Jurnal
Teknologi

Full Paper

ARTIFICIAL BARRIER FOR RIVERBANK FILTRATION AS IMPROVEMENT OF SOIL PERMEABILITY AND WATER QUALITY

Nur Aziemah Abd Rashid, Mohd Hafidz Roslan, Nurulezzah Abd Rahim, Ismail Abustan*, Mohd Nordin Adlan

School of Civil Engineering, Universiti Sains Malaysia, 14300 Nibong Tebal, Penang, Malaysia

Article history
Received
24 April 2015
Received in revised form
4 May 2015
Accepted
9 May 2015

*Corresponding author
ceismail@usm.my

Graphical abstract

Abstract

Soil strata abilities to drain water at high volume is the essential properties in RBF (Riverbank Filtration). An artificial barrier (AB) is a man-made vertical barrier to pre-treat water abstraction intake. It is a mixture of sand (local soil), granular activated carbon (GAC) and zeolite. In this work, AB was made to enhance the flow of groundwater as well as water quality. The soil analysis of borehole near Kerian River featured clay, sandy clay loam and sandy loam. In the study, a local soil was mixed Granular Activated Carbon (GAC) at 9:1 (10% GAC), 7:3 and 1:1 ratios. The immediate results are the permeability increased with the percentage of GAC. Further, similar tests were conducted with a mixture of local soil, GAC and zeolite in ratio of 5:2:3 in a laboratory scale physical model. The removal of turbidity and iron in a local soil (without GAC and zeolite) in the range of 59% - 88% and 74% - 87%, respectively. However, a better removal capacity of turbidity and iron were found in the mixture of local soil, GAC and zeolite up to 76% - 98.8% and 73% -92% removals respectively. In sum, the initial study indicate that the mixture of local soil, GAC and zeolite with a specific ratio could provide a pre-treatment of turbidity and iron removal in RBF abstraction.

Keywords: Riverbank filtration, physical model, granular activated carbon, zeolite, permeability

Abstrak

Kebolehan strata tanah untuk mengalirkan air pada halaju tinggi adalah sifat penting untuk penapisan tebing sungai (RBF). Halangan tiruan (AB) ini ialah satu penghalang menegak buatan manusia sebagai pra-rawatan dalam abstraksi air. Ia adalah campuran pasir (tanah setempatan), butiran karbon diaktifkan (GAC) dan zeolite. Dalam kerja-kerja ini, AB telah dibuat supaya dapat meningkatkan aliran air bawah tanah serta kualiti air. Analisis tanah untuk lubang telaga berhampiran Sungai Kerian memaparkan tanah liat, tanah liat berpasir gembur dan berpasir gembur. Dalam kajian ini, tanah tempatan bercampur GAC pada 9:1 (10% GAC), 7:3 dan 1:1 nisbah. Keputusan serta-merta kebolehtelapan adalah meningkat dengan peratusan GAC. Seterusnya, ujian yang sama telah dijalankan dengan campuran tanah tempatan, GAC dan zeolite dalam nisbah 5: 2: 3 dalam model fizikal skala makmal. Penyingkiran kekeruhan dan ferum di dalam tanah tempatan (tanpa GAC dan zeolite) dalam lingkungan 59% - 88% dan 74% - 87%, masing-masing. Walaubagaimanapun, kapasiti penyingkiran yang lebih baik untuk kekeruhan dan ferum didapati untuk campuran tanah tempatan, GAC dan zeolite iaitu sehingga 76% - 98.8% dan 73% - 92% penyingkiran. Kesimpulannya, kajian awal menunjukkan bahawa campuran tanah tempatan, GAC dan zeolite dengan nisbah tertentu boleh memberikan satu pra-rawatan untuk penyingkiran kekeruhan dan ferum dalam pengekstrakan RBF.

Kata kunci: Penapisan tebing sungai, pemodelan fizikal, butiran karbon diakrifkan, zeolite, kadar alir air

1.0 INTRODUCTION

During a prolong dried season, Malaysian consumers are facing and experiencing potable water crisis. Various measures have been taken by the government to solve these water issues. Further, the crisis is worsening by the increasing numbers of polluted rivers in our country that cause several closures of potable water intakes. Due to this glitch, there are several proposals by water agencies to switch on the partial usage of groundwater as a supplementary water resource1. However, the continuous and over pumping groundwater abstraction will become a great pressure on a natural aquifer and eventually will lead to abstraction beyond its capacity. Based on overseas experiences, several countries have utilized riverbank filtration (RBF) system as pre-treatment technique in order to meet the demands for water since water is needed in mass quantity in a short time. Further, the transition of shallow groundwater will be flushed away during rainy season.

