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ENVIRONMENTAL CHARACTERISATION OF THE SULPHIDIC TAILINGS IN LAVRION

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ABSTRACT

Intensive mining and metallurgical activities in Lavrion over a time span of over 2700 years resulted in the formation of huge spoils of mining, milling and metallurgical wastes and tailings, most of them characterised as toxic and hazardous. Toxic elements are released by a number of mechanisms and migrate to the surrounding area, contributing to the widespread soil contamination. Three main types of spoils exist: sulphidic flotation tailings, oxidic–carbonaceous–silicate beneficiation tailings and metallurgical slags. This paper deals with the sulphidic flotation tailings. For the estimation of the risk that these tailings pose to the environment and for the conceptual development of a remediation strategy, complete characterisation was done according to the following methodology: Drillholes were placed within the spoils and undisturbed core samples were taken and characterised chemically and mineralogically; their net neutralisation potential (NNP) was determined using static tests and their toxicity using the EPA TCLP test; speciation of the toxic metals was determined in some cases using the sequential extraction technique and the bioavailable fraction determined by EDTA extraction. Some geotechnical characteristics of the spoils, as density and permeability were determined in-situ. Piezometers were installed within the boreholes and the pore water quality and level was monitored. The above information is being critically assessed and employed for the selection and design of the optimum rehabilitation scheme.

Keywords
Environmental characterisation; tailings; Lavrion

INTRODUCTION

The city of Lavrion is situated 75 km SW of Athens; the wider area bears mixed sulphide ore bodies (argentiferous galena, sphalerite and pyrite) developed along contacts of schist with marble and has been a centre of intensive mining and processing activities for over 2700 years. The ancient Athenians developed ingenious techniques in order to mine and process the ore to produce silver and lead [1]. It has been estimated that over 3500 t of Ag and 1400000 t of Pb were produced in antiquity, 70% of which during the 5th and 4th centuries B.C. The decline of the activities began in the 3rd century, and during the 1st century B.C. all activities in the area were halted. Modern time activities began in the mid-19th century and lasted until 1980.

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The particularly intensive mining activities of the past 100 years have generated huge volumes of mining and metallurgical wastes and tailings that are characterised as toxic and hazardous. Under the action of the wind, rain, atmospheric oxygen and bacteria, toxic elements are mobilized and migrate by a number of mechanisms to the surrounding areas, contributing to the widespread and serious soil pollution that has been identified in Lavrion. Previous studies have shown that the soils around Lavrion are heavily contaminated with toxic metals [2]; the effect of contamination on human population has also been studied [3].

Three distinct types of spoils with different chemical and mineralogical composition can be identified in Lavrion (Figure 1):

- sulphidic flotation tailings (positions A, B, C, D); total quantity estimated at 800000 m^3.
- tailings from hydromechanical separation stages containing mainly oxidic–carbonaceous–silicates (positions E, F), estimated to more than 5000000 m^3.
- metallurgical slags (positions G, H, I, J); quantities are estimated to 7000000 t.

