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journals.uoz.edu.krd

Science Journal of University of Zakho

Vol. 10, No. 3, pp. 140 –146, July-September 2022

p-ISSN: 2663-628X
e-ISSN: 2663-6298

TREATMENT OF OIL WELL DRILL CUTTINGS UTILIZING DIFFERENT BINDER OPTIONS

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Received: *03 Jun., 2022 /* ***Accepted:*** *03 Jul., 2022 /* ***Published:*** *24 Aug., 2022* https://doi.org/10.25271/sjuoz.2022.10.3.945

ABSTRACT:

A lab-scale treatability experiment was conducted on oil well drill cuttings (waste generated during petroleum exploration) using two different binders (Portland Cement and Lime) as a Solidification and Stabilization S/S agent. Seven ratios for each binder to waste (Drill cuttings) have been separately prepared (0.25:10, 0.5:10, 1:10, 2:10, 3:10, 4:10, 5:10) in which effects for each ratio and curing time (90 days) have been investigated on pH, chloride, and leachate for heavy metals (Ba, Pb, Cd, Ag, and Cr) through Toxicity Characteristic Leaching Procedure (TCLP). Results showed that the leaching of heavy metals (Ba, Cd, Cr, and Ag) was under the US EPA TCLP limit for all ratios with both binders. However, the Pb concentrations for the ratios of 0.25:10, 0.5:10, 2:10, and 3:10 were (39.47, 38.64, 20.67, and 8.97 mg/kg, respectively) for the cement-treated drill cuttings and the ratios of 0.25:10 and 0.5:10 were (34.6 and 12.94 mg/kg respectively) for the lime-treated drill cuttings have exceeded the proposed limit by the US EPA TCLP limit. Chloride also failed to meet the Nigerian chloride limit for drill cutting in the ratios of 0.25:10, 0.5:10, 1:10, and 2:10 with both binders by (7677, 7039, 6580, and 5226 mg/kg, respectively) for cement-treated drill cuttings and (7881, 7498, 6247 and 5277 mg/kg respectively) for lime-treated drill cuttings; meanwhile, the chloride concentrations were under the same limit within the ratios 3:10, 4:10, and 5:10 in both binders. The overall results indicated that the binder options had affected the S/S product. Furthermore, the ratios of 1:10 and 2:10 had better performance considering the weight of the binders used for both options. The ratios of 4:10 and 5:10 also performed well, but they are not considered economically feasible due to the significant quantities of the binders used. The present investigation demonstrated that both binders could be used and relied on as an S/S agent aiming at treating drill cuttings.

KEYWORDS: Oil, Drill Cuttings, Soil, Solidification and Stabilization, Heavy metals, Chloride.

1. INTRODUCTION

Drilling fluids (also known as drilling muds) are purposed as coolants and lubricants during the drilling of oil wells. They also contribute to maintaining hydrostatic pressure, wellbore stabilization, and lifting the cuttings to the surface (Doyle et al., 2008; Melton et al., 2004). Drilling fluids are classified according to the base fluid (Water, Oil, or Synthetic materials) (Sadiq et al., 2003); and are considered more hazardous to the environment. However, synthetic drilling fluids pose a lower toxicity level and high biodegradation ability (Breuer et al., 2004). Oil and synthetic-based drill fluids, a drill cleaner for wells, may generate a lower cuttings volume than the water-based fluid (Growcock et al., 2002). Management of drill cuttings are generated using water-based fluid, but still they need to be managed under strict laws (Melton et al., 2004). Drill cuttings are a mixture of drilling fluids and tiny rocks from formations formed during the drilling process; they are soil-like, hazardous, heterogeneous, and contain vast concentrations of heavy metals, hydrocarbon, and soluble salts. Drill cuttings are among the oil industry's most complicated types of waste. The chemo-physical characteristics of drill cuttings are based on the local geology, kind of the drilling fluid, and the drilling techniques used. As the drill bit passes through rock formations, small pieces of rocks (cuttings) which are trapped in the well will be transported to the surface by the fluid flow (Bell et al., 1998).