RBF has long been used as a pre-treatment for water treatment plant in other countries such as Germany, Korea, Egypt and India2,3,4,5. RBF is a type of filtration that works by passing water to be purified through the banks of a river or lake and then drawn off by extraction wells some distance away to be used as potable water. The process may directly yield potable water or be a relatively uncomplicated way of pre-treating water for further purification6. Due to natural attenuation processes such as filtration, sorption, acid-base reaction, oxidation, reduction, hydrolysis, biochemical reactions and others, RBF has higher potential to filter contaminants. Thus, RBF can be classified as a low-cost and efficient pretreatment method for portable water abstractions.

One of the main disadvantages of bank well barrier is a significant decrease of porosity of river bed sediments and clogging of the hydrogeological environment7. Clogging may happen at riverbed which caused by mechanical particle impingement, biological growth, or geochemical reactions within the aquifer/riverbed interface. Nevertheless it may cease during rainy season because of swift current of the river act as backwash.

However, the deficit application of RBF is in terms of some heavy metals and microbiology existence and accumulates. In order to mitigate these issues, some RBFs implement an artificial barrier system. This barrier is deemed necessary because the possibility of accidental contamination enables on water resources is inevitable. This has already been voiced by Sontheimer8, for example, since the late 1950s, the water quality of large rivers in Europe began to deteriorate. High quantity of wastewater mass input has threatened the use of bank filtrate. The spectacular spills, for example, the Sandoz accident on November 1, 19868, underlined the need of artificial barrier for sanitation measures and pollution abatement. Further, Chitaranjan & Ramakar 9 stated that their findings from observing production (abstraction) wells suggested the need of subsequent purification process which is called as second protective barrier. However, from the analytical model of RBF system, Zainal *et al.* 10 mentioned there is still lacking of monitoring program especially for pesticide and pathogen. Due to these findings, the fate of the contaminants is still hard to predict.

Countries like India and Poland have been using barrier 4,11 with different design for their RBF system. In India, the RBF barrier was made for hydraulic barrier by channeling to a drain (Najafgarh drain). Unlike in Poland, the barrier is applied to control the contaminant from passing through into abstraction well by constructing a barrier upstream of the well. These shown that the main purpose for all barriers are the same as to control the quality of riverbank filtrated water. These cases indicate that it is important to design and implement an artificial barrier in order to sustain RBF system. Thus, study on this artificial barrier should not only focus on the development of RBF but also how to improve specific water quality parameter and soil hydraulic conductivity.

In this study, the artificial barrier is consist of the mixture of local soil, GAC and zeolite. Activated carbons and zeolite are unique and versatile adsorbents due to their large surface area, microporous and mesoporous structure, universal adsorption effect, high adsorption capacity for many nonpolar molecules including organic molecules, and high degree of surface reactivity12. Zeolite has a structure with great resistance to strong acid13.

The objective of this study is to enhance the hydraulic conductivity of artificial barrier medium and to improve pretreatment water quality for abstraction well of RBF system. The study was divided into two phases. For the first phase, the soil samples were collected at an interval of 1 m up to 33 m depths at the selected boreholes in Lubok Buntar, Kedah. The particle grain size distribution and soil permeability were tested from the collected borehole samples. These will provide a basic soil strata characteristic. Further, in order to enhance local soil permeability, the local soil was mixed with GAC and a laboratory physical model experiment focused on the horizontal flow through the media. In the second phase, the experiment was conducted by placing local soil, zeolite and GAC layers in flux flow orientation in the physical model in order to determine pretreatment capacity.

2.0 EXPERIMENTAL

The sequence of this study is shown in Figure 1 and each step is discussed below.

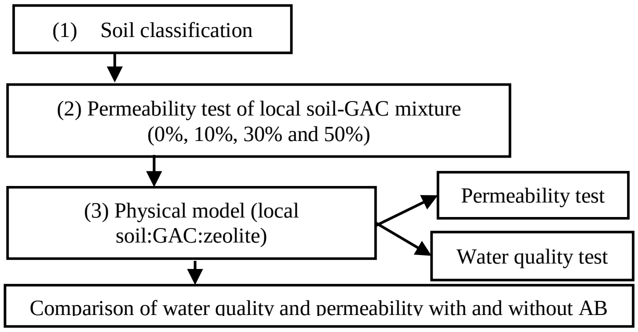

Figure 1 Sequence of the study methodology

There are two set of permeability tests were conducted (a) local-soil with GAC and (b) local-soil, GAC and zeolite. These steps are to indicate the effect of each mixture medium materials towards permeability changes.