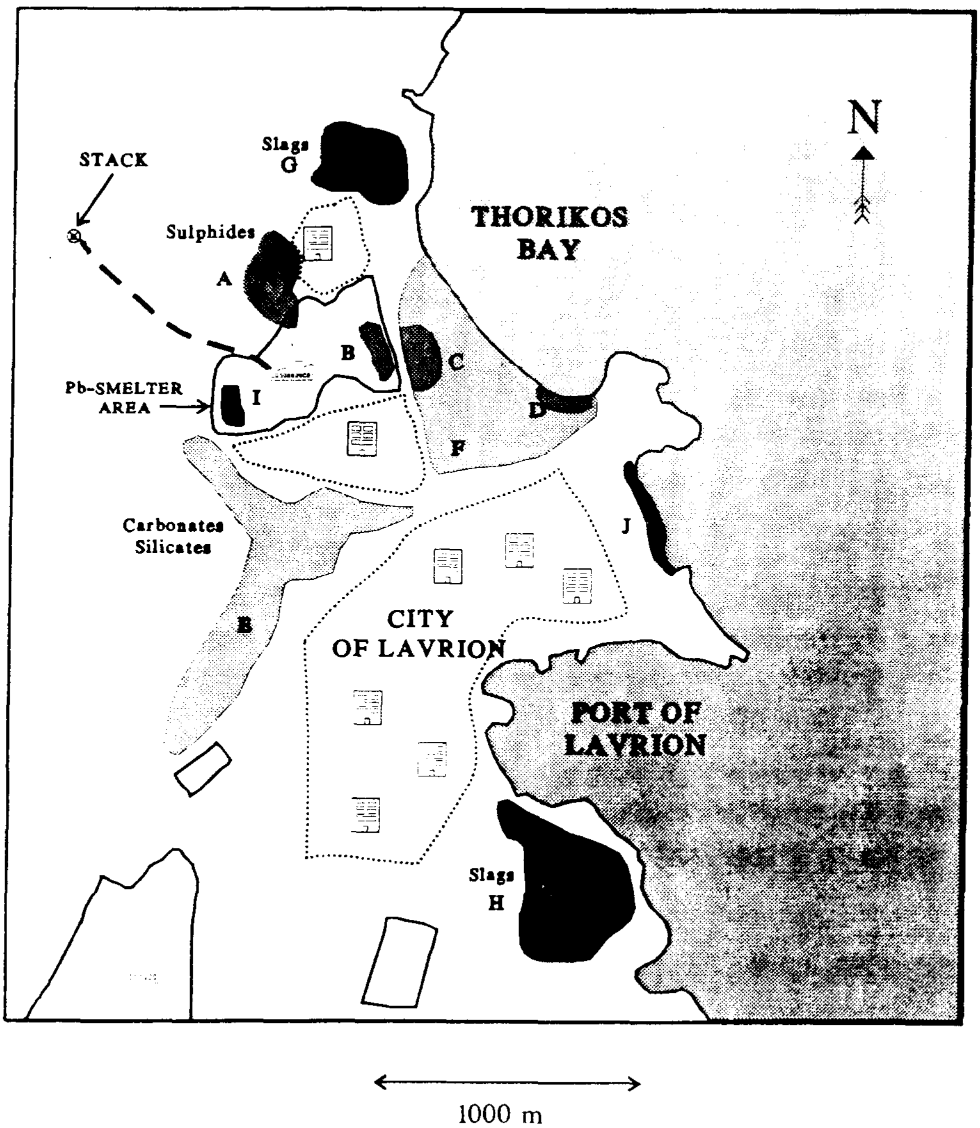

Fig.1 The main pollution sources in the Lavrion area

The present paper deals with the sulphidic tailings. For the estimation of the potential risk that these tailings pose to the environment and for the conceptual development of a remediation strategy, the following methodology has been adopted:

A detailed sampling procedure was carried out, involving the collection of surface and drill-core samples, the determination of several geotechnical parameters of the materials and the monitoring of pore water level and quality through piezometers installed in the drill holes. The drill core samples were subjected to chemical and mineralogical analysis, determination of their acid generation potential using static tests (acid–base accounting) [4,5] and their toxicity using the EPA TCLP test [6,7]. Finally, several samples were subjected to leaching by EDTA to determine the bioavailable fraction of the toxic metals; a limited number of samples was also subjected to the sequential extraction procedure [8] to determine the speciation of the heavy metals.

A critical evaluation of the data thus generated identified the environmental liabilities and risks associated with the spoils. For this, the following criteria were applied:

Chemical analysis

The toxic elements content was checked against the Netherlands and Canadian guidelines for soils which are presented in Table 1. Although these guidelines refer to total element content, it was seen more appropriate to compare the bioavailable fraction rather than the total elemental content.

