Research on the Pollution Characteristics of Pavement Runoff of the Expressway Project in Qiandao Lake District

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Abstract: This research focuses on the Expressway Project of Qiandao Lake District, investigates the meteorological conditions, traffic volume, as well as the relationship between the quality of runoff at drainage facilities and the asphalt concrete pavement and sewage discharge rules through artificial rainwater and natural rainwater, studies and determines the time scale of the initial rainwater flow on the expressway and the spatial scale that needs to be collected and processed.

1 Introduction

Qiandao Lake and the upper reaches of Xin'an River, as strategic drinking water sources of the Yangtze River Delta, are of great importance to the control of water pollution and ecological environment protection. The Chun'an Section of Qiandao Lake-Huangshan Expressway (hereinafter referred to as "Qianhuang Expressway") Project is located within the Chun'an Grade II Water Source Protection Zone of Xin'an River. The ecological and water environments along the route of this section are sensitive, and there is a high requirement for safety level of the water environment. As one of the first green highway demonstration projects built by the Ministry of Transport of China, with water environment safety protection as its feature, Qianhuang Expressway has carried out pioneering demonstrations for excellence in the environmental protection and water environment safety protection of expressway construction in China' reservoir area.

The runoff rainwater on the pavement of the expressway is caused by the scouring of the pavement by natural rainwater (snow) and its source is uncontrollable. Although many scholars have paid great attention to the research on pavement rainwater, and predicted and analyzed the pollution of pavement runoff rainwater in the environmental impact assessment of highway projects, the actual engineering control measures have been rarely applied. The drinking water of China mainly comes from large rivers and lakes. With the increase in the intensity of economic activities in the water source protection zones, the difficulty in the water quality pollution and protection of water source protection zones becomes larger as well.

In recent years, the pollution of water source protection zones and frequent pollution accidents caused by road transportation has aroused prominent social problems. For example, in the water pollution accident that occurred in Huazhou, Guangdong on May 19, 2005, a tanker carrying 40 tons of benzene (a toxic chemical) overturned, causing at least 10 tons of the benzene to leak into Lingjiang River in Baohao Town, Huazhou City. This accident has caused serious water source pollution and forced all water supply facilities at both sides of the polluted river, including Huazhou City, to stop water supply. On October 4, 2009, a traffic accident occurred when a tanker loaded with concentrated sulfuric acid was passing though Chaotian District, Guangyuan City. The 12 tons of concentrated sulfuric acid loaded on the truck was dumped into the water source protection zone of Qianxi River, causing the around 7-kilometer part of Xuanhe Section of the river to be polluted, the urban area and Xuanhe Town of Chaotian District to suspend water supply for 22 hours and the fishes and shrimps of this section to die. Unexpected water pollution accidents are uncertain, seriously harmful and hard to handle, which seriously affects the safety of water supply systems and presents immeasurable losses to China and the society. How to avoid the water safety related problems with the water source protection zone around the expressway is becoming more and more urgent. And it is particularly urgent and necessary to carry out research on pavement runoff in the water source protection zone.

This research focuses on the Expressway Project of Qiandao Lake District, investigates the meteorological conditions (intensity, duration and volume of rainfall, cumulative sunny days), traffic volume, as well as the relationship between the quality of runoff at drainage facilities (intercepting ditches, side slope chutes of cuts and embankments, side ditches, and drainage ditches) and the asphalt concrete pavement and sewage discharge rules through artificial rainwater and natural rainwater, studies and determines the time scale of the initial rainwater flow on the expressway and the spatial scale that needs to be collected and processed.