2.1 Field Site

The study site was located at coordinates of 5° 7'37.60"N, 100°35'42.97"E, Lubok Buntar, Kedah as shown in Figure 2. The pumping well was located near to water pumping station of Lubok Buntar water treatment plant. At this location, water and soil samples were taken for the physical model test. A borehole with 33 m depth below the ground surface was made near the Kerian River. The upper stream of Kerian River is Selama and the downstream is Nibong Tebal. As expected by Zulkarnain & Sobri[14], the upper stream of Kerian River will face an increase of annual rainfall, while the downstream of the river will face a decrease of annual rainfall from 2011 until 2099.

Figure 2 Location of study area and coordinate of borehole one

Due to that, the site has experienced flooding for several times. Soil samples were taken for every one meter and brought to the lab for soil analysis. These soil samples were then dried and analysed for their characteristics. From the observation, the well is surrounded with palm oil plantation.

2.2 Classification of Soil

Collected borehole soil samples were sieved and analyzed in accordance with ASTM D 2487-06 standard procedure. The sieves were fixed in order of 14 mm, 10 mm, 6.3 mm, 5.0 mm, 3.35 mm, 2.0 mm, 1.18 mm, 600 µm, 425 µm, 300 µm, 212 µm, 150 µm , 63 µm and the pan from the bottom to top over a clean dry tray.

2.3 Experiment Setup for Permeability Enhancement (Local Soil with GAC)

There were three types of soils used during the experiments. They were clay, sandy clay loam and sandy loam. All soil samples were collected from borehole samples which have been constructed along Sungai Kerian riverbank at Lubok Buntar, Kedah. The constant head permeability test was done according to ASTM D2434-68 and ASTM D2435 / D2435M. A mixture of local soil and GAC were tested on the ratio of 10%, 30% and 50% of GAC. This experiment only focused on vertical permeability since the main objective is enhancement of permeability. However, in the physical hydraulic model, the effect of vertical permeability will be tested on the horizontal flow capacity. Local soil and GAC were mixed thoroughly before tested. Each experimental trial was conducted with two (clay) and five (sandy clay loam and sandy loam) duplications. Each replicate samples (clay, sandy clay loam and sandy loam) were tested with different GAC percentage. From the result, permeability was calculated using Darcy law in Equation (1).

$$Q=-kAi. \qquad (1)$$

Where, k is the coefficient of hydraulic conductivity (cm/s), A is the area of the soil column (cm2) and i is inclination of water table.

2.4 Experimental Setup for Physical Model Test (Local-soil, GAC and Zeolite)

A hydraulic physical model with dimension of 152 cm x 54.5 cm of Perspex Model was constructed as shown in Figure 3. The main objective of the test is to determine of optimal water quality improvement to remove heavy metal and turbidity with different ratios by weight of medium. The water quality improvement was measured by layering the local soil with GAC and zeolite. In this physical hydraulic model, the effect of vertical permeability will be tested on the horizontal flow capacity. The layered media was placed in the physical model. Ratio of local soil: GAC: zeolite were setup for 6:3:1, 6:2:2, and 5:2:3. The flux flow permeability for this three different ratios were tested. Based on the results of permeability tests, the mixture ratio of 5:2:3 are continue further testing for water quality treatment. The synthetic iron pollutant and Kerian River water were used in the water quality enhancement test. The model flow rate was set at 8 L/min. Firstly, river water was pumped into the model until all the medium were saturated. The circulation of water from effluent to influent was preset at 8 L/min. to ensure that the water sample was flowing through the adsorbent medium with constant flow rate. The water samples (effluent) were collected and tested analytically in every 15 minutes interval for 3 hours and then analyzed. The water inflow and outflow of the physical model were tested for water turbidity for turbidity and iron contents.

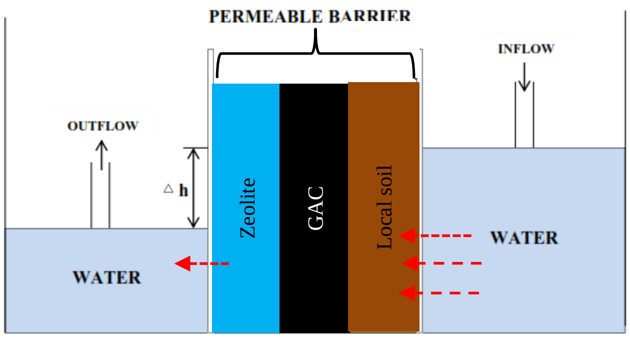

Figure 3 Physical model experiment setup

3.0 RESULTS AND DISCUSSION

3.1 Soil Classification

The particle size distribution (PSD) of 33 samples are shown in Figure 4 based on British Standard for Soil Classification System (BSSCS). The samples could be lassified into three types of soils namely clay (C), sandy clay loam (SCL) and sandy loam (SL). Sandy clay loam soil samples were normally existed at the depth of 1 to 3m and 6 to16m. Clay soil samples were found at 4 to 5m depth. Meanwhile, sandy loam soil type samples were existed at the bottom part of borehole from 17 to 33m depth. The range of D_{10}, D_{50}, and D_{90} for sandy loam, sandy clay loam and clay were showed in Table 1 with permeability value from Copp & Hornbeger[15]. This three types of soils were used in the permeability test of mixture of local soil-GAC.