TABLE 1 Netherlands and Canadian guidelines for heavy metals in soils (ppm)

	Netherlands			Canadian		
	A Reference values	B Detailed examination	C Clean-up needed	Agricultural land	Residential area	Industrial area
Pb	50	150	600	375	500	1000
Zn	200	500	3000	600	800	800
Cd	1	5	20	3	4	8
Cu	50	100	500	150	200	300
As	20	30	50	20	25	50
Cr	100	250	800	750	1000	1000
Ni	50	100	500	150	200	200
Hg	0.5	2	10	0.8	1	2

Toxicity characterisation

The toxicity characteristics of the spoils, as determined by the EPA TCLP test, were determined and compared against the toxicity limits (Table 2).

TABLE 2 TCLP test toxicity limits and Greek effluent quality standards

	EPA TCLP Test Toxicity Limits (ppm)	Effluent quality standards in Greece (ppm)
As	5	0.5
Ba	100	20
Cd	1	0.1
Cr	5	2
Pb	5	0.1
Hg	0.2	0.005
Se	1.0	0.1
Ag	5	0.3

Capacity for acid generation

The Net Neutralisation Potential (NNP) of the samples was determined by the acid–base accounting method and expressed as kg of $CaCO_3$ equivalent per t of material. Negative NNP values indicate capacity to produce acidity, but it is generally considered that samples with small positive NNP values may also generate acidity.

Pore water — surfacial water quality

The pore water quality in the spoils was monitored and checked against existing effluent standards in Greece (Table 2); also the quality of acidic waters originating from the spoils was checked against these standards.

EXPERIMENTAL PROCEDURE

Sampling

For the characterisation of the several types of spoils, surface bulk and drillhole samples were collected. Surface and bulk samples up to a depth of 4 m were collected by mechanical excavator. Drillhole samples were collected up to a depth of 15 m where possible. For the determination of some geotechnical characteristics in the laboratory, undisturbed core samples were also taken. For the monitoring of the quality of pore water piezometers were installed in each drillhole at a proper depth and above the water table. The diameter of the piezometer was 75 mm and pore water was sampled from its lower 50 cm non-porous part.

Chemical and mineralogical analyses

Elemental assays in solids were performed by digestion techniques and measurement of the ion concentration in solution by Atomic Absorption Spectrophotometry (A.A.S). Aqueous solutions were also analysed with AAS. Total S was measured with a LECO Sulphur analyser. Mineralogical analysis was carried out mainly by XRD techniques.

Geotechnical characteristics

The main geotechnical characteristics of the spoils such as permeability and wet bulk density were measured *in situ* using the sand-cone method. True density measurements were also carried out in the laboratory.

Determination of the Net Neutralisation Potential (NNP)

In order to examine the potential of the spoils for acid generation, the commonly used acid base accounting technique was employed [4]; this is a static test that has proven to be a dependable criterion by which overburden materials, wastes and tailings in general can be evaluated [5]. It involves the determination of the total S content (S_t, wt%) of the sample through chemical analysis and calculating the Maximum Acid Generation Potential (MAP) under the assumption that all sulphur is present as FeS_2,which generates sulphuric acid that is neutralised with calcite according to the reaction

$$FeS_2 + 15/4\ O_2 + 11/2\ H_2O + 2\ CaCO_3 \Rightarrow Fe(OH)_3 + 2\ CaSO_4{\cdot}2H_2O + 2\ CO_2$$

Following the stoichiometry of this reaction, MAP is calculated as = $31.25{\cdot}S_t$ (kg $CaCO_3$/t). The Neutralisation Potential (NP) of the sample is then determined by neutralising the sample with 0.1 M HCl solution at 90°C and expressing the result in kg $CaCO_3$/t. The Net Neutralisation Potential (NNP) is then calculated as NNP = MAP – NP and is expressed in kg of $CaCO_3$ needed to neutralise the acidity produced from 1000 kg of material.