2 Progress of Domestic and International Research

A lot of research results show that there are many sources that cause pavement runoff pollution. Among them, the operation of motor vehicles is considered as the most important source. According to different traffic volumes, operating habits, pavement and vehicle conditions, the pollutants emitted include tire particles, road building material particles, fuel combustion emissions, leaked engineering oil and transported materials, fuel and other vehicle-related liquids, particulate matters generated by the brake connections, etc. These substances accumulate on the pavement on sunny days, and are scoured by runoff and enter the water body together with the runoff on rainy days. Abroad, a large number of studies have been conducted on the migration of pollutants from the pavement to the receiving water body. For example, Hube and Diekenson published in 1988 the accumulation model of pollutants on sunny days. The model believes that the accumulation of pollutants on sunny days is an exponential function of time. Metcalf and Edd et al. proposed in 1971 a surface pollutant wash-off model, which believes that the scouring velocity of impervious surface sediments during runoff is proportional to the amount of pollutants deposited. Deletic et al. (1995) [1] used automatic monitoring equipment to continuously measure the pH value, temperature, turbidity and conductivity of the runoff water quality at the urban surface storm inlet, obtained a large amount of data and got the equation of correlation between the solid discharge rate and the surface runoff amount. Sansalone et al. reported the test results of heavy metal pollutants in the runoff of urban pavements, and analyzed the runoff discharge characteristics of dissolved and insoluble metals.

Currently, many countries in the world have conducted statistical analysis and computer simulation of the monitoring data on storm runoff over years, and established many mathematical models for describing the runoff process. The common ones include SWMM, NPS, MOSQITO, FLUPOL, etc.

3 Analysis of the impact of pollutants on the water quality of the receiving water body

After the pollutants aforementioned enter the water body together with runoff, they will produce a big impact on the water quality of the water body; many physical and chemical properties of the water body will change accordingly; and the chemical properties of the receiving water body will sometimes be dominated by the pavement runoff discharged into it. According to the research of J. B. Ellis [2], 35% to 75% of the metals in the receiving water body come from road pavement runoff. Among them, the Cd, Cu, Pb and Zn from the highway surface runoff account for 46%, 78%, 47% and 13% of the total water content respectively. Through his research, G.Stotzlz concluded that the PAHS content in highway pavement runoff is 50 to 60 times that of the polluted river or lake water. The environmental protection authorities of Hong Kong have identified road runoff as a potential source of pollution in Victoria Harbour. The CH4 and N2O detected from the Bodden River are related to the pavement runoff in the Peene Area.

According to the requirements of the Federation Highway Administration (FHWA), Maestri and B. N. Lordl [3] studied several storm runoff management and control measures with the purpose of reducing the pollution load presented by pavement runoff into the receiving water body. They believed that vegetation control, wet retention ponds, infiltration systems and wetlands are several effective highway surface runoff pollution control measures. The results of research by G. Buehberger et al. showed that PET (partial exfiltration trench) can effectively remove heavy metals, SS, PAHS and other pollutants in highway pavement runoff. Y. A. Yousef and T. Hvitved-Jaeobsenl et al. conducted a 9-month research on the efficiency of removing nutrients and heavy metals in pavement runoff through the grass planting channel on a highway in the Orlando area of Florida. The results showed that this channel has a good effect of intercepting heavy metals, especially those in the ion state, and its efficiency of removing Zn, Pb, Ni and C are 62%, 57%, 51% and 43% respectively. Alexandre Gordine studied infiltration systems, dry retention tanks, wet retention tanks, sedimentation tanks and other runoff control measures and analyzed the pollutant removal mechanism, design method and removal efficiency of various measures for pollutants. He believed that the seepage pit in the infiltration system represents the most effective method of runoff control and a well-designed and well-maintained seepage pit can remove up to 98% of pollutants. The results of research by J. D. Sarte and D. R. Gaboury showed that although pavement cleaning has a poor effect of removing small-size pollutants, the pavement cleaning work is still of great significance for runoff control in some special cases. Additionally, controlling the use of deicing agents in snow and ice seasons is vital to the pollution of pavement runoff to the receiving water body.