Table 1 Soil characteristic and their permeability values

Soil Type	D_{10}	D_{50}	D_{90}	K (m/s) [15]
Sandy Loam	0.04 - 0.6	0.6-2	2 - 3.35	10^{-5}
Sandy Clay Loam	0.002 - 0.001	0.06 - 0.43	0.6 -1.18	10^{-6}
Clay	0.0	0.006 - 0.011	0.6 -1.18	$< 10^{-6}$

3.2 Permeability of Local Soil-GAC Mixture

Clay soil is found to be the lowest permeability compared to the other soil types as refer to Figure 5. The average permeability for clay (local soil) was 4.0 x 10^{-5} m/s. It gradually increases after mix with GAC in the range of 10% to 50%. The highest permeability of the mixer of clay and 50% of GAC was found to be 6.0 x 10^{-5} m/s.

A similar fact was found for the sandy clay loam (local soil) soil type when mixing with GAC. The addition of GAC slightly increased the permeability of sandy clay loam soil. The average permeability for sandy clay loam was found to be 4.2 x 10^{-5} m/s. The permeability of the mixture of sandy clay loam and GAC of 10%, 30% and 50% were found to be 4.7 x 10^{-5} m/s, 6.7 x 10^{-5} m/s and 8.2 x 10^{-5} m/s respectively.