Toxicity Characteristics Leaching Procedure

The EPA Toxicity Characteristics Leaching Procedure (TCLP) [6,7] has been used to characterise the spoils in terms of toxicity. The test involves leaching of 100 g of the sample with 0.5 N acetic acid at pH=5 for 24 hours and determining the level of dissolved toxic elements in the extract after bringing it to 2000 ml; if the levels of metals exceed the specified limits, the spoil is characterised as toxic.

Bioavailable fraction through leaching with EDTA

This technique is used to evaluate the bioavailable fraction of metals, mainly from soils. 10 g of sample is mixed in a beaker with 100 ml solution 1 N CH_3COONH_4 + 0.02M EDTA and leached under stirring for 1 hour. The fraction of metals reporting to the leachate is characterised as bioavailable.

Sequential extraction [8]

Sequential extraction techniques are conducted to evaluate the actual and potential mobilisation of metals under typical environmental conditions. With this method the metals are separated into five fractions : exchangeable, carbonate, reducible, oxidisable and residual. The first two are considered to represent the soluble or readily available fractions of the contained metals. The reducible and oxidisable fractions are the ones potentially mobilised under reducing or oxidizing conditions. Finally the residual fraction represents the inert form of metals.

One gram of sample is mixed with 8 ml of $MgCl_2$ solution, stirred for 1 hour at room temperature and centrifuged. The metals reporting to the leachate represent the exchangeable fraction. The solid residue is then added to 8 ml CH_3COONa solution, stirred for 5 hours and centrifuged for the determination of carbonate fraction. The residue is then mixed with 20 ml of $NH_2OH.HCl$ solution, stirred for 6 hours at 96°C and centrifuged for the determination of the reducible fraction. The residue is mixed with 10 ml of HNO_3:H_2O_2 solution, stirred for 5 hours at 85°C and centrifuged for the determination of the oxidisable fraction. The final residue is digested to near dryness with HF:$HClO_4$ solution for the determination of the residual fraction.

Pore Water Monitoring

Monitoring of pore water quality and level was done on a bi-monthly basis for a 6 month period. The parameters measured *in situ* included: pH, EMF, temperature, dissolved oxygen, conductivity and total suspended solids. Elemental analysis was done by AAS in the laboratory.

RESULTS AND DISCUSSION

The sulphidic tailings are contained in three main spoils, with quite different characteristics. Each spoil is also strongly inhomogeneous vertically and horizontally.

Spoil A (Kavodokanos)

This consists of flotation tailings deposited over an area of 40000 m^2 with an average height of 10 m. Total quantity is estimated at 600000 t. It is quite inhomogeneous in nature. A complete characterisation of the spoil was done and the results are presented in Table 3.

A typical wet screen analysis of a composite sample is shown in Table 4.

TABLE 3 Characteristics of Spoil A (Kavodokanos)

Quantity: 600000 t Average Density: 2.7 g cm^{-3} Average Wet Bulk Density: 1.62 g cm^{-3} Average Permeability: $4x10^{-5}$ cm s^{-1}							
Chemical analysis, wt% (total concentration)							
Fe	S	Pb	Zn	Cd (ppm)	As	Ca	Al
5-17	5-10	0.2-1	0.5-2.9	40-100	0.2-0.6	13-15	0.6-1.0
Bioavailable fraction (EDTA Leachable, ppm)				Seq. leaching (exch. + carbon., ppm)			
Pb	Zn	Cd	As	Pb	Zn	Cd	As
124	10525	45	<20	396	12526	51	<20
Pore water analysis, ppm (pH = 2.5, EMF = 520 mV)							
Fe	SO_4	Pb	Zn	Cd	Mg	Ca	
300	15500	1.0	5000	20.0	1000	500	
EPA TCLP Test: Reported solubilities, ppm							
Pb	As	Cd					
5-25	0.1-2	0.1-5					
NNP, kg $CaCO_3$/t							
Surface: -200		Lower levels: 0 to +600					
Mineralogical anal. %		FeS_2 16, FeAsS 0.7, PbS 2, $CaCO_3$ 8, $FeCO_3$ 20, Insol. 32.5					

