Use of Alkaline Additives and a Soil Cover for Prevention of Acid Mine Drainage from Sulphidic Tailings in Lavrion

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NATO CCMS Pilot Study
Prevention and Remediation Issues
In Selected Industrial Sectors Pilot Study
Non-Ferrous Mining Sector

Baia Mare, Romania

Overview

- The Lavrion site
- Sulphidic tailings
- Rehabilitation Approach
- Laboratory Experiments
- Field Tests
- Full Scale Application
- Monitoring
- Conclusions

The Lavrion History

- Lavrion, Greece is an historical mining site
- The great era of the Athens city state was based on the exploitation of Lavrion argentiferous ores
- Mining started in 7th century BC
- Mining during 5th-4th Century BC:

  3,500 t Ag

  1,400,000 t Pb
- Modern-era mining: 1865-1980

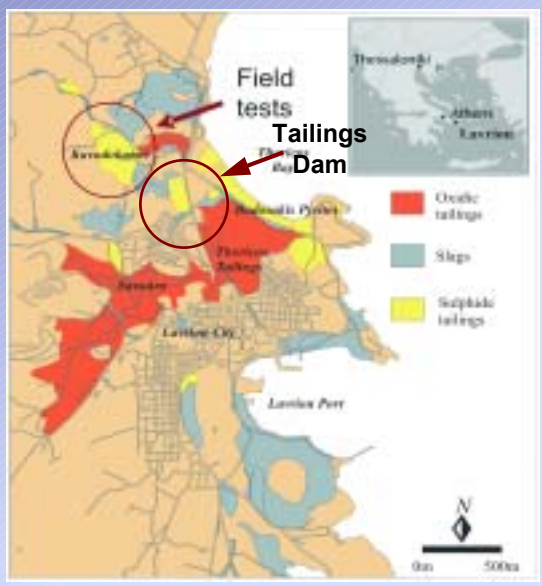
  860,000 t Pb

The Lavrion Site

- Generation of hazardous wastes:
  - ✓ Mining wastes
  - ✓ Beneficiation tailings
  - ✓ Metallurgical slags

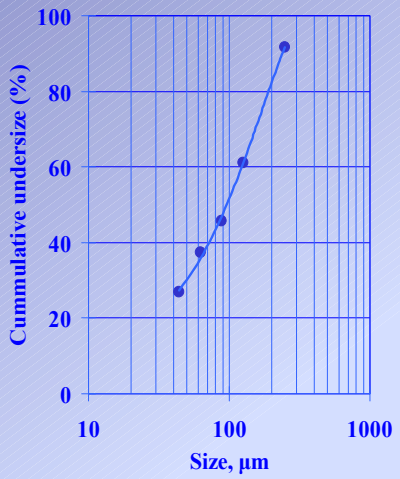
- Severe contamination of soils:
  - ✓ Pb: 800 - 23,000 mg/kg (limit 530)

The Lavrion Site



Physical Properties Tailings Dam	
Total quantity	150,000 t
Total area	25,000 m^2
Average dry bulk density	1.26 $g.cm^3$
Specific gravity	2.71 $g.cm^3$
Moisture	8 - 14.3 %
Hydraulic Conductivity, k	1.44 x 10^{-4} $cm.s^{-1}$

Sulfide tailings dam



Physical Properties Tailings Dam	
d_{50}	100 µm
Average wet bulk density	1.40 g.cm^3
Average dry bulk density	1.26 g.cm^3
Specific gravity	2.71 g.cm^3
Moisture	8 - 14.3 %
Hydraulic Conductivity, k	1.44 x 10^{-4} cm.s^{-1}

Material Description

Chemical Analysis

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

Mineralogical phases

calcite, quartz, chlorite, muscovite, epidote, pyrite, gypsum, limonite, chalcopyrite, sphalerite, arsenopyrite, baryte

Material Description

Pore Water Quality

Element	Pore water (mg/l)	Greek effluent limits (mg/l)
Pb	2.5	0.1
Zn	1,300	2
Cd (ppm)	6	0.02
As	0	0.5
Ca	400	
Mg	2,200	
Fe	3,200	
SO_4	50,000	1000
pH	2.3	6-8.5
Oxidation potential (mV)	400	
Dissolved O_2 (mg/l)	1	
Total Suspended Solids (mg/l)	2,000	40
Conductivity (mS/cm)	26	
NNP (kg $CaCO_3$/t): -250 (surface) + 310		

Risk Assessment

- Performed on the Source – Pathway – Target basis
- The main significant pollutant pathways identified for the Lavrion tailings dam were
  - ✓ Wind/water erosion
  - ✓ Direct contact
  - ✓ Seepage

Rehabilitation techniques examined

ARD control techniques		Objective of control
Treatment of sulfidic wastes	⇒	Sulfide removal or isolation
Alkaline additives (Carbonates/phosphates/silicates)	⇒	pH control, Fe^{3+} control stabilisation of sulfides
Bactericides	⇒	Control of bacterial action
Water cover	⇒	Exclusion of oxygen
Dry covers (soils and/or synthetic membranes)	⇒	Exclusion of water and oxygen

