

Pilot scale field performance of a reclamation scheme for sulphidic waste rock

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ABSTRACT

For the environmentally safe management of the sulphidic waste rock produced from the Stratoni lead-zinc sulphide mine in Greece, the effectiveness of an alternative scheme to conventional disposal methods management, involving the segregation of the -4mm sulphide rich fraction of waste rock and its amendment with the engineered application of limestone was examined. Following successful laboratory test results, pilot field tests were carried out in order to assess the performance of the above reclamation scheme and compare it with the behaviour of the "as-it-is" waste rock, i.e. increased drainage volume with acidic pH and elevated metals concentration. Based on the results of a three-year (1,114 days) monitoring programme, it was deduced that for the "as-it-is" waste rock, the amount of infiltration corresponded to 20% of the precipitation received; the leachates collected were acidic to alkaline, i.e. pH: 3.5-7.7 and mainly contaminated with Zn, Mn and Cd. The separation of the -4mm waste rock fraction and its placement above the coarse size material, reduced the overall infiltration and improved the quality of drainage collected. Homogeneous mixing of the fine waste rock fraction with limestone was recorded to further reduce the infiltration rate and resulted in the production of alkaline drainage throughout the test period. Complete inhibition of water percolation was achieved by the successive layering of the homogeneous -4mm waste rock/limestone mixture and coarse waste rock fraction, where no leachate was collected after three years of testing. © 2004 SDU. All rights reserved.

Keywords: Reclamation; Sulphidic waste rock; Drainage; Environment

1. INTRODUCTION

The Stratoni mine, the largest mixed sulphide mining operation in Greece and part of the Cassandra Mines Complex, is situated in Chalkidiki, Northern Greece. The sulphide deposits encountered in the area are massive, stratabound, replacement bodies developed within calcite-rodochrosite marbles of the Kerdilia formation in the Servo Macedonian Massif. The hydrothermal mineralization consists of galena, sphalerite, pyrite, arsenopyrite, and chalcopyrite. The Mavres Petres and Madem Lakkos orebodies are exploited in the Stratoni mines, with the application of the cut-and-fill method. The mined ore is processed in a crushing-grinding-flotation plant to produce lead and zinc concentrates, which are exported to European smelters. The waste rock produced from Stratoni mining operations corresponds to approximately 10% of Run-Of-Mine (ROM), averaging 40,000t/year. In the past, the major part of the waste rock was used as construction material in mine roads, tailings dams, etc., whereas the remaining quantities were disposed in various locations around the mine, resulting in the formation of various active acid generating sources in the area, which adversely affected the water and soil quality. During the last decade, the waste rock has been disposed in a controlled manner at the Karakoli disposal area (Figure 1).

