

Chemical and mineralogical evidence for solubility and mobility of lead from lead mine-affected soils to aqueous environments

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Abstract: The mobility of Pb binding in mine-affected soils to aqueous environments was studied using a combination of chemical and mineralogical methods. Leaching test was supplemented by mineralogical investigation of both soil samples and Pb mineral fractions using X-ray diffraction analysis (XRD) and scanning electron microscopy (SEM). The level of Pb determined by ICP-MS showed maximum concentration of 2.550 ppm and 3225 mg/kg Pb, which is far higher than the World Health Organization (WHO) and Soil Guidelines Value (SGV) for water and soil, respectively. Thus, the leachability of Pb in the area established. Concomitantly, the potential release of Pb into the environment was further revealed by SEM XRD for mineralogical analysis of Pb forms and soil components. The results showed that Anglesite among the five lead-bearing phases observed was the most abundant pool of soil Pb and most soluble fraction. Thus, the geochemical partitioning, potential mobility and bioavailability of soil-associated Pb are established, which perhaps accounted for the transportation of Pb to nearby river water. However, XRD showed high proportion of quartz (81%), aluminosilicates (14%) and traces of feldspars, of which aluminosilicates perhaps cause the retention of some forms of Pb in the area.

Keywords: Mobility, Solubility, Mineralogy, Rhandirmwyn, Environment, Pollution

1. Introduction

Rhandirmwyn lead mine is one of numerous abandoned lead mine in the South Wales, where early mining practices have resulted in spoil heaps, adits and tailing ponds of mine waste, rich in Pb being exposed to weathering and leaching. Thus, spoil heaps, adits and tailing ponds have the potential to cause environmental pollution due to remobilization of Pb from these metal rich environments. Mining activities ceased long in the UK before statutory controls on mining waste were established and thus, lead pollution load of the mine waste sites in Rhandirmwyn lead mine requires lead pollution inventory scan. In this case, the primary fear is the influence of the old mine on the environment and on the local population who have been making calls for reclamation/remediation of the abandoned mine site. The

sloppy topography of the terrain (Fig. 1) suggests that lead contamination from the spoil heaps (Fig. 2) could easily be carried to the nearby Nant Bai river channel.

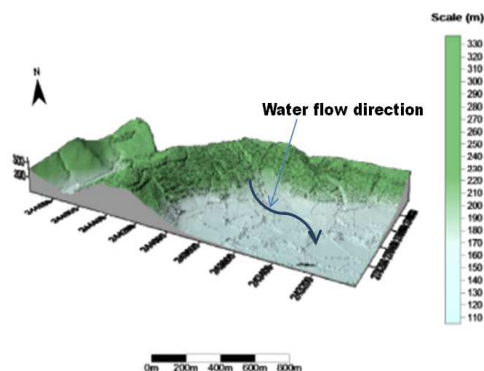


Fig 1. The sloppy topography of the terrain of the study area.

Also, mine adits could potentially serve as conduits through which contaminated ground water from reservoirs at the upper Boat level and tunnels below the mine (Fig. 2)

discharges to the surface which could drain down to Nant Bai river channel and eventually to Towy river.

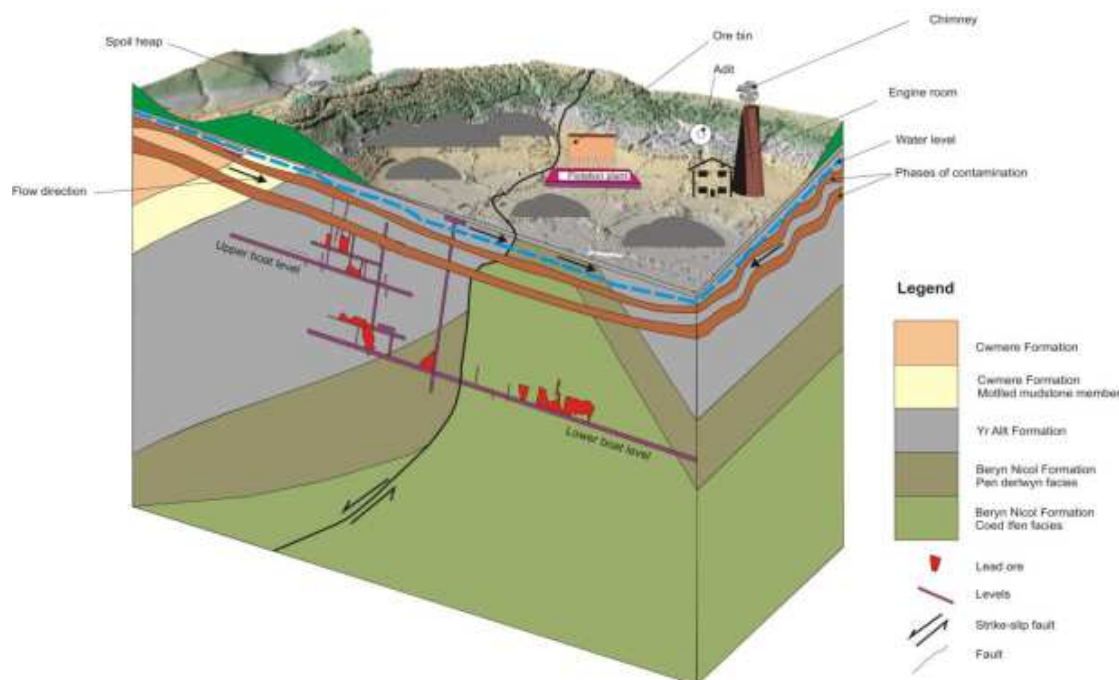


Fig 2. The Rhandirmwyn abandoned lead mine site conceptual model

However, as soil matrix is heterogeneous, attention has to be focused on the interaction of various forms of lead with different soil constituents. This is because accurate description of complex interactions of lead forms in soils is a pre-requisite tool in predicting their behavior in soil environment [1-3]. In addition, the dispersion of lead contaminants from the abandoned mine site into the immediate water courses depends on its release and transport tendencies [4, 5]. Therefore, characterization of lead in soil has to go beyond a simple determination of total content. It has been argued that determination of total metal concentrations provide little or no insightful information on the potential mobility and bioavailability of toxic metals [3, 4]. It is the geochemical phases of toxic metals that will yield information more pertinent in the transfer of metals along soil-water-plant-animal-human chain [2, 6].