Parameters considered:

Climatic conditions in Lavrion ⇒ Low precipitation, long dry period
Tailings characteristics ⇒ Heterogeneous and oxidised

Dry covers the most suitable remediation technique

Remediation Alternatives

- **Conventional covers**

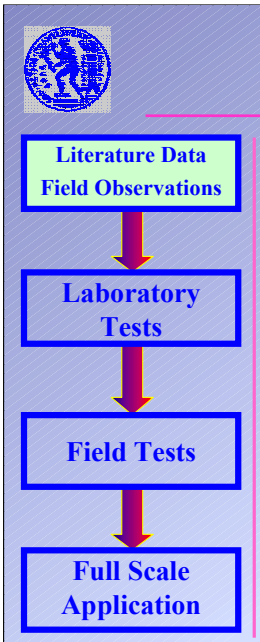
  A cover incorporating a **low hydraulic conductivity soil layer and/or synthetic liner** would limit the infiltration of rainfall waters and/or oxygen within the tailings mass, thus minimising the contaminants load to the downstream environment and inhibiting further oxidation of sulfides.

- **Geochemical barrier (hardpan)**

  Artificial formation of a low permeability geochemical barrier at the tailings surface that would act as a water transport and oxygen diffusion barrier.

  Based on previous laboratory studies, the addition of limestone to partially oxidised sulfide wastes and subsequent neutralisation of the acidity released would promote the precipitation of secondary oxidation-neutralisation products (gypsum, ferric hydroxides) thus enhancing the formation of a hardpan layer.

Methodology



- Hard Pan formation is reported worldwide
- Hard Pan is also reported at the Lavrion Site (Bodossakis Pyrites)

Laboratory tests

Literature Data
Field Observations

Laboratory Tests

Field Tests

Full Scale Application

- Lysimeter kinetic tests

- Humidity Cells

- Column Kinetic tests

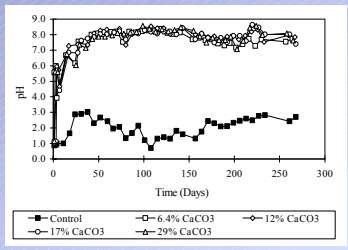
Laboratory tests

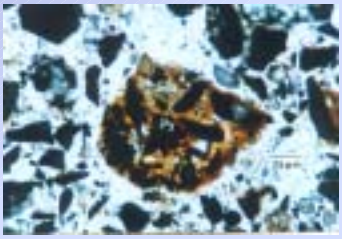
Literature Data
Field Observations

Laboratory Tests

Field Tests

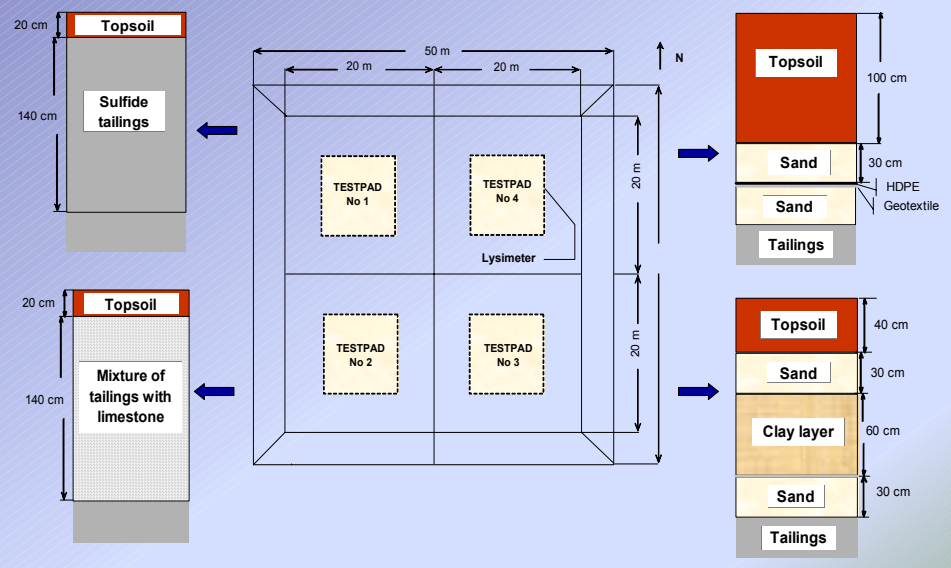
Full Scale Application





- **Limestone Addition:**
  - ✓ Neutralization of the acidity
  - ✓ Precipitation around the pyrite particles
  - ✓ Decrease of the permeability (Hard Pan formation)

