Assessment of Heavy Metal Attenuation and Mobility in Compacted Soil Columns
(Penilaian Pembantutan dan Kemobilan Logam Berat dalam Turus Tanah Terpadat)

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ABSTRACT

Groundwater pollution from unlined landfill is a worrying problem nowadays. In order to reduce the pollution, a good soil liner is very important. Natural compacted soil is used to prevent leachate from reaching the groundwater. The soil column study was performed to investigate the retention capability of three soil types in Malaysia, namely marine clay (SBMC), weathered metasediments (HMS) and river alluvium soil (ARA). All soil columns were tested against four types of heavy metals, i.e. lead (Pb), copper (Cu), nickel (Ni) and zinc (Zn). The breakthrough curves show that the SBMC has better retention capability on heavy metals compared to other soils; indicating less migration of heavy metals through SBMC soil column. The affinity of heavy metals for adsorption were also varied with soil types and can be ranked as follow: SBMC (Pb>Cu>Ni ≈ Zn) and HMS/ARA: Zn ≈ Cu>Pb>N. Soil SBMC showed very high resistance to acidic test solution (i.e. high buffering capacity), where the pH values throughout the test were in an alkaline region with the values of pH 8 to 7. The study also discovered that heavy metals entered the soil columns were retained predominantly at the top 30 mm. Engineering applications of these findings show that soil SBMC has a very good potential to function as soil liner material compared to two other soils (ARA and HMS).

Keywords: Breakthrough curves; column experiment; heavy metals; retention profile; soil liner

ABSTRAK

Pencemaran air bawah tanah dari tapak pelupusan sisa tidak berlapik adalah suatu masalah yang membimbangkan pada masa kini. Untuk mengurangkan pencemaran, pelapik tanah yang baik sangat penting. Tanah semula jadi yang dipadatkan digunakan untuk mencegah cecair larut resapan daripada mencemari air bawah tanah. Kajian turus tanah dilakukan untuk mengkaji keupayaan penahanan tiga jenis tanah di Malaysia, iaitu lempung marin (SBMC), tanah metasedimen (HMS) dan tanah aluvium sungai (ARA). Kesemua tanah diuji terhadap empat jenis logam berat, iaitu plumbum (Pb), kuprum (Cu), nikel (Ni) dan zink (Zn). Graf lengkung penembusan menunjukkan bahawa tanah SBMC mempunyai keupayaan penahanan logam berat yang lebih baik berbanding dengan tanah lain. Ini menunjukkan logam berat kurang mengalami migrasi melalui ruang tanah SBMC. Pemilihan logam berat untuk penjerapan juga berbeza-beza dengan jenis tanah dan boleh disenaraikan seperti berikut: SBMC (Pb>Cu>Ni ≈ Zn) dan HMS/ARA: Zn ≈ Cu>Pb>Ni. Tanah SBMC menunjukkan rintangan yang sangat tinggi terhadap larutan berasid (iaitu kapasiti penampan tinggi), dengan nilai pH sepanjang ujian berada dalam keadaan alkali antara pH 8 hingga 7. Kajian ini juga mendapati bahawa logam berat yang memasuki liang tanah mengalami penahanan terutamanya pada bahagian 30 mm teratas. Aplikasi kejuruteraan penemuan ini menunjukkan bahawa tanah SBMC mempunyai potensi yang sangat baik untuk berfungsi sebagai bahan pelapik tanah dibandingkan dengan dua tanah lain (ARA dan HMS).

Kata kunci: Lengkung penembusan; logam berat; pelapik tanah; profil penahanan; ujian turus

INTRODUCTION

Soil has been regarded as the cheapest material that can be used as compacted clay liner in waste disposal landfills to prevent seepage of leachate containing heavy metals into the subsoil and groundwater. It is well known that soil has the capability to physically and chemically retard the movement of contaminants (Calace et al. 2001; Rubinos & Spagnoli 2019; Yanful et al. 1988; Zarime & Wan Yaacob 2016). Soil can be compacted to achieve very low hydraulic conductivity of less than 1×10^{-9} m/s and acts as a final protection for groundwater against pollutants underneath the landfill sites. The most suitable types of soils are those which possess high cation exchange capacity (CEC), large

specific surface area (SSA) and high chemical buffering capacity (Bohác et al. 2019; Yong et al. 1992). Soils are effective agents for metal sorption because of their high surface area and the presence of various surface functional groups (Davis 1984; Tessier et al. 1985). The compatibility of clay liner to a specific contaminant depends on two factors; the ability of the clay in the liner to resist increases in hydraulic conductivity caused by the contaminants and its capacity to retard the migration of contaminants through sorption (Li & Li 2001).

Soil is a product of accumulation of different active components such as clay minerals, organic matters, carbonate fractions and oxy/hydroxides amorphous

materials. These components are chemically reactive and can react with various types of contaminants resulting into the retention of contaminants in the soil system. Competency assessment of soil to be used as compacted clay liner is very important and can be investigated using soil column experiment. According to Yong et al. (1992), soil column experiment can provide information concerning the capability of natural soil to function as proper clay liner.