The geochemical status and potential mobility of lead could be estimated via mineralogical method. The solid metal phases can be determined directly or indirectly. The indirect method involves identification of fractions of a metal binds to soil, whereas the direct method uses spectroscopic instruments such as SEM and/or XRD to quantify mineral components [1]. Gee et al. [7], for example, investigated mineralogy of smelting slags and the response of specific mineral forms to natural weathering processes and potential release into the environment. Likewise, the objective of this research was to investigate and predict the likely release and dispersion of lead contaminants from the abandoned mine site as the spoil heaps, adits and tailing ponds in the area of the mine site

represent the major sources of contamination of Pb in the area. Coniferous woodland above the mine and on slopes of the river valley is a possible source of acidic water which could influence Pb contamination from soil to surface-and-ground water sources. Transport of some metals is function of pH [8, 9] and therefore, perhaps, the lower the pH of soil-water routes the greater solubility and mobility of Pb.

2. Sampling and Methods

2.1. Study Area



Fig 3. Location map showing the study area in regional context. Digimap

The Rhandirmwyn mine (Fig. 3) is located in the village of Rhandirmwyn (52.0790° N, 3.7750° W) which is 10 kilometres (6.23 miles) north of the market town of Llandovery in the Dinefwr District of South East Dyfed which before the local government reorganization lay in Carmarthenshire [10]. Rhandirmwyn village extends along both sides of the Tywi (Towy) river, some two miles north of Cilycwm village and extends up the Gwenffrwd valley towards Cwrt-y-Cadno as far as Bwlchyrihw and then east across the mountains into Ceredigion and Breconshire (Powys).

2.2. Soil Sampling

Soil samples were collected from seven sites in the study area (Fig. 4), selected to represent a spectrum of Pb contamination histories and Pb concentration. Samples were picked from the mine spoil heaps (Fig. 5) in the area. The heaps from which the samples are taken are all different in terms of grain size, color and constituents e.g. some contain more proportion of clay than others.

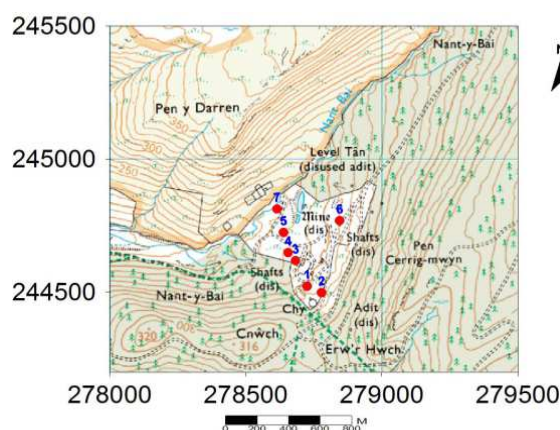


Fig 4. Soil sampling locations.



Fig 5. Mine spoil heaps from which samples were picked.

2.3. Water Sampling

The water samples were obtained from areas of interest during the field work. Samples were taken from the existing adits [278235, 243799] and [278541, 245412] (Fig. 6); localized water pools in various locations in the area and along the Towy stream that truncated the area (Fig. 7).



Fig 6. The adits [278541, 245412], where water samples were collected for laboratory analyses.

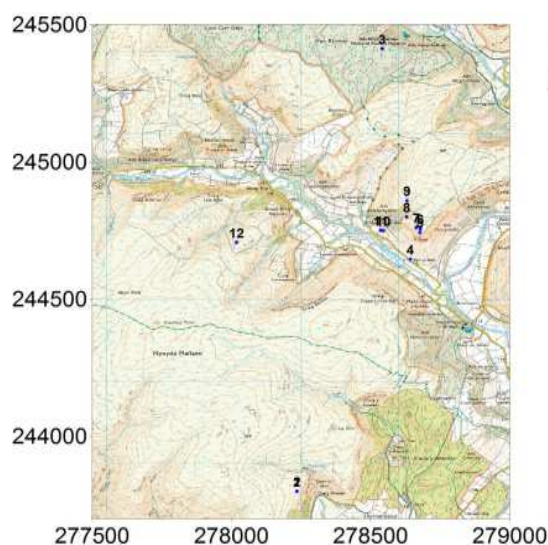


Fig 7. The water sampling locations.

2.4. The Experiment

In order to understand the leachability of Pb for different media (acid, water and alkali), soil samples were collected from the field and leached in three different pH conditions- acidic, basic and neutral aqueous environments. Approximately 1.0 g each of the seven samples was transferred into a clean plastic weighing boat and the mass accurately determined using a 4 decimal place analytical balance. The samples were then separately transferred to clean level test tubes. Upon each of the sample, acid, base and water leaching tests were then carried out differently.

During the leaching test, 10 ml of 2 moles of each of nitric acid, sodium hydroxide and water was added to each 1.0 g of the samples and left for 24 h for the acid, base and water to leach Pb from the samples. The mixture were centrifuged at 4000rpm for 10 minutes after 24 h. 2ml was removed from the top of each of the samples and transferred into new test tubes, which were then diluted with deionized water (with a conductivity of >18.2 M Ω) to make up to 10ml and used for the determination of Pb leachate concentration using ICP – MS. Similarly, water samples collected from the field were analyzed for Pb concentrations. The samples were first filtered through a

0.45 μm filter and then 10ml was transferred into a test tube, followed by addition of 1ml 20% nitric acid solution to ensure that all the Pb ions remain in the solution for its concentration determination using ICP – MS.

To go beyond total metal content since it is well recognized that it does not provide a definitive insight of Pb forms, a methodology to separate the lead-bearing phases was also employed since it is impossible to consider the presence of lead and its compounds in the environment and its potential toxicity to the ecosystem and to the human population without considering its geochemical forms [11]. Therefore, the use of SEM in this project made it easier to image objects such as minerals and microfossils at a magnification far exceeding the capabilities of an optical microscope. The samples were crushed to smaller sizes and sprinkled onto Agar scientific carbon tab fixed to a 12.5mm aluminium specimen stubs, which were used for the SEM analysis for elemental identification present in various lead-bearing phases.

Furthermore, in order to provide a genuine audit of the mineralogical components of the soil samples. For such reason, X-ray diffraction technique was applied to explicitly identify the mineral components of the soils, from which to gain insight into specific minerals controlling the potential release of Pb into the environment. All the samples used for the x-ray diffraction were oven dried and packed inside clean aluminium holders. The samples were mounted inside the sample chamber of the diffractometer and bombarded with X-rays. Each pure mineral or compound has a specific X-ray diffraction patterns and it is with these that were matched against the unknowns.