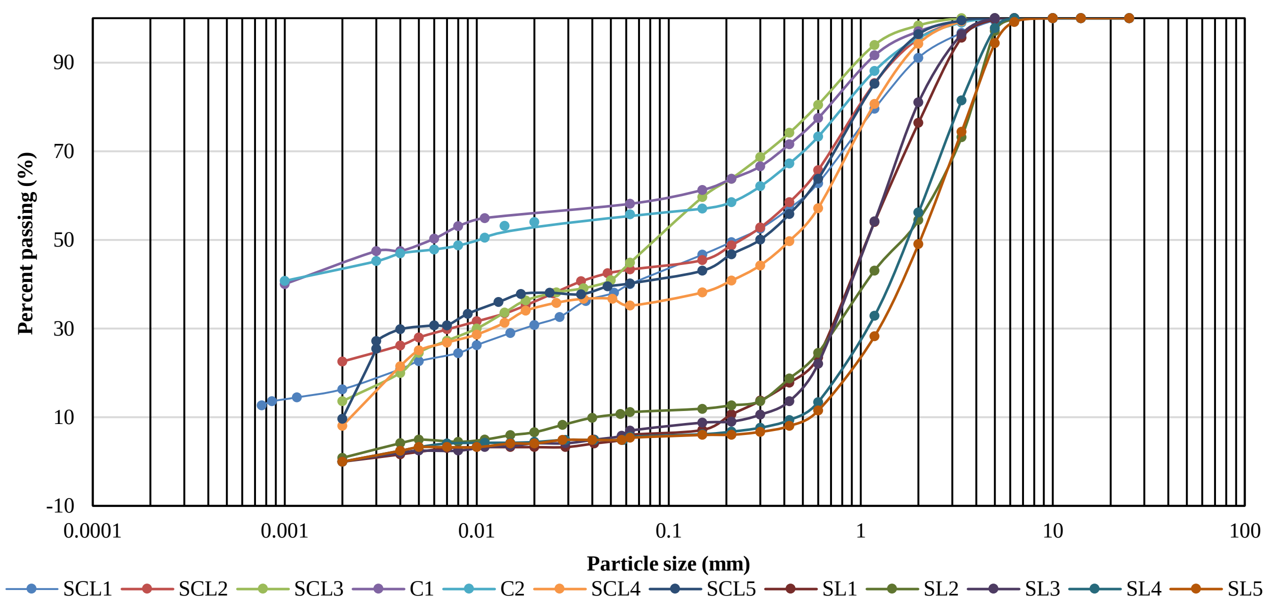

Figure 4 Particle size distribution for all samples

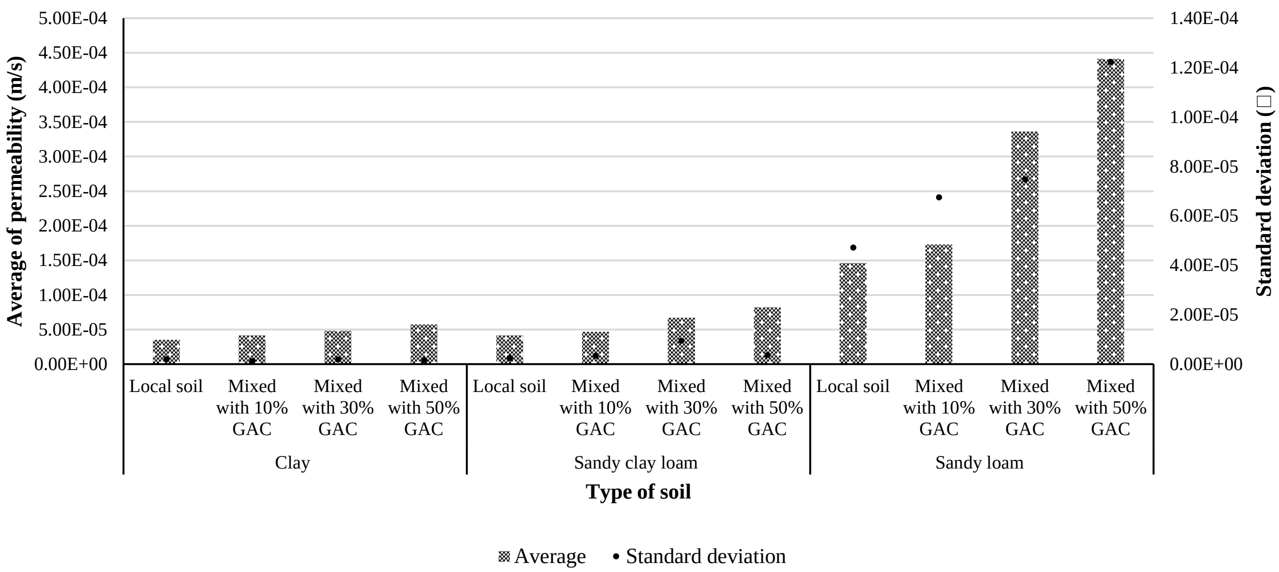

Figure 5 The average for permeability test of mixture of GAC and local soil (Clay, sandy clay loam and sandy loam)

However, the significant increase in permeability of the mixture of sandy loam soil and GAC of 10%, 30% and 50% were 1.7 x10-4 m/s, 3.4 x10-4 m/s, and 4.4 x 10-4 m/s, respectively. The average permeability of the sandy loam sample (local soil) was 1.46 x 10-4 m/s. In RBF, it is important to maintain the permeability of soil starata in groundwater flow. The percentage of silt and clay influence the potential of water flow via the connectivity of pore in the soil. High content of silt and clay may change the permeability as well as will influence water quality.

From the results proved that the additial mixture of GAC increases the potential of soil permeability as depicted in Figure 5. The mixture of GAC with local soil has created pore structure and thus water can flow within the pore increase the soil permeability. The increment was also influenced by type of soil. Clay and sandy clay loam showed insignificant changes in permeability compared to sandy loam soil. Even after 50% of GAC mixture, the standard deviation (clay and sandy clay loam) was found less than 0.002 (can consider not significant). While, the capability of sandy loam to improve soil permeability was more consistent with standard deviation (sandy loam) from local-soil to mixture 50% are 0.005, 0.007, 0.007 and 0.01 respectively in Figure 5. This may be due to the movement of air bubbles in micro joints when GAC was mixed with granular soil (sandy loam)16. Furthermore, the size of the void space is related to the rate of permeability. Therefore, when larger void space is created in local soil after mixing with GAC, more it produces a higher rate of filtration. Therefore, by mixing the soil and GAC, it can help to increase the conductivity of the barrier hence increases the groundwater lateral flows.

