Engineering geological evaluation of Mfensi and Afari clay deposits for liner application in municipal solid waste landfills

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Abstract

Mfensi and Afari clay deposits in the Ashanti Region of Ghana were evaluated for their suitability as liner materials to curtail leachate migration in municipal solid waste landfills. Chemical, mineralogical, physicochemical, geotechnical, and thermal analyses were conducted to characterize the clays as well as to evaluate their potential as suitable barrier materials. The test results were compared with standard requirements for clay liner applications. The findings revealed that the chemical compositions of both clays were analogous with dominant oxides being silica, aluminum, and iron. Quartz, kaolinite, and magnetite were the minerals identified in both clays. The effective cation exchange capacity of the Mfensi and Afari clays was 5.45 meq/100 g and 28.99 meq/100 g, respectively. The clays were fine-grained (< 0.06 mm), with fines contents of approximately 80% and 56% for Mfensi and Afari clays, respectively. The Atterberg limits consisting of the liquid limits and plasticity indices of the Mfensi and Afari clays were 42.85%, 22.43%, and 64.78%, 40.52%, respectively. The unconfined compressive strengths were 331.73 kPa and 242.92 kPa for Mfensi and Afari clays, respectively. The hydraulic conductivities of the clays were of the order $\times 10^{-7}$ cm/s. The average thermal conductivities of the clays were found to be 0.025 Wm/K for Afari clay and 0.215 Wm/K for Mfensi clay. The results demonstrate that both clays generally passed the requirements for clay liner application and hence could be used as liner materials in municipal solid waste landfills to minimize leachate migration.

Keywords Municipal solid waste · Clay liner · Landfill · Mfensi clay · Afari clay

1 Introduction

Since the dawn of humanity, humans have generated and discarded waste. Discarding waste in the past did not pose a significant threat due to the nomadic pattern of settlement. However, with the advent of stable societies came waste accumulation in these communities, posing severe health and environmental risks. Developing a proper system for managing these wastes has posed a difficult and complex challenge for society in present

times [1]. However, some conventional methods of dealing with solid wastes include composting, incineration, recycling, and landfilling, to name a few. Landfills have proven to be a common and frequently used waste disposal method due to its cost-effectiveness, simplified technique, and large capacity [2–5]. Notwithstanding, landfills also pose challenges such as environmental degradation and groundwater contamination resulting from the generated leachate and gas [6, 7]. To prevent groundwater contamination and environmental degradation by

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the generated by-products, geosynthetic clay liners and/or natural clayey soils are commonly used as liner materials in engineered landfills, and their merits and demerits have been discussed extensively by [8, 9]. However, natural clayey soils are commonly used because the materials are naturally occurring, readily available, and relatively inexpensive when on-site or in close proximity [10–12]. Rowe [13] found that although both geosynthetic clay liners and natural clay liners are susceptible to desiccation and crack development, natural clays are capable of healing the cracks when there is an influx of water (self-healing property). As such, there is a growing interest in the use of natural clays as liner materials for landfill development in developing countries like Ghana, where enormous quantities of waste are generated.

Kumasi, the capital of the Ashanti Region of Ghana, is burdened with waste management problems. In 1995, the rate of municipal solid waste (MSW) generation in Kumasi was estimated at 600 tons per day. By 2005, 1000 tons of solid waste was generated each day in the city; three years later, 1200 tons was generated a day, and by 2010, 1500 tons of waste was generated in Kumasi each day [14]. Currently, there exist no data on MSW in Ghana. However, a survey conducted by Meiza et al. [15] revealed that 0.47 kg rate of waste is generated per person per day in Ghana, which translates into about 12,710 tons of waste per day per the current population of 27,043,093 [16, 17]. Nonetheless, these numbers are expected to increase due to rapid urbanization. Because there is only one landfill site at Dompoe (Oti landfill) in the Kumasi area, open refuse dumping is commonly practiced, usually around the city's perimeter in open lots, wetland areas, or next to surface water sources [18]. This practice poses a lot of danger to the environment. In 2014, the French government granted two million Euros to construct additional cells with geosynthetic liner materials at Dompoe in the Ashanti Region [19]. These new cells are not adequate to fully cater to the ever-growing waste generated in Kumasi and its environs. Also, the problems associated with using the geosynthetic liner material, such as cost, technical limitations, and uncertainty of its performance over a period of time, are significant challenges. Therefore, the need to construct more landfills and the use of suitable liner materials such as natural clays within economic haulage distances is of importance.