TABLE 4 Wet screen analysis of Spoil A

Size (mm)	Weight (%)	Fe (%)	As (%)	S (%)	Zn (%)	Pb (%)	Mg (%)	Ca (%)	Insol. (%)
+0.25	39.16	13.74	0.20	8.38	0.69	1.56	0.01	3.59	45.34
-0.25+0.125	9.93	18.31	0.30	10.08	0.85	1.37	0.01	4.48	33.02
-0.125+0.088	5.49	14.83	0.20	8.17	0.69	1.08	0.01	5.98	36.76
-0.088+0.063	2.55	17.97	0.40	5.66	0.78	1.28	0.02	1.16	45.60
-0.063+0.044	2.66	17.23	0.30	5.18	0.80	1.26	0.03	1.95	46.08
-0.044	40.21	25.8	0.40	10.80	0.68	2.58	0.01	2.20	17.60
Total	100.00	19.30	0.30	9.36	0.71	1.91	0.01	3.15	32.52

A critical analysis of the above data reveals the following:

- The material is characterised as toxic according to the TCLP test because of the high solubility of Pb.
- The permeability of the material is high, therefore rain water may infiltrate into and react with the mass to produce acidity and/or dissolution of elements.
- The bioavailable (EDTA leachable) fraction of the heavy metals is extremely high; despite the fact that this is considered to be the phytotoxic fraction, some plants are growing on the spoil. The exchangeable and carbonate fractions as determined by sequential leaching tests are also extremely high.
- The top layer of the spoil exhibits negative NNP, indicating the potential of acid generation. Indeed, after raining, pools of acidic waters are forming at the lower levels of the spoil, with the following indicative analysis: pH=1.9, Pb=0.5 ppm, Zn=760 ppm, Cd=1.8 ppm, As=43 ppm.
- Pore water quality is very poor, with very high concentrations of Zn and Cd. This is mainly due to dissolution of the elements under the influence of the generated acidity.
- Because of poor pore water quality and ability to generate acidity, the spoil is classified as highly hazardous for soil, surface and underground water contamination; also hazardous because the high bioavailable fraction poses problems due to dusting and fine particle transportation by the wind.
- No remarkable differentiation in composition vs grain size is seen from Table 4.

Spoil B (Tailings dam)

This consists of flotation tailings deposited into a tailings dam constructed within the metallurgical plant area. It occupies 20000 m^2 with height between 3.5–7 m. Total quantity is estimated at 150000 t. It is quite inhomogeneous in nature. A complete characterisation of the spoil was done and the results are presented in Table 5. A typical wet screen analysis of a composite sample is shown in Table 6.

TABLE 5 Characteristics of Spoil B (Tailings dam)

Quantity: 150000 t							
Average Density: 2.7 g cm^{-3}							
Average Wet Bulk Density: 1.4 g cm^{-3}							
Average Permeability: $1.4x10^{-4}$ cm s^{-1}							
Chemical analysis, wt% (total concentration)							
Fe	S	Pb	Zn	Cd (ppm)	As	Ca	Al
3-15	2-5	1-3	0.5-5	50-200	0.1-2.5	4-16	1-4
Bioavailable fraction (EDTA Leachable, ppm)				Seq. leaching (exch. + carbon., ppm)			
Pb	Zn	Cd	As	Pb	Zn	Cd	As
302	442	3.8	<20	272	737	9.2	<20
Pore water analysis, north part, ppm (pH = 2.3, EMF = 420 mV)							
Fe	SO_4	Pb	Zn	Cd	Mg	Ca	
3200	50000	2.5	1300	6	2200	400	
Pore water analysis, south part, ppm (pH = 7, EMF = 330 mV)							
Fe	SO_4	Pb	Zn	Cd	Mg	Ca	
0	1000	0	4	0.05	300	200	
EPA TCLP Test: Reported solubilities, ppm							
Pb	As	Cd					
1-18	0	0.1-4					
NNP, kg $CaCO_3$/t							
Surface: -200		Lower levels: -100 to +300					
Mineralogical anal. %		FeS_2 9, FeAsS 0.7, PbS 0.3, $CaCO_3$ 35, $FeCO_3$ 12, Insol. 30.2					