The study of interaction and behaviour of heavy metals in soils has been extensively studied during the past 20 years. Most of the studies involved the sorption assessment of heavy metals onto soils (Wan Zuhairi 2003a, 2003b; Wan Zuhairi et al. 2004), migration of heavy metals through clay (Antoniadis et al. 2007; Griffin et al. 1976; Yong & Phadungchewit 1993; Yong et al. 2001) and partitioning of heavy metals from active soil components (Gupta & Chen 1975; Rendina & de lorio 2012; Tessier et al. 1979). Heavy metals were used in this study because they possess a very serious threat not only to the environment but also to human health due to their toxicity, persistence and non-degradability (Chotpantarat et al. 2011).

The objectives of the study were to assess the capability of three natural soils to function as engineered clay liner in landfill; to evaluate the long-term performance of compacted clay when it is exposed to aggressive chemicals of leachate in landfills; to investigate the retention/migration profiles of heavy metals through the soil column.

MATERIALS AND METHODS

PHYSICAL CHEMICAL EXPERIMENTS

Fifteen samples from three different type of soils, namely Sungai Besar marine clay (SBMC1-5), weathered metasediments from Batang Berjuntai (HMS1-5) and river alluvium from Ampar Tenang (ARA1-5) were collected from different part of Selangor (Figure 1; Table 1). Sungai Besar marine clay is a quaternary deposit, consists predominantly of clay that is located near the costal and offshore (marine origin). Meanwhile, metasediment soil is a weathering product of metamorphic rocks. River alluvium soil is a product of sediments deposition by water along the river banks. All samples were subjected to physical and chemical tests. Physical tests comprised of particle size distribution, Atterberg Limits, compaction, specific gravity and permeability (falling head test). All tests follow the standard methods of British Standard (BS1377 1990). Chemical tests consisted of soil water pH (1:10 ratio), organic matter (Hesse 1972), carbonate contents (Hesse 1972), amorphous oxides/hydroxides (Segalen 1968), specific surface area (SSA) and cation exchange capacity (CEC) followed the method by McGill University Geotechnical Research Centre Laboratory Manual (Geotechnical Research Centre Laboratory Manual 1985). The clay mineralogy of the soil was determined using X-Ray Diffraction analysis.

COLUMN EXPERIMENTS

Soil column was utilized in this study to investigate the migration characteristics of heavy metals when passing through the compacted soil column. The column method is better to simulate natural soil conditions (Abollino et al. 2003; Sahu et al. 2012). Column experiment was designed to stimulate slow, saturated, anaerobic flow of leachate through the clay materials (Yong et al. 1992). This new physical model was redesigned and rebuilt based on previous model from Wan Zuhairi (2000) and Yong (2001) to reduce leakage especially along the joint/

FIGURE 1. The sampling locations of three different soil in Selangor, Malaysia

TABLE 1. Soil designations

Group	Samples	Description
SBMC	SBMC1-SBMC5	Marine clay (Silty clay)
HMS	HMS1-HMS5	Weathered metasediments (Clayey silt)
ARA	ARA1-ARA5	River alluvium (Clayey silt)

contact of different column components after they were attached together. This rather new soil column consisted of plexiglass cylinder with a diameter of 100 mm and length of 104 mm. Column apparatus is comprised of two parts; top part is a leachate reservoir and the bottom part is a place for compacted soil (Figure 2). Glass microfiber filters (Whatmann) were placed on the porous disc at the top and bottom ends of the columns to prevent influx and outflux of particles. Each sample was tested in a series of duplicate with a label of 3PV and 5PV, where PV represents the pore volume of soil. A pore volume (PV) is defined as the volume necessary to displace the volume of interstitial liquid in the pore spaces within the soil column. Soils at their optimum moisture content (W_{opt}) were compacted into three separate layers in the plexiglass cylinder according to a Standard Proctor compaction test using 25 kg weight hammer. All components were attached together and screwed tightly to prevent leakage.

There were two stages of leaching for column test: saturation stage using deionized distilled water; and leaching stage using a test solution (i.e. spiked leachate) that was prepared by dissolving exact amount of salt nitrates. The leaching experiments were conducted under constant air pressure of 10 psi (i.e. equivalent to hydraulic gradient, i ~ 68) to reduce the time factor for test solution transport through the soil columns. The

chemical composition of spiked test solution is given by Table 2. The use of spiking is to increase the contaminant concentrations and is very useful to study more extreme conditions of contaminant attack to soil, i.e. a procedure that maximize the contaminant-soil interaction. The pH of the leachate was also reduced to 1.4 to increase the mobility of the heavy metals and to prevent any accumulation of the heavy metals in the reservoir (i.e. heavy metals are precipitated when pH>5.5). After every 0.5PV of leaching, the effluents were collected and analysed using ICPMS. All effluents were filtered using Whatmann cellulose nitrate filter papers (<0.2 μm pore with 47-mm diameter) prior to analysis to prevent blockage of ICPMS tubing system. The pH of the effluents was measured using pH meter subsequently after 0.5 PV.