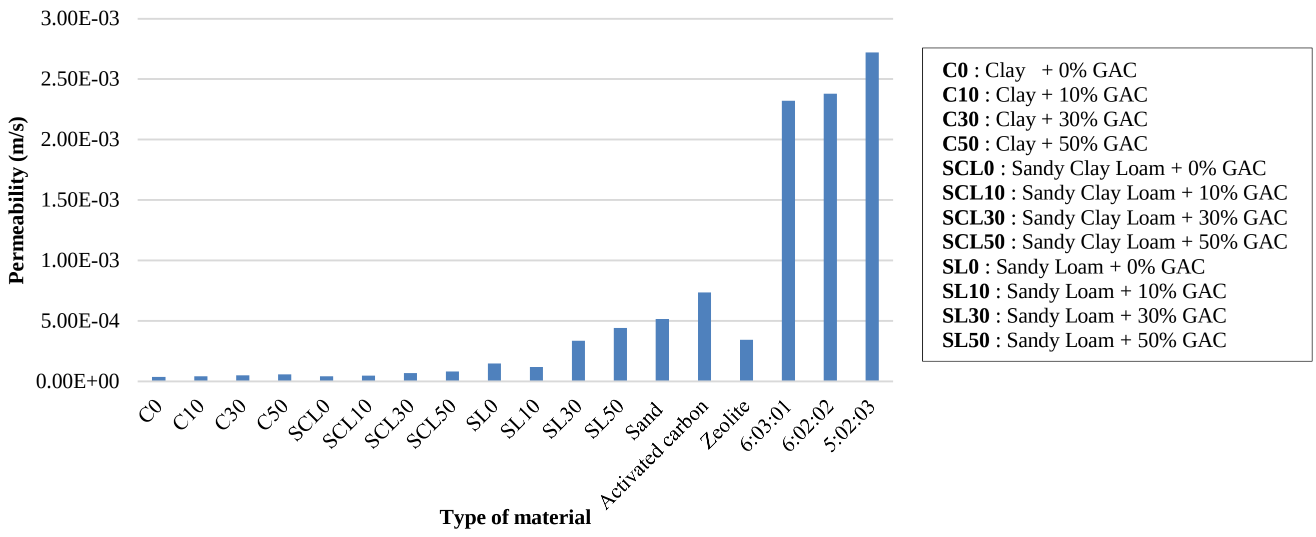

Figure 6 Permeability test of all samples tested

3.3 Comparison of Permeability for All Media and Mixture

The average of permeability for samples tested in permeability experiment (refer 2.3) is shown in Figure 6 in order compare the permeability result with other samples tested in hydraulic model (refer 2.4). The permeability performance of the mixture of local soil, GAC and zeolite showed that the permeability became higher compared to the mixture of local soil and GAC (refer Figure 5). Even though permeability of zeolite showed the lowest value, but it hardly affect the permeability even after it was mixed layers with local soil and GAC.

Figure 6 shows the permebility values of the mixtures of 5:2:3, 6:3:1 and 6:2:2 in the physical hydraulic model, and they could be classified as a rapid permeability since the values are more than 2.4x10-3 m/s. Furthermore, by layering mixtures of local-soil, GAC and zeolite as in Figure 3, the permeability values (horizontal and vertical) for the layered local-soil, GAC and zeolite were 2.32 x 10-3 m/s, 2.38 x 10-3 m/s, and 2.72 x 10-3 m/s, respectively. In the hydraulic model, it shown that with different direction of flows (horizontal and vertical), the different value permeability of the soil will be determined. From Abel15 study, it proved that the k values of vertical and horizontal at site were different. The horizontal permeability (kh) was high with 40 – 120 m/day, but vertical permeability (kv) was smaller with 7 – 20 m/day16.

3.3 Water Quality Performance In Physical Model of Horizontak Artificial Barrier

GAC is capable in removing pollutants due to it characteristic of high surface area (650 – 1000 m^2/g) is well described in literatures[17]. Firstly, the experiments were conducted to determine the ability of activated carbon to increase the flow rate of water in the local soil starta. The results confirmed that the increased and improved of water flow rate. The increase of water flow rate was proportionated with the amount of activated carbon added in the soil mixture. Further, the values of permebility were varied according to types of existing local soil. The sandy soil type in which content a high quantity of sand, when the sandy soil mixed with GAC, it significantly enhanced the flow rate compared to soils that have low content of sand and higher clay content. This is probably due to the intrinsic structure of silt and clay with have smaller void spaces among them. When GAC was added, small particles of silt and clay filled up the pore space voids and limited continuous flow in the media mixture.

In determining the water quality performance, different ratio of local soil : GAC : zeolite layers were tested with synthetic iron (Fe) and river water (for turbidity). A continuous 180 minutes of water pumping flow was conducted in the physical hydraulic model. The results of turbudity and iron removal are shown in Figure 7. Results indicated that water quality was better improved with the layers ratio of 5:2:3 than sandy medium only.

Based on Figure 7, the removal of iron in this physical model showed that removing of iron increased significantly for 15 minutes and then plateaued untill 180 minutes with removal range of 73.4 % to 92.3 %. Despite removing of iron, the adsorbent used for horizontal physical model was also capable in removing turbidity. By using river water from Sungai Kerian at Lubok Buntar, Kedah, with initial concentration of 45.1 NTU. Figure 7 shows that the percentage of turbidity removal increased gradually from 76.1 % to 98.8 %. With these values of removals, it is expected that the RBF could be utilized as pretreatment of potable water abstraction.

GAC appears to be highly suitable for use in impermeable barriers[18]. Further, GAC is chemically stable materials and widely considered as suitable adsorbents for on-site or off-site treatment of polluted groundwater[19]. Due to its large specific surface area and the presence of different types of surface functional group, the addition of activated carbon shows a high absorption capacity. Further, in this study, zeolite could be used to increase permeability rate in the artificial barrier as it can act as an absorbent agent as well for water quality purposes. In sum, a right mixture ratio of thse mixtures could act as a good media for the artificial barrier in terms of water quantity and quality and fincally could be applied at the RBF.