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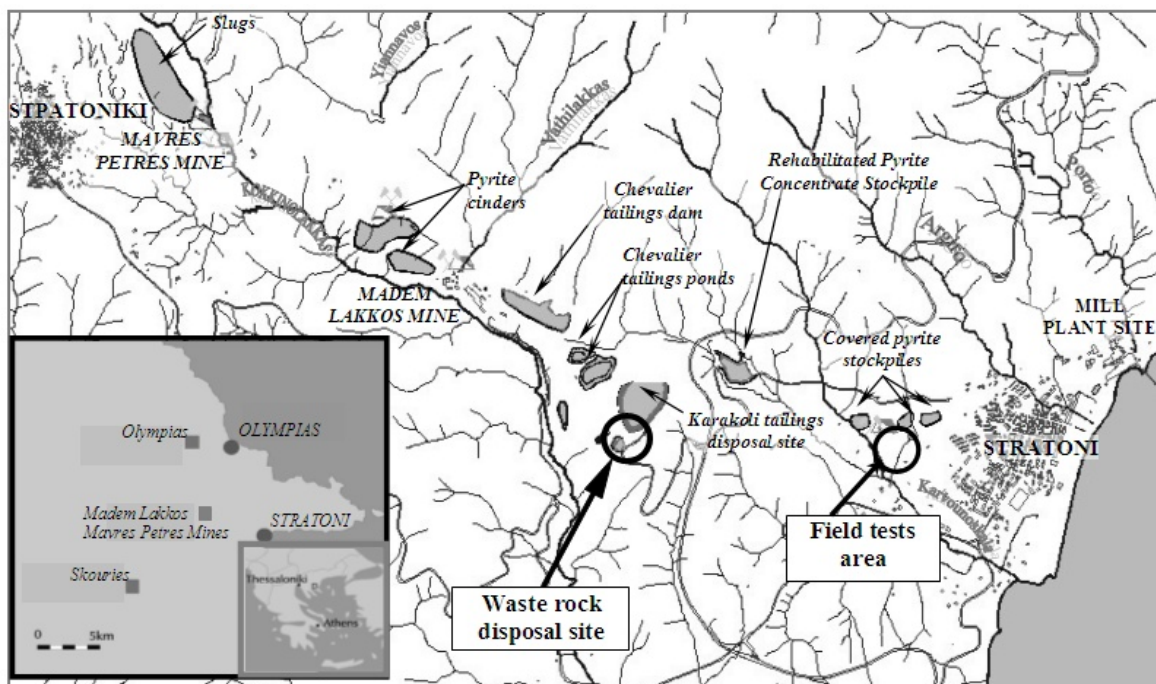


Figure 1. Waste rock disposal area at Stratoni mining facilities, Greece

The waste rock produced from the Stratoni mine is a heterogeneous material both physically and chemically. Its grain size varies from tens of centimetres (boulders) to $<63\mu\text{m}$ (silt and clay fraction), typical of the waste produced from mining activities. Moreover, the waste rock due to its varying sulphides and alkaline minerals content, such as calcite and dolomite, was classified from potentially acid generating to non-acid generating, PRAMID (1996), Klohn-Crippen (1996), TVX (1996), ROLCOSMOS (2000). Detailed chemical analyses of the different waste rock size fractions suggested that the contained sulphur is mainly distributed in the finer grain sizes. Field measurements indicated the occurrence of sulphide oxidation and subsequent production of acidic surface runoff waters at the Stratoni waste rock disposal sites i.e. pH: 3.0, contaminated with Fe, Zn, Pb, As, Cd and Mn.

Given the characteristics of Stratoni waste rock, the technique envisaged to be applied in order to control acid generation at the disposal sites during operation and after closure involves the separation of the sulphide-rich fraction and the addition of limestone, a reactive alkaline material available near the mining site. The effectiveness of limestone in preventing the production of acid drainage from sulphide mine wastes, and relative mechanisms involved has been reported in a number of recent studies, Day (1994), Morin and Hutt (1994), Rose and Daub (1994), Payant *et al.* (1995), Mylona *et al.* (1996, 2000), Lapakko *et al.* (1997). However, the overall effectiveness of this technique when applied to sulphide waste rock piles, is inhibited from factors such as inadequate mixing, lack of contact between sulphides and alkaline minerals, preferential water flow paths through acid generating layers, and reduced reactivity of coarse sized neutralising mineral grains, Morin and Hutt (2000), Lapakko *et al.* (2000). Separation of the sulphide-rich fraction of the waste rock, should it be feasible, and subsequent addition/mixing of limestone, would result in the formation of homogeneous mixtures of the acid generating waste rock with the alkaline material. In these solid mixtures, water flow is more uniform and controlled and thus the overall effectiveness of the technique in preventing acid generation is greatly enhanced.

For the design of the above reclamation technique, an extensive laboratory testwork was performed on representative waste rock samples collected from the Karakoli stockpile. The experimental testwork included static and kinetic tests, in accordance with the standard methodology used to predict and prevent acid drainage in a sulphide mine, Environment Australia (1997), Price *et al.* (1997). The laboratory test results were used to determine the sulphide-rich waste rock fraction and the establishment of the required alkaline addition rates to ensure the long term control of acid generation.