3. Results and Discussion

3.1. Soil Leachate

The result of the leaching tests is presented in Table 1. The highest amount of Pb was recorded in sample 7 and the least in sample 4 with concentration of 3226 and 1558 ppm, respectively for acid test. Similarly, in alkaline soil condition, sample 7 also had the highest concentration of 3298 ppm of Pb followed by sample 6 with 1089 ppm, whereas all the remaining five samples showed concentration of less than 1000 ppm. However, the water leaching test showed the lowest values of the Pb recovered. Therefore, from the soil leaching tests carried out, acid leaching had recovered the highest concentration of Pb, which suggests that the toxic metal is more soluble and liable to be released into the environment when soil solution is acidic. This is consistent with what has been reported in similar works [5, 12]. Generally, Pb is soluble and bioavailable in acidic soil condition [11]. In addition, it has been reported that solubility of Pb in soil solution decreases with increasing pH, which is the usual trend with cationic metals. This is attributed to the fact that for all cationic metals adsorption increases with increasing pH [13]. Thus, at higher pH the toxic metal might

be adsorbed on the clay surfaces or formed lead PbCO_3 [14]. Post classified map was used to show the concentrations of Pb obtained at different sampling locations (Fig. 8), which can ease identification when it comes to reclamation/remediation of the area, since acid and base leaching tests admitted high pollution load in the study area (Table 1).

Table 1. Leaching test results of soil samples.

Sample locations	Location description	Lead (Pb) Concentration (ppm)		
		Acid	Base	Water
1	Spoil heap	1732.9	259.1	7.8
2	Spoil heap	3169.8	751.5	248.7
3	Tailing drain	2774.6	733.8	67.1
4	Tailing drain	1558.1	405.2	107.5
5	Spoil heap	2901.9	559.7	229.9
6	Spoil heap	3216.2	1088.7	206.9
7	Spoil heap	3225.9	3298.7	228.8

The concentration of lead in the samples show anomalously high values in the spoil heaps indicating leachable values higher than the acceptable concentration for Pb the in soil guidelines values for both residential with/without plant uptake (450 ppm) and commercial/industrial (750 ppm) [15]. Therefore, from this analysis, the Nantymwyn (Rhandirmwyn) mine is regarded as polluted and could be source of lead contamination to soils and surface-and-ground water sources in the vicinity of abandoned mine spoils, since significant amount Pb can leach out especially when the soil solution is acidic or alkaline, but more leachable in acidic condition. The maximum Pb concentration found here is compared with the soil maximum tolerable value of 450 ppm (Fig. 9) aiming to visualize the abundance of Pb in the soil samples even though total content is less important in determining Pb lability and/or affinity, but suggests Pb pollution plume in the study areas.

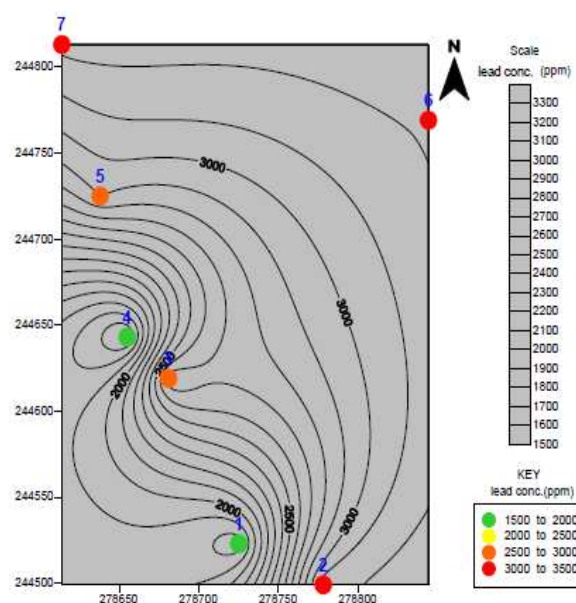


Fig 8. Classified post map showing lead concentration at soil sampling locations after analysis.

Similarly, the result of Pb concentration in water samples is presented in Table 2. Water is the vehicle for transport of solutes, including toxic metals, from/through soil. It is worthwhile to note that solubility is a prerequisite of mobility and thus, Pb concentration in the water sample could provide gainful information to this regard, although the surface water chemistry affects the transport of toxic metals. The water samples analyzed for Pb concentrations, ten out of the twelve samples were higher than the World Health Organization standard of 0.01 mg/l (ppm). The highest value 2.550 ppm was recorded in sample 4 obtained from the tailing ponds (Table 2). Post classified map (Fig. 10) shows a plot of the concentration of Pb obtained at each location after the analysis. Accordingly, in order to see the impact conspicuously, the maximum concentration of Pb obtained was also compared with current World Health Organization (WHO) standard (Fig. 11). The increase in the dissolved concentration of Pb represented mobility of Pb from soil-rich-Pb to water courses around and suggested toxicity and contamination problems in water environment in the vicinity of derelict Pb mine. This in effect revealed that Pb found in the water samples was transported from the soil-rich-Pb and perhaps exists in the water environment mostly in the water soluble form, from which could easily be released out to Towy river or leached down to underground water in the district and as a result, could impact detrimental effect on both environment and human health in the locality. This is because water soluble is the most mobile and plant available form. However, as the pH of the water samples were slightly acidic, the result obtained from the water analysis suggests that solubility of Pb in the water increased as the pH decreased. The toxic metal pH-dependent solubility suggests that dissolved Pb concentrations in water samples are controlled by Pb carbonates or/and sulphates and may be, were the most abundant species of Pb forms existing in the derelict mine site, even though this assertion could be inconclusive. Consequently, this implies that leachability of Pb from the surface water courses around the derelict mine site to underground water could increase with pH decrease, which is consistent with the similar reported work [16].

Table 2. Lead (Pb) concentration in water samples.