Mfensi and Afari clay deposits are extensively distributed in the Ashanti Region of Ghana. Both clays occur in significant quantities, covering an approximate reserve (tons) of 396,548 and 2,055,900 for Mfensi and Afari clays, respectively [20]. The clays are derived from the various rock formations through weathering, erosion, and sedimentation and are mostly alluvial or residual in origin [20]. Due to their high water content, the clays are naturally

soft and composed mainly of silicon, aluminum, and iron oxide. The main mineral constituents of both clays are quartz and kaolinite in different concentrations [21]. Previous studies have revealed that, since the establishment of the Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, the Ceramics, Sculpture, Design, and Foundry Departments, as well as the Department of Integrated Rural Art and Industry, have depended solely on these clays for teaching, research, and the fabrication of ceramic products [22]. They have also been evaluated for pozzolana and bricks production by the Building and Road Research Institute (BRRI), Ghana. Moreover, the availability of these clays in commercial quantities have caused indigenes in the Afari and Mfensi communities to establish small-scale pottery industries, producing wares such as grinding bowls, palm wine pots, water coolers, burnt bricks, and building materials. [22].

Aside the numerous applications of these clays, it appears that little to no study has been done to determine their suitability as liner materials in MSW containment systems. The traditional geotechnical properties of both clays have been studied in the past. The findings indicate that both clays possess suitable geotechnical properties to be used in the construction of landfill bottom liners in terms of particle size, plasticity characteristics, and swelling properties [21, 22]. Besides, their low thermal conductivity, chemical inertness over a relatively wide range of pH, as well as the economic appeal for using the natural geomaterial for liner application may boost their utilization as liner materials. In this context, compacted natural Mfensi and Afari clays could be used to construct landfill bottom liner materials. Despite this great potential, their use as liner materials is still not fully embraced due to the limited information available on their engineering geological properties. In view of this, this study sought to assess the engineering geological properties of Afari and Mfensi clay deposits in the Ashanti Region (Ghana) to determine their suitability for use as liner materials in MSW landfills. The findings of this study would provide a detailed understanding of the engineering geological properties of both clays, and it will motivate the utilization of the clays as bottom liner materials in MSW landfills.

2 Materials and methods

2.1 Materials

Because natural clays are known to vary spatially, steps were employed to choose a specific geographical site presumably containing the representative Afari and Mfensi clays (Fig. 1). An extensive literature review was conducted on previous studies of Afari and Mfensi clays in the Ashanti

Fig. 1 Geological map of the Ashanti Region indicating sampled locations

Region of Ghana to acquire both clays' location. Consequently, it was found that the Afari and Mfensi clay samples utilized by Amoanyi et al. [22] had possessed high fine (clay + silt) size content in their natural states, both of which generally could be suitable for liner application based on their particle size. Hence, the sites used by Amoanyi et al. [22] were chosen and tracked for soil collection. The clay samples were collected by disturbed sampling from pits located in Mfensi and Afari, both villages in the Ashanti Region of Ghana. The locations of the sites are shown in Fig. 1. The Mfensi area lies within longitudes 6°, 45' and 6°, 36.5'N and latitudes 01°, 46' and 01°, 53.3'W, whereas Afari is bounded by longitudes 6°, 42' and 6°, 11' N and latitudes 01°, 46' and 01°, 56.5'W. The Afari site is underlain by hornblende–biotite tonalite, minor granodiorite, and minor quartz diorite, while the Mfensi site is underlain by sericite-schist, quartz-sericite schist, and locally with garnet [23]. A total of eight points/areas were selected, four in each village for sampling using a trial pit

method. The dimensions of the pits were 1.5 m length by 1 m breadth by 3.0 m depth. The test pits were dug using a pickaxe and shovel up to a depth of 2.5 m and augered employing a hand-operated auger to 3 m. Sampling was done laterally and vertically to minimize the effect of variations in the clays' physical properties. Samples from each area were combined to produce one representative material for analysis because the physical variations (color and texture) were not so different, probably due to similar soil formation processes. The samples were bagged, labeled, and transported to the laboratory for studies. Approximately 50 kg of each clay type was obtained. Typical grab samples of both Afari and Mfensi clay samples are presented in Fig. 2a, b, respectively.

