Research on Slow Sand Filtration Simulation System for Salty, Phosphate and Zinc Removal

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Abstract. The research focuses on slow sand filtration (SSF) simulation system for salty, phosphate and zinc removal. Salty, phosphate and zinc are all the polluted compositions of rainwater runoff. SSF system is an ideal way to purify the rainwater runoff due to its simplicity of construction and low cost. The paper also introduces the practical applications of SSF system nowadays. With the remarkable economic and human population developments, our world faces the challenges of water scarcity. SSF system has great potential in filtering rainwater to provide no-potable water even potable water.

1. Introduction

1.1 Introduction of slow sand filtration system
Slow sand filtration system (SSF) has been used for providing potable water since nineteenth-century. This technology was the earliest attractive process of filter water. The advantages of the system are simple design and construction, convenient installation and operation, no pre-treatment required, no chemical required, no power required and low cost. This system is ideal for installation in rural areas without centralized water treatment facility.

Slow sand filtration system has many applications throughout the world[1]. For example: In Europe and North America, the system is used to improve the quality of surface water and fight against diseases, such as cholera and typhoid. In Africa and South America, the system helps to improve drinking water conditions and provides enough clean drinking water for many villages. In China, there are many rural mountain villages that have no complicated water treatment facilities. Slow sand filtration system is the only way to collect and filter rainwater.

1.2 Basic structure of slow sand filtration system
The main compositions of slow sand filtration system are supernatant water, a sand bed, a drainage system with inflow and under-drainage, filter control device[2].
2. Research on slow sand filtration simulation system

2.1 Main Apparatus

Slow sand filtration simulation system is composed by four transparent plastic columns. The inner diameters of four columns are all 10cm but they are filled by different filtration materials.

As shown on Figure 2: The column 1 is only filled by 30cm fine sand. The column 2 and the column 3 firstly are filled with 10cm zeolite and 10cm activated carbon at the bottom layer respectively, and then put 30cm fine sand at the top of columns respectively. The column 4 is filled by 30cm fine sand, 10cm activated carbon and 10cm zeolite from top to the bottom.

In the experimental process, there are four pumps that are used to pump inlet water from 20 liters water tank. Pump D, C, B, A work for column 1, 2, 3, 4 respectively.

2.2 Introduction of filling materials in columns

The details of filling materials: fine sand, zeolite and activated carbon in columns are as follows.

Fine sands (0.075 to 0.425 mm) are formed of crushed stone sand or natural sand. The character of fine sand is hard, durable, and clean and they are always innocent of organic matter. In this experimental process, the total weight of filling fine sand is approximately 3433g and each of column is filled with approximately 858g fine sand.

Activated carbon are produced by raw materials such as petroleum, coal, wood and nutshells that are consisted by more than 90% carbon element which are always applied to the organic matters and residual disinfectants removal in water treatment. In this experimental process, the weight of 10cm activated carbon is 351g.

Zeolite are microporous, aluminosilicate minerals that have high ion exchange capacity which can be used as adsorbents and catalysts. Zeolites are relatively low cost which can be applied in waste water
treatment, heavy metal removal and water filters and so on. In this experimental process, the weight of 10cm zeolite is approximately 584g.

2.3 Pump calibration
Before untreated water is pumped into columns, it is necessary to calibrate pumps and find the steady flow rates of 4 columns. This is because steady flow rates can reach the highest removal rate. Pumps are all have 9 speed. During the process of pump calibration, keep every pump speed on 1. When the water inlet volume is almost equal with outlet volume and the volume of outlet almost no change, that is the steady flow rate of the pump. The steady flow rates of pump A, D, B, C are approximately 3.6m/s, 3.58m/s, 3.6m/s and 3.6m/s respectively.

![Figure 3: The results of pump calibration](image)

Figure 3 shows the results of pump calibration. It can be seen the growth of flow rate is steady with the increasing of pump speed and the calibration lines are basically in coincidence. It is not difficult to find the data of pump A, speed 7 is incorrect. There are two reasons that affect the pump speed: timing and water collected are non-synchronous, starting a new speed so fast that water flow is not stable.