The runoff pollution on the highway pavement mainly comes from the scouring of pavement accumulation by rainfall and unexpected dangerous goods accidents. So, pavement sediment is the main source for pavement runoff pollution and the nature of the pavement runoff is determined by the composition of the pavement sediment. The types and sources of pollutants accumulated on the highway pavement are rather complex, including the passage of motor vehicles (harmful substances from motor vehicle exhaust emission, leakage of motor vehicle oil, tire wearing, etc.), pollution caused by rainwater (related to near-surface air pollution and pollutants caused in the formation of cloud and rain), deposit of atmospheric particles on the highway surface, wearing of road building materials, leakage of harmful substances caused by the unexpected accidents of motor vehicles loaded with harmful substances, and so on. It can be seen that these pollutants are mainly caused by highway traffic activities. Some of these substances are directly deposited on the highway surface or near the highway. When rainfall arrives, due to the effects of rainfall dissolution and scouring, the pollutants accumulated on the pavement will be loaded into the rainwater runoff and other parts will be dispersed in the air or enter the pavement or side slope and the soil surface of the greening belt together with the fallen dust or rainfall, and then enter the water body on the surface through rainfall or snowfall. Additionally, pollutants from road traffic accidents, toxic and hazardous chemicals spilled, emitted and leaked during road traffic transportation, [4] and most pollutants in the vehicle exhaust will eventually migrate to the water environment under the effect of natural precipitation or rainfall washing.

Transportation activities are the main source for highway pavement runoff pollution. Some of the pollutants are directly deposited on the pavement or near the highway, and other parts float in the air or enter the highway runoff together with rainfall. The deposition of pollutants on the highway pavement is not a linear function of time, but related to the traffic frequency, road conditions, vehicles' operating habits and road cleaning frequency.

4 Research on the characteristics of pavement runoff water pollution

4.1 Identification of characteristic substances from pavement runoff water pollution

Some research results show that the pollutants in pavement sediments have the following sources:

(1) SS

SS is the most important pollutant on the highway pavement, and other pollutants such as heavy metals and the toxic compound Hs are mostly adhered to the pavement. Its main sources include worn tire particles, worn particles on road building materials, leaked transported goods, participles from brake connections and other particles related to vehicle operation, atmospheric dust and deicing agents, etc.

(2) COD

Pb and Zn are the most heavy metals in highway pavement sediments. The former mainly comes from the emission of vehicle exhaust and partially from fuel or lubricating oil leakage and deicing agent spreading (on highway pavements using deicing agents); and the latter mainly comes from tire wearing.

(3) NH4+-N nutrients

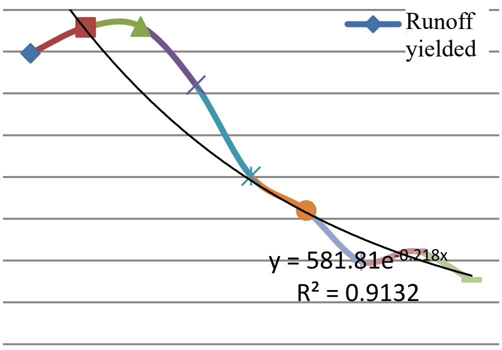
The chloride in the pavement sediment mainly comes from deicing salt.

(4) Oil and grease

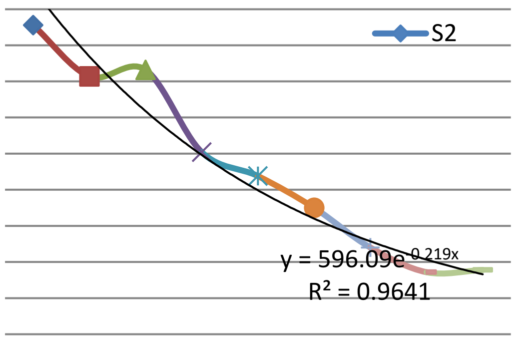
The oil and grease in pavement deposits mainly come from the leakage of lubricating oil.

4.2 Pavement runoff water pollution characteristics and sewage pollution laws under different meteorological conditions

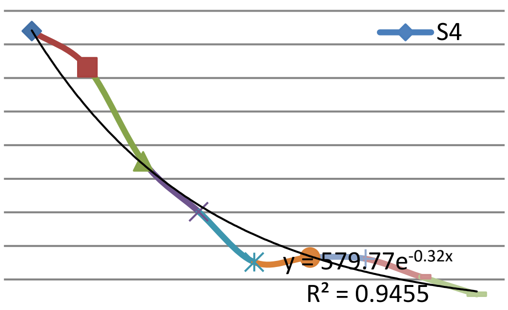
By studying the results of pavement runoff water quality monitoring on the main expressway, the characteristics of runoff water quality can be seen as follows:



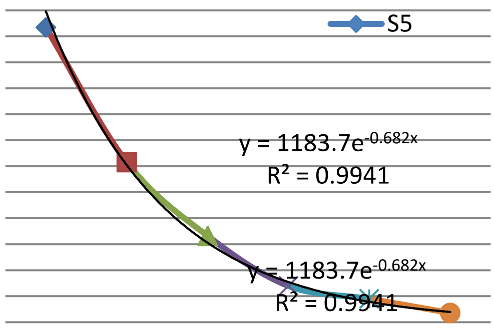
The curve chart of TSS variation with rainfall intensity (rainfall intensity: 16.3mm/h)



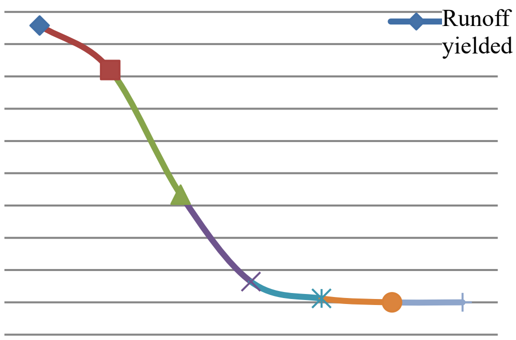
The curve chart of TSS variation with rainfall intensity (rainfall intensity: 36.4mm/h)



The curve chart of TSS variation with rainfall intensity (rainfall intensity: 58.53mm/h)



The curve chart of TSS variation with rainfall intensity (rainfall intensity: 96.6mm/h)



The curve chart of TSS variation with rainfall intensity (rainfall intensity: 108mm/h)

Note:
① In each curve chart shown above, the ordinate is the total suspended solids (TSS) content, in mg/L;
②The abscissa is the sampling interval upon runoff is generated under artificial rainfall conditions, with each interval being 5 minutes;
③The TSS value in each curve chart is the absolute value after the background value is subtracted.

Figure 1 The TSS content in highway pavement runoff under different rainfall intensities

This research highlights the characteristics of pavement runoff water pollution and sewage discharge laws under different meteorological conditions. According to the main meteorological indicators of runoff, the research mainly focuses on the water pollution characteristics and sewage discharge laws under the conditions of rainfall intensity. A pavement washing experiment in moderate to extremely heavy rain was simulated through artificial rainfall. As shown in the curve charts, the total amount of SS generated from road traffic activities is 450mg/L, and the overall trend is obvious. In the case of high rainfall intensity, under the same road conditions, greater changes in the concentration of SS (suspended solids) means higher leaching rates. According to the S-1 curve in the figure, the rainfall intensity is 16.3mm/h, and the SS content in pavement runoff shows a fluctuating decrease, but the content changes slowly. When runoff starts to be yielded, the SS content is 350 to 400mg/L. And when the rainfall lasts till 40min, the SS content is 87mg/L. And when the rainfall lasts till 15min, the SS content is 390mg/L. In the runoff experiment of ring rain intensity S-2 (36.4mm/h), the pavement runoff SS is 264mg/L at 15min. When the rain intensity increases to 58.53mm/h, the SS content in pavement runoff at 15min is less than 150mg/L. And in the simulation test with the maximum rainfall intensity of 108mm/h in this experiment, the SS content in the sample after 15-minute rainfall is basically the background value of the water source used for artificial rainfall.

When the pavement pollution source is the same traffic line, different artificial rainfall intensities will cause a huge difference. The reason may be that in the pavement runoff experiment, insoluble suspended solids are absorbed on the pavement material, and their release speed and cumulative amount are related to the runoff of the pavement. When the rainfall intensity is less than the expected release parameter, as shown in S-1 and S-2 experiments, a longer release period means higher content of the sample volume per unit sample and slower changes. When the rainfall intensity is larger than the release parameter, as shown in the S-6 experiment, a breakpoint will occur when the test lasted till 15min, including that the test intensity is higher than the release parameter requirements. When the tested rainfall intensity is 96.6mm/h, for the SS content change curve in the pavement runoff, the trend line regression equation y = 1183.e-0.68x; the fitting index R2=0.994; and relevant indexes are high, indicating that the suspended solids release model of the tested pavement is an exponential function, y = 1183.e-0.68x