2.2 Methods

The clay samples were air-dried at room temperature (25–28 °C) for about three weeks. The dried samples were

Fig. 2 **a** Afari clay samples. **b** Mfensi clay samples

then pulverized prior to testing using a mortar and pestle. The pulverized samples were then subjected to chemical, mineralogical, physicochemical, geotechnical, and thermal analyses employing standard methods and are briefly discussed. The physical properties of the clays, thus soil color and texture, were determined based on visual and feel, respectively.

The clays' chemical compositions were determined using the X-ray fluorescence spectrometer (SPECTRO Analytical Instruments Inc.-X-LAB 2000, Kleve, Germany) method at the Geological Survey Department in Accra. Clay samples passing through sieve No. 200 were used for the test; 4 g of the samples was mixed with 0.9 g of powder Licowax binder and later placed in a homogenizer for complete mixing at a frequency of 15 Hz for 3 min. The samples were removed and placed in a compressor and pressed under 5000 g of load to obtain the sample pellets of 15 mm in diameter. Finally, the pellets were transferred to the Spectro X-LAB 2000 for their chemical analysis determination. Measurements were taken using an excitation source that emits Ag-K X-rays (22.1 keV), in which case all elements with lower characteristic excitation energies were accessible for detection in the samples. The system consists of a Si(Li) detector with a resolution of 170 eV for the 5.90 keV line, coupled to a computer-controlled ADC card. Duplicate tests were conducted on both clay samples to improve the accuracy, and the mean values were reported. The major oxides and minor elements of the duplicate tests are also presented in Table 1 of the supplementary material, for the sake of completeness.

The physicochemical characteristics of the clays, such as pH, organic matter content, and cation exchange capacity (CEC) were determined using standard procedures at the Soil Science Laboratory of the Faculty of Agriculture and Natural Resource, Kwame Nkrumah University of Science & Technology. The CEC of the samples was determined by

summing the exchangeable cations, including calcium, magnesium, potassium, and sodium, extracted using the Mehlich-3 (M3) extraction solution and methods [24]. The exchangeable acidity was determined using the titration method [25]. Walkley and Black method was employed to determine the organic matter content [26]. The pH was determined using the pH meter (Palintest Micro800 MULTI, Gateshead, UK) following standard procedures outlined in [27]. In order to improve the accuracy of the results, duplicate tests were conducted on both clay samples, and the mean values were reported. For the sake of completeness, the physicochemical characteristics of the duplicate tests are also presented in Table 2 of the supplementary material.

The mineralogical compositions of the clays were determined by the X-ray diffraction method (XRD) (Siemens D5000, Munich, Germany) with copper tube anode at a generated current of 40 mA and voltage of 40 kV. The scan performed was recorded at an angle scan (2θ) between 10° and 50° with a step size of 0.02° .

The geotechnical properties determined included particle size distribution, specific gravity, natural moisture content, Atterberg limits, and linear shrinkage. These tests were performed according to standard procedures outlined in [27]. The moisture–density relationships of the clays were determined using the Standard Proctor method in accordance with [27]. The unconfined compressive strength (UCS) test was performed on the samples remolded at optimum moisture content (OMC), so as to achieve maximum density. The tests were conducted on cylindrical samples with length and diameter of 100 and 50 mm, respectively. The samples were then tested for the UCS using the ELE compression test machine with a rate strain of 1 mm/min applied by the ramp until the failure of the sample, following standard procedures presented in [27]. The hydraulic conductivities of the

clays were determined using the falling head permeameter following standard procedures presented in [27]. A detailed discussion of the saturation procedure, hydraulic conductivity testing procedures, and termination criteria are reported in [11]. The falling head was used because it is most suitable for fine-grained soils such as clays. The thermal conductivities of the clays were determined by a steady-state method using the Lee disc apparatus, and a detailed description of this method is stipulated in [28]. Duplicate tests were conducted on both clay samples, and the mean values were reported. For the sake of completeness, the geotechnical properties of the duplicate tests are also presented in Table 3 of the supplementary material. The data obtained were analyzed using IBM SPSS statistic 20 and Origin 9.0 softwares.