Methodology - Field tests



Methodology – Field Tests

Literature Data
Field Observations

Laboratory Tests

Field Tests

Full Scale Application

- Before Construction

- After Construction

Methodology – Field tests

Literature Data
Field Observations

Laboratory Tests

Field Tests

Full Scale Application

Formation of a hardpan layer

Soil, 20 cm

Oxidised sulfide tailings, 20 cm

Hardpan layer, 50 cm thick

Full scale application

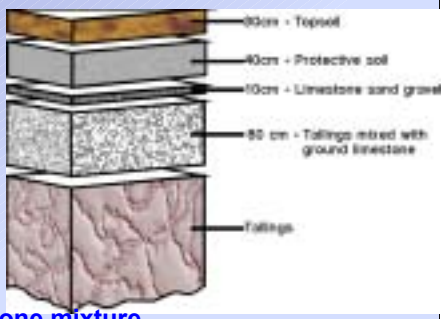
Literature Data
Field Observations

Laboratory Tests

Field Tests

Full Scale Application

Remediation Scheme



Functions:

- Tailings + Limestone mixture
  - ✓ Provide alkalinity
  - ✓ Decrease water permeability
- Limestone sand gravel – Drainage
- Protective soil – Topsoil
  - ✓ Vegetation
  - ✓ Reduce the risks associated with wind erosion and direct contact

Full scale remediation of Tailings Dam

Literature Data
Field Observations

Laboratory Tests

Field Tests

Full Scale Application

Before Construction

West

East

- East part was partially empty
- During the winter was full of rain water

Full scale remediation of Tailings Dam

Literature Data
Field Observations

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Laboratory Tests

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Field Tests

↓

Full Scale Application

1st step : Initial Leveling (transportation of tailings from the West to the East part – 1% gradient to the East)

2nd step : Placement of ground limestone

Full scale remediation of Tailings Dam

Literature Data
Field Observations

Laboratory Tests

Field Tests

Full Scale Application

3rd step : Mixing of tailings with limestone
(Agricultural – mechanical equipment)




Full scale remediation of Tailings Dam

Literature Data
Field Observations

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Laboratory Tests

↓

Field Tests

↓

Full Scale Application

3rd step : Mixing of tailings with limestone

Limestone chemical analysis and physical properties

Zn (%)	Pb (%)	Cd (ppm)	Fe (%)	Ca (%)	Mg (%)
0.01	0.02	16	0.08	35	2.53

Grain size : -0.8 mm (40% -0.4 mm)

Bulk density : 1.65 $t.m^{-3}$

- Limestone Application rate : 200 kg/t tailings
- Total limestone cost (purchase and transport) : 8.4 USD/m^3

Full scale remediation of Tailings Dam

Literature Data
Field Observations

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Laboratory Tests

↓

Field Tests

↓

Full Scale Application

4th step: Placement of limestone sand gravel (drainage layer)

5th step: Placement of protective soil and topsoil

Soil Analyses (mg/kg)

	Pb	Zn	Cd	As
Topsoil	40	81	3	25
Protective soil	45	7	3.8	72
topsoil layer limit	375	600	3	20
protective soil limit	500	800	4	25

Full scale remediation of Tailings Dam

Literature Data
Field Observations

↓

Laboratory Tests

↓

Field Tests

↓

Full Scale Application

Final View

Full scale remediation of Tailings Dam - Monitoring

Literature Data
Field Observations

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Laboratory Tests

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Field Tests

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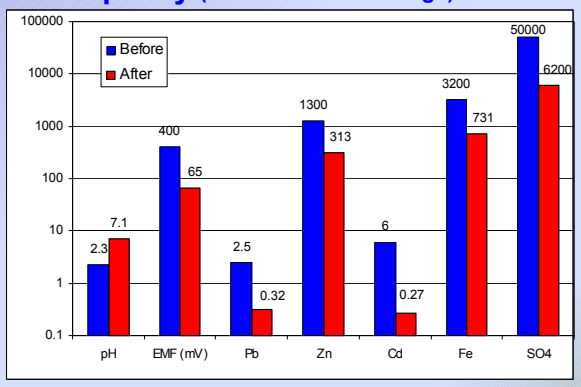
Full Scale Application

- Drillholes – piezometers were installed for pore water monitoring
- Significant improvement of the pore water quality (elements conc. In mg/l)



Full scale remediation of Tailings Dam – Cost data

Literature Data
Field Observations

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Laboratory Tests

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Field Tests

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Full Scale Application

Cost Breakdown

Cost Categories	Quantity (m^3)	Cost per Unit (USD/m^3)	Total cost (USD)
Sand	5000	8.4	42,000
Sand gravel	2500	2.5	6,250
Protective soil	7500	5.9	44,250
Topsoil	10000	7.1	71,000
Cost of personnel and machinery			171,500
Total cost			335,000
or			13.4 USD/m^2

Conclusions

- A low cost remediation scheme was applied for the Tailings Dam in Lavrion
- It involves neutralisation of the upper part of sulphidic tailings with limestone followed by a sequence of layers (drainage, protective soil and topsoil)
- The cost of the remediation was 13.4 USD per square meter.
- Monitoring results indicated that the applied scheme resulted in significant improvement of pore water quality