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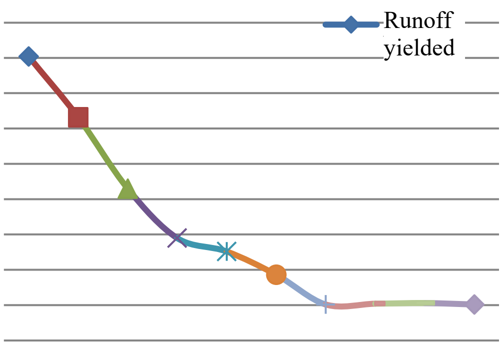
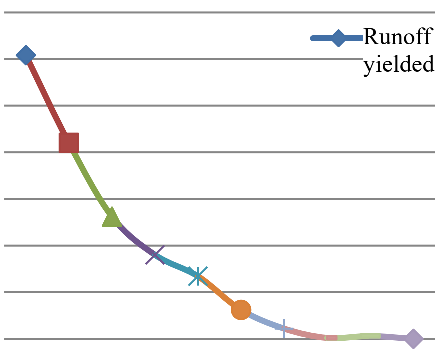
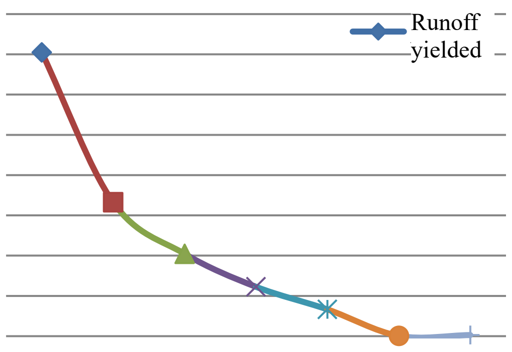


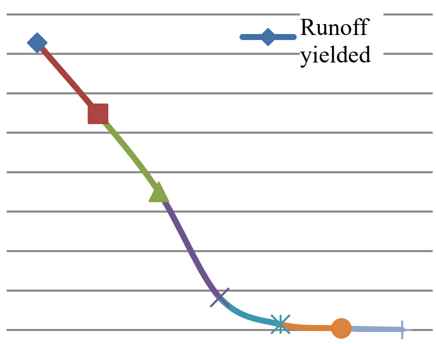
The curve chart on the variation of rainfall intensity with rainfall intensity (rainfall intensity: 43.8mm/h)



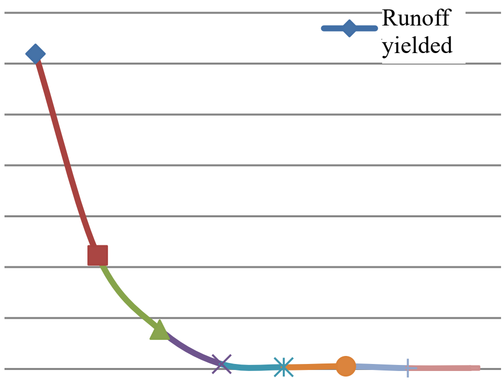
The curve chart on the variation of rainfall intensity with rainfall intensity (rainfall intensity: 47.1mm/h)



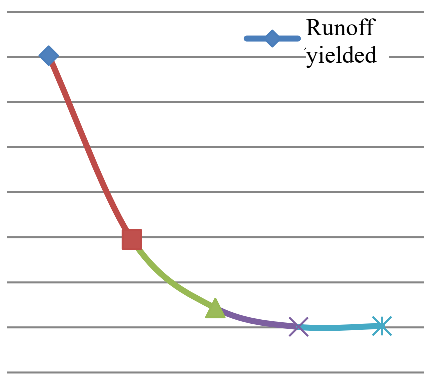
The curve chart on the variation of rainfall intensity with rainfall intensity (rainfall intensity: 79.2mm/h)