To assess the effectiveness of this mitigation technique under actual conditions, field trial tests were performed from October 1999 to October 2002, and the results obtained after a monitoring period of three years are presented in this study.

2. DESCRIPTION OF FIELD TESTS

2.1. Design and construction of field tests

Following the successful laboratory test results, the design of the field scale tests was based on the following principles:

- Separation of the -4mm waste rock size fraction that would result in a) segregation of sulphides and b) reduction of permeability, increasing thus the efficiency of acidity neutralization by dissolution of alkaline minerals contained or added in the material.
- Homogeneous mixing of the -4mm size fraction with limestone to increase the Neutralisation Potential to Acid Potential ratio value to $\text{NPR} \geq 1$, and inhibit thus acid generation.
- Placement of the amended -4mm waste rock fraction above the $+4\text{mm}$ material, preventing thus the contact of less reactive coarse material with acidic leachates and further reduction of acid generation and metals solubilisation.

The field trial testpads covering a total area of 900m^2 were constructed at a plateau area, 1.2km east from the Karakoli waste rock stockpile (Figure 1). Preparation workings included clearing, grading and compaction of the underlying soils. Then, the area was subdivided into equal quadrants, for the construction of four different testpads. A lysimeter was constructed beneath the centre of each testpad quadrant (Figure 2). The lysimeter consisted of a PVC liner, 2mm thick, placed within a depression, 5.5m wide and 6.0m long, excavated into the testpad foundations. A non-woven geotextile was placed on the compacted excavation surface to provide protection for the PVC liner. The lysimeter was backfilled with clean silica sand, having a grain size finer than 3mm . For the collection of pore water, a PVC pipe network was installed at the bottom of each lysimeter, which was draining to a sample collection vessel installed at a distance of 20m .