3. Slow sand filtration simulation system for salty removal

3.1 Solution preparing and taking water samples
Preparing 1 liter Sodium chloride (NaCl) solution and make sure the conductivity of salty solution is 19-20ms. Dissolving NaCl in tap water and using conductivity meter to measure the conductivity of salty water.

Firstly, pumping the whole 1 liter salty water into the column and then pumping tap water sequentially. When salty water begins to flow into column, sampling is started immediately. Taking samples every 1 minute and sample values are measured immediately. The process requires at least two people to cooperate. The process of sampling is persistent until the conductivity of outlet salty water is almost equal with the outlet tap water.

3.2 The result analysis of salty removal
Conductivity is an ideal method to measure how well a solution conducts electricity. The charged particles and ions come from electrolytes are the reasons why a solution carries a current. In this experiment, NaCl is an only electrolyte. Water is not an electrolyte but it also has a very little conductivity. Therefore, the total measured conductivity is the conductivity of sodium and chloride ions, tap water and impurities in water.

The retention times of salty water in column 1, 2, 3, 4 are 38 minutes, 49 minutes, 54 minutes and 48 minutes respectively. The retention time has no direct relation with removal efficiency. It just shows the speed of flow rate of salty water. The figure 4 shows the conductivity changing with time for column 1, 2, 3, 4. It can be seen that topmost of conductivity values for column 1, 2, 3, 4 are 7.28ms/cm, 10.57ms/cm, 9.97ms/cm and 6.55ms/cm respectively.
Figure 4 shows the conductivity changing with time for column 1, 2, 3, 4. It can be seen that the efficiency of salty removal in slow sand filtration simulation system is very high. Salty removal efficiency in column 1, 2, 3, 4 are all almost reach 50%. The column 4 is filled by fine sand, activated carbon and zeolite that has the highest removal efficiency of salt even up to 65%. The column 1 with only 30cm fine sand has the second highest removal efficiency. In contrast, the column 2 and the column 3 are filled with fine sand, zeolite and fine sand, activated carbon separately that have the lower removal efficiency than the column with only fine sand. For activated carbon, this is because activated carbon is a non-polar molecule. In generally, it only can absorb non-polar and very low-polarity substances. Salt is polar ionic compound which is difficult to be adsorbed by activated carbon. For zeolite, zeolite has no removal efficiency for Cl⁻. This is because the adsorption for Cl⁻ is non-specific adsorption.

Zeolite and activated carbon are packed in the porous bags to avoid the materials mixing. It causes materials filled under tighten with tiny cracks and crevices. These tiny cracks and crevices affect the salt retained on columns that make it easy to be washed away. Finally, affecting the removal efficiency of salt.

4. Slow sand filtration simulation system for phosphate removal

4.1 Solution preparing and taking water samples
Preparation of the 50mg/l phosphate (PO₄³⁻) solution. In this experiment, using analytical balance to weight 1.5g sodium hydrogen phosphate (Na₂HPO₄), dissolving Na₂HPO₄ by tap water in a breaker and stirring well. And then pouring phosphate (PO₄³⁻) solution into 20 liters water tank and shake tank to ensure mixing uniform. After that pumping phosphate solution into column 1, 2, 3, 4 in turns and taking samples every 2 hours.

According to the mass balance: The mass of PO₄³⁻ removal (Retained on columns) = The mass of PO₄³⁻ inlet the mass of PO₄³⁻ outlet. The mass of PO₄³⁻ is measured by Ion Chromatography.

4.2 Ion Chromatography (IC) Calibration
It is necessary to calibrate Ion Chromatography before measuring phosphate samples concentration. In this experiment, calibrating Ion Chromatography with the standard phosphate samples and the concentration of phosphate samples are 1ppm, 10ppm, 50ppm.