The curve chart on the variation of rainfall intensity with rainfall intensity (rainfall intensity: 89.4mm/h)



The curve chart on the variation of rainfall intensity with rainfall intensity (rainfall intensity: 112.2mm/h)



The curve chart on the variation of rainfall intensity with rainfall intensity (rainfall intensity: 153mm/h)

Figure 2 The content diagram of the total suspended solids content of pavement runoff under different rainfall intensities during the expressway building period

(Note: ① In each curve chart shown above, the ordinate is the total suspended solids (TSS) content, in mg/L; ②The abscissa is the sampling interval upon runoff is generated under artificial rainfall conditions, with each interval being 5 minutes; ③The TSS value in each curve chart is the absolute value after the background value is subtracted; ④The rainfall intensity is simulated through artificial rainfall.

In the research experiment on the characteristics of pavement runoff water pollution under different meteorological conditions, the project team selected the Qianhuang G4012 Highway under construction as the supporting project for the reference experiment. In contrast to the above curve trend, the extreme value of SS content in the road pavement runoff during the construction period is within the range of 300 to 350mg/L, lower than that of the Highway 306 in the operation period. In the artificial rainfall experiment, the rainfall intensity of 43.8mm/h, a moderate rainfall intensity type, was adopted in G-1. After 20-25 min, the SS content in the pavement runoff dropped to 43.0mg/L. In the first 15min of the entire process, the SS content decreased in a linear form, from 352mg/L when the runoff was generated to 95.0mg/L. In the second half section of the G-1 rainfall experiment (from 15min to 30min), due to the relatively small SS content in the pavement runoff, the leaching rate started to be decrease. In the experiment of G-2 experiment, the rainfall intensity was 47.1mm/h, basically in line with that of G-1experiment. The experimental results also showed similar laws. That is, when the rainfall progressed to about 25 minutes, the SS leaching was basically completed, and the content had approached the background value. In the G-3 experiment, the rainfall intensity grew to 79.2mm/h, and the content of SS in pavement runoff decreased more significantly. Compared with the previous results, the SS content was 30.4mg/L at 20min, approaching the background value. With the increase in the rainfall intensity, after 10-15min in the G-4 experiment, the SS content in the pavement runoff decreased from the original 364.2mg/L to 41.2mg/L. And in the G-5 experiment (rainfall intensity: 112.02mm/h), the SS content in the pavement runoff dropped to 38.7mg/L after about 10 minutes, and completely leached at 15min. And in the G-6 experiment with the highest rainfall intensity, the SS content in the pavement runoff dropped to 21.6mg/L after less than 10 minutes. By combining the above curve trends, just the same as Highway S306, the duration of removing suspended solids on the pavement becomes shorter with the increase in rainfall intensity, and the SS content in the pavement runoff decreases linearly with the increase in rainfall intensity.

