass proportion of dust particle size less than 1mm on the road surface of Yuwu Expressway and Ring expressway reached 62.84 % and 80.0 % respectively. And mass fraction of the dust particles with diameter less than 2 mm was more than 90 %. The concentration of the same pollutant in different particle sizes various largely, the smaller the particle size, the higher the concentration of pollutants. More than 80 % of the contaminants accumulated in the dust with diameters below 2.0 mm.

4) Enhancing the removal of small particles (<2 mm) from suspended solids (SS) in road runoff was the key direction to improve the runoff purification efficiency. Road runoff contaminants were less biodegradable. Physicochemical treatment methods (such as filtration, percolation, sedimentation, etc.) should be considered primarily to achieve better results in runoff pollutant purification and treatment. Based on the theoretical analysis, engineering measures of percolating-draining combined ecological ditch were proposed to be applied on runoff treatment of asphalt pavement.

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