On the ground, the solid phase (drill cuttings) is removed from the fluid by a shale shaker in which the fluid will be reused to support drilling, whereas the cuttings are collected in a pit for treatment. Settling by gravity is frequently used to remove fine particles further to reuse the fluid as these particles will impact drilling performance. The contaminants in the drill cuttings are mainly aliphatic and aromatic hydrocarbons and heavy metals such as (Ba, As, Zn, Ni, Pb, Cr, and Hg) as reported by (Johnson & Graney, 2015; Neff, 2005). Knowing the presence of these contaminants, treatment of drill cuttings before disposal is crucial to prevent the dispersion of the contaminants. Drill cuttings can be handled by stabilization and solidification, S/S, thermal treatment, bioremediation, and landfilling (Ball et al., 2012).

S/S, on the other hand, is known to be highly effective in the chemical fixation and contaminant encapsulation (Conner & Hoeffner, 1998). Metal mobilization can well be contained in high pH media. An effective S/S binder cement has a high enough pH to immobilize the media for most metals (Kogbara, 2014). However, the efficiency of the S/S product remained uncertain for a long time. (Perera et al., 2005) identified various mechanisms that could impair the long-term efficiency of S/S. CO2 uptake leads to carbonation, reducing the initial alkalinity of specific materials (Kogbara, 2013; Kogbara et al., 2012). The possible health and environmental effects of contaminants generated in the petroleum industries, mainly drill cuttings, have accelerated awareness and criticism among communities.

The present study aimed to evaluate the use of different S/S binders (Portland cement and lime) and determine each binder's feasibility in treating the drill cuttings generated in petroleum industries.

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2. MATERIALS AND METHODS

2.1 Description of the study area

The study area is approximately 23 km west of Kalar District, about 93 km southwestern of Sulaymaniyah City. The study area encompasses a primarily undulating terrain, including ranges and relatively flat valley beds in between. Land use in the study area consists mainly of agricultural land and grazing pastures. The high relief in the area makes farming in the region challenging. Coordinates of sampling sites and a study area map exist in **Table 1 and Figure 1.**

Table 1. Coordinates of sampling site in the study area

Study site	Sarqala Oil field / Garmiyan / Kurdistan region/ Iraq	
Sampling date	13-09-2021	
coordinates	**Northing**	34°42′59.44″
	Easting	45°12′57.63″
Elevation	333m	

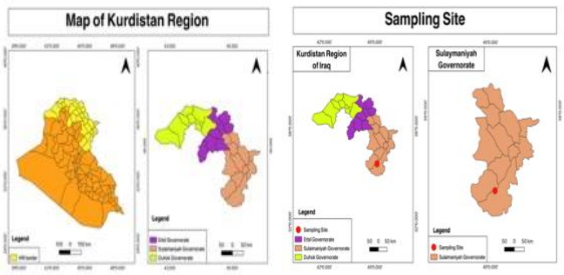

Figure 1. Map of sampling site – Kurdistan Region - Iraq

2.2 Drill cutting sample

In Sep. 2021, a drill cutting sample was taken from a cutting (reserve) pit (A pit where the drill cutting is collected after the drilling process) from an oil field whose detail is provided in Table 1. The obtained sample (composite) was made from samples taken from different pit points and then transported to the laboratory in a polyethylene bag for the pre-and post-treatment analysis.

2.3 Binders

Lime and Ordinary Portland Cement, whose inside chemicals are presented in **Table 2**, are used as two different binders to investigate their effectiveness and reliability as S/S agents in containing the contaminants present in the drill cuttings. The inside chemicals of each binder will significantly be solidified with the waste materials aimed to be solidified and stabilized which play a crucial role in not having an adverse impact of binder content on the environment. Furthermore, both binders used in this study are widely available at very reasonable prices.

Table 2. Chemical composition (%) of Portland cement and lime

Chemical compounds	Portland Cement	Lime	Reference
B_2O_3	4.6128± 0.0202	3.4397± 0.1390	(Kurudirek et al., 2010)
Na_2O	0.2811± 0.0154	0.2505± 0.2190	
MgO	0.3224	0.0347	
Al_2O_3	3.3542	0.662	
SiO_2	5.0472± 0.0296	0.1508	
P_2O_5	17.8728	0.4991	
SO_3	0.0864	0.0302	
Cl	3.7725	0.6648	
K_2O	0.0463	0.0332	
CaO	0.7990	0.0450	
TiO_2	60.0441± 0.0410	93.9802± 0.3495	
Na_2O	0.2966	–	
MnO	0.0588± 0.0248	0.0215	
Fe_2O_3	3.0584± 0.0518	0.0817	
NiO	0.0613	0.0082	
CuO	0.0447	–	
ZnO	0.0056	–	
Ga_2O_3	0.0016	–	
As_2O_3	0.0121	0.0013	
Rb_2O	0.0018	–	
SrO	0.1243	0.0367	
PbO	0.0079	–	
Y_2O_3	–	0.0014	
BaO	0.0514	0.0419	
V_2O_5	0.0061	0.0317	

2.4 Experimentations

Treatment of the drill cutting has been conducted by mixing the drill cutting with the binders in seven different ratios, as detailed in Table 3. Considering the present experiment as a lab-scale study, the total weight of each ratio for drill cutting and binders is prepared not to exceed 1000 g to prevent more waste generation.