3 Results and discussion

3.1 Nature, color, texture, and chemical characteristics of the clays

Both clays were soft with high water content. Afari clay was yellowish with shades of orange, while Mfensi clay was greenish grey in color in their dry states. Both clay types were fine-grained and lumpy.

The chemical compositions of the clays in terms of the major oxides and minor elements are presented in Table 1. It is observed that the clays have similar chemical composition with variations in their concentrations. The dominant oxides in both clays were SiO_2 , Al_2O_3 , and Fe_2O_3 , which constituted about 89.85% of Mfensi clay and 80.01% of the Afari clay. The Mfensi clay had an Al_2O_3 content of 25.60%, making the clay fall under the class of aluminosilicate refractories [29]. Other major oxides in both clays included Na_2O , MgO , MnO , TiO_2 , CaO , and K_2O , among others. The concentrations of these oxides were much higher in Afari clay than Mfensi clay except for TiO_2 , Al_2O_3 , and K_2O . It is also noted that, among the minor elements analyzed, the concentrations of Co, Ni, Sr, Ba, La, and Ce were more prominent in Afari clay than in Mfensi clay. In the Mfensi clay, Zr, Ba, Rb, Ce, Sr, La, and Zn were higher than the other minor elements. Ba was found to have the highest concentration in Afari clay with 886 ppm, while in the Mfensi clay, it was Zr with 553 ppm.

3.2 Physicochemical characteristics of the clays

The physicochemical characteristics of the clays are presented in Table 2. The pHs of the clays were 5.37 and 5.29 for Afari and Mfensi clays, respectively, which indicates that they are acidic. The organic matter contents of the clays were 0.48% and 1.65% for Afari and Mfensi clays,

Table 1 Chemical analysis of both Afari and Mfensi clays

	Afari clay		Mfensi clay	
	Mean (%)	SD	Mean (%)	SD
<i>Major oxides</i>				
SiO_2	51.47	0.21	61.19	0.25
TiO_2	0.77	0.07	0.83	0.06
Al_2O_3	21.58	0.04	25.6	0.88
Fe_2O_3	7.06	0.03	3.06	0.04
SO_3	0.09	0.01	0.06	0.00
MgO	2.29	0.03	1.69	0.10
K_2O	0.63	0.03	1.57	0.10
CaO	0.79	0.01	0.12	0.03
MnO	0.03	0.00	0.02	0.01
Na_2O	1.32	0.03	0.94	0.00
P_2O_5	0.005	0.00	0.08	0.04
LOI (%)	12.62	0.08	4.00	1.48
<i>Minor elements (ppm)</i>				
Co	34.7	0.28	< 19	0.00
Ni	96	4.24	15.9	0.85
Cu	14.1	0.85	4.8	0.57
Zn	49.2	0.28	31.3	1.56
Ga	22.5	0.57	17.8	0.99
Pb	1.2	0.00	2.4	0.42
Ge	1.5	0.14	1.3	0.42
As	2.1	0.00	1.4	0.00
Rb	11.6	0.28	52.8	0.99
Sr	443.6	0.71	37.8	0.71
Y	19.9	0.99	< 0.6	0.00
Zr	339	0.00	553	4.24
Nb	19.5	0.28	18	2.97
Sn	< 2.1	0.00	1.3	0.42
Cs	< 10	0.00	17.9	0.57
Ba	886	2.83	369.6	0.85
La	181	2.83	34.2	0.28
Ce	408	1.41	51	2.83

Table 2 Physicochemical properties of both clay samples

Properties	Afari clay		Mfensi clay	
	Mean	SD	Mean	SD
pH	5.37	0.23	5.29	0.08
Organic matter (%)	0.48	0.08	1.65	0.06
Potassium (meq/100 g) ^a	0.10	0.00	0.20	0.04
Sodium (meq/100 g) ^a	1.17	0.07	0.25	0.01
Calcium (meq/100 g) ^a	12.16	0.08	4.02	0.03
Magnesium (meq/100 g) ^a	15.56	0.07	0.98	0.06
Aluminum (meq/100 g) ^b	1.67	0.06	1.00	0.00
Hydrogen (meq/100 g) ^b	1.67	0.08	1.34	0.06
CEC (Σ cations) meq/100 g	28.99	0.23	5.45	0.14

CEC cation exchange capacity

^aExchangeable cations; ^bexchangeable acidity

respectively. The CEC of the clays, which is the measure of the adsorption characteristics or exchange capacity of the clay minerals and an indicator of the type and amount of free cations that are adsorbed, expressed in milliequivalent per 100 g of the clays [30] was found to be 28.99 meq/100 g for Afari clay and 5.45 meq/100 g for Mfensi clay. There are no widely accepted minimum specifications for CEC values for liner materials. However, researchers such as Rowe et al. [31] and Kayabali [32] have recommended that soil liner materials should have at least a CEC of 10 meq/100 g for a better adsorption characteristic; thus, Mfensi clay failed to meet the requirement.