TABLE 2. The composition of test solution

Parameter	Value
Pb	538.6
Cu	556.8
Zn	516.8
Ni	567.9
pH	1.4
Conductivity	5.93 mS/cm

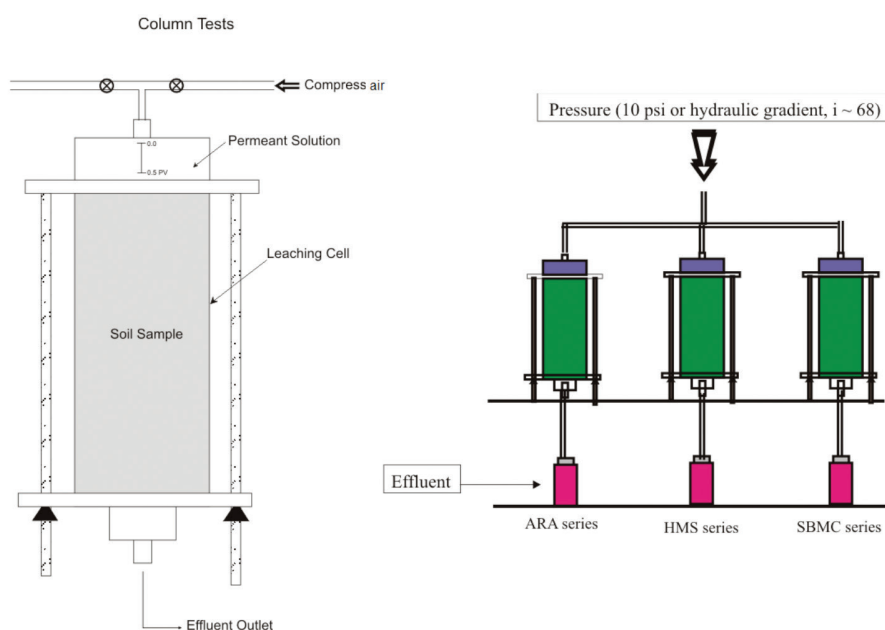All concentration in mg/L except for pH and conductivity

FIGURE 2. The schematic diagram of column experiment on three different soils

At the end of the experiments (i.e. after permeated with test solution for up to 3PV and 5PV, respectively), the compacted soils were extruded and sliced into six equal slices for soil analysis. Each slice measuring about 17 mm thick and digested using microwave digestion technique to determine the amount of heavy metals retained in the soil. Microwave digestion is a new instrument that uses microwaves and acids to digest the soil materials.

RESULTS AND DISCUSSION

THE PROPERTIES OF SOILS

Soils were characterized in terms of their physical and chemical constituents using standard procedures as mentioned in methods. These properties are very important and greatly influenced the suitability of the soil to function as engineered clay liner material. The physical-chemical data were also used as input data for setting up the physical column.

Soils have different capacity to adsorb heavy metals and are largely controlled by their physicochemical properties (Wan Zuhairi 2003a, 2003b, 2001, 2000; Wan Zuhairi et al. 2004). Wan Zuhairi and Abdul Rahim (2012) also showed that different soils have different sorption capacity for different heavy metals. The retardation factor (Kd values) are proportional to the sorption capacity of the soils. The relatively low hydraulic conductivity and high adsorption capacity of clay soils make them prime candidates for constructed or engineered clay barrier (Yong et al. 1993). The physical properties of the soils are important in relation to their capability to be compacted to achieve a minimum requirement of hydraulic conductivity of 1×10^{-9} m/s such as a requirement made by DOE (1995). On the other hand, the chemical characteristics of the clay materials are also very important to assess the capability of the soil to attenuate the contaminants. Tables 3 and 4 show the physical and chemical properties of all soils used

in this study. The specific gravity values for all soils were found to be very similar and did not show much variation between soils, being in the range of 2.2 and 2.7. Soil HMS and ARA contained high percentage of sand with the values ranged from 11% to 45%. Note that SBMC soil contained higher composition of fine fractions (i.e. 46-60% and 33-52% for silt and clay, respectively). High clay content in SBMC gives a very good advantage for landfill liner material because clay can increase the sorption capability and reduce the hydraulic conductivity values of the soil. The average hydraulic conductivity values for SBMC soils were one order of magnitude lower than HMS and two orders of magnitude lower than ARA. This difference is due to high percentage (amount) of fine fractions in SBMC soil. SBMC and HMS soils were classified according to Unified Soil Classification System (USCS) as clay with high plasticity (CH), while soil ARA was classified as silt with low plasticity (ML). This classification was made based on the particle size distribution and soil Atterberg limits values (i.e. LL, PL, and PI). Even though SBMC and HMS were classified as the same type of soil, their other chemical and physical properties were different.

The chemical parameters for all soils are presented in Table 4. The pH values for all soils were varied; ARA soils were acidic, ranged between 4.2 and 4.5. pH values for SBMC soils were alkaline, in the range of 7.2 to 7.5. The pH readings for HMS were intermediate - values between 6.2 and 7.4. SBMC soils contained slightly higher organic and carbonate compared to HMS and ARA soils. Interesting to note the CEC and SSA values for SBMC were far beyond other soils, with the values of 25-75 meq/100 g for CEC and 90-138 m^2/g for SSA. Chalermyanont et al. (2009) stated the marine clay in Thailand had the value of 26.05 meq/100 g and this higher CEC indicates a higher negative charge of the clay fraction and hence, a higher heavy metal sorption capacity.