Although SS is the most important pollutant on the highway pavement, it does not cause pollution. Anyhow, most of the other pollutants such as heavy metals and the toxic compound Hs adhere to its surface. Its main sources include worn tire particles, worn particles on road building materials, leaked transported goods, participles from brake connections and other particles related to vehicle operation, atmospheric dust and deicing agents, etc. European and American countries started their research on pavement runoff as early as the 1970s, and carried out a lot of investigations and data analysis on highway pavement runoff pollution. Major research achievements have been made, mainly shown in the following three aspects: 1. identifying the pollution source, pollutant composition and content, as well as influencing factors for pavement runoff. Research shows that there are many sources of pavement runoff pollution. Among them, the most important source is the operation of vehicles. Research also indicates that the pollutants for pavement runoff mainly include suspended solids, CODs, nitrogen nutrients, heavy metals, polycyclic aromatic hydrocarbons and chlorides, etc., and pointed out the factors that affect the content of each component [13]. DraPper et al. spent 18 months in monitoring and studying the pavement runoff caused by rainfall on the highway near Brisbane, Australia, and analyzed the concentration of suspended solids (SS), heavy metals and other substances, as well as the relationship among the concentration of pollutants in the runoff, traffic volume, pavement type and land use status of the monitored point. In 2003, WesteriundCam studied the pavement runoff water quality in different seasons. The results showed that the concentration of pavement runoff pollutants in winter is higher than that of other seasons, with the highest concentration in rain and snow time, and the concentration of suspended solids during the snowmelt was about three times that at the usual time. The Norwegian expert EGjessing et al. pointed out the sources for various pollutants and measured the content of PAHs and heavy metals in highway pavement runoff [16]. Mariaviklander (1998) studied the relationship among runoff, traffic volume and the environment of the surrounding area [17]. Chui et al. tested the runoff caused by more than 500 rains on nine highways in Washington, USA. The results showed that the concentration of total suspended solids and other pollutants in pavement runoff is proportional to the traffic volume during the rainfall, and also proved that the concentration of pavement runoff pollutants is related to the pavement type [18]. The results of Maestri's research showed that the concentration of Pb, Zn, COD and TOC in asphalt pavement runoff is three to five times that of cement concrete runoff under the same conditions [19]. The results of research by Ellis J. B and Revitt D. M showed that suspended solids in pavement runoff contributed 50% to the pollution of the receiving water body, and the concentration of SS in the early of rainfall may be up to 2,000 to 3,000mg/L. As rainfall continues, SS concentration will decrease rapidly, producing an obvious initial effect [20]. Through research, Allan and Saunders et al. showed that the initial effect of SS is highly related to the traffic volume, rainfall intensity and other factors during the rainfall.

In the experimental tests of different rainfall intensities, the COD in pavement runoff water body is also a key indicator highlighted in this project. According to the above figure, the initial COD in the pavement runoff of Highway S306 has the maximum value of 326.54mg/L and minimum value of 212.40 mg/L, higher than the Class II standard of the Integrated Wastewater Discharge Standard. The results of S1 to S6 experiments showed that the COD content in the runoff water sample decreases as the rainfall continues and exhibits similar regularity under different rainfall intensity conditions.

4.3 Large range of pollutant concentration changes

The results of pavement runoff test in the case of artificial rainfall shows that the concentration of pollutants in sewage differs greatly, which are not only in different highways but also in the pollutant concentration at different monitoring times on the same highway. The SS in the pavement runoff of Highway S306 and Yongwu Expressway ranges from 300 to 550mg/L. The reasons for such difference are as follows:

(1) Different pavements or even the same pavement have the same amount of sediments accumulated on the pavement before rainfall, which is related to the characteristics of the natural environment around the highway (including climate and the nature of the use of surrounding lands), pavement type, traffic volume, number of sunny days before the rainfall, atmospheric dust on sunny days, traffic volume on sunny and rainy days, cleaning frequency and other factors.

(2) Different rainfall conditions, mainly including rainfall, rainfall intensity and rainfall duration, etc. Greater rainfall intensity and faster runoff flow rate means stronger force of scouring on the pavement and more powerful pollutant-carrying capacity.

(3) The rain collecting area, which is mainly related to the length of rain collecting section and pavement length.

According to the values of test data, most of the low values are mostly the values of monitoring in the late of the rainfall. This is because the pollutants on the pavement in the late of the rainfall have been basically taken away by the initial rainfall runoff. So, the concentration values are low. It can be seen that the pollution intensity of highway pavement runoff is very high. As the operating duration of the highway increases, its impact on the surrounding environment will inevitably increase. Especially, it will cause serious impact on the surrounding water body.

5 Conclusions

In this research, the types of highway pavement pollutants were identified, and their characteristic volumes of water pollution were measured. Through the research on the leaching laws of pavement runoff pollutants, the following conclusions were drawn:

(1) Pollutants have an initial effect. It can be seen from the test data values that the low values are mostly the monitoring values in the late of the rainfall. This is

because the pollutants on the pavement in the late of the rainfall have been basically carried away by the initial rainfall runoff. So, the concentration is rather low.

(2) Since the concentration of pollutants in the flowing rainwater is jointly affected by the duration and intensity of rainfall, the nonlinear exponential index fitting method is adopted for fitting their relationship.

(3) The characteristics of removing SS, COD and petroleum substances through runoff control can be obtained by studying the effluent runoff from different drainage facilities.

Acknowledgement

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