2.4.1. Curing time and sub-sample collection: All mixes were cured under sunlight and open space (atmosphere) for 90 days, which is considered enough time for the comprehensive chemical reactions to take place. After the curing date, samples were taken and stored for analysis in triplicate from each mix (14 ratios for both binders), yielding 42 sub-samples plus one untreated drill cutting.

2.4.2. Analysis: Analysis for pH, leaching of heavy metals (Ba, Pb, Ag, Cd, and Cr) through the Toxicity Characteristic Leaching Procedure (TCLP) and Chloride have been conducted. However, testing methodologies for each concerned parameter are outlined below.

2.4.2.1. pH: The pH of all samples has been measured by a pH meter (OAKTON pH 2100 series model). 50 gm of dry sample was mixed with 50 ml DW, in which the mixture was agitated and settled for one hour as described by (Estefan, 2017).

2.4.2.2. Toxicity Characteristic Leaching Procedure test
The ability of heavy metals (Ba, Pb, Ag, Cd, and Cr) to leach into the ground formations after landfilling the treated drill cuttings into the ground or reusing it has been investigated through the Toxicity Characteristic Leaching Procedure (TCLP) test with a solid extraction solution ratio of 1:20 as described by USEPA procedure (US EPA, 2015). Given the pH of all samples above 5. 5 gm of the sample was mixed with the 100 ml of the extraction solution, whereas the extraction solution was prepared from 5.7 ml of glacial acetic acid completed to 1 L by DW. Heavy metals were extracted from samples by soaking them in the extraction solution for 24 hrs. and then shaking the suspension for two hrs at 160 RPM. After the shaking process, the suspension was taken through a filtration process. Furthermore, the pH of extracted fluid was brought down to pH<2 by concentrated nitric acid and stored at 4°C for heavy metal detection and quantification.
Detection and quantification of Ba, Pb, Ag, Cd, and Cr in the extracted fluid have been conducted by the Atomic Absorption Spectrometer model (Agilent 280 FS AA) in the labs of Ministry of Natural Resources in the Kurdistan Region of Iraq, and results being expressed in mg/kg.

Table 3. Nomenclature and sample component details

Sample ID	ID Detail	Weight of PC	Weight of DC	Total Weight of Mix	Unit
Cement-Treated Drill cuttings					
CDC1	P. Cement + Drill Cutting	25	975	1000	g
CDC2	P. Cement + Drill Cutting	50	950	1000	
CDC3	P. Cement + Drill Cutting	100	900	1000	
CDC4	P. Cement + Drill Cutting	200	800	1000	
CDC5	P. Cement + Drill Cutting	300	700	1000	
CDC6	P. Cement + Drill Cutting	400	600	1000	
CDC7	P. Cement + Drill Cutting	500	500	1000	
Lime-Treated Drill cuttings					
LDC1	Lime + Drill Cutting	25	975	1000	g
LDC2	Lime + Drill Cutting	50	950	1000	
LDC3	Lime + Drill Cutting	100	900	1000	
LDC4	Lime + Drill Cutting	200	800	1000	
LDC5	Lime + Drill Cutting	300	700	1000	
LDC6	Lime + Drill Cutting	400	600	1000	
LDC7	Lime + Drill Cutting	500	500	1000	

Table 4. Maximum permissible limits of heavy metals (TCLP range)

Heavy metals	Symbol	Maximum permissible limit (mg/kg)	References
Arsenic	As	5	(US EPA, 2015)
Barium	Ba	100	
Cadmium	Cd	1	
Chromium	Cr	5	
Lead	Pb	5	
Mercury	Hg	0.2	
Selenium	Se	1	
Silver	Ag	5	

2.4.1.1 Chloride: Samples were tested for soluble chloride from the same suspension prepared for pH as described by (Estefan, 2017). Moreover, 5 ml of the soil suspension was added into a flask with 4 drops of K2CrO4 and titrated with AgNO3 (0.01 N). The concentration of chloride in meq/l was obtained by using the following equation.

$$\text{Cl meq/l} = \frac{(\text{V1} - \text{B})\ \text{X Normality of AgNO3 X 1000}}{V2} \quad (1$$

Where: V1 = Volume (ml) of AgNO3 used during titration
B = Blank volume (ml)
V2 = Volume (ml) of sample filtrate used for titration

Normality of the AgNO3 was obtained using the below equation

$$\text{N AgNO}_3 = \frac{10\ X\ N\ NaCl}{V\ AgNO3} \quad (2$$

Where: N NaCl = Normality of NaCl
V AgNO3 = Volume of AgNO3 utilised during titration (ml)

2.5 Data analysis

Statistical data analysis was conducted using Microsoft Office Excel 2021 and GraphPad Prism software V. 9.3. $p \leq 0.05$ is considered a significant level (Steel, 1960).

3. RESULTS AND DISCUSSIONS

3.1 Characteristics of pre-treated drill cuttings

The chemical characteristics of untreated drill cuttings are presented in
Table *5*. Some parameters have been shown to have far exceeded

pH		8.3
Moisture content (%)		25
Chloride mg/kg		10,352
Heavy metals (TCLP range) mg/kg	**Pb**	99.4
	Cd	0.096
	Cr	1.082
	Ba	33.92
	Ag	0.016

the permissible limits, including chloride (10,357 mg/kg) and Pb (99.4 mg/kg), indicating that the untreated drill cutting is unsafe to be disposed of or reused. However, heavy metals such as Ba, Cd, Cr, and Ag were 33.92, 0.096, 1.082, and 0.016 mg/kg, respectively, with a pH value of 8.3.

Table 5. Characteristics of pre-treated drill cuttings

pH		8.3
Moisture content (%)		25
Chloride mg/kg		10,352
Heavy metals (TCLP range) mg/kg	**Pb**	99.4
	Cd	0.096
	Cr	1.082
	Ba	33.92
	Ag	0.016

3.2 Characteristics of Post-treated drill cuttings

3.2.1 pH: The pH values for all ratios are presented in **Table 6** and ranged from 9.43 to 11.78 for both binders, with the majority of the samples being over 11.5 compared to the untreated drill cuttings of 8.3.

Table 6.Mean Values of pH, Chloride, and Heavy metals

Sample ID	pH Value	Chloride mg/kg	Heavy metals mg/kg				
			Pb	Ba	Ag	Cd	Cr
Cement-Treated Drill cuttings							
CDC1	9.43[a]	7677[a]	39.47[a]	29.43[a]	0.002[a]	0.04[a]	0.34[a]
CDC2	10.7[a]	7039[a]	38.64[a]	28.17[a]	0.0025[a]	0.06[b]	0.26[a]
CDC3	11.3[a]	6580[a]	4.99[a]	40.11[a]	0.002[a]	0.03[a]	0.34[a]
CDC4	11.55[a]	5226[a]	20.67[a]	32.87[a]	0.001[a]	0.03[a]	0.45[a]
CDC5	11.6[a]	3312[a]	8.97[a]	45.26[a]	0.0025[a]	0.02[a]	0.37[a]
CDC6	11.67[a]	3133[a]	0.21[a]	43.89[a]	0.003[a]	0.01[a]	0.64[a]
CDC7	11.78[a]	2852[a]	0.21[a]	44.66[a]	0.008[a]	0.013[a]	0.58[a]
Lime-Treated Drill cuttings							
LDC1	10.58[a]	7881[a]	34.6[a]	29.33[a]	0[a]	0.07[a]	0.51[b]
LDC2	11.69[a]	7498[a]	12.94[a]	35.03[a]	0[a]	0.06[a]	0.65[b]
LDC3	11.78[a]	6247[a]	1.07[a]	40.01[a]	0[a]	0.02[a]	0.71[b]
LDC4	11.75[a]	5277[a]	0.66[a]	41.83[a]	0.002[a]	0.02[a]	0.86[b]
LDC5	11.77[a]	4256[a]	0.71[a]	51.55[a]	0.004[a]	0.02[a]	0.93[b]
LDC6	11.75[a]	4384[a]	0.73[a]	42.87[a]	0.0015[a]	0.02[a]	0.75[b]
LDC7	11.7[a]	3082[a]	0.58[a]	53.02[a]	0[a]	0.01[a]	1.01[b]
Untreated	8.3[b]	10352[b]	99.4[b]	33.92[b]	0.016[b]	0.096[b]	1.082[b]

- Dunnett's multiple comparisons test is conducted to compare the mean differences of each ratio with the mean of untreated drill cuttings.
- The mean difference is significant at a p-value ≤ 0.05.

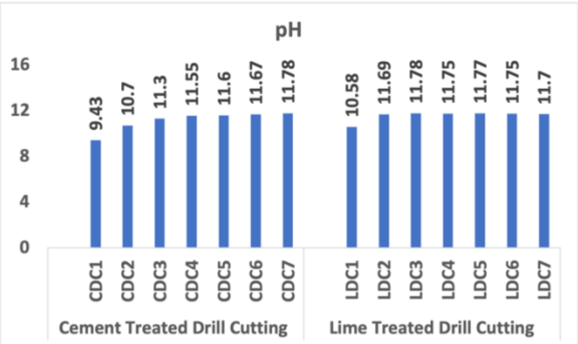

Figure 2. Figure 2. pH values of Cement and lime-treated drill cutting

pH is determined to have a significant role in evaluating the chemical stability of the treated drill cuttings. Considering the chemical compositions of both Portland cement and lime **Table 2**, the pH results of all treated drill cuttings with both binders were expected to be comparable. It has been observed that pH is primarily used to indicate how the heavy metals and chloride will behave in the treated cuttings (Conner & Hoeffner, 1998). However, pH values higher than 10, it indicates a stable physical structure of the treated cuttings (Stegemann & Zhou, 2009). Both binders showed a significant effect of pH at $p \leq 0.05$.

The Pearson's correlation test results showed that the pH is positively correlated with Ba (r = 0.675), Ag (r = 0.115) and Cr (r = 0.444) and negatively correlated with EC (r = -0.536), chloride (r =-0.750), Pb (r = -0.506), and Cd (r = -0.468) in cement-treated drill cuttings, while in the line-treated drill cuttings pH has shown to be positively correlating with Ba (r = 0.254), Ag (r = 0.165) and Cr (r = 0.264) and negatively correlating with EC (r = -0.073), chloride (r = -0.401), Pb (r = -0.854), and Cd (r = -0.694).

3.2.2 Metal leachability: The details of the leachability of the studied heavy metals (Pb, Ba, Cd, Cr, and Ag) are presented in **Table 6**. However, the concentration of all heavy metals except Pb for all ratios
in the drill cuttings with both binders have significantly reduced compared to the untreated samples, and the US EPATCLP limit
Table 4.
Pb concentration **Figure 3** in the ratios of CDC1, CDC2, CDC4, and CDC5 in the cement-treated drill cuttings (39.47, 38.64, 20.67, and 8.9 mg/kg, respectively) and LDC1 and LDC2 in the lime-treated drill cuttings (34.6 and 12.94 mg/kg) have failed to meet the US EPA TCLP limit of 5 mg/kg.

These exceedances of Pd in some ratios resulted from the high concentrations of Pb in the drill cutting sample, which was mainly sourced from the formation lithology, caustic soda, oil wastes from the machinery, and the drilling fluid used (Al-Haleem et al., 2013). However, the poor leaching of the Pb in the ratios of CDC1, CDC2, CDC4, CDC5, LDC1, and LDC2 may be due to the organic compounds, mainly hydrocarbons leading to inhibit the stability of heavy metals (Burhan & Trihadiningrum, 2018). Both binders showed to have significantly affected Pb concentrations at $p \leq 0.05$.

For the cement-treated drill cuttings Pb is positively correlated with Ag (r =0.032), and Cd (r =0.925) and negatively correlated with Ba (r =-0.421) and Cd (r =-0.301). However, for the lime-treated drill cuttings Pb is positively correlated with Cd (r =0.884) and negatively correlated with Ba (r = -0.309), Ag (r = -0.206) and Cr (r = -0.360).

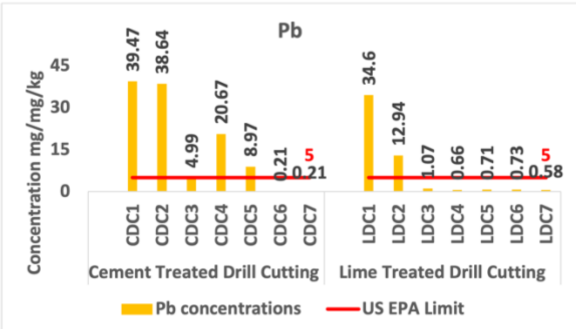

Figure 3. Pb concentrations in the cement-lime-treated drill cuttings

The concentrations of Ba **Figure 4**, Ag **Figure 5**, Cd **Figure 6**, and Cr **Figure 7** in all studied ratios, including untreated drill cuttings, were below the US EPA TCLP limit. However, the Ba, Ag, Cd, and Cr concentrations in untreated drill cuttings were 33.92, 0.016, 0.096, and 1.082 mg/kg, respectively. Furthermore, both binders have significantly affected the concentrations of Ba and Ag in all ratios, whereas the concentrations of Cd in all ratios except CDC2 were significantly affected by both binders. On the other hand, Cr concentrations in Cement-treated drill cuttings were significantly affected by cement compared to the drill cuttings treated with lime did not show any significantly affected Cr concentrations.

Solidification and Stabilization of S/S will not reduce the content of heavy metals in the treated drill cutting. Instead, the heavy metals will significantly lose mobility (Kumpiene et al., 2006). Ba, Ag, Cd, and Cr studied heavy metals with much less ability to move as per the US EPA TCLP limit in the treated drill cuttings with both binders for almost all ratios. Furthermore, heavy metals may be chemically bonded to other substances throughout chemical extraction, resulting in lower overall concentrations such as adsorption by carbonates, bounding to sulfides, oxides of Mn, and Fe (Tessier et al., 1979). Meanwhile, as another TCLP member, Pb can still move in the CDC1, CDC2, CDC4, and CDC5 for the cement-treated drill cuttings and LDC1 LDC2 ratios for the lime-treated drill cuttings **Table *6***.

In the cement-treated drill cuttings, Ba is positively correlated with Ag (r =0.190) and Cr (r =0.355) and negatively correlated with Cd (r =-0.493). Ag is positively correlated with Cd (r =0.016) and Cr (r =0.154). Cd is negatively correlated with Cr (r =-0.326). Whereas for the lime-treated drill cuttings, Ba is negatively correlated with Ag (r =-0.023), Cd (r =-0.274), and Cr (r = -0.361). Ag is positively correlated with Cr (r = 0.038) and negatively correlated with Cd (r =-0.281). Cd is negatively correlated with Cr (r = -0.291)

The most leachable heavy metals are those that are in exchangeable forms. Heavy metals maintained in residual forms (remained even after adsorbing and bounding with other compounds) are the most recalcitrant (Lu et al., 2016). The cement-treated drill cuttings have a slight edge over lime-treated drill cuttings because of the formation of insoluble metal hydroxides in the concert form in the cement-treated drill cuttings (Wiles, 1987). As a part of chemical reactions, experiments conducted by (Conner & Hoeffner, 1998; Zhao et al., 1999) have also shown that the cement-treated drill cuttings have a lower permeability rate and highly influence the low leaching rate of the heavy metals in the S/S product.

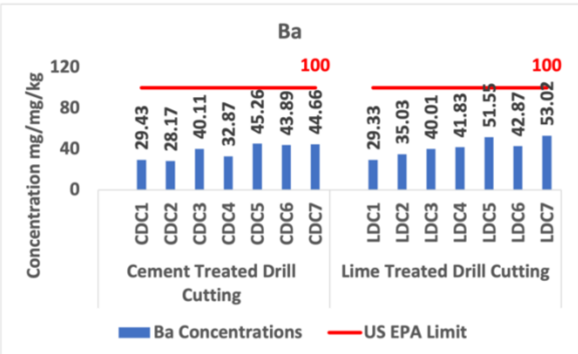

Figure 4. Ba concentrations in the cement-lime-treated drill cuttings

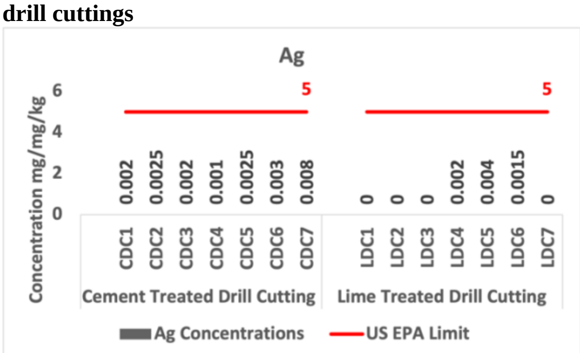

Figure 5. Ag concentrations in the cement-lime-treated drill cuttings

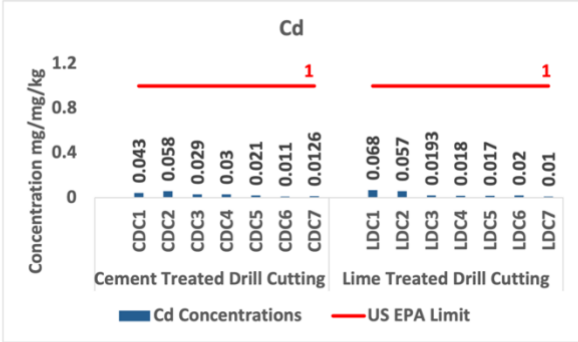

Figure 6. Cd concentrations in the cement-lime-treated drill cuttings

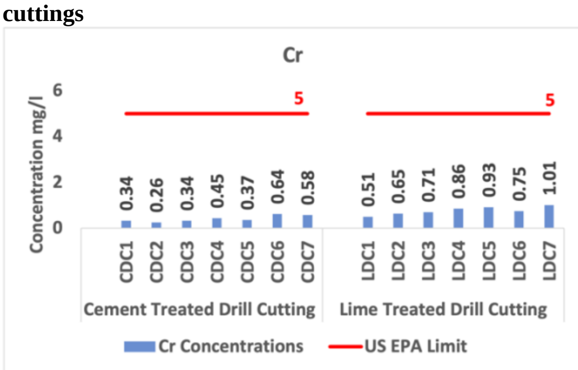

Figure 7. Cr concentrations in the cement-lime-treated drill cuttings

3.2.3 Chloride

The concentration of soluble Chloride **Table *6*** in the treated drill cuttings for both binders **Figure 8** ranged between 2,852 to 7,881 mg/kg. However, the chloride concentration in pre-treated drill cutting was 10,357 mg/kg. For the cement-treated drill cuttings, CDC1, CDC2, CDC3, CDC4 (7677, 7039, 6580, and 5226 mg/kg, respectively) and LDC1, LDC2, LDC3, and LDC4 (7881,7498, 6247 and 5277 mg/kg respectively) for the lime-treated drill cuttings have failed to meet the Nigerian limit of 5000 mg/kg for chloride. Furthermore, the ratios of CDC5, CDC6, and CDC7 (3312, 3133, and 2852 mg/kg, respectively) for the cement-treated drill cuttings and LDC5, LDC6, and LDC7 (4256,438,4 and 3082 mg/kg respectively) in the lime-treated drill cuttings have met the Nigerian limit of chloride. The use of both binders showed to have significantly affected chloride concentrations in all ratios at p≤0.05.

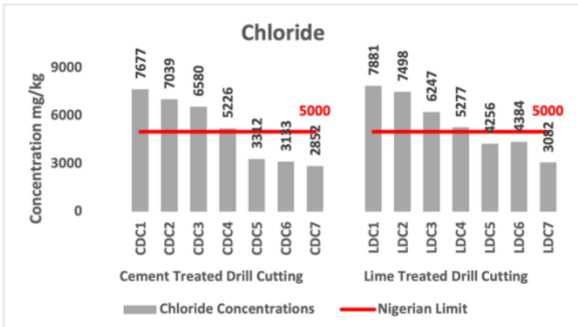

Figure 8. Chloride concentrations in the cement-lime-treated drill cuttings

Chloride in cement-treated drill cuttings was positively correlated with Pb (r =0.443), Cd (r =0.471) and negatively correlated with Ba (r =-0.668), Ag (r =-0.324) and Cr (r =-0.545). Furthermore, in lime-treated drill cuttings, chloride was positively correlated with Pb (r =0.704) and Cd (r =0.781) and negatively correlated with Ba (r =-0.668), Ag (r = -0.198) and Cr (r = -0.439). Considering the geological formations that crossed while drilling, high salt contents are expected due to the extensive usage of drilling mud, which contains more salts, mainly calcium bentonite (Li et al., 2020). This has highly appeared in the first four ratios of both binders, with the chloride concentration over 5000 mg/l. However, the first four ratios for both binders had a higher portion of drill cuttings than those with a chloride concentration of less than 5000 mg/kg because the last three ratios had a higher binder portion.

Table 7. Person's correlation between the studied parameters in cement-treated drill cuttings

	pH	Chloride	Pb	Ba	Ag	Cd	Cr
pH							
Chloride	r = -0.750 p = <0.0001						
Pb	r = -0.506 p = 0.0193	r = 0.443* p = 0.0444					
Ba	r = 0.675 *** p = 0.0008	r = -0.668 p = 0.0009	r = -0.421 p = 0.0577				
Ag	r = 0.115 p = 0.6187	r = -0.324 p = 0.1515	r = r = 0.032^{ns} p =0.8921	r = 0.190^{ns} p = 0.4103			
Cd	r = -0.468 p = 0.0326	r = 0.471* p = 0.0310	r = 0.925**** p = <0.0001	r = -0.493 p = 0.0232	r = 0.016^{ns} p = 0.9448		
Cr	r = 0.444 * p = 0.0437	r = -0.545 p = 0.0107	r = -0.301 p = 0.1849	r = 0.355^{ns} p = 0.1142	r = 0.154^{ns} p = 0.5057	r = -0.326 p = 0.1491	

- Correlation is significant at ($p \leq 0.05$).

Table 8. Person's correlation between studied parameters in lime-treated drill cuttings

	pH	Chloride	Pb	Ba	Ag	Cd	Cr
pH							
Chloride	r = -0.401 p = 0.0717						
Pb	r = -0.854 p = <0.0001	r = 0.704*** p = 0.0004					
Ba	r = 0.254^{ns} p = 0.2658	r = -0.382 p = 0.0871	r = -0.309 p = 0.1736				
Ag	r = 0.165^{ns} p = 0.4739	r = -0.198 p = 0.3902	r = -0.206 p = 0.3705	r = -0.023 p = 0.9224			
Cd	r = -0.694 p = 0.0005	r = 0.781**** p = <0.0001	r = 0.884**** p = <0.0001	r = -0.274 p = 0.2300	r = -0.281 p = 0.2178		
Cr	r = 0.264^{ns} p = 0.2472	r = -0.439 p = 0.0464	r = -0.360 p = 0.1093	r = -0.361 p = 0.1076	r = 0.038^{ns} p = 0.8704	r = -0.291 p = 0.2001	

- Correlation is significant at ($p \leq 0.05$).

4. CONCLUSIONS

Drill cuttings are complicated hazardous waste produced during oil drilling activities. The present study evaluated the capabilities of the two widely available binders (Portland Cement and Lime) as the stabilization and solidification agents to contain the contaminants in the drill cuttings.

Below are the main findings of the study:

- The results of the heavy metals showed that Ba, Cd, Ag, and Cr are under the limit of US EPA TCLP. However, the ratios of 0.25:10, 0.5:10, 2:10, and 3:10 for the cement and 0.25:10 and 0.5:10 for the lime-treated drill cuttings showed Pb had surpassed the US EPA TCLP.
- Chloride concentrations in the ratios of (0.25:10, 0.5:10, 1:10, and 2:10) have surpassed the Nigerian limit of chloride.
- The solidification and stabilization process are considered highly efficient in immobilizing the contaminants in the drill cuttings.
- The results indicated that both binders could be used as an S/S agent for the drill cuttings to stabilize and solidify.
- The pH for most studied ratios was over 11.5, indicating the success of the experiment, in which most of the heavy metals are immobilized in pH 11 or above.
- Leaching concentrations of the contaminants are significantly decreased, indicating the effectiveness of both binders in immobilizing the contaminants in the drill cutting.
- As the portion of binders increased, the waste turned into non-reactive form and later could be classified as the non-hazardous type of waste.
- Further investigation is required to contain more chloride concentrations in the ratios surpassing the Nigerian limit to re-assess the binders' performance.
- The ratios of 1:10 and 2:10 have performed very well for most of the parameters examined during the treatment of the drill cuttings, which can also be relied on economically. However, the ratios of 3:10, 4:10, and 5:10 have also given excellent results, but due to their high binder content, they will not be considered economically feasible.
- As a part of the heavy metals studied, Total Petroleum Hydrocarbons (TPH) also have to be investigated.
- The results also indicate that the S/S product can be considered a safe and inert waste to be landfilled or reused for road construction.
- Landfills or areas excavated (primarily onsite pits) to receive the S/S product must be lined with High-Density Polyethylene (HDPE) or geotextile liners as double safety precautionary steps to prevent any possible leachate that might occur when the S/S product ages.

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