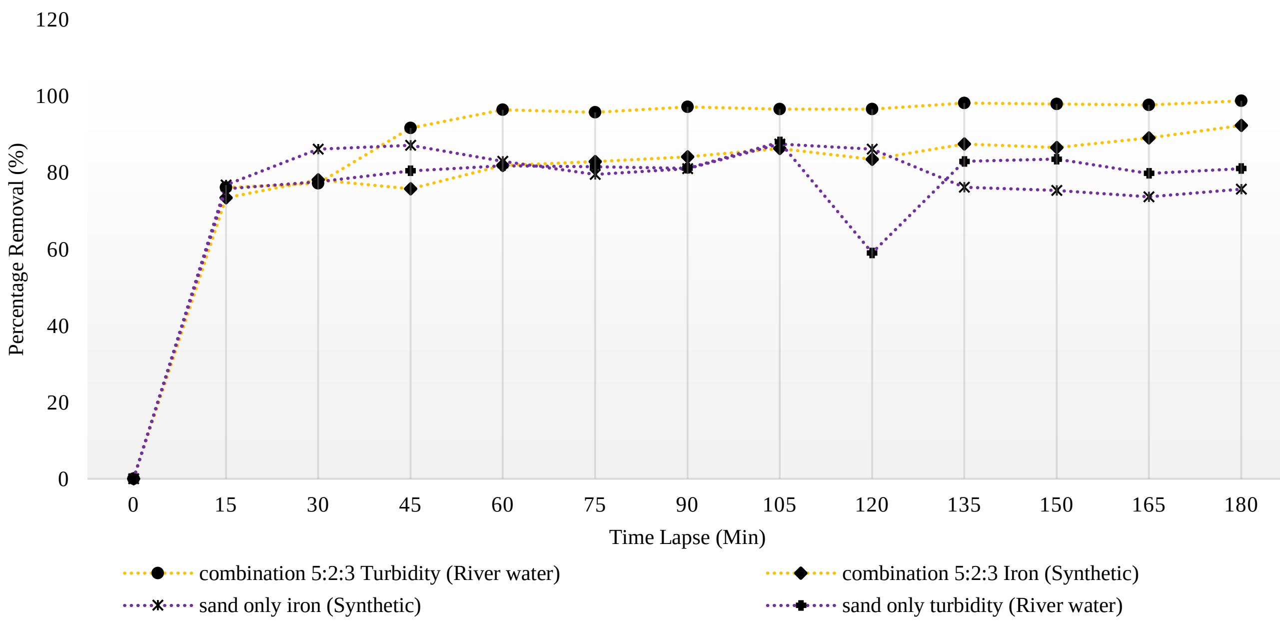

Figure 7 Water quality for turbidity and iron in physical model for using (a) local soil only and (b) AB with combination of 5:2:3 (local-soil:GAC:zeolite)

4.0 CONCLUSION

The permeability of sandy clay loam and sandy loam can be improved by combining them with GAC. Permeability of clay soil could not be significantly enhanced by the GAC. The range of permeability found for local soil was in the range of 0.0033 to 0.024 m/s. The range was increased to 0.004 and 0.056 m/s after the local soil were mixed with GAC in the ration of 10% to 50%. Enhancement of permeability was found higher when the local soils were mixed GAC and zeolite. Initially, the value of local sand soil permeability was 5.0 x 10-4 m/s, however, when the sands were mixed with GAC and zeolite, the permeability significantly increased to the range 2.3 x 10 -3 m/s to 2.7 x 10-3 m/s.

In this study, it was found that GAC appears to be highly suitable to be used in permeable barriers due to its ability to enhance the medium permeability and absord pollutant due to its high surface value. It is expected that by mixture local sandy soil with GAC and zeolite, it is expected that the water yielded from RBF could meet the potable water requirement.

The suitability and capability of the zeolite and GAC used as a artificial barrier medium has been proven in this study. The removal of turbidity and iron could reach 98 and 92 removal respectively. In conclusion, a mixture of local sandy soil with zeolite and GAC in an appropriate ratio will be best artificial barrier components in pretreatment of water abstraction in RBF system. Nevertheless, with a site specific nature of RBF and artificial barrier, it is essential to conduct a detail study to ensuring the proposed medium ratio will act optimumly.

Finally, this study conclude that the proposed artificial barrier could provide optimum hydraulic properties and able to provide a large quantity of water without overstressing the groundwater system. With the in stream recharge, the over abstraction of RBF is very unlikely to occur and thus this provide a sustaibnable use of unclaimed water.