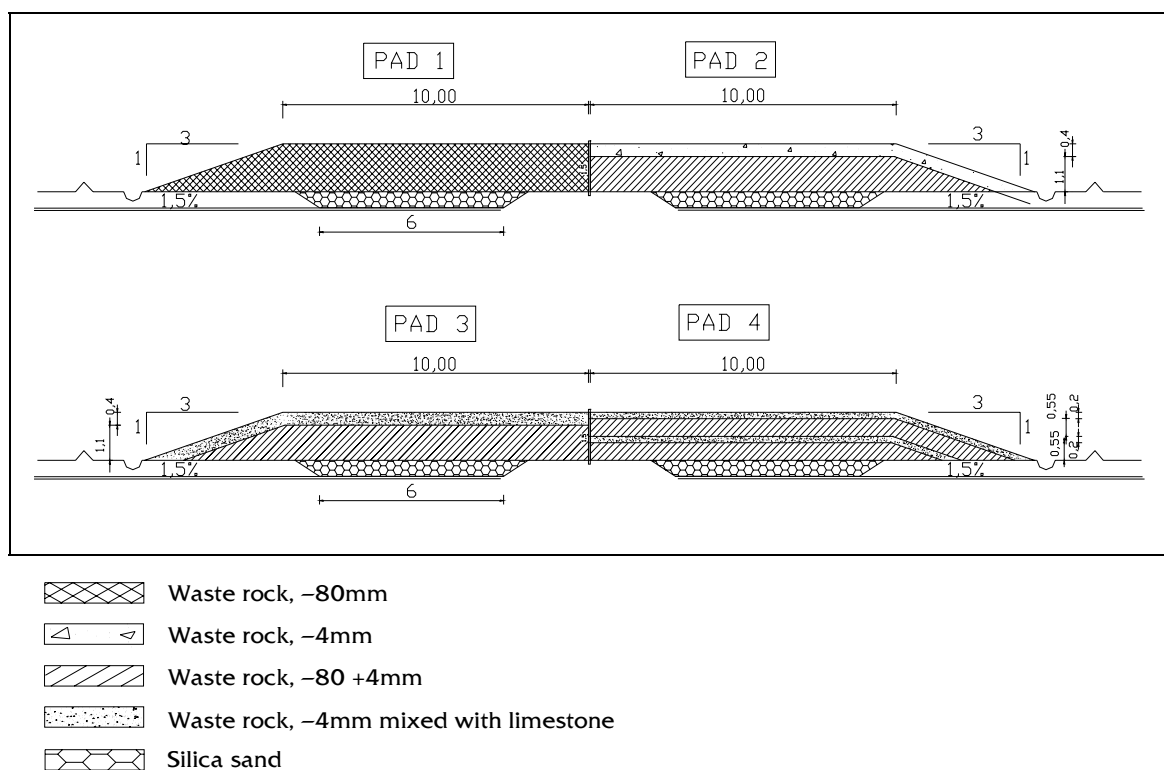


Figure 2. Cross-section of field testpads (dimensions in meters)

Following the installation of the lysimeters, four (4) testpads, isolated from each other by a 2mm thick HDPE liner were constructed, see Figure 2, as follows:

Pad No 1: Control pad, waste rock -80mm

Pad No 2: Control pad, -4mm waste rock size fraction placed above $+4\text{mm}$ fraction

Pad No 3: Homogeneous mixture of –4mm size fraction with 14 weight per cent (14% w/w) limestone placed as a single layer above +4mm fraction. Based on the laboratory kinetic test results, addition of this amount of limestone to the waste rock would inhibit acid generation even under acidic conditions

Pad No 4: Successive layers of +4mm and limestone amended –4mm waste rock size fractions

The waste rock material used to construct the testpads was collected from the Karakoli stockpile. The material was placed as level, uniform layers with a thickness of 300mm. Each layer was compacted with a drum compactor. Limestone material with particle size finer than 4mm, supplied by a local quarry located 20km from Stratoni, was used as the alkaline additive. The alkaline material was initially placed over the entire testpad quadrant. Then, the –4mm waste rock size fraction was mixed with the limestone using an agricultural rotovator. The final surface of each testpad was graded at 1% slope from the centre of the pad to the margins in order to prevent ponding of surface water. The monitoring instrumentation installed at the testpads is given in Table 1.

Table 1
 Monitoring instrumentation of the waste rock field testpads at Stratoni

a/a	Parameter	Installation/Instrument	Frequency of monitoring
1	Volume and quality of drainage	Lysimeter/Collection vessels (600L)	Twice a week
2	Temperature, moisture	Nine (9) combined moisture / temperature sensors of ELE Int. Manuf. Co. installed at the different layers of the testpads	Twice a week
3	Irrigation	Sprinkler system installed in the centre of the testpad area, water supply system	Watering rate: 0.35m ³ twice a week during the 1 st year of operation
4	Precipitation	Automated meteorological station, Stratoni mine area, Rain gauge installed at the testpads area	Continuous Twice a week

To assess the performance of the rehabilitation scheme examined, the volume and quality of the drainage produced from the testpads, was continuously recorded. Furthermore, a total of nine sensors were placed to monitor water content and temperature as function of depth in the testpads, parameters strongly related with the pyrite oxidation and subsequent acid generation processes. The sensors employed consist of two stainless steel plates separated by fibreglass binding, which provides a coupling that varies with soil moisture content. The temperature and resistance readings from the installed sensors were taken with a portable meter, having a resistance range of 0–2.0M Ω (10⁶Ohm) and a temperature range of –10 to 44°C.

To accelerate the hydrological and geochemical processes the testpads were irrigated twice a week, particularly during the first year of monitoring. A rain gauge was installed to record the rainfall for the testing period. For the calculation of a water balance for each pad, meteorological data were also obtained from the meteorological station installed at the Chevalier area, i.e. 2.5km from the testpads, where rainfall, temperature and evaporation are automatically recorded.

2.2. Characterization of materials

Representative samples of the –80+4mm and –4mm waste rock size fractions as well as limestone material used in the field tests were collected during testpad construction.