TABLE 6 Wet Screen Analysis of Spoil B

Size (mm)	Weight (%)	Fe (%)	As (%)	S (%)	Zn (%)	Pb (%)	Mg (%)	Ca (%)	Insol. (%)
+0.25	8.39	5.62	0.10	0.70	0.32	0.16	0.07	17.27	36.38
-0.25+0.125	30.48	4.25	0.20	2.45	0.42	0.20	0.08	15.30	33.00
-0.125+0.088	15.34	12.40	0.28	5.02	0.45	0.25	0.10	13.09	31.12
-0.088+0.063	8.48	14.72	0.44	6.83	0.49	0.29	0.10	12.63	29.04
-0.063+0.044	10.46	16.68	0.68	7.30	0.51	0.42	0.10	12.26	26.96
-0.044	26.83	15.46	0.56	5.32	0.52	0.53	0.12	12.44	26.14
Total	100.00	10.81	0.37	4.34	0.46	0.32	0.10	13.81	30.19

A critical analysis of the above data reveals the following:

- The material is characterised as toxic according to the TCLP test because of the high solubility of Pb.
- The permeability of the material is high, therefore rain water may infiltrate into and react with the mass to produce acidity or dissolution of elements.
- The bioavailable (EDTA leachable) as well as the exchangeable and carbonate fractions of the heavy metals in terms of Zn and Cd exceed the Canadian standards set for agricultural land use.
- The surface layers exhibit negative NNP, indicating the potential of acid generation. However, no surface acidic waters have been observed following rainfalls.

- Pore water quality on the north part is poor, with high concentrations of Zn. This is mainly due to dissolution of the elements under the influence of the generated acidity. Quality is good at the south part.
- The spoil is classified as medium hazardous; no major risk for soil, surface and underground water contamination is seen through aquatic migration mechanisms; however, being characterised as toxic according to the TCLP test, the material poses problems due to dusting and fine particle transportation by the wind.
- No remarkable differentiation in composition vs. grain size is seen from Table 6.

Spoil D (Bodossakis Beach pyrites)

This consists of pyritic flotation tailings deposited over an area of 14000 m^2 with an average height of 3.5 m. over the beach at Thorikos bay. Total quantity is estimated at 120000 t. The results of the characterisation are presented in Tables 7 and 8.

TABLE 7 Characteristics of Spoil D (Bodossakis Beach Pyrites)

Quantity: 120000 t							
Average Density: 3.4 g cm^{-3}							
Average Wet Bulk Density: 1.756 g cm^{-3}							
Average Permeability: $6x10^{-6}$ cm s^{-1}							
Chemical analysis, wt% (total concentration)							
Fe	S	Pb	Zn	Cd (ppm)	As	Ca	Al
18-28	10-32	0.6-6	0.5-1.2	10-60	0.3-4.5	1-10	0.1-1
Bioavailable fraction (EDTA Leachable, ppm)				Seq. leaching (exch. + carbon., ppm)			
Pb	Zn	Cd	As	Pb	Zn	Cd	As
2781	386	4.5	220	3436	360	6.4	280
Pore water analysis, ppm (pH = 3-5, EMF = mV)							
Fe	SO_4	Pb	Zn	Cd	Mg	Ca	
80	1000	2-3	40	1-6	700	500	
EPA TCLP Test: Reported solubilities, ppm							
Pb	As	Cd					
2-40	0.1-10	0.1-2					
NNP, kg $CaCO_3$/t							
Surface: -1000		Lower levels: 0 to -200					
Mineralogical anal. %		FeS_2 43, FeAsS 4.5, $CaCO_3$ 3.5, Insol. 30.1					

TABLE 8 Wet Screen analysis of Spoil D

Size (mm)	Weight (%)	Fe (%)	As (%)	S (%)	Zn (%)	Pb (%)	Mg (%)	Ca (%)	Insol. (%)
+0.25	6.45	9.5	0.5	17.23	0.04	0.36	0.01	7.14	46.58
-0.25+0.125	21.73	16.24	0.4	21.88	0.03	0.25	0.01	2.10	51.20
-0.125+0.088	12.54	22.32	0.5	26.55	0.02	0.24	0.01	1.06	5.90
-0.088+0.063	8.59	26.66	0.6	29.83	0.02	0.26	0.01	0.15	35.72
-0.063+0.044	11.85	28.2	0.7	31.00	0.02	0.40	0.01	0.12	29.86
-0.044	38.84	23.92	5.2	21.93	0.14	2.20	0.01	0.86	22.30
Total	100.00	21.86	2.34	23.95	0.46	1.03	0.01	1.41	30.14

A critical analysis of the above data reveals the following:

- The material is characterised as toxic according to the TCLP test because of the high solubilities of Pb, As and Cd.
- The permeability of the material is high, therefore rain water may infiltrate into and react with the mass to produce acidity or dissolution of elements.
- The bioavailable (EDTA leachable) as well as the exchangeable and carbonate fractions in terms of Pb, Cd and As are very high.

- The whole deposit exhibits very negative NNP, indicating a very high potential of acid generation. Indeed, following a rainfall, acidic ponds are formed on the tailings with the following indicative water analysis: pH=1.9, Pb=0.7 ppm, Zn=1150 ppm, Cd=3.9 ppm, As=800 ppm.
- Pore water quality is poor, with high concentrations of Cd and Zn. This is mainly due to dissolution of the elements under the influence of the generated acidity.
- The spoil is classified as extremely hazardous because of its very high acid generation capacity, toxic character of the material, high bioavailable fractions of Pb, Cd and As and poor pore water quality; the polluted waters generated within the spoil drain into the sea but the effect on the marine environment has not been assessed.
- The −44 μm fraction is enriched in As, Zn and Pb.

SELECTION OF A REMEDIAL TECHNOLOGY

The wider area around the city of Lavrion is heavily contaminated by heavy metals; the sulphidic tailings described in the present paper are classified as hazardous and constitute an active and serious source of soil, surface and groundwater contamination. Obviously, before any effort for decontamination of the soils, action should be taken to impede, retard or arrest further pollution from the sulphidic tailings.

Remediation technologies should be selected after a detailed cost/benefit analysis and they should fulfil the following criteria :

- Protection of human health and the environment
- State acceptance
- Community acceptance
- Reduction of volume and toxicity of wastes
- Short-term effectiveness
- Long-term effectiveness and permanence
- Implementability
- Affordable cost

The methods for cleaning up hazardous waste sites have been modified since 1980 when the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) was issued. Remedial technologies for wastes and tailings include:

- excavation and removal of the waste from the site and controlled disposal at a suitably prepared landfill [9] or in the underground mining works.
- application of dry covers [10,11]. Topsoil is often applied on top of the covers and suitable vegetation grown for improved aesthetics and stability.
- application of wet covers [12], including marine disposal.
- blending of sulphidic acid-generating tailings with alkaline tailings or additives.
- chemical treatment for the formation of a thin impermeable layer on top of the tailings (hardpan).
- separation of the hazardous and toxic compounds of the spoil by beneficiation techniques and controlled disposal.

Given that Lavrion is an arid area, application of wet covers is not feasible; furthermore, marine disposal generally meets strong public opposition, although it probably is an environmentally acceptable and technically viable solution. Dry covers with or without alkaline additions and a vegetative top cover appear at the moment to be the first option. The main function of these covers is to minimize the transport of water and oxygen into the underlying tailings. The principal parameters which affect the ability of a soil cover to prevent the infiltration of oxygen and water are hydraulic conductivity and oxygen diffusion coefficient. A low diffusion coefficient is required to minimise the flux of oxygen and therefore the infiltration of acidic waters into the wastes. The covers consist of different materials such as soils, tills, sands, clays and bentonite in successive layers. The geotechnical and physical properties of the cover materials such as grain size distribution, clay content, porosity, permeability and moisture-density relationship are very important parameters for a good function. A successful dry cover should have the following characteristics:

- Minimum liquid migration through the waste
- Minimum oxygen transfer
- Low maintenance requirements
- Efficient site drainage and
- High resistance to cracking

Following the recommendation of EPA [13] the dry cover to be applied in Lavrion should consist of the following (Figure 2):

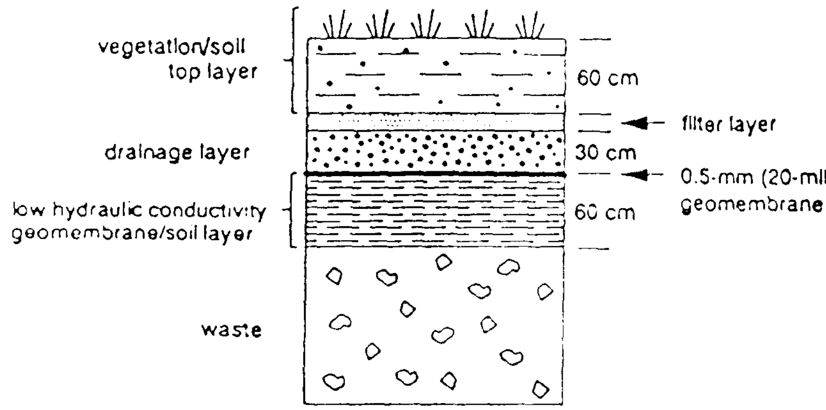

Fig.2 Schematic diagram of the proposed dry cover [13]

- On top of the tailings a barrier layer of low impermeability is placed. It consists of a low hydraulic conductivity soil (possibly mixed with bentonite). Thickness of this layer should be 60 cm and permeability $<10^{-7}$ cm·s^{-1}.
- A 0.5 mm synthetic geomembrane is placed on top of the barrier layer.
- A 30 cm thick drainage soil layer with permeability 10^{-2} cm·s^{-1} is placed on top of the geomembrane
- A 10 cm sand filter layer follows
- Finally a 60 cm vegetative soil is placed as top layer

A conceptual strategy for rehabilitation of the sulphidic tailings is: removal of spoils D (Bodossakis beach pyrites) and B (tailings dam) and transportation on top of the spoil A (Kavodokanos pyrites), probably with admixture of an alkaline additive. In this way the surface of the Kavodokanos pyrites, which is currently highly irregular, will be flattened out. On top of the flat surface, an impervious cover will be placed; the whole spoil may have to be vertically contained with the slurry trench wall technique.

A second option is transportation and controlled disposal of the spoils in the extensive underground mining works. The material may be mixed with alkaline additives, cement or other fixation additives that will ameliorate its toxicity and leachability, but also decrease its permeability and then placed underground as a slurry. The underground areas should be properly prepared so as to become impermeable or inaccessible to groundwater.

CONCLUSIONS

The sulphidic tailings in Lavrion have been characterised in terms the environmental liabilities and risks that they pose. All three major spoils were classified as toxic and hazardous in terms of the TCLP test, the bioavailable fraction of the toxic metals, the pore water quality and the acid generation capacity. A conceptual environmental rehabilitation strategy of the area must have as first priority to render these sources of pollution inactive; this may be achieved through transportation of all the spoils to Kavodokanos and applying a dry cover in association with a vegetative cover. Controlled disposal in the underground mining works is a second option.

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