Acknowledgement

The authors would like to acknowledge the Ministry of Education Malaysia for providing LRGS Grant on Water Security entitled Protection of Drinking Water: Source Abstraction and Treatment (203/PKT/6720006).

References

[1] Ismail, Y. 2013, 13 May. Air Bawah Tanah Penyelesaian Tangani Krisis, Sumberselamat Duguna, Bebas Pencemaran. *Berita Harian*. p.rencana 6.

[2] Jurgen, S. 2003. Water Quality Improvement with Riverbank Filtration at Dusseldorf Waterworks in Germany. *Water Science and Technology Library.* 43: 267-277.

[3] Jeong–Hwan, L., Se-Yeong, H., Jae-Yeol, C., Hyoung-Soo, K., Eun-Joung, K., Kwang-Sik, L., & Sang-Il, L. 2009. Characterizing Riverbank-filtered Water and River Water Qualities at a Site in the Lower Nakdong River Basin, Republic of Korea. *Journal of Hydrology*. 376(1-2): 209-220.

[4] Ray, C. & Shamrukh, M. 2011. Riverbank Filtration for Water Security in Desert Countries. DOI 10.1007/978-94-007-0026-0_16, Springer Science, Business Media B.V.

[5] Gupta, P., Pandey, G., Gore,M., Srivastava, D. K., & Misra, B. R. 2014. Study on the Presence of Faecal Coliform (E.Coli) in Groundwater Samples of Gorakhpur City, India. *International Research Journal of Environment Sciences.* 3(1): 9-12.

[6] Thomas, H. 2002. Occurrence, Fate, and Removal of Pharmaceutical Residue in the Aquatic Environment: A Review of Recent Research Data. *Journal of Toxicology letters*. 131: 1-17.

[7] Gorski, J. 2011. Chapter 16: Quality of Riverbank Filtrated Water on the Base of Poznan Cuty (Poland) Waterworks Experience.

[8] Sontheimer, H. 1991. *Drinking water from the Rhine?* Academia Verlag, Sankt Augustin.

[9] Chitaranjan, D. & Ramakar, J. 2014. Review on Water Treatment Technique Used for Riverbank Filtration. *International Journal of Civil Engineering Research*. 5(3): 221-226.

[10] Zainal, A. A., Shaymaa, M., Arifah, B., & Saim, S. 2014. Review of the Role of Analytical Modelling Methods In Riverbank Filtration System. *Jurnal Teknologi*. 71(1): 59-69.

[11] Pandolfo, A. G., & Hollenkamp, A. F. 2006. Carbon Properties and Their Role in Supercapacitor. *Journal of Power Sources.* 157: 11-27.

[12] Perot, G. & Guisnet, M. 1990. Advantages and Disadvantages of Zeolite as Catalysts in Organic Chemistry. Journal of Molecular Catalyst. 61(2): 173-196.

[13] [13] Zulkarnain, H. & Sobri, H. 2013. Impact of Climate Change on Rainfall Over Kerian, Malaysia with Long Ashton Research Station Weather Generator (LARS-WG). Malaysia *Journal of Civil Engineering*. 25(1): 33-44.

[14] Salman, T. S., Somaye, A., & Mohammad, G. 2014. The Evaluation of Changes in Permeability and Chemical Composition of Gypseous Soil Through Leaching In Southern Mashhad, Iran. *Malaysia Journal of Civil Engineering.* 26(3): 337-348.

[15] Clapp, R. B., & Hornberger, G. M. 1978. Empirical Equation for Some Soilhydraulic Properties. *Journal of Water Resources Research*. 14: 601-604.

[16] Abel, C. D. 2009. Impact of Biodegradadability of Natural Organic Matter and Redox Conditions on Removal of Pharmaceutically Active Compounds During Riverbank Filtration. MSc thesis, UNESCO-IHE Institute for Water Education.

[17] American Water Work Association, and American Society of Civil Engineers. 2005. Water Treatment Plant design. Ed. Edward, E. B. Fourth ed. New York: McGraw-Hill Handbooks.

[18] Han, I., Schlautman, M. A., & Batchelor, B. 2000. Removal of Hexavelent Chromium from Groundwater by Granular Activated Carbon. *Journal of Water Environment Resources.* 72: 29-39.

[19] Roehl, K. E., Huttenloch, P., & Czurda, K. 2001. Permeable Sorption Barriers for In-Situ Remediation of Polluted Groundwater-Reactive Materials and Reaction Mechanisms. In: Sarsby, R.W. & Meggyes, T. (eds.), GREEN 3, 3rd International Symposium on Geotechnics Related to the European Environment, June 21-23, 2000, Berlin, Germany. Thomas Telford, London. 466-473.