Based on the ABA test results, Sobek *et al.* (1978), Adam *et al.* (1997) for the different waste rock fractions and the waste rock–limestone mixtures, the Net Neutralization Potential (NNP) of the composite material placed in each testpad is given in Table 2.

Table 2
 Total NNP values of each testpad material

Layer	Pad No 1	Pad No 2	Pad No 3	Pad No 4
	NNP (kg CaCO ₃ /t)			
Waste rock (–80mm)	–17.9	–	–	–
Waste rock (–80+4mm)	–	+65.3	+65.3	+65.3
Waste rock (–4mm)	–	–204.1	–	–
Mixture of waste rock (–4mm) with 14% w/w limestone	–	–	–56.2	–56.2
Total NNP value	–17.9	–17.9	+34.8	+34.8

The -80mm waste rock layer placed as control in testpad No 1 and the composite material comprising of layers -4mm and -80+4mm in testpad No 2, present a negative NNP value, equal to -17.9kg CaCO₃/t (NPR<1.0) indicating that the material is potentially acid generating. The addition and the homogeneous mixing of limestone with the -4mm waste rock fraction placed a) in testpad No 3, as a separate cover layer above the -80+4mm fraction and b) in testpad No 4 as alternative layers in between the -80+4mm material increased the NNP value to 34.8kg CaCO₃/t (NPR: 1.2), minimising the potential of material to generate any acidity.

3. RESULTS AND DISCUSSION

3.1. Drainage volume of testpads

The total precipitation and the drainage volumes collected from the testpads after a monitoring period of 1,114 days (10/99-10/02) are summarized in Table 3.

Table 3
 Precipitation and volume of drainage for the field testpads

Parameter	Pad No 1	Pad No 2	Pad No 3	Pad No 4
Rainfall ¹ (m ³)	58.30	58.30	58.30	58.30
Irrigation (m ³)	4.37	7.32	7.20	12.82
Total precipitation (m ³)	62.67	65.62	65.50	71.12
Drainage (m ³)	12.72	7.04	1.57	-
Drainage (% of precipitation)	20.30	10.70	2.40	-

¹The figure corresponds to 1767mm of rain

The amount of rainfall recorded during the monitoring period corresponded to 590mm/year. The irrigation applied resulted in the increase of the precipitation received by the testpads to 633-718mm/year, similar or higher to the average yearly amount of rainfall experienced in the study area, i.e. 650mm/year (Arnea meteorological station, 1978-present, TVX Hellas internal reports).

During the monitoring period, the volume of drainage collected from the control testpad No 1 represented 20.3% of the total amount of precipitation (rainfall plus irrigation), received. The placement of a fine fraction cover layer on top of the coarse fraction in testpad No 2, reduced the amount of infiltrated water, as evidenced by the smaller drainage volume collected during the test period, 10.7% of the total precipitation. This reduction may be attributed to the capillary barrier effect, observed, when a layer of fine grained material is placed over coarse material. Due to this phenomenon, infiltrating water is retained in the fine layer by capillary forces and does not drain into the coarse fraction until the fine material near the interface reaches saturation, Khire *et al.* (1996). The amount of leachates collected from testpad No 3, with limestone-amended fine layer cover, was even lower and represented 2.4% of the total precipitation. The reduction in the amount of water percolated through testpad No 3, may be attributed to changes in the physical- and geo-chemical characteristics of the fine size layer induced by limestone addition, e.g. filling of the pores by the precipitation of oxidation-neutralisation products such as gypsum and ferric oxy-hydroxides. This phenomenon, combined with capillary barrier, was more evident, in testpad No 4 comprising of successive layers of limestone amended -4mm size waste rock and coarse -80+4mm size material. In testpad No 4, no leachates were collected after 1,114 days of testing.

3.2. Moisture and temperature within the test pads

The range of resistance/temperature measurements recorded from the sensors inserted at various testpads depths is given in Table 4. It is noted, that measured resistance values are inversely related with conductivity and solids moisture content.