Firstly, preparing 50ppm phosphate (PO₄³⁻) solution. Weighting 50mg Na₂HPO₄ and dissolved it in tap water. And then diluting 50ppm phosphate (PO₄³⁻) solution to 10ppm and 1ppm phosphate (PO₄³⁻) solution. It should be noticed that it is necessary to use tap water as solvents. This is because every inlet samples are prepared by tap water and distilled water will affect the accuracy of analytical results. The figure 5 shows the calibration curve’s determination coefficient R²=0.9998, so the calibration curve is extremely reliability.
4.3 The result analysis of phosphate removal

Figure 6 shows the column absorption capacity of phosphate for four columns. It can be seen that the total removal efficiency of column 1, 2, 3, 4 are around 21%, 33%, 41%, 45% separately. The column 1 with fine sand has the most common removal efficiency. The column 2 with fine sand, zeolite and the column 3 with fine sand, activated carbon have almost the same phosphate absorption capacity. The column 4 which is filled three kinds of filter materials has the maximum of phosphate absorption capacity.

After many times water inlet, the removal efficiency of column 2, 3, 4 are not very stable. However, the column 2, 3 total absorption capacity have not big difference. Some matters should be paid attention to. When filter materials are used more than once time, it may cause saturation of absorption and lead to the higher concentrations of outlet water samples than the inlet concentrations of inlet water samples. There are two many reasons may lead to the abnormal high concentrations of outlet water samples. For example: The flow rates are not enough steady and sometimes the overflow occurred due to the porous bags’ barrage. The gap may exist in the column inwall and porous bags which can cause the water flow run down the wall directly without any filtrations. The long-standing time of water samples can also result in incorrect results.

5. Slow sand filtration simulation system for zinc removal

5.1 Solution preparing and taking water samples

Preparing 50mg/l zinc (Zn²⁺) solution. In this experiment, using analytical balance to measure 3.37g zinc acetate dehydrate (Zn(O₂CCH₃)₂(H₂O)₂) and dissolving it by tap water in a breaker and stir well.
After that pouring zinc (Zn\(^{2+}\)) solution into 20 liters water tank and shake tank to ensure mixing uniform.
After that pumping zinc solution into column 1,2,3,4 in turns and taking zinc samples every 1 hour.

5.2 Atomic absorption spectrometer (AAS) calibration

Same as the Ion Chromatography calibration, it is necessary to calibrate Atomic absorption spectrometer before measuring zinc (Zn\(^{2+}\)) samples concentration. In this experiment, the concentrations of zinc (Zn\(^{2+}\)) samples are 1ppm, 10ppm, 50ppm, 150ppm and 200ppm that are applied to the Atomic absorption spectrometer calibration.

At the beginning, preparing 200ppm standard zinc (Zn\(^{2+}\)) samples. Weighing 67mg ZnAC\(\text{-}2\text{H}_2\text{O}\) and dissolved in 100ml 1% HNO\(_3\) solution. And then diluted 200ppm zinc (Zn\(^{2+}\)) samples to 150ppm, 50ppm, 10ppm and 1ppm separately. It should be noticed that the standard zinc (Zn\(^{2+}\)) samples are all prepared by 1% HNO\(_3\) solution without water. The figure 7 shows the calibration line’s determination coefficient R\(^2\)=0.9993, so the calibration line is extremely reliability.

During the process of Atomic absorption spectrometer calibration, it may appear the entered zinc (Zn\(^{2+}\)) concentration is not same with calculated zinc (Zn\(^{2+}\)) concentration. The following questions need to be analyzed for such problem occurs. If the calculated zinc (Zn\(^{2+}\)) concentration values of low concentration standard zinc (Zn\(^{2+}\)) samples such as 1ppm, 10ppm are right but the calculated zinc (Zn\(^{2+}\)) concentration values of high concentration zinc (Zn\(^{2+}\)) standard samples such as 150ppm, 200ppm are wrong, the error can be attributed the problem of Atomic absorption spectrometer. This is because low concentration zinc (Zn\(^{2+}\)) samples are all diluted by high concentration zinc (Zn\(^{2+}\)) samples, the solution preparing process is right. In contrast, it should be considered that the solution diluting process is wrong. If all the calculated zinc (Zn\(^{2+}\)) concentration values are wrong, solution reconfiguring and apparatus testing are essential.