The major difference in soil chemical properties between SBMC and HMS/ARA soils was due to high amount

TABLE 3. Physical properties of three soils from Selangor, Malaysia

Soils	Gs	S (%)	M (%)	C (%)	LL (%)	PL (%)	PI (%)	W_{opt}	γ_{dmax}	K ($\times 10^{-9}$) m/s	Class
SBMC	2.2-2.3	2-8	46-60	33-52	50-68	18-28	27-45	29.32	1.4-1.4	7.9	CH
HMS	2.4-2.7	11-15	45-56	20-30	39-57	21-27	14-35	21-30	1.3-1.5	23.8	CH
ARA	2.2-2.4	2-45	42-71	10-27	39-50	24-32	11-25	10-22	1.5-1.6	513	ML

Gs= Specific gravity; LL=liquid limit; PI=plasticity index; ; S=Sand; M=Silts; C=Clay; γ_{dmax}=Maximum dry density; W_{opt}=Optimum moisture content; K = Hydraulic conductivity; CH = clay with high plasticity; CL = clay with low plasticity; ML = silt with low plasticity

TABLE 4. Chemical properties of three soils from Selangor, Malaysia

Soils	pH	Organic (%)	Carbonate (%)	CEC (meq/100 g)	SSA (m^2/g)	Mineralogy
SBMC	7.2-7.5	5-14	9-13	25-75	90-138	M > I
HMS	6.2-7.4	3-13	8-13	1-6	20-36	K > I
ARA	4.2-4.5	3-11	4-15	1-9	12-16	I

SSA = specific surface area, CEC = cation exchange capacity; K = Kaolinite; I = Illite; M = Montmorillonite; SBMC = Marine clay from Sg Besar; ARA = River alluvium soils from Ampar Tenang; and weathered metasediments of Batang Berjuntai (HMS)

of clay fractions and the presence of active clay mineral (i.e. montmorillonite) in SBMC soils (Tables 3 and 4). Montmorillonite is an active clay mineral that increased the CEC and SSA values in SBMC soils. In other soils (HMS and ARA), montmorillonite is absent and mainly contain kaolinite and illite, resulting small values of SSA and CEC. Montmorillonite has higher SSA with the values range from 600-800 m²/g and CEC of 80-100 meq/100 g values compared with kaolinite/illite (SSA 5-20 m²/g and CEC 3-15 meq/100 g) (William 1997). Montmorillonite has a better potential for liner because of highest attenuation capability (Griffin & Shimp 1978) and lower permeability (CIRIA 1996) compared to illite and kaolinite. Musso et al. (2014) stated that the total amount of metal sorption is strongly influenced by the total specific surface area, the presence of carbonates and the content of the clays in soil.

Based on the physical and chemical properties of the soils, one may conclude that the adsorption capability and the hydraulic conductivities of these materials were different, resulting in a difference in the rate of heavy metals movement in soils (Lo & Liljestrand 1996). Soil SBMC has a better potential for liner material compared to ARA and HMS.

THE BREAKTHROUGH CURVES OF HEAVY METALS THROUGH SOIL COLUMN

The column experimental results are presented as breakthrough curves (BTCs) which were plotted between relative concentration (C_e/C_o) against the pore volumes (PV). Relative concentration (C_e/C_o) is a ratio between concentration of heavy metals in the effluents and concentration of heavy metals in the influent. The relative concentration equals 1.0 represents the total breakthrough of heavy metals through the compacted soil column.

Figure 3(a) and Figure 3(b) shows the BTCs of Pb, Cu, Ni and Zn for SBMC soil as observed in both PV3 and PV5 soil columns. It can be seen that C_e/C_o values increased with the increasing numbers of pore volumes. The plots also showed that Ni and Zn were the most mobile heavy metals, with the C_e/C_o after 3 PV and 5PV were 0.006 and 0.6, respectively. Low C_e/C_o values (i.e. BTCs < 1.0) indicates that sorption of heavy metals was high in both soil colums. The curves in both columns also indicated that different heavy metals have different affinity (or selectivity) for sorption, where the affinity of heavy metals sorption can be ranked as Pb>Cu>Ni ≈ Zn. The selectivity order is assumed to be inversely proportional to the hydrated radius of the metal with a smaller radius being more favourable for sorption (Chotpantarat et al. 2011). Pb has highest affinity for sorption compared to other metals, and according to Chotpantarat et al. (2011), the retention (sorption) of Pb was mainly regulated by the formation of strong covalent bonds as well as the possibility of formation of salts of metal. Zn and Ni were the least metal sorbed, as a consequence, they were more mobile and would move far in the soil.

The sorption of heavy metals in soil column in Figure 3(a) and Figure 3(b) also corresponded very well with the buffering capacity of the soil as indicated by the pH lines in both columns. The pH lines were almost constant from the start to end, with the values ranged from 7-8 for PV3 and 6.5-8 for PV5. The pH of the test solution used in this experiment was 1.4. The pH profile indicated that SBMC soil has a very good buffering capacity, i.e soil has good capacity to resist any changes from an acidic test solution to maintain its pH from start to the end of the test. A number of adsorption studies indicate that within the pH range of soils (4 to 11), heavy metals adsorption increases with increasing pH (Bittel & Miller 1974; Griffin & Shimp 1976; Scrudato & Estes 1975; Yang et al. 2012). High pH of soils increases the amount of heay metals sorbed due to the formation of heavy metals carbonate precipitates which is observed when the solution pH values exceeded 5 or 6 (Griffin & Shimp 1976). Yang et al. (2012) also stated that chemical precipitation is considered as the dominant mechanism at pH>9.

Figure 3(c) and Figure 3(d) shows the breakthrough curves of HMS soil after 3PV and 5PV of column leaching tests. The C_e/C_o values were below the total breakthrough value (1.0), although Ni showed higher mobility (less sorption) in both 3PV and 5PV soil columns with the values of 0.7 and 0.8, respectively. Further leaching will definitely resulting total breaktrough for Ni in column PV3, but interesting to note in column PV5, after 3 pore volumes of leaching, Ni breakthrough was slowly decreased (25% decreasing from C_e/C_o = 0.8 to C_e/C_o =0.6). This could not be justified whether Ni curves in column PV3 will follow the trend as shown by column PV5. Other heavy metals were highly retained in both columns. It is interesting to note that the mobility of Pb in both column s was quite high as compared to Pb in SBMC soil columns. However, the C_e/C_o values were small, i.e. less than 0.3. The affinity for sorption in these two columns can be ranked as Zn ≈ Cu>Pb>Ni. This new affinity order for sorption in HMS is so much different as shown earlier by SBMC soil (Figure 3(a) and Figure 3(b); probably due to different physical and chemical properties of these two soils. The pH lines also showed a drastic plunging in both HMS soil columns with an early pH values was 7.0 to a final pH values of 5.0 in both HMS columns. Based on the pH lines behaviour, one may conclude that HMS soils possess low buffering capacity, and this was an explanation to the behaviour pattern for Ni in both columns (i.e. poor buffering will increase the mobility of heavy metals and decreasing the ability for sorption in soils). Musso et al. (2014) stated that adsorption of heavy metals on soil surfaces can be considered as an evidence of clay–metal electrostatic interaction.

Figure 4(a) and Figure 4(b) shows the BTCs for ARA soils. The C_e/C_o values for PV3 and PV5 soil columns were below 0.2 and 0.14, respectively. Ni showed highest mobility in both columns, similar to that observed earlier in soil HMS. Zn and Cu showed the least mobile of HMs in both columns. The affinity for sorption in these two columns
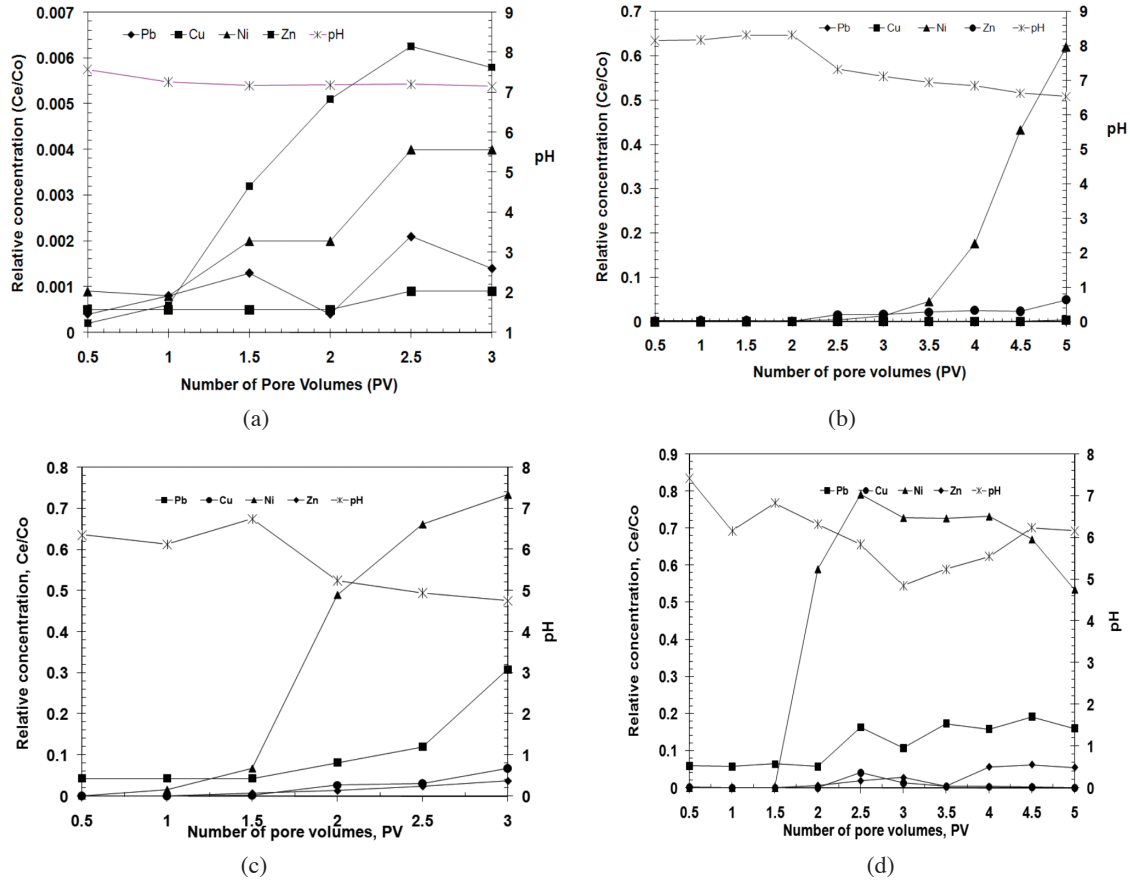
FIGURE 3. The breakthrough curves for (a) SBMC-3PV; (b) SBMC-5PV; (c) HMS-3PV and (d) HMS-5PV

can be ranked as Zn ≈ Cu>Pb>Ni; which is similar as previously observed in HMS soil columns. ARA soil columns showed the lowest buffering capacity as shown by the pH lines. The pH decreased from the value of 5 to 4 after three pore volumes of leaching. However, the pH values were quite constant (pH4.0) in another soil column (5PV). The pH values shown in both columns were in an acidic region and may well indicate the poor buffering capacity of this soil. Figure 5(a) shows the pH lines of three compacted soils after 5PV of leaching. It was observed that after 5PV of leaching using pH~1.4 test solution, soil SBMC showed very high resistance to an acidic test solution, where the pH values throughout the test were in an alkaline region with the values of pH8 to 7. This undoubtedly shows that soil SBMC has a very good buffering capacity and capable to buffer an acidic solution that act upon it. Since the pH values for the effluents showed a range of 6 to 8, one may conclude that all the heavy metals were precipitated in the soil columns. The amount of heavy metal ions (Cu, Zn, Cd, Pb) adsorbed by clay in acid media increases with increasing pH, and it has been proposed that this effect is due to decreased competition from protons for adsorption sites. Beyond a threshold pH (e.g. pH > 6 for Pb, pH > 7 for Cd) virtually all the metal ion is removed from the aqueous phase, presumably as hydroxy species adsorbed on the surface of the suspended solid particles (Farrah & Pickering 1977). Soils HMS and ARA were not good enough

to buffer the acidic test solution. The pH values for HMS were in an alkaline region (pH7.5) at the start of the test (~PV1) but the pH decreased to an acidic region with further addition of test solution (final pH measured was 6.0). The worst soil to buffer an acidic test solution was shown by soil ARA, where the pH values were in an acidic region from start to the end of testing (final pH 4.0). This demonstrated that soil ARA could not resist an acidic attack that was applied to it by an acidic test solution. In terms of soil buffering capacity of these soils, one can make a conclusion that soil SBMC has the highest buffering capacity then followed by soil HMS and ARA. The buffering capacity of these three soils can be ranked as SBMC>HMS>ARA.

The buffering capacity parameter plays very important role in the retention of heavy metals (Wan Zuhairi 2003). Soil with high buffering capacity retains most of the heavy metals as compared to soil with lowest buffering capacity. Soil SBMC had a capacity to retain all heavy metals in the test solution as given by Figure 5(b) (only Pb is shown here). Soils ARA and HMS had a lower retention capacity which were given by high values of C_e/C_o. However, the retention behaviors of ARA and HMS in Figure 5(b) was very confusing, as it was contradicted with the soils' buffering capacity (Figure 5(a)) and physical chemical properties (Tables 2 and 3). Based on the soils buffering capacity and soils physical chemical properties for HMS and ARA soils, soil HMS was better than soil ARA in terms
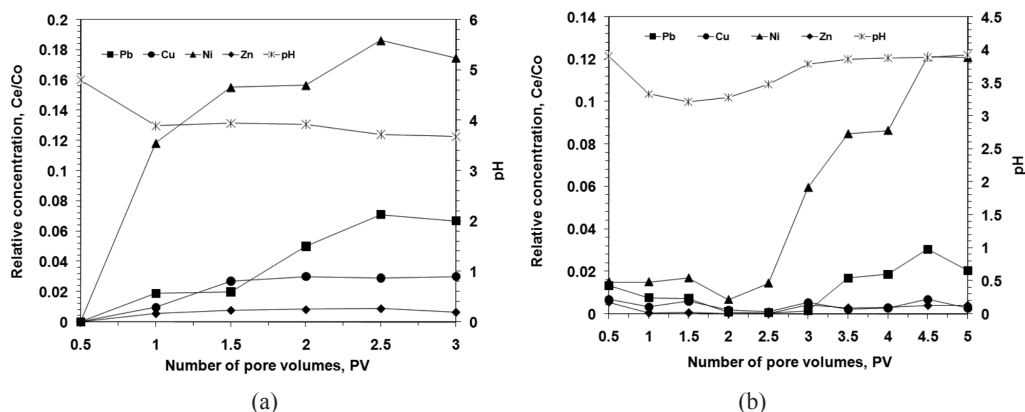
FIGURE 4. The breakthrough curves for (a) ARA-3PV and (b) ARA-5PV

of its capability to retain the heavy metals. However, the breakthrough curves in Figure 5(b) shows otherwise, whereby the retention of ARA was better than HMS. The reason for this behavior was probably due to the appearance of channel (micro fracture) in HMS soil column, resulting more heavy metals seeped through the compacted soil column. Further investigation is required to clarify this phenomenon. In terms of retention mechanism of heavy metals in compacted soil, there are a number of processes capable of attenuating leachate during its migration through natural materials. Four main mechanisms are identified consist of sorption/ion exchange, sorption by particulate organic matter, precipitation and dilution (Bright et al. 1996, Yong et al. 2001). These mechanisms are greatly controlled by the buffering capacity of the soil (i.e. resistance of soil against any changes to its pH). Therefore, soil with high buffering capacity can predominantly retain the heavy metals via precipitation of soluble heavy metals into insoluble forms and stick to the soil solid particles. Meanwhile, soil with low buffering capacity will increase the mobility of heavy metals that can seep easily through the soil column. The uptake of heavy metal species by clay soil increases very significantly as the pH increased (Farrah & Pickering 1976; Frost & Griffin 1977).

HEAVY METALS RETENTION PROFILES THROUGH COMPACTED SOIL COLUMN

Figure 6(a), 6(b) and 6(c) shows the retention profiles of heavy metals from top to exit-end of the soil column after 5PV of leaching. The results were determined after an acid digestion technique of soil slices for each compacted soil. The retention profiles showed that most of the heavy metals were retained at the top 30 mm of the compacted soils. All figures also showed that Pb was predominantly retained at the top part of compacted soil (i.e. first 30 mm) compared to other heavy metals. Pb retention profile in SBMC was high throughout the soil column, while Zn was the lowest metal retained in SBMC soil. This behavior is in agreement with BTCs shown previously in Figure 3(b), where Zn showed the highest mobility in this column (i.e. highest mobility means very small amount of Zn was retained in the soil column).

In the HMS compacted soil - Figure 6(b), Pb was the highest retained at the top 30 mm of the column (0.029 mg/g), but decreased very rapidly towards the end of the column (0.003 mg/g). Ni was observed to be very mobile in this soil, with the concentration of Ni in the soil was constant throughout the column, i.e. 0.002 mg/g. It is also interesting to note that the retention profile for Cu increased
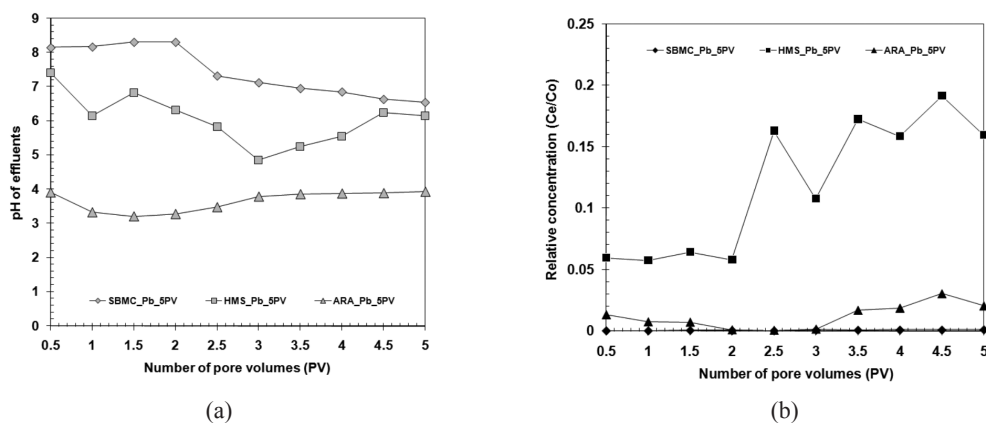

FIGURE 5. (a) The pH lines of three compacted soil columns SBMC, HMS and ARA, and (b) The comparison of Pb retention in three different soil columns SBMC, HMS and ARA

below 30 mm and replaced Pb as the highest HM retained. Similar observation was discovered in ARA compacted soil, where Pb was the highest HM retained at the top 30 mm and then was replaced by Cu below 30 mm until at the exit-end of the column. However, Zn was the least HM retained in ARA soil resulting very small concentration of Zn being retained in this soil (with the average concentration of 0.003 mg/g).

The Pb retention profiles in all compacted soils after 5PV of leaching are presented in Figure 6(d). It showed very clearly that SBMC had a capacity to retain high amount of Pb compared to ARA and HMS compacted soils. HMS only retained high concentration of Pb at the top 30 mm of the column, and below 30 mm the retention of Pb decreased very rapidly. The results in Figure 6(d) illustrated that SBMC was a good soil to retain heavy metals (Pb) and followed by ARA and HMS soils. It was still puzzling why ARA showed better sorption for Pb as compared to HMS, as the physical and chemical properties (Tables 2 and 3) were in favor for HMS as a best material to retain heavy metals. However, this discrepancy between ARA and HMS was also discovered in the breakthrough curves of Pb in these soils - Figure 5(b). Recall back the physico-chemical properties of SBMC, most of the physical and chemical properties of SBMC were in-

favor for high sorption. CEC and SSA values for SBMC were higher compared to other soil materials due to active mineral montmorillonite. According to Chalermyanont et al. (2009), higher CEC indicates a higher negative charge of the soil and hence, a higher heavy metal sorption capacity. Finally, due to discrepancy in soil physico-chemical properties and different buffering capacity of these soils, hence, they have difference adsorption capability and different rate of heavy metals mobility.

The retention of heavy metals by these three different soils was greatly contributed by their clay contents. SBMC had higher amount of clay content with 33-52%, followed by HMS and ARA with 2.2-2.7%. As a result, SBMS showed higher sorption (retention) of heavy metals compared to other soils. Clay particles in soil increase the SSA and CEC values of the soils, hence increase the negatively charged of the soil and increase the sorption capability of the soil. The other factor that can contribute to higher sorption capability of the soil is the type of clay presents in the soil. SBMC soil had high percentage of clay fraction also contains active clay mineral montmorillonite. This active mineral increased the CEC, SSA and sorption values of the SBMC soil. According to Li et al. (2017), the column tests in their study showed
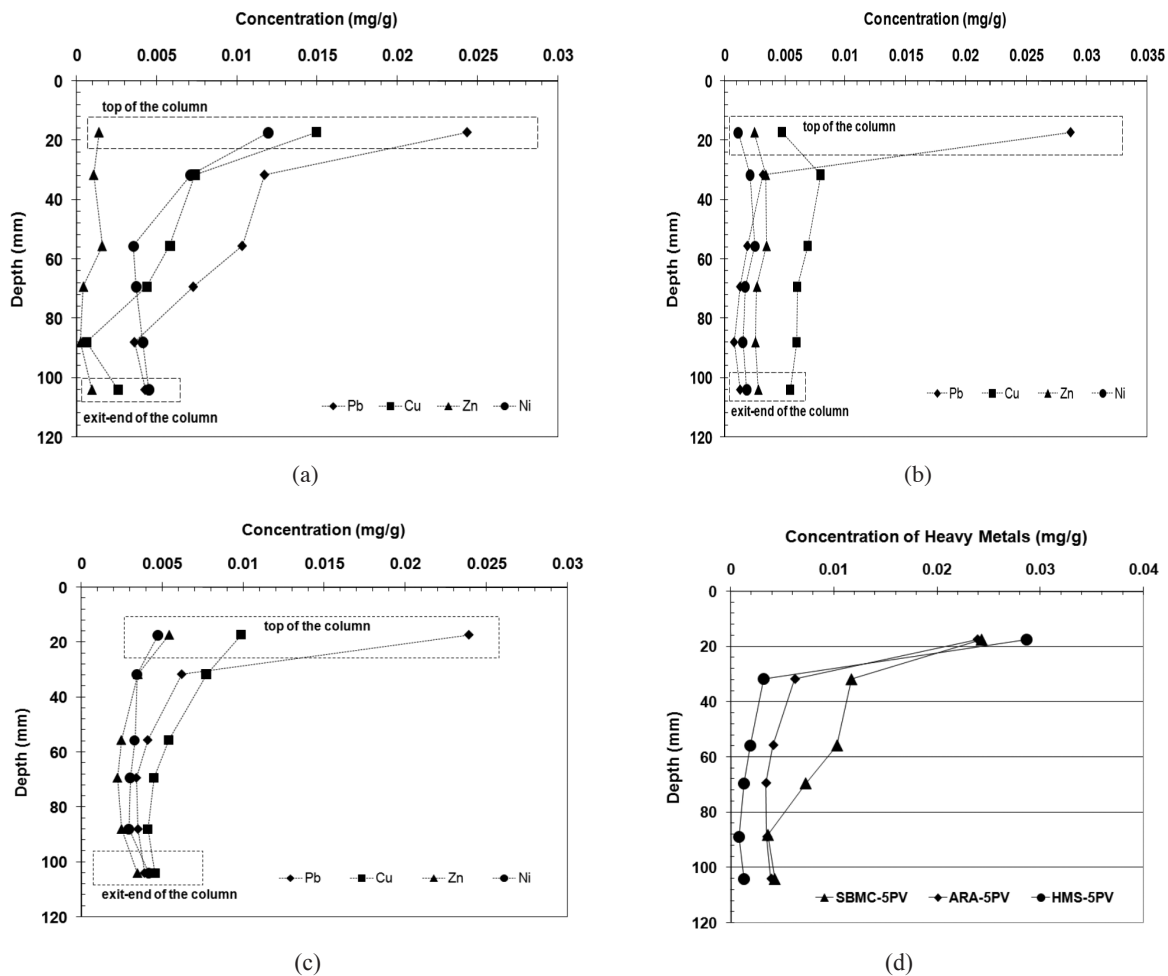

FIGURE 6. The retention profiles of (a) SBMC (b) HMS and (c) ARA after 5PV of leaching, (d) retention profiles of Pb for soil columns SBMC, ARA and HMS

that as the shale content increased, the retardation factors of Zn, Cd, Pb, and Cr also increased.

CONCLUSION

This study has showed that soils have different capacity to retain heavy metals and very much depending on their physical and chemical properties. The affinity or selectivity of heavy metals for sorption (or retention) also varies in different types of soils, as been proven by the study. The study discovered that heavy metals entered the soil columns were retained predominantly at the top 30 mm. Most of heavy metals were retained and only certain heavy metals species were allowed to migrate through the soil column. Soil SBMC has a capability to retain most of the heavy metals, and also has good buffering capacity to maintain its pH against an acidic solution (pH1.4), therefore increasing the chances of retaining most of heavy metals via natural attenuation (i.e. precipitation). Engineering application of these findings is that soil SBMC has a very good potential to function as liner material compared to two other soils (ARA and HMS) due to its low hydraulic conductivity and its high heavy metal attenuation capability.

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