Table 4
 Range of temperature and resistance measurements in the testpads

Testpad	Description	Depth (cm)	T (°C)		R (kΩ)	
			Min.	Max.	Min.	Max.
No 1	Waste rock -80mm	75	0.0	33.0	0.05	2.2
No 2	Waste rock -4mm placed above +4mm size material	25	1.0	34.0	0.10	100.0
		75	2.0	32.0	0.06	15.0
No 3	Waste rock -4mm mixed with limestone and placed above +4mm size material	25	3.0	33.0	0.02	90.0
		75	5.0	32.0	0.03	8.0

continued (Table 4)

Testpad	Description	Depth (cm)	T (°C)		R (kΩ)	
			Min.	Max.	Min.	Max.
No 4	Successive layers of -4mm waste rock fraction mixed with limestone and +4mm size material	15	1.0	33.0	0.05	110.8
		50	0.1	32.0	0.05	1.8
		85	0.0	32.0	0.10	2.0
		100	2.0	31.0	0.10	2.5

T_{air} : 2–35°C

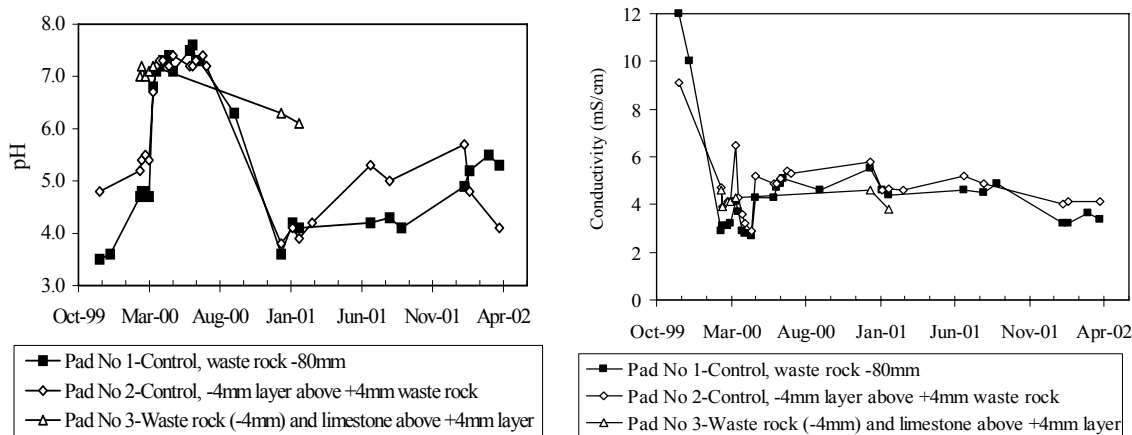
In the control testpad No 1, the temperature at the 75cm depth ranged from 0°C in the winter months to 33°C in summer, 7° higher to 8° lower respectively as compared to air temperature. In testpad No 2, the temperature at the depth of 25cm ranged from 1 to 34°C, being 5° to 10° lower as compared to air temperature. In testpad No 2, at greater depth, i.e. 75cm, the temperature was slightly higher (winter) or lower (summer) as compared to the values measured at the surface layers. Similar observations were made for the testpads No 3 and No 4. Temperature recordings for this test period were seen to more closely reflect surface temperatures and did not indicate the occurrence of any significant heating within the waste rock material as a result of pyrite oxidation. In agreement with the above, previous studies, Harries and Ritchie (1981), have indicated that diurnal air temperature changes have no significant effect at depths greater than 0.5m, whereas weakly and monthly weather pattern changes could affect the temperature down to about 6m of the waste rock dump.

The resistance values measured at the surface layer of the testpads No 2, 3 and 4, involving the fine -4mm waste rock layer with or without limestone addition ranged from ≤0.1kΩ in the wet period to 100kΩ in the summer period, indicating a strong seasonal variation of the moisture content. At greater depth, where the +4mm waste rock fraction was placed, a narrower distribution of the resistance values was recorded.