![Figure 7: AAS calibration](image)

5.3 The result analysis of zinc removal

Figure 8 shows the column absorption capacity of zinc for four columns. It can be seen that the total removal efficiency of column 1, 2, 3, 4 are around 5%, 18%, 47%, 64% separately. The column 1 with fine sand has the minimum removal efficiency. Compared with the column 2 with fine sand, zeolite, the removal efficiency of column 3 with fine sand, activated carbon has more than doubled. The column 4 which is filled three kinds of filter materials still has the maximum of zinc absorption capacity.
6. The disadvantages of slow sand filtration system

Chapter 1.1 has already introduced the advantages of slow sand filtration system. However, there are still disadvantages. It is worth noting that 4 points when operating a slow sand filtration system[3].

Firstly, the removal efficiency of slow sand filtration system is instability. In generally, slow sand filtration systems adopt physical absorption. The different temperature, pH and other factors such as impurities all can lead to instability removal efficiency.

Secondly, it is necessary to ensure the water flow continually through the system and make sure water flow cannot excess the head of sand bed. The wrong operating steps may reduce the removal efficiency of slow sand filtration system.

Thirdly, when fine sand is clogged, it must be cleaned. The range of cleaning time is uncertainly that from several weeks to a year due to the quality of raw water. The clogged fine sand also can reduce the removal efficiency of slow sand filtration system.

Finally, it should be noticed that slow sand filtration system building requires large areas of land. It may difficult to be applied in the limited area of land.

7. Application prospects of slow sand filtration system for rainwater runoff

7.1 The analysis of rainwater runoff contaminants composition

Rainwater runoff pollution is attributed to contaminants in the atmosphere, the ground and the soil that diffuse into surface water and groundwater under the rainwater runoff’s leaching and scouring and finally can cause water pollution[4]. Rainwater runoff pollutant mainly comes from following aspects: the excessive application of fertilizer and pesticide, soil erosion, livestock manure, urban surface runoff and deforestation. The main pollutants of rainwater runoff are suspended solid (SS), nutrients such as N, P that come from agriculture water and domestic sewage, COD, BOD, heavy metals such as Pb, Cu, Zn and Ca. The pollutant also has some insecticide, Polycyclic Aromatic Hydrocarbons (PAHs) and fecal coliform and so on.

7.2 The examples of slow sand filtration system for treatment of rainwater runoff

Chapter 1.1 shows the slow sand filtration system’s applications throughout the world roughly. Then some practical examples of slow sand filtration system for treatment of rainwater runoff will be shown on below.

In 2013, Abdel Majid Nassar1 et al. simulated the slow sand filter on stormwater purification[5]. The research objectives are finding the removal efficiency of suspended solid and fecal coliform on stormwater and finding the most effective depth of slow sand filter. After 3 days slow sand filtration, when the sand depth is 37.5cm, the removal efficiency of suspended solid reaches 83%. In addition, the removal efficiency of fecal coliform peaks at 80% at the sand depth of 75cm and the efficiency of fecal coliform also can reach 60% when the sand depth is between 50cm to 75cm. The research aims at the
relationship between removal efficiency and the depth of sand but lack the analysis of the stormwater final use. After slow sand filter treatment, the practical applications on stormwater still should also be recognized.

Airports consume a large number of water to maintain their infrastructure and operational routine[6]. The Tancredo Neves international airport in Brazil aims at how to reducing the consuming water by reusing the rainwater runoff. In general, the surroundings of airports usually have large roof areas where is benefit to establish and implement the slow sand filtration systems. Lab studies show that after slow sand filtration, the quality of rainwater’s pH, turbidity, total hardness, TSS, COD and coliforms are excellent. Almost 99% rainwater can be reused in toilet flushing which can meet 100% non-potable demand during the rainy period and meet 70% non-potable demand average monthly. This technology can help Tancredo Neves international airport save $13400000 each year.

8. Conclusion
The paper focuses on the slow sand filtration system for salty, phosphate and zinc removal and introduces the rainwater runoff contaminants composition. It is observed that the slow sand filtration system for treatment of rainwater runoff contaminants has the promising application. The slow sand filtration system has advantages of simple structure, low cost and easy method of operation. It can be regarded as the ideal system to effectively control rainwater runoff pollution and provide no-potable water even potable water after treatment. The slow sand filtration system has the positive development prospect.

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