Sample locations	Location description	pH	Pb concentrations (ppm)
1	Near shaft 1	6.9	0.202
2	Shaft 1	6.4	0.096
3	Shaft 2	6.4	0.330
4	Tailing pond	6.2	2.550
5	Pond	6.2	1.590
6	Reddish brown pond	6.3	0.633
7	Pond	6.0	0.007
8	Stream I	6.5	1.007
9	Stream II	6.8	0.006
10	Stream III	6.5	0.869
11	Stream IV	7.0	0.017
12	Stream V	6.9	0.091

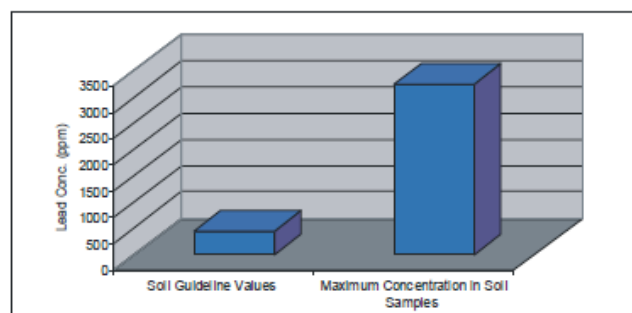


Fig 9. The comparison of maximum lead concentration with soil guideline value.

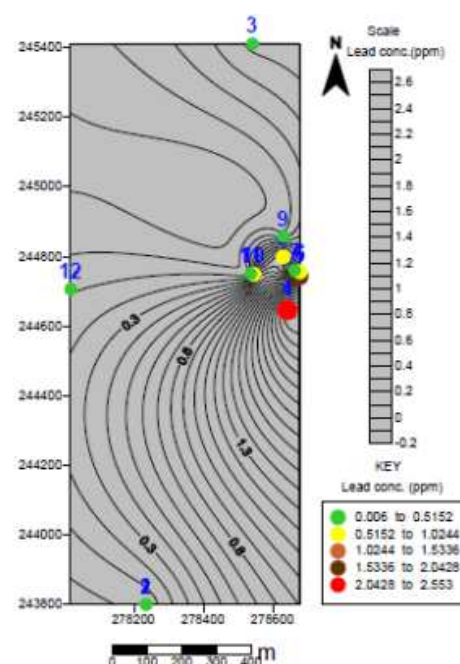


Fig 10. Classified post map showing Pb concentration at water sampling locations after analysis.

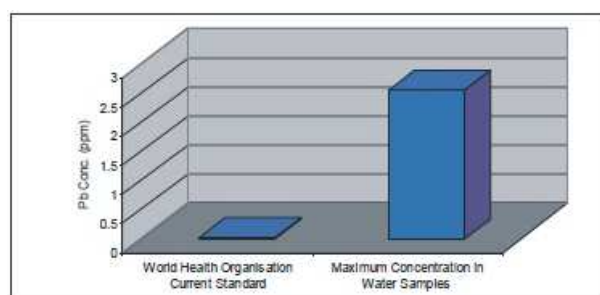


Fig 11. The comparison of the maximum Pb concentration in water samples with current World Health Organization standard.

3.2. Scanning Electron Microscopic Analysis

It is impossible to consider the presence of lead and its compounds in the environment and its potential toxicity to the ecosystem and to the human population without considering its chemical and mineral forms [11]. The scanning electron microscope reveals the differences in the distribution of the minor phases within a given sample [17].

From the analysis carried out, five forms of lead were observed (Table 3). Most of the samples indicated the present

of Anglesite, Cerussite and traces of Galena Pyromorphite and Mimetite in some of the samples (Fig. 13).

Table 3. Forms of lead observed during SEM analysis.

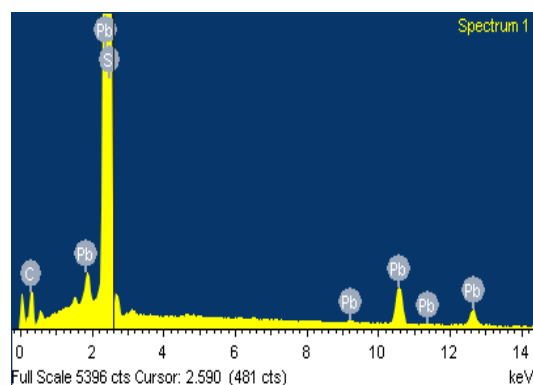
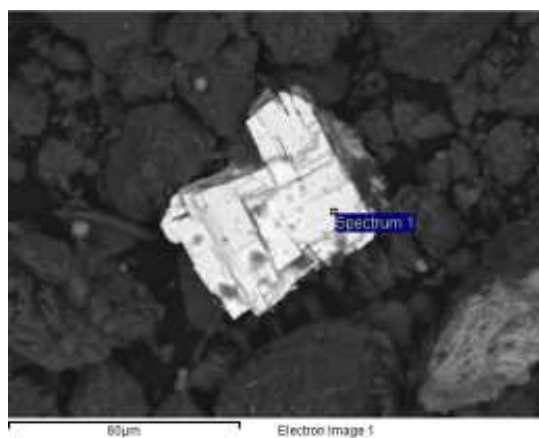
Locations	Forms of lead observed				
	Galena	Anglesite	Cerussite	Mimetite	Pyromorphite
	PbS	PbSO ₄	PbCO ₃	3Pb ₃ As ₂ O ₈ PbCl ₂	3Pb ₃ P ₂ O ₈ PbCl ₂
1	1	2	1		
2	2	3			1
3		1	7		
4		8	1		
5		4			1
6		2	1	2	
7	5				

Note: Any number greater than 1 under the mineral forms means that the mineral form was observed in more than one location within the sampling area.

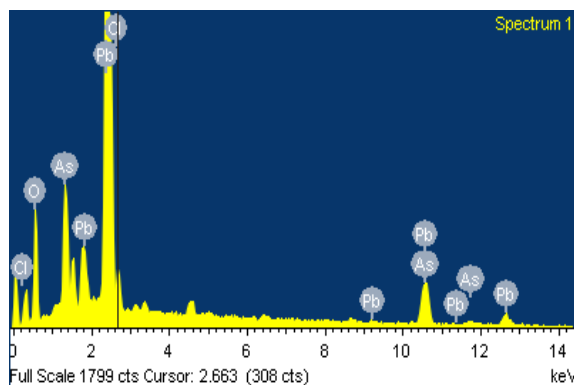
The form in which metal exists in the environment is a crucial factor in determining its mobility, bioavailability and toxicity [11]. In addition to galena (lead sulphide, PbS) which is the primary ore of the lead in the area, the SEM analysis revealed the present of lead in different forms (Table 2) which indicated that the area has undergone a series of secondary mineralization which resulted in the formation of Mimetite, Cerussite, Anglesite and Pyromorphite. Bevins et al. [18] confirmed that secondary mineralization is well developed in the study area especially around the lode outcrop on Pen Cerrig-mwyn and is also present in small tips immediately to the west of the outcrop (NS 791443) which resulted in the formation of Mimetite, Cerussite, Anglesite and Pyromorphite but

stressed that the primary source of the arsenic in Pyromorphite is yet to be determined.

Galena which is the primary ore of lead and one of the forms of lead observed in the SEM analysis is known to be easily oxidized in their outer parts into oxy-salts [19]. In general, lead is changed by natural processes from compounds such as lead chloride to less soluble one such as lead sulphate, carbonate and phosphate [11]. Therefore, from the result of SEM it is possible that most of the Galena (PbS) ore might have been oxidized during the process of secondary mineralization which resulted in prevalence of secondary minerals in the area (Table 3). Hester and Moore [20] also confirmed that secondary minerals of lead are formed when galena weathers.



Compound present: Pbs(galena)



Compound present: 3Pb₃As₂O₈PbCl₂ (Mimetite)

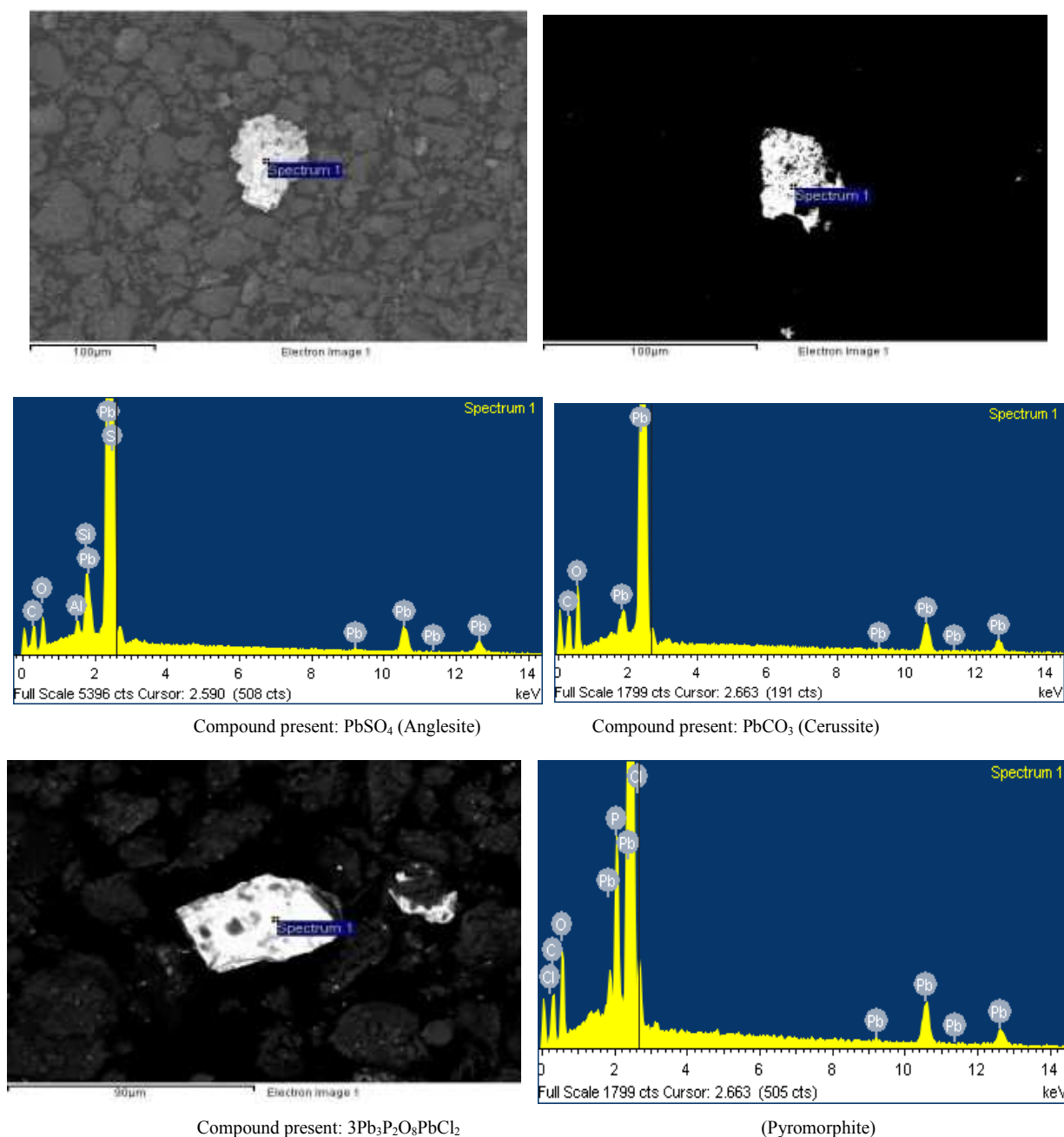


Fig 12. The mineral forms of lead observed in the samples by SEM analysis.

Pyromorphite is regarded as the most stable form of lead mineral under acidic to neutral conditions [21, 22]. Cerrusite has a small stability field. Anglesite was observed more than any of the five minerals and is considered to be soluble than Cerrusite, Mimetite, and Pyromorphite [23].

However, in sample 7, of all the five different sites of interests observed within the sample had shown only galena and from all the leaching tests carried out it has the highest recoverable concentration of Pb which may be attributed to its solubility when compared to other Pb minerals observed. This indicated that the solubility of galena can exponentially increase with the proton activity, which can be adduced from the acid leaching test conducted on sample 7 and conformed to the observed phenomenon in

the past [13]. Thus, the dissolution of galena in acid solution can be held as a significant reaction administering the transport and transformation of Pb in natural environment.

3.3. Mineralogical XRD Analysis

The X-ray diffraction shows the bulk mineralogy of the compounds that may be present in samples [17]. The diffractograms obtained (Appendix 1) shows abundant quartz, Aluminosilicates e.g. Kaolinite and Illite with traces of Feldspars e.g. Albite and Orthoclase (Table 4). Quartz is the most abundant having the highest peak in all the samples.

Table 4. Soil mineralogical components observed during XRD analysis

Locations	Soil minerals observed					
	Quartz	Pyrite	Albite	Kaolinite	Illite	Orthoclase
1	√			√	√	
2	√			√	√	
3	√			√	√	
4	√			√	√	
5	√			√	√	√
6	√			√	√	
7	√	√	√	√	√	

Furthermore, semi quantitative analysis was carried out on all the samples to show the percentage mineral composition of all the minerals shown on all the diffractograms of the samples. The percentage of the each of the minerals is presented in Table 5. It shows that quartz ranges from 60 – 91%, illite 3 – 22%, Kaolinite 1-5%, and traces of Albite and Pyrite in sample 5 and 7 indicated the presence of 1% Orthoclase.

The X-ray diffraction results obtained indicated that lead was not represented in the diffractograms (Appendices) implying that the bulk chemistry of the spoil heaps (where most of the samples were obtained) is dominated by abundant Quartz (Table 5), Aluminosilicates e.g. illite, Kaolinite, and traces of Pyrite and Feldspars e.g. Albite, Orthoclase. Pyrite oxidation is frequently mediated by Oxygen dissolved in the waters bathing the mineral surface [24].

Table 5. Percentage mineral composition of all the soil samples

Samples	Minerals	Percentages
1	Quartz	86
	Illite	11
	Kaolinite	3
2	Quartz	80
	Illite	15
	Kaolinite	5
3	Quartz	93
	Illite	5
	Kaolinite	2
4	Quartz	91
	Illite	6
	Kaolinite	3
5	Quartz	75
	Illite	22
	Kaolinite	2
	Orthoclase	1
6	Quartz	60
	Illite	35
	Kaolinite	5
7	Quartz	87
	Illite	3
	Kaolinite	1
	Albite	4
	Pyrite	5

Acid-buffering capacity of a pyritic mine tailing is largely controlled by its constituent Aluminosilicates e.g. illite [25]. Puura and Neretnieks [26] suggested that Aluminosilicates provide buffering capacity over the short term. The buffering capacity of Aluminosilicates, may have served as absorbent for the lead and other heavy minerals in the Nantymwyn mine which may have possibly served reduce their mobility in the environment. Salomons [27] also confirmed the long term buffering capacity of silicates. In addition, mobility can also be described in terms of adsorption-desorption reactions, pH and migration of colloids bound metal through leaching [17]. Therefore, this may be attributed to the fact that some Pb forms found in the study area consist of Pyromorphite and Mimetite, which are found to be very insoluble and relatively insoluble Pb forms, respectively [28].

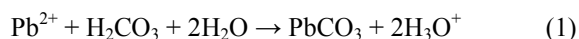
In terms of soil mineralogy, Pb can be adsorbed onto the clay minerals and remains within the sediments [29]. The clay minerals have ability to adsorb metals e.g. lead due to their high surface area. Thus, the clay minerals (aluminosilicates) observed during the X-ray diffraction (Appendices) can be a sink for the lead and therefore, may reduce the mobility of the lead in the area.

3.4. Pollution Potential and Future Environmental Impact

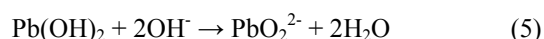
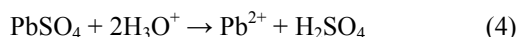
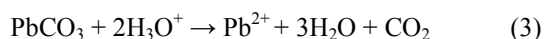
The risk of toxic metals pollution, health effects or environmental harm occurring as a result of soil and surface-and-ground water contamination is dependent upon the mobility of metals, which pivots strongly on their mineralogical, chemical forms and the pH of the environment they exist in [30]. However, it has been suggested that pH is the major player in controlling the migration mechanism of Pb in soil [30]. Because, increasing pH leads for the precipitation of insoluble compounds, such as carbonates, oxides and hydroxides and thus improves the tendency for adsorption and exchange reactions [31], which in turn hinder mobility. Therefore, it can be asserted that maximum mobility of Pb occurs in soils with a relatively low pH, of which the soil leaching tests conducted in this work can adduce the observation. Besides, the high concentration of Pb found from the acid leaching test indicated that majority of Pb geochemical forms are in the acid-soluble phases, which suggest that the scenario under which these forms of Pb could be released (beyond guideline values) from the storage in the soils of Nantymwyn (Rhandirmwyn) abandoned mine is that of acidic environmental condition. Consequently, as the pH recorded in the study locations was between 6 and 7 indicating slightly acidic to neutral suggests that Pb forms could be soluble in the soil solutions and thus, Pb in the area is relatively bioavailable.

Galena as the primary lead bearing mineral, which when oxidized, forms a rim in its outer parts to prevent further oxidation [32]. The rim is formed by Cerussite (PbCO_3) (reaction 1) and Anglesite (PbSO_4) (reaction 2), both of which were identified as the major phases of Pb found in

the soils of Nantymwyn (Rhandirmwyn) abandoned mine. This result is consistent with the solubility pattern of Pb in water samples, as we earlier claimed that dissolved Pb concentrations in water samples are controlled by Pb carbonates or/and sulphates and may be, were the most abundant species of Pb forms existing in the derelict mine site. However, the solubility products of Cerussite and Anglesite are 3.0×10^{-28} and 2.53×10^{-8} , respectively [23]. As such, Cerussite is relatively soluble Pb form; unlike Anglesite which is more soluble. As the more soluble Pb phase and the most abundant one among the five minerals observed, dissolution of Anglesite downstream of the abandoned mine is highly possible and could be a source of contamination of soils and surface-and ground water sources in the vicinity of the derelict mine site.



Noticeably, in an acidic environmental condition, both Cerussite (reaction 3) and Anglesite (reaction 4) can release Pb into the environment. As a result, as the soils of the study area were found between 6 and 7, the Pb from the spoil mines is potentially in the mobile form and may pose a serious environmental health threat. In addition, Pb can also dissolve in alkaline environmental condition because of its amphoteric character and solubility of plumbites [33, 34], which is presented in reaction 5. Therefore, the leachability of Pb in the area is established, as also found is even leachable in water leaching test.



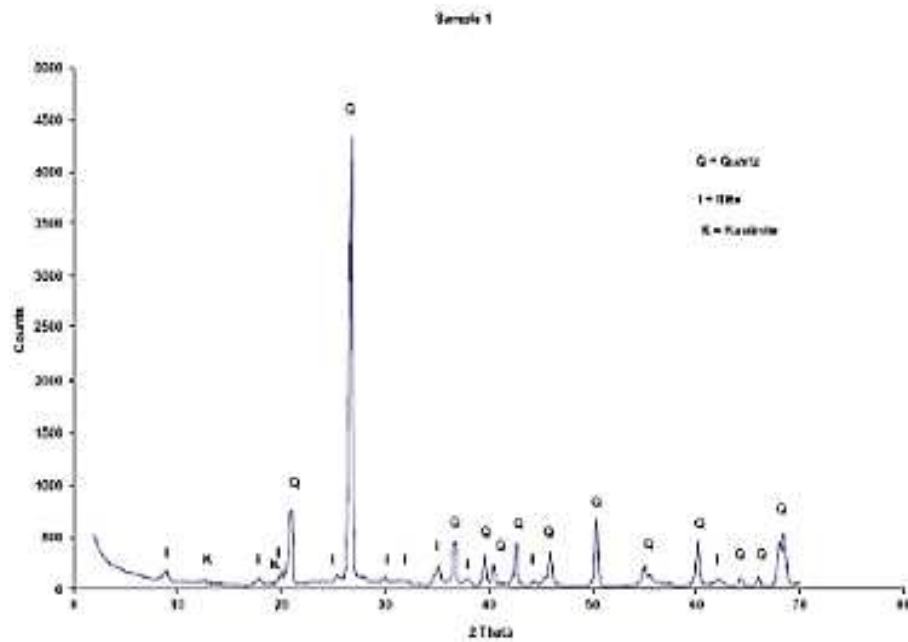
From the viewpoint of XRD results, the bulk chemistry of the spoil heaps (where most of the samples were obtained) is dominated by abundant Quartz, Aluminosilicates e.g. illite, Kaolinite, and traces of Pyrite and Feldspars e.g. Albite, Orthoclase. Therefore, the Quartz and Aluminosilicates may serve as sink for the Pb and other heavy minerals in the Nantymwyn mine, which may possibly reduce their mobility in the environment. However, because of the complexity of the soil-waste system, with its myriad of surface types and solution composition, such a generalization may not hold true. In addition, the natural sorption capacity of the major minerals observed also

largely depends on the pH of the soil environment, which either directly or indirectly affects several mechanisms of metal retention by soils [13]. In addition, It has been pointed out that Pb maximum retention onto soil surface increases with high pH value of soil system, since in general, maximum retention of cationic metals occurs at $\text{pH} > 7$ [35]. Therefore, as the pH of the soil and water environment of the spoil mines, adits and tailing ponds were between 6 and 7, therefore, the retention of Pb on the soil and in the water was relatively weak. Thus, there could be high possibility of incessant release of Pb from the abandoned mine site to the immediate environment and that may pose a serious environmental health threat.

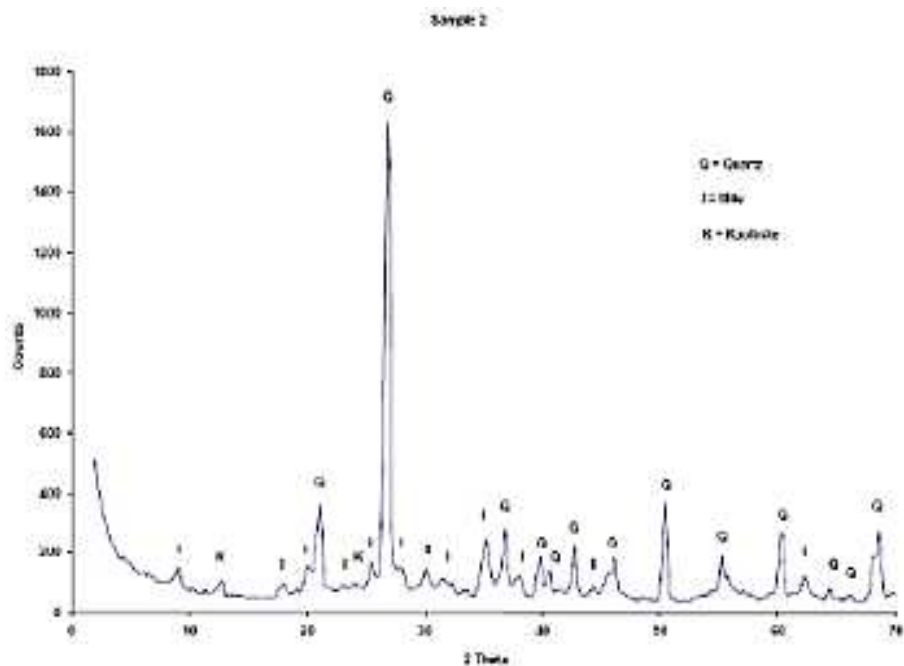
4. Conclusion

Based on the results obtained from the water, soil leaching test and mineralogical analysis of the of Nantymwyn (Rhandirmwyn) derelict mine still consists of Pb of different phases, which are originated from the primary lead bearing mineral (PbS) as a result of secondary mineralization process. From the leaching tests, it was found that the Pb in the area is quite leachable and therefore, there could be high tendency of Pb release into environment, particularly aqueous environment. Concomitantly, the SEM results revealed that Anglesite was found to be the most frequent and soluble, followed by Cerussite among the five forms of Pb observed in the area. Hence, as the soil of spoil heaps, adits and tailing ponds of Nantymwyn (Rhandirmwyn) derelict mine found between 6 and 7, the acid soluble phases of Pb are potentially mobile and therefore, could be a source of contamination of Towry river downstream the mine site or/and leaching down to underground water of the areas. Thus, for the sake of environmental management and even as the inhabitants of the Rhandirmwyn village are also very interested in turning the area into a recreational and/or residential purposes, the Nantymwyn (Rhandirmwyn) derelict mine must first be remediated before reclamation of the site in order to avoid Pb poisoning in future. Historically, the occurrence of Pb poisoning in Dareta in Zamfara-Nigeria still stands the very conspicuous reference of Pb poisoning disaster in our today's world and therefore, Pb solubility and mobility status from the site deserve periodic monitoring and evaluation until the site is completely remediated and reclaimed.

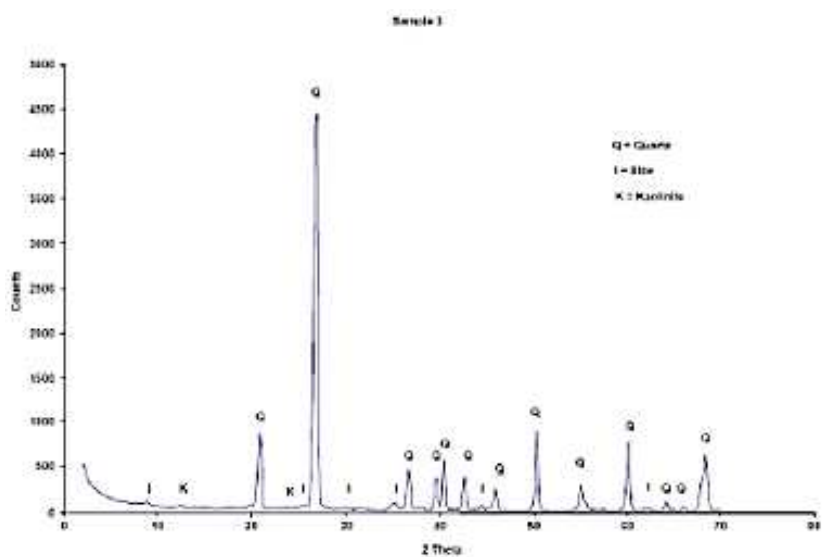
Appendices: Diffractograms of the Samples Obtained from the XRD Analysis



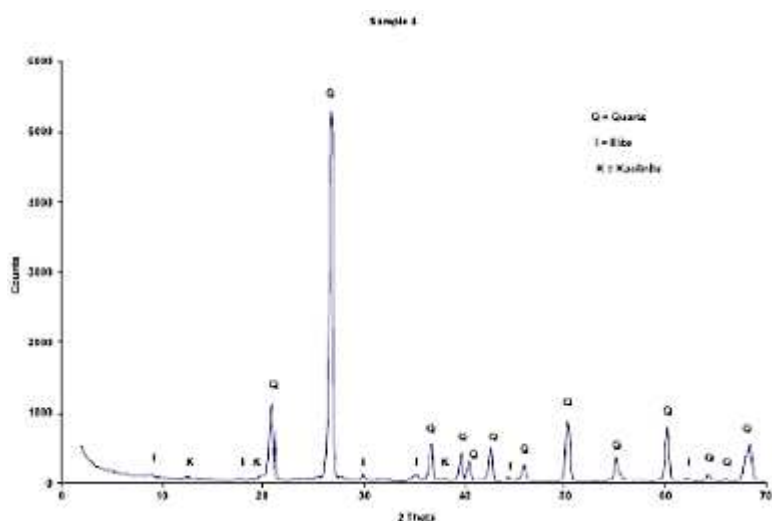
Appendix 1. Diffractogram of soil sampled from sampling site 1.



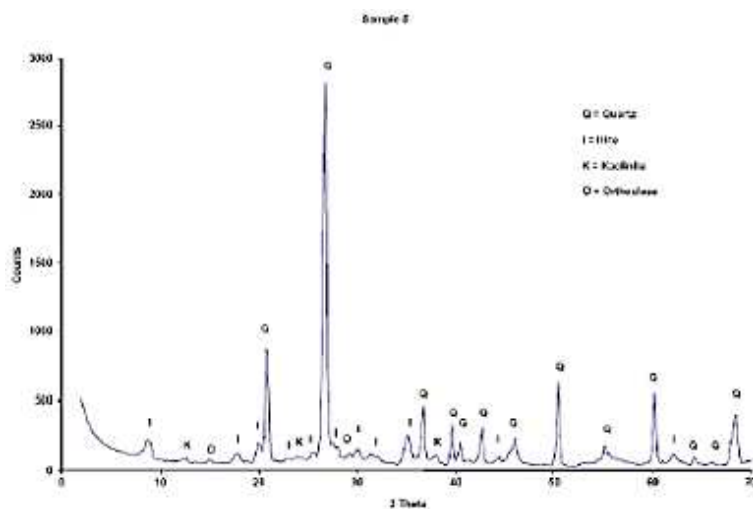
Appendix 2. Diffractogram of soil sampled from sampling site 2.



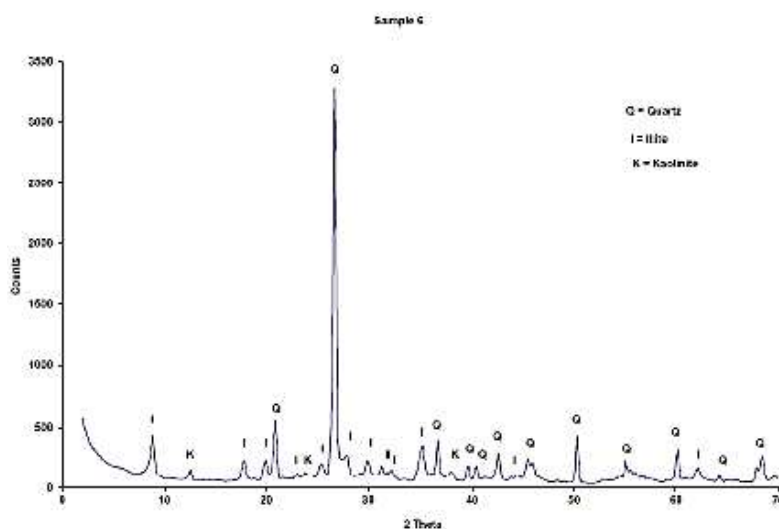
Appendix 3. Diffractogram of soil sampled from sampling site 3.



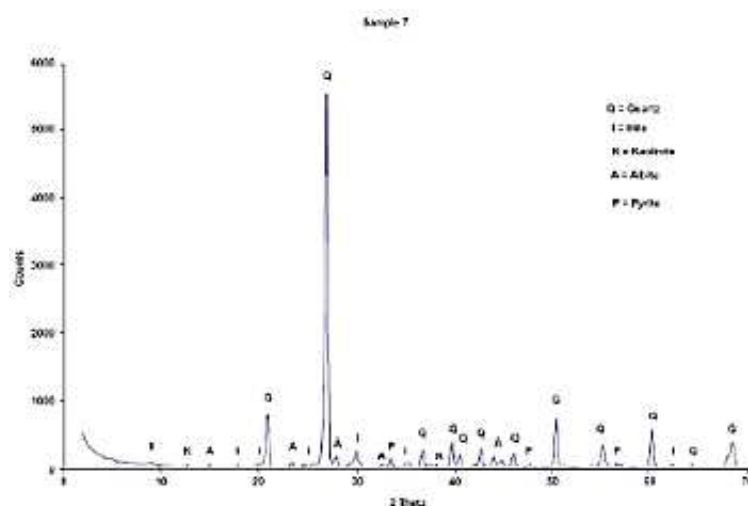
Appendix 4. Diffractogram of soil sampled from sampling site 4.



Appendix 5. Diffractogram of soil sampled from sampling site 5



Appendix 6. Diffractogram of soil sampled from sampling site 6.



Appendix 7. Diffractogram of soil sampled from sampling site 7.

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