All but one resistance values measured in the lower coarse layer of testpad No 4 were above 0.18kΩ throughout the monitoring period as compared to values of <0.1kΩ, recorded at similar depths of testpads No 1, 2 and 3. The higher resistance values, i.e., the lower conductivity values at a specific depth of testpad No 4, documents the lower moisture content of the waste rock material at that depth, due to the reduced amount of infiltrated water.

3.3. Leachates quality

The temporal variation of pH and conductivity of the leachates collected from the test pads are shown in Figure 3.



(a) (b)
 Figure 3. Temporal variation of pH and conductivity in the testpads leachates

The leachates initially collected from testpad No 1 (-80mm waste rock) were acidic (pH: 3.5) and had a conductivity value of 12mS/cm, suggesting the dissolution of pre-existing oxidation products. Less acidic pH was observed in the leachate of testpad No 2 constructed from layers of fine and coarse waste rock, attributed to the lower permeability of the fine material and thus the higher residence time allowed for the infiltrating water to react with the alkalinity contained in the waste rock.

After 150 days of operation, the leachate pH values from testpads No 1 and No 2 coincided, drifting to alkaline levels and suggesting that during that period the kinetics of neutralization reactions exceeded the acid generation ones. This alkalinity can be also attributed to the creation of selective pathways for the infiltrating waters. The alkaline leachates continued for almost one year and became again acidic following a record-high flood event (1/650 years return period) in October 2000 (day 380). During this flood event, excessive moisture within the testpads triggered the oxidation of the pyrites contained in the waste rock. During the third year of monitoring, less acidic leachates were collected from the testpad, i.e. pH: 4.3 – 5.3, suggesting that dissolution of the carbonates contained in the waste rock resulted in the partial neutralisation of the acidity produced.

From testpad No 3, constructed with material with a positive NNP value, see Table 2, leachate appeared for the first time after 124 days of testing, and had alkaline pH. The pH of leachates was close to neutral, even under the adverse conditions occurred after the flood event in October 2000.

The leachate quality recorded from the testpads is summarized in Table 5. The temporal variation of Fe_{total} sulphates and dissolved zinc and manganese in the leachates are shown in Figure 4.

Table 5
 Drainage quality of the waste rock testpads

Testpad /Parameter	Description	Fe _{total}	Cd	Mn	Zn mg/L	Pb	As	SO ₄
Irrigation water	Quality of the water used for irrigation	<0.1	<0.002	<0.05	0.11	0.018	<0.045	–
No 1	Control, waste rock –80mm	0.2– 124.1	0.17– 1.27	6.1– 527.0	42.0– 308.0	0.009– 0.049	<0.045	2,428– 17,772
No 2	Control, waste rock fraction –4mm above +4mm size material	0.1– 18.6	0.12– 1.05	1.4– 774.0	5.1– 153.0	0.008– 0.158	<0.045	2,970– 11,667
No 3	Waste rock fraction –4mm mixed with limestone above the +4mm size material	0.2– 2.2	0.04– 0.35	2.3– 16.9	6.7– 143.0	<0.02	<0.045	1,948– 3,288
Limits ¹	Existing limits for effluent discharge	15.0	0.02	2.0	2.0	0.1	0.5	–

¹ Limits for industrial effluent discharge in the natural receivers of Chalkidiki Prefecture, Government Gazette 573, vol. B, 24/9/85

The trend of metals and sulphate concentration in drainage for testpads No 1 and No 2 followed closely the temporal variation of pH, i.e. elevated levels at the first days of operation, gradually reduced within the first year (especially for manganese) and increased again after the flood event of October 2000 (day 380). The separation of the –4mm waste rock fraction and its placement as a lower permeability barrier above the coarse size material (testpad No 2) resulted in reduced leachate volumes and lower dissolved metals levels as compared to testpad No 1. Zinc, manganese and cadmium concentrations, however exceeded the environmental limits set for industrial effluent discharge in the Chalkidiki Prefecture, limits that coincