

ENVIRONMENTAL ASPECTS OF WASTE-DERIVED BOTTOM BLEND CLAY LINERS INCORPORATING ZEOLITE AND BENTONITE

Rungroj Piyaphanuwat^{1,*} and Suwimol Asavapisit²

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Abstract

This research investigated the effects of incorporating bentonite and zeolite into bottom blended clay liners (BBCLs) on their engineering properties and adsorption capacity. BBCLs composed of clay, water treatment residue, and calcium carbide in a 40:40:20 ratio by volume were investigated with the addition of 1, 2, and 3 wt.% bentonite or zeolite. The experimental results indicated that bentonite and zeolite had positive effects on the slake durability index and the equilibrium time for the adsorption of lead (Pb) and chromium (Cr) from the leachate, whereas the unconfined compressive strength (UCS) and coefficient of permeability were negatively affected compared to those of the samples without bentonite and zeolite. At 56 days, the UCS of BBCLs with bentonite and zeolite decreased from 3.4 to 2.2MPa, while the coefficient of permeability of all the samples met the regulatory limit of sanitary landfills, which was given at 1×10^{-7} cm/s. The slake durability index of all samples was lower 50% but it remained higher compared to BBCLs without bentonite and zeolite (approximately doubled). Both additives enhanced the equilibrium time and percentage of Pb and Cr adsorption by about 20% and 200%, respectively. SEM-EDS results show the adsorption of Pb and Cr onto the raw materials, calcium silicate hydrate (CSH), zeolite, and bentonite. Therefore, the addition of zeolite can increase the ability to adsorb heavy metals from leachate, which is suitable for use in secured landfills.

Keywords: Bentonite; Bottom landfill liner; Clay; Heavy metals; Water treatment residue; Zeolite

¹ Innovative Environmental Management and Smart Construction Material Laboratory, Ratchaburi Learning Park, King Mongkut's University of Technology Thonburi, Rang Bua, Chom Bueng, Ratchaburi 70150, Thailand. E-mail: rungroj.piy@kmutt.ac.th

² Environmental Technology Program, School of Energy, Environmental and Materials, King Mongkut's University of Technology Thonburi, Bangmod, Thung-kru, Bangkok 10140, Thailand. E-mail: suwimol.asa@kmutt.ac.th

* Corresponding author

Introduction

Landfills are carefully engineered and constructed for the disposal and long-term storage of municipal solid wastes and industrial residues on the ground to minimize the

transmission of contaminants to the environment. These contaminants contain toxic components such as heavy metals and soluble salts, which are released via leachates in the downwards direction to the bottom of the landfill (Xue *et al.*, 2014). Inappropriate minimization of toxic component infiltration to the surrounding soil as well as ground or surface water has negative effects on public health and the environment. To prevent negative impacts from the bottom of the landfill, a drainage system combined with a low-permeability barrier with a hydraulic conductivity as low as 1.0×10^{-7} cm/s was designed to collect the leachate and retard the migration of these contaminants (Prakongwittaya *et al.*, 2020). A clayey soil is generally considered as the most economically and environmental friendly material. As a consequence, clay is commonly used as natural lining material at the bottom of the municipal solid waste landfills. Several research works reported that hydraulic conductivity, degree of compaction, moisture content, clay composition, field placement technique and liner thickness are the main factors affecting the quality of compacted clay liners (Prakongwittaya *et al.*, 2020; Aloulou *et al.*, 2020).

These heavy metals are present in batteries, paints, cosmetics, pesticides and fluorescence tubes, which are household hazardous wastes, or in electroplating, mining, tanneries and ore refining industrial wastes. Heavy metals such as lead (Pb), chromium (Cr), cadmium (Cd), mercury (Hg), and arsenic (As), released from landfill leachates to the environment are usually retained within the bottom clay liner through adsorption on the surface of clay particles, but the retention capacity is rather low (Piyaphanuwat and Asavapisit, 2018; Kostenko *et al.*, 2019). To improve the retention capacity of clay liners, several adsorbents, including fly ash, zeolite, bentonite and activated carbon, have been suggested as additive materials (Kostenko *et al.*, 2019; Muhammad and Siddiqua 2021). Data on leachate from landfills in Bangkok, Thailand, revealed the presence of heavy metals such as Pb, Cr(III), Cr(VI), Cd, Hg, and As. However, the concentrations of Pb and Cr(III) exceeded the standard criteria set by the Ministry of Industry, while those of Cr(VI), Cd, Hg, and As did not. Therefore, this research focused on Pb and Cr(III) to assess the potential of bottom blend clay liners (BBCLs) as a solution for leachate problems in Thailand.

Among the abovementioned adsorbents, bentonite and zeolite are the most commonly used natural materials for constructing bottom clay liners (Tetik *et al.*, 2009; Xiao *et al.*, 2018; Zheng *et al.*, 2021). Bentonite is a clay-based material consisting of montmorillonite as a major clay mineral, while zeolites are crystalline aluminosilicate materials with a three-dimensional tetrahedral framework. Both bentonite and zeolite are known to have high cation exchange capacities (CECs), with the highest values reaching 150 and 400 meq/100 g for bentonite and zeolite, respectively (Devi and Dutta, 2017). Consequently, bentonite and zeolite are of interest for use in several applications to remove heavy metals from wastewater (Devi and Dutta 2017; Aloulou *et al.*, 2020).

According to Prakongwittaya *et al.* (2020), a composite clay liner containing clay, WTR, and CCR at a mix ratio of 40%, 40%, and 20% by weight, respectively, achieved an optimal compressive strength of 2.95 MPa and a coefficient of permeability of 6.6×10^{-8} cm/s. However, the study did not investigate the composite clay liner's heavy metal adsorption capacity from landfill leachate. This is important because the liner as the final barrier to prevent the release of heavy metals in the leachate. This research therefore focuses on enhancing the heavy metal adsorption capacity of BBCLs through the incorporation of bentonite and zeolite for preventing the infiltration of heavy metals present in landfill leachates through bottom clay liners into groundwater. The effects of bentonite and zeolite addition to the bottom clay liner at 1, 2 and 3 wt.% on the engineering properties, including compressive strength, coefficient of permeability and slake durability index, were investigated. The abilities of bentonite and zeolite in the bottom clay liner to contain heavy metals, especially lead (Pb) and chromium (Cr), which are defined by the USEPA as priority metal pollutants, were studied. The microstructures of the bottom clay liner containing bentonite and zeolite before and after contact with landfill leachate containing Pb and Cr were also examined.

Materials and Methods

Materials

Clay was collected from the construction site of KKK Products Co., Ltd., in Chachoengsao Province, Thailand, at a depth of 6-8 metres. Water treatment residue (WTR) was collected from the Banglen water treatment plant, which uses raw

water from the Tha Chin River. This water treatment plant was in Nakhon Pathom Province, Thailand. Calcium chloride residue (CCR) was collected from the metal welding process used for acetylene gas production in Samutprakan Province, Thailand. Clay, WTR and CCR were dried in a hot-air oven at $105\pm 5^\circ\text{C}$ for 24 hours and ground with a Los Angeles abrasion machine to reduce the particle size. The sizes of the particles were controlled by passing through sieve No. 40 ($425\mu\text{m}$). All the dried raw materials were kept in airtight containers. The chemical compositions and crystalline phases of the raw materials were analyzed using X-ray fluorescence (XRF) and X-ray diffraction (XRD) techniques, and the results are shown in Table 1 and Table 2. Bentonite in the form of sodium bentonite was obtained from Bentonil Co., Ltd. Natural zeolite was obtained from Amonchai Co., Ltd., which is located in Kanchanaburi Province. Both bentonite and natural zeolite are commercial-grade materials.

Table 1. Chemical composition of materials

Element	Percentage by weight				
	Clay	WTR	CCR	Bentonite	Zeolite
SiO ₂	62.29	59.59	7.15	64.7	70.12
Al ₂ O ₃	20.27	26.51	4.76	12.1	21.89
CaO	1.78	1.29	85.92	3.2	0.16
Fe ₂ O ₃	7.37	7.36	0.46	2.0	1.77
SO ₃	3.78	0.79	0.54	-	-
K ₂ O	2.55	2.29	-	1	0.94
MgO	0.19	1.12	1.09	2.1	-
P ₂ O ₅	0.12	0.48	-	-	-
Na ₂ O	1.46	0.34	0.08	-	-
MnO	0.19	0.24	-	-	-

Table 2. Physical properties of bentonite and zeolite

Physical Properties	Clay	Bentonite	Zeolite
Swell Index (times)	5.5	27	2
Moisture (%)	10.7	11.5	7.5
pH	7.88	8.78	10.8
Particle size less than 200 mesh (%)	86.5	83	93.5
CEC (meq/g material)	1.24	1.56	5.6

Mixed proportions of BBCLs and sample preparation

The control sample of BBCL was prepared using mixtures of clay, WTR and CCR at a ratio of 40:40:20 (Prakongwittaya *et al.*, 2020). Bentonite and natural zeolite were added to the control at 0, 1, 2 and 3wt.%. The water content for each mix proportion was obtained through the determination of the optimum moisture content (OMC) using the modified Proctor compaction test in accordance with ASTM D1557-02, as shown in Table 3.

The compacted samples were prepared in cylindrical moulds 5 cm in diameter and 10 cm in height. All the samples were compacted using the modified Proctor compaction method, which uses the same compaction energy. All the samples were wrapped with cling film and stored in a controlled temperature and humidity chamber to prevent water evaporation.

Table 3. Optimum moisture content of compacted clay liner incorporating bentonite and zeolite

Samples	Optimum Moisture Content (OMC) (%)
Control	31.7
Bentonite 1%	33.8
Bentonite 2%	35.5
Bentonite 3%	37.9
Zeolite 1%	34.6
Zeolite 2%	37.2
Zeolite 3%	39.1

Methods of Testing

Unconfined compressive strength (UCS)

After 14, 28 and 56 days of curing, the cling film was removed from the sample and air-dried at room temperature for 4 h. An automatic unconfined compression machine was used to determine the compressive strength development following ASTM D1633-00. The specification of the UCS machine is a maximum capacity of 50 kN with a resolution of 0.05 kN. The displacement rate of the test was 1 mm/min. A set of five samples was used for the compaction test, and the arithmetic average with a 95% confidence interval was calculated.

Hydraulic Conductivity test

The compacted samples were prepared in cylindrical molds with diameters of 50mm and heights of 100mm. The samples were demolded after 1 day, wrapped with cling film and cured in an airtight plastic box for 28 days prior to testing. The hydraulic conductivity of the BBCLs was determined by applying a rigid wall permeameter. The sample was wrapped with a rubber membrane with porous disc paste on top and bottom of the sample. During the test, the deionized water was permeated at a constant pressure of 1.4 bar. A constant head permeability set with a diameter of 150 mm was used (Figure 1). The volume of the outflow was collected after 48 hours, and the hydraulic conductivity (k) was calculated using the following equation:

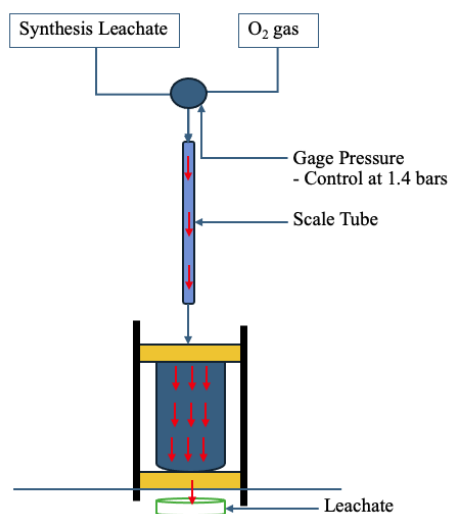


Figure 1. Flow and details of the permeability apparatus

$$\text{Hydraulic Conductivity}(k) = \frac{Q}{iAt} \quad (1)$$

where Q is the rate of the outflow water (cm^3/s), which is the hydraulic gradient equal to the head of water ($\text{cm H}_2\text{O}$) divided by the height of the sample (cm); A is the cross-sectional area of the sample specimen (cm^2); and t is the elapsed time (s).

Adsorption of heavy metals

Synthetic landfill leachate containing Pb and Cr was used in this research. A leachate with a mixture of Pb and Cr nitrates at a concentration of 3 mg/L for each metal was prepared using deionized water. The ability of BBCL to incorporate various amounts of bentonite and zeolite was investigated in a similar manner to that of the hydraulic conductivity test except that synthetic leachate was used throughout the experiment. The synthetic leachate was allowed to permeate through the BBCL sample. The volume of the leachate, time to reach saturation for each sample and the equilibrium time were recorded. The outflow of the leachate was collected every 10 min to determine the amount of Pb and Cr adsorbed during permeation through the sample containing bentonite and zeolite. The equilibrium time was obtained when the concentrations of Pb and Cr in the inflow were equal to that of the outflow leachate. The concentrations of Pb and Cr in the permeate were analyzed using an atomic absorption spectrophotometer (AAS). The heavy metal adsorption percentage (HA%) was calculated using the following equation:

$$\text{HA}\% = (\text{TCI} - \text{TCE}) / \text{TCI} \times 100\%$$

When:

TCI = Total concentration of heavy metal influence.

TCE = Total concentration of heavy metal effluent.

Slake Durability Index of the BBCL

The slake durability index (SDI) was determined for the BBCL samples using a modified slake durability test apparatus in accordance with the ASTM D4644-08 standard test method. The oven-dried samples were weighed before being placed in the drum holder within troughs filled with water. The drums were rotated at 20rpm for a period of 10min. All the samples were removed carefully from the drums and oven-dried at 110°C for 12 h, after which the weights of the samples were recorded. All the test samples were subjected to the slake durability test again for the second time. The weight data after testing for two cycles were used for the calculation of the SDI values.

Microstructure analysis

Scanning electron microscopy (SEM) (JEO model JSM-6610 LV) and energy dispersive spectroscopy (EDS) (Oxford Instruments model INCA-Xart) were used to analyze the microstructures of the selected samples. The development of crystalline phases in each sample was detected by X-ray diffraction (XRD) (Bruker Model D2, XE-T). Microstructure investigations were performed on selected samples consisting of clay:WTR:CCR at a ratio of 40:40:20 with 3wt.% bentonite and natural zeolite at a curing age of 28 days. All samples were dried by soaking in acetone for 1 h and kept in a desiccator until analysis. The samples used for SEM-EDS analysis were coated with pure gold in a sputter coater (CRESSINGTON Model 108 Auto).

Results and Discussion

Effect of bentonite and zeolite on the compressive strength

The compressive strength of the control sample consisting of clay mixed with WTR and CCR at a ratio of 40:40:20 increased from 2.09MPa to 2.95 and 3.34MPa, respectively, with increasing curing time from 14 days to 28 and 56 days (Figure 2a). The increase in strength with curing time is due to pozzolanic reactions. Calcium oxide present in CCR reacts with SiO_2 and Al_2O_3 present in clay and WTR, forming calcium silicate hydrate (CSH) with a binding capacity resembling that of ordinary Portland cement (OPC) (Makarata et al., 2011; Piyaaphanuwat et al., 2018; Oluremi et al., 2019;

Najafi *et al.*, 2021). The addition of 1, 2 and 3wt% bentonite to the control sample reduced the strength of the BBCL samples at all curing times. The strength reduction was caused by increase in the OMC of the samples (Table 3). OMC water was absorbed by bentonite during sample compaction and desiccated when the samples were cured, which led to the shrinkage of bentonite particles, thus leaving an empty space around the bentonite particles and reducing the UCS (Shaour *et al.*, 2011; Kostenko *et al.*, 2019; Adeboje *et al.*, 2020; Azhar *et al.*, 2020; Muhammad and Siddiqua, 2021; Yong *et al.*, 2021).

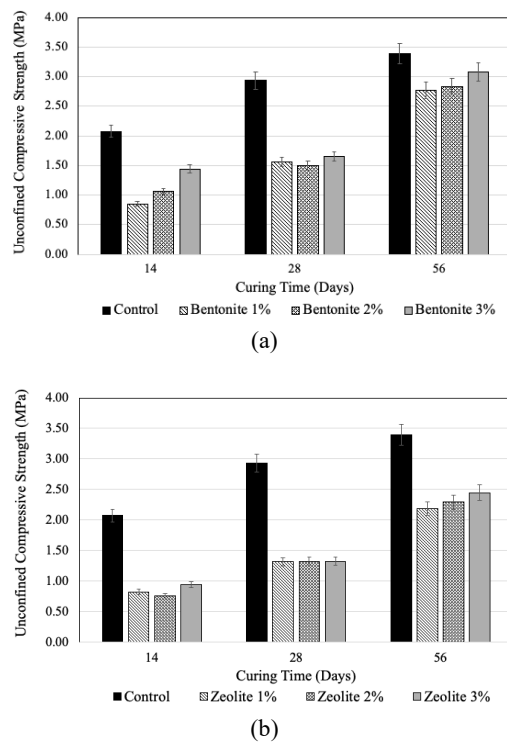


Figure 2. Strength development of bottom blend clay liners incorporating various amounts of a) bentonite and b) zeolite

Similar strength development results were observed for the bottom clay liners incorporating various amounts of zeolite (Figure 2). Zeolite is a microporous material and therefore is widely used as a natural water absorbent. The zeolite in the BBCL can absorb water, resulting in an increase in the amount of water needed during sample mixing. The excess mixing water in the pores and water absorbed in the zeolite leaves behind pores in the BBCL during the progress of pozzolanic reactions and is the cause of strength reduction. In addition, zeolite does not react with the BBCL and makes the

structure inhomogeneous, causing gaps within the structure and resulting in a decrease in the compressive strength. In comparison, zeolite had a greater negative impact on the strength development of the BBCL than did bentonite (Figure 2a-b). The strength of the BBCL containing 1-3wt.% zeolite was between 0.6 and 2.35MPa at all curing times. These findings agree with those of Zheng *et al.* 2021, who reported that concrete containing zeolite has greater porosity, pore sizes and pore connectivity, which lead to a decrease in the strength of blended concrete. The compressive strengths of all the samples with zeolite and bentonite were greater than 2MPa; this is a suitable solution for use as a cover and bottom BBCL and as a daily covering material in landfills.

Coefficient of permeability of the bottom clay liner incorporating zeolite and bentonite

In addition to the compressive strength, the water permeability coefficient is an essential factor for BBCLs in landfills; this is because the BBCL prevents the leakage of leachate, which contains heavy metals and hazardous contaminants. The coefficients of permeability of the BBCLs in the presence of various amounts of bentonite and zeolite are shown in Table 4. The results showed that the water permeability coefficient of zeolite and bentonite mixed with BBCL was lower than $1 \times 10^{-7} \text{ cm/s}$, which is the standard value for compacted clay liners in secure landfills. BBCL (without bentonite and zeolite) has a permeability coefficient of $6.64 \times 10^{-8} \text{ cm/s}$, while 1 and 2wt.% bentonite or zeolite had permeability coefficient values of 3.21 and $5.34 \times 10^{-8} \text{ cm/s}$ for samples with bentonite and 2.98 and $4.92 \times 10^{-8} \text{ cm/s}$ for samples with zeolite, respectively. The lower permeability coefficient of the BBCLs containing 1 and 2 wt.% bentonite or zeolite is due to swelling. Both bentonite and zeolite, when in contact with water, expanded and filled the meso- and micropores of the BBCL samples. Consequently, the pores were closed by the expanded bentonite and zeolite. This phenomenon reduces the degree of pore connectivity within the BBCL samples, and thus, the water can flow through the sample in a meandering manner at a reduced rate and increase the compacted density. (Wan *et al.*, 2014).

At 3wt.%, bentonite or zeolite had permeability coefficients of 8.12 and $7.61 \times 10^{-8} \text{ cm/s}$, respectively, for samples with bentonite and zeolite that were higher than 1 and 2wt.%, respectively. For BBCL with 3 wt.% bentonite, the large amounts of absorbed water on the surface of bentonite particles were desorbed and evaporated during the curing of the sample at higher amounts, leaving more spaces surrounding the bentonite particles. However,

BBCL with 3wt.% zeolite cannot desorb and evaporate during curing and blending with clay, WTR or CCR; this was because of the small spaces surrounding zeolite particles through which liquid can flow. These spaces act as channels for water to flow through and are the cause of an increase in the coefficient of permeability (Wan *et al.*, 2014; Monteiro *et al.*, 2018; Xiao *et al.*, 2018). Although increased values of the coefficient of permeability for samples with 3wt.% bentonite or zeolite were obtained compared to those of the control sample, all samples had permeability coefficient values within the standard limit of BBCL for secure landfills (1×10^{-7} cm/s).

Table 4. Coefficient of permeability and slake durability index of bottom blend clay liners with bentonite and zeolite

Samples	Coefficient of Permeability (cm/s)		Slake Durability Index (%)	
	Average (10 ⁻⁸)	Standard deviation (10 ⁻⁹)	Average	Standard deviation
Control	6.64	1.72	33.03	0.285
Bentonite 1%	3.21	1.12	24.68	0.212
Bentonite 2%	5.34	1.05	29.55	0.185
Bentonite 3%	8.12	0.75	39.75	0.125
Zeolite 1%	2.98	0.15	26.65	0.111
Zeolite 2%	4.92	0.11	32.83	0.057
Zeolite 3%	7.61	0.52	45.68	0.085

Slake Durability Index (SDI) of BBCLs incorporating bentonite and zeolite

Under flooding conditions, the BBCL will be immersed in water, causing expansion and resulting in loosening of the structure. The SDI of the compacted clay liner was 79.5%, while that of the BBCL decreased to 33.03% (Table 4). This index was calculated from the sample weight change after being subjected to two standard cycles of wetting and drying. The SDIs of BBCLs with 1 and 2wt.% bentonite and zeolite were lower than those of the

control sample. With the addition of 1 and 2wt.% bentonite and zeolite, the pores and voids within the BBCL samples were filled and blocked by the expanded bentonite and zeolite particles. As a result, the water could not flow through the sample during the wetting test or could flow at a reduced rate, thus leaving the sample facing less disturbance. Therefore, the BBCL weakens and disintegrates under the service environment due to the expansion effects of bentonite and zeolite. From the experimental results, the presence of zeolite at all levels made the bottom clay liner less durable in an aggressive environment than did bentonite. It is possible that bentonite is a clay-based material and is therefore more compatible with and homogenous to BBCL than zeolite. Similar effects of bentonite and zeolite on the variations in the SDI and coefficient of permeability were obtained.

Adsorption of Pb and Cr from synthetic landfill leachate.

The percentages of Pb and Cr adsorbed on BBCL containing various amounts of bentonite and zeolite are shown in Table 5. The time to saturation for the control sample containing clay, WTR and CCR was 650 min and increased to 720, 780 and 870 min in the presence of 1, 2 and 3wt.% bentonite, respectively. An increase in the saturation time was caused by the 27-fold increase in the expansion of bentonite when it was in contact with water (Table 2). The decrease in saturation time with increasing amounts of zeolite from 1, 2 and 3wt.% was 638, 604 and 588 min, respectively, in comparison to that of the control sample. Although small zeolite particles can act as fillers in the pores and voids of BBCLs, the small swell index (2 times, Table 2) of zeolite allows water to flow around zeolite particles more easily than bentonite. The 3 wt% zeolite and bentonite in the liner could absorb 2 times more chromium than BBCL (controls) and 3 times more chromium than the compacted clay liner. In addition, the leaching time of 3 wt% of both zeolite and bentonite in the BBCL increased by approximately 50-75%.

Table 5 Percentages heavy metals adsorption by BBCL incorporating bentonite and zeolite

Samples	Saturation time (mins)	Equilibrium time (mins)	Total amounts of leachate (ml)	Heavy metals adsorption (%)			
				Pb		Cr	
				Avg.	SD	Avg.	SD
Control	650	6,770	1,925	45.89	0.12	34.33	0.35
Bentonite 1%	720	7,200	1,969	55.32	0.11	42.43	0.34
Bentonite 2%	780	7,620	2,082	65.35	0.15	55.75	0.25
Bentonite 3%	870	8,070	2,182	82.50	0.25	63.45	0.28
Zeolite 1%	638	7,478	1,914	64.56	0.35	64.22	0.26
Zeolite 2%	604	7,804	2,025	76.89	0.27	73.35	0.27
Zeolite 3%	588	8,148	2,090	89.56	0.38	84.65	0.29

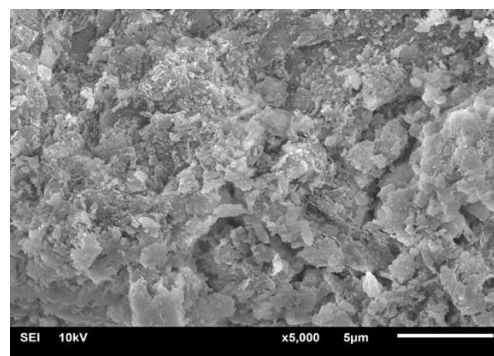
The equilibrium time for BBCL was 6,120 min (Table 5) and increased when bentonite and zeolite were present. BBCL containing zeolite had the longest equilibrium time, followed by BBCL containing bentonite and the control sample; this could be caused by the cation exchange capacity (CEC) property of the materials. The CEC of clay soil generally ranges between 0.25 and 4.0 meq/g (Choo and Bai, 2016; Rujikarn *et al.*, 2020) depending on the type of clay, soil pH and organic matter, whereas those of bentonite and zeolite are 1.56 and 5.6 meq/g, respectively (Table 2). A higher CEC of zeolite leads to greater adsorption of Pb and Cr from the leachate, and thus, it takes a longer time to reach equilibrium where the amounts of Pb and Cr adsorption/desorption are equal. The presence of 3wt.% zeolite and bentonite could adsorb as much as 90% and 83% Pb and 85% and 64% Cr, respectively; this agrees with previous research reporting that Pb is adsorbed by bentonite better than Cr (Hamidpour *et al.*, 2010; Aloulou *et al.*, 2020; Özdemir *et al.*, 2020)

SEM images of compacted clay liners incorporating bentonite and zeolite.

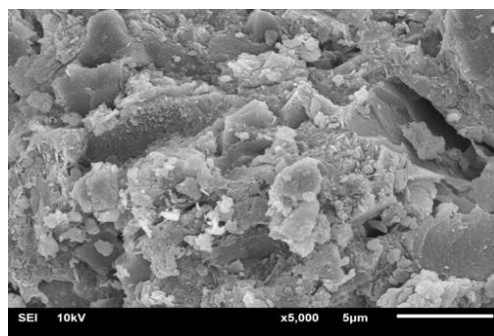
SEM micrographs of the control sample containing clay, WTR and CCR (BBCL) at a ratio of 40:40:20 are shown in Figure 3a. A heterogeneous appearance of the microstructure after curing for 28 days was observed with pore and void scattering throughout the matrix. Clay sheets and flakes were partially covered by the unreacted CCR and gel-like CSH, which is formed by the pozzolanic reaction between clay or the WTR and CCR (Lahori *et al.*, 2019; Prakongwittaya *et al.*, 2020). When bentonite and zeolite were added at 3 wt.%, the heterogeneous microstructures revealed more large pores and voids than did the control sample (Figure 3b and Figure 3c). A higher OMC of the BBCL containing bentonite and zeolite leaves behind the large pores and voids from the evaporation of excess water. In addition, a cubic crystalline structure of zeolite appears in the middle of the SEM micrograph in Figure 3c.

SEM-EDS of the BBCL after being subjected to leachate containing Pb and Cr is shown in Figure 4. SEM revealed that the microstructure of the sample was not significantly disturbed during the test, except that more pores and voids were observed; this could be induced by the dissolution of some unreacted raw materials, such as CCR, Na or K, which are readily soluble species from clay or the WTR upon contact with the leachate. Four areas

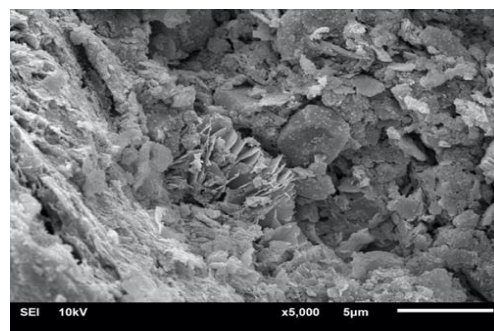
with extra brightness within the image were selected for point analysis, and the percentages by weight of all the elements were determined. Pb and Cr were detected from all selected areas at different amounts in combination with silicon, aluminum, oxygen and calcium. It is generally known that clay and clay-based materials such as WTRs are capable of heavy metal adsorption due to their negative surface charges.



(a)

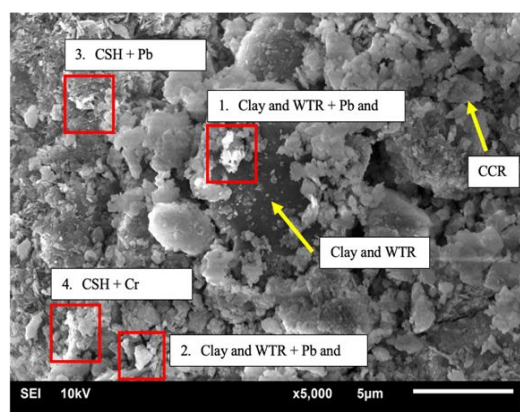


(b)



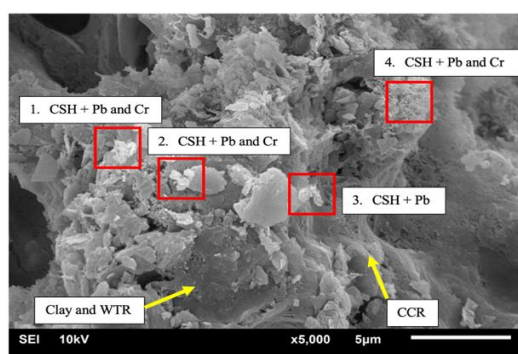
(c)

Figure 3. Microstructure of bottom blend clay liners with a) Controls, b) 3wt.% bentonite and c) 3wt.% zeolite



Element	Percentage by weight			
	Area 1	Area 2	Area 3	Area 4
C K	3.13	7.86	7.30	5.61
O K	42.17	38.54	41.59	52.69
Mg K	0.85	1.02	1.73	0.63
Al K	16.46	13.86	18.02	8.57
Si K	25.01	22.3	9.56	11.61
Ca K	3.74	5.80	10.07	8.01
Fe K	0.56	5.06	4.57	7.12
Cr K	4.52	2.45	1.45	4.54
Pb K	3.56	3.11	5.71	1.22

Figure 4. SEM-EDS of bottom blend clay liners after Pb and Cr adsorption test



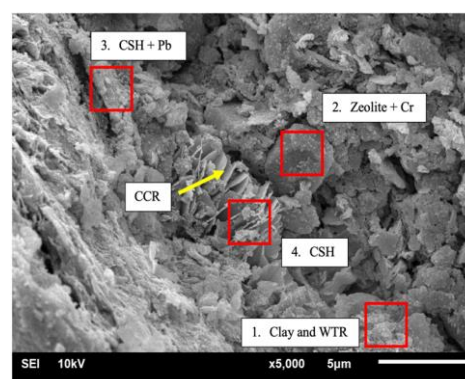
Element	Percentage by weight			
	Area 1	Area 2	Area 3	Area 4
C K	3.04	7.23	6.85	5.61
O K	33.17	35.14	45.59	32.19
Mg K	0.72	1.12	1.73	2.63
Al K	14.46	12.19	8.02	11.27
Si K	28.01	18.20	17.56	17.51
Ca K	10.64	11.34	10.07	11.01
Fe K	1.11	2.06	3.50	7.12
Cr K	4.89	4.11	0.45	4.54
Pb K	3.96	8.61	6.23	8.12

Figure 5. SEM-EDS of bottom blend clay liners with 3wt.% of bentonite after Pb and Cr

The addition of 3wt.% bentonite to the BBCL after contact with Pb- and Cr-containing leachate is shown in Figure 5. Pb and Cr were detected at greater percentages in all areas than in the control sample (without bentonite), except in area 3, where

only 0.45wt.% Cr was present. Bentonite is a clay-like material with a CEC of 1.56meq/g bentonite (Table 2), which is beneficial for the adsorption of Pb and Cr and agrees with the results of (Burham and Sayed, 2016) and (Mohajeri *et al.*, 2018).

SEM-EDS images of BBCL with 3wt.% zeolite after Pb and Cr adsorption are shown in Figure 6. Zeolite is cubic crystalline with a CEC of 5.6meq/g zeolite (Table 2). Pb and Cr were adsorbed both on the surface and within the pores of the zeolite. However, the percentages of Pb and Cr detected by SEM-EDS do not agree with the calculated amounts of Pb and Cr adsorbed during the adsorption test (Table 5). This could be caused by the limitations of the SEM-EDS technique, which allows the analysis of the elemental composition of a material down to the submicron level. As a result, Pb and Cr adsorption within the pores of zeolite is hardly detected.



Element	Percentage by weight			
	Area 1	Area 2	Area 3	Area 4
C K	3.01	7.67	7.13	6.31
O K	32.41	36.11	39.5	49.69
Mg K	0.82	1.08	0.73	0.63
Al K	18.17	13.18	17.12	8.01
Si K	25.01	22.3	14.51	11.51
Ca K	18.01	5.80	10.07	18.01
Fe K	0.51	5.06	0.14	3.12
Cr K	1.50	8.31	2.10	1.50
Pb K	0.56	0.49	8.70	1.22

Figure 6. SEM-EDS of bottom blend clay liners with 3wt.% of zeolite after Pb and Cr adsorption test

Conclusions

This research revealed that the incorporation of bentonite or zeolite into BBCLs containing clay, WTR and CCR at a ratio of 40:40:20 improved the

overall performance of the liner. Based on the experimental results obtained, the incorporation of bentonite or zeolite at 3 wt.% was suggested for use in providing the maximum adsorption of Cd and Pb from the leachate and allowing good workability for ease of compaction of the waste-derived clay liner. It is also recommended that the introduction of bentonite to real landfills should apply to areas with mild ambient temperature and humidity to prevent the shrinkage of bentonite from the loss of moisture during compaction of waste-derived bottom blend clay liners; this could lead to an increase in porosity around bentonite particles and allow the release of hazardous constituents to the surrounding environment. The limitation of this research is that the mixing amount of zeolite and bentonite more than 3% will have a negative effect on all engineering properties except the adsorption ability, which makes it unsuitable for liner in both sanitary and secure landfill.

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