3.3 Mineralogical composition of the clays

The X-ray diffractograms of both clays showed similar phases indicating similar mineralogy, as shown in Figs. 3 and 4. They indicate that both clays were composed of Kaolinite (as clay mineral) and Quartz and Magnetite as non-clay minerals in varying concentrations, as reflected in the intensities and peak heights of the X-ray diffractograms. Overlapping of the clay and non-clay minerals in both clays are common. The presence of the clay mineral kaolinite in both clays implies that the clays are likely to perform effectively as barrier soils in containment and attenuation of contaminants generated [33]. The presence of kaolinite also indicates that they will exhibit low to moderate shrinkage on drying and low to moderate expansion on wetting since kaolinite has the least affinity for water among the clay minerals with greater stability and confining ability [34]. It is noted that strong quartz peaks were detected in both diffractograms,

Fig. 3 X-ray diffraction pattern of Afari clay sample

Fig. 4 X-ray diffraction pattern of Mfensi clay sample

which can be attributed to the high concentration of SiO_2 in both clays [22], which is also demonstrated in the XRF analysis.

3.4 Geotechnical characteristics of the studied clays

The geotechnical characteristics of the clays are summarized in Table 3.

3.4.1 Specific gravity and natural moisture content

The average specific gravities of Afari and Mfensi clay samples were 2.68 and 2.72, respectively, and were found to be above 2.5, which is the minimum recommended for liner materials by the [35, 36]. The natural moisture contents of both clays were 29.09% and 33.40% for Afari and Mfensi clays, respectively.

3.4.2 Atterberg limits and plasticity characteristics

The Atterberg limits of Afari clay were higher than those of Mfensi clay. The liquid limit and plasticity index of the Afari clay were 64.78% and 40.52%, whereas those for the Mfensi clay were 42.85% and 22.43%, respectively. Qian et al. [37] recommended that clays with a plasticity index $> 10\%$ should be utilized for liner application. Also, Mitchell and Jaber [38] suggested that, for materials to be used as baseliners, the liquid limit should be $\geq 30\%$, and the plasticity index should be $> 10\%$. Besides, Declan and Paul [39] also indicated that liner materials should not have liquid limits of more than 90%. From the results, it is found that the Atterberg limits of both clays met the requirement for use as clay liner. Furthermore, the plasticity indices of both clays exceeded 10% and therefore passed the

Table 3 Summary of results of the geotechnical characteristics of the clays

Parameters	Afari clay		Mfensi clay	
	Mean	SD	Mean	SD
Atterberg limits				
Liquid limit (%)	64.78	3.75	42.85	4.33
Plastic limit (%)	24.26	3.07	20.42	3.35
Plasticity index (%)	40.52	0.68	22.43	0.98
Liquidity index (%)	0.12	0.04	0.58	0.16
Linear shrinkage (%)	17.7	0.57	10.4	0.57
Specific gravity (Gs)	2.68	0.04	2.72	0.03
Natural moisture content (%)	29.09	0.13	33.4	2.29
Activity	1.2	0.07	0.6	0.00
Grading				
Sand (%)	43.51	0.82	20.5	0.10
Silt (%)	22.31	2.29	41.5	0.33
Clay (%)	34.17	1.46	38.33	0.16
Fines contents (silt + clay) (%)	56.48	0.83	79.5	0.17
Strength				
MDD (Mg/m ³)	1.539	0.05	1.625	0.04
OMC (%)	18.98	2.73	20.00	1.56
UCS (kPa)	242.92	8.40	331.73	9.04
Conductivities				
Hydraulic conductivity (cm/s)	4.637×10^{-7}	4.02	3.448×10^{-7}	3.40

MDD maximum dry density, OMC optimum moisture content, UCS unconfined compressive strength

requirements [38]. However, Daniel [40] found that soils with plasticity index exceeding 35% are expected to display excessive shrinkage and settlement. Thus, Mfensi clay is better in terms of its suitability for clay liner with respect to shrinkage potential than Afari clay since its plasticity index is < 35% based on the recommendation of [40].

The plot of the liquid limit and plasticity index of the clays on the Casagrande's plasticity chart, as shown in Fig. 5, indicates that both clays lie above the A-line. Jones et al. [41] stated that materials that fall above the A-line are suitable or marginal for use as liners, and those below the A-line are unsuitable. Based on the Unified Soil Classification System (USCS), the Afari clay could be classified as inorganic clay of high plasticity (CH) and Mfensi clay as inorganic clay of intermediate plasticity (CI).

3.4.3 Linear shrinkages of the clays

Both samples had linear shrinkages less than 20%, though Afari clay recorded a higher value than Mfensi clay. Mfensi clay recorded a value of 10.40%, while Afari clay had a value of 17.7%. Cracks were observed on the Mfensi clay

Fig. 5 Plasticity characteristics of both clays

samples after shrinkage test. Cracks were, however, absent in the Afari clay. Despite the low linear shrinkage of Mfensi clay, the formation of cracks could make it unsuitable for use as a liner material.

3.4.4 Colloidal activity of the clays

The colloidal activities of the clays, which is the ratio of the plasticity indices to the clay size content of the soils, were found to be 1.2 and 0.6 for Afari and Mfensi clays, respectively. This indicates that the Mfensi clay has low expansion potential, and the Afari clay has medium expansion potential, according to [42] classification. Rowe et al. [31] recommended that soils with an activity of 0.3 and above are suitable as liner material and can achieve a hydraulic conductivity of order $\times 10^{-7}$ cm/s.

Fig. 6 Particle size distribution curves of the clays

3.4.5 Particle size distribution

The particle size distributions of the two clay samples are shown in Fig. 6. The grading curves of the clays indicate that they are well graded within the sand (0.06–2 mm) and clay size (< 0.002 mm) zone. It is found that the sand size contents were 43.51% for Afari clay and 20.5% for Mfensi clay, and the results are within the range proposed by [43]. They indicated that liner materials should contain adequate quantities of sand greater than 20%, which would offer significant protection from volumetric shrinkage and impact adequate strength.

The silt and clay size contents were 22.31% and 34.17%, respectively, for Afari clay, whereas those for Mfensi clay were 41.5% and 38.33% for silt and clay size, respectively. Both clays satisfied the recommendations of Declan and Paul [39], who proposed a minimum clay content of 10% for barrier soils. The fines content was approximately 56% and 80% for Afari and Mfensi clays, respectively, and these values fall within the recommended limits of $\geq 30\%$ fines [44]. Brunner and Keller [45] recommended the use of finer soils as barrier materials because they have a high specific surface area. They added that there is low migration of leachate as soil texture becomes finer. EPA [46] found that liner materials should have at least 20% fines in order to achieve a hydraulic conductivity of less than 1×10^{-7} cm/s. It can, therefore, be concluded that both clays satisfy the above-mentioned requirements for grading characteristics.

3.4.6 Strength characteristics of the clays

The compaction characteristics of the clays are presented in Fig. 7. It is noted that the maximum dry density (MDD) of Mfensi clay (1.62 Mg/m^3) was higher than that of Afari clay (1.54 Mg/m^3). The optimum moisture contents (OMC) were

Fig. 7 Compaction characteristics of the clays

18.98% and 20.00% for Afari and Mfensi clays, respectively. These values were significantly lower than their respective natural moisture contents of the clays.

The unconfined compressive strengths (UCS) of the clays were 331.73 kPa and 242.92 kPa for Mfensi and Afari clays, respectively. The high UCS recorded for Mfensi clay could be due to the high percentage of fine fractions filling the void spaces and the interlocking of the coarse grains, hence reducing compressibility, porosity, and deformation and thus increasing the shear strength characteristics. Both clays meet the strength requirement of not less than 200 kPa proposed by Daniel and Wu [44] for baseliner materials.

3.4.7 Hydraulic conductivity of the clays

The hydraulic conductivity for Mfensi clay was found to be lower than that of Afari clay with values of 3.45×10^{-7} cm/s and 4.64×10^{-7} cm/s, respectively. The low hydraulic conductivity value of Mfensi clay could be attributed to its high clay and silt size contents, which filled the voids between the coarse particles, thus reducing the size of the pores controlling the flow and decreasing the hydraulic conductivity. The hydraulic conductivities of both clays satisfy the requirements of the order $\times 10^{-7}$ cm/s or less recommended for clay baseliner materials [47].

3.4.8 Thermal conductivities of the clays

A study of the thermal conductivity of Afari and Mfensi clays was performed with a view of understanding their ability to conduct or transfer heat mainly for application as liner materials since the effects of heat on liner materials can result in desiccation, changes in shear strength, and hydraulic conductivity of the liner material. The Afari clay had thermal conductivity values, ranging between 0.02 Wm/K and 0.03 Wm/K, with a mean value of 0.025 Wm/K. On the other hand, Mfensi clay recorded thermal conductivities, which range between 0.21 Wm/K and 0.22 Wm/K with a mean of 0.215 Wm/K. According to Ayugi [48], thermal conductivity increases with increasing percentage of smaller particle size (fine particles). This can be explained on the basis that smaller particles will mesh closely, leading to a better transfer of heat between them. The low thermal conductivity of the Afari clay relative to Mfensi clay could be due to its lower amount of fines contents. Afari clay had 56.48% fines, while Mfensi had 79.5% fines content and hence that explains the phenomena observed. The clays, however, possessed the required thermal conductivities to be used as liner materials; thus, less than 2 Wm/K recommended by [49].

4 Conclusion

The study investigated the engineering geological properties of Afari and Mfensi clays in their natural state for possible use as liner materials for municipal solid waste landfill sites in Ghana. From the research, the following conclusions were made:

- The most abundant oxides of the clays are SiO_2 , Al_2O_3 , and Fe_2O_3 , which constituted about 89.85% of Mfensi clay and 80.01% of the Afari clay. The mineralogy of the clays from XRD analyses is similar and is composed of kaolinite, quartz, and magnetite as the main minerals.
- The effective cation exchange capacity of the Mfensi and Afari clays was 5.45 meq/100 g and 28.99 meq/100 g, respectively. Thus, Mfensi clay failed to meet the minimum recommendation of at least 10 meq/100 g for clay liner materials.
- The clays were fine-grained (< 0.06 mm), with fines contents of approximately 80% and 56% for Mfensi and Afari clays, respectively. Hence, these values fall within the recommended limits of $\geq 30\%$ fines for liner materials.
- The unconfined compressive strengths were 331.73 kPa and 242.92 kPa for Mfensi and Afari clays, respectively. Hence, these values met the minimum UCS specification of ≥ 200 kPa for liner materials.
- The average thermal conductivities of the clays were found to be $0.025 \text{ Wm}^{-1} \text{ K}^{-1}$ for Afari clay and $0.215 \text{ Wm}^{-1} \text{ K}^{-1}$ for Mfensi clay.
- Both Mfensi and Afari clays presented low hydraulic conductivities of the order $\times 10^{-7} \text{ cm/s}$, which corresponded with a higher content of silt and clay size fractions. The hydraulic conductivities of both clays satisfy the Ghanaian regulatory specification of the order $\times 10^{-7} \text{ cm/s}$ or less recommended for clay base-liner materials.

From the study, some of the requirements for liner utilization that were met included the hydraulic conductivity, thermal conductivity, unconfined compressive strength, plasticity characteristics, and particle size. However, the Mfensi clay failed to meet the recommended value for the cation exchange capacity for liner materials, and it had the tendency to develop cracks. Nevertheless, this should not be used as a basis for rejection of the material if suitable materials are not readily available within economical haulage distances. Therefore, it can be concluded that both clays are suitable for use as liner materials in MSW landfills. However, field investigations are vital for ascertaining this experimental

observation. Besides, since leachate will be the main permeant experienced in the field, future works are recommended to evaluate the clays' engineering geological properties using field leachate as the permeant. Chemical stabilization may also be considered as an attractive alternative to further improve the engineering properties of the clays. Likewise, other important parameters such as diffusion and retention capacity of the clays need to be evaluated before deciding their full potential as hydraulic barriers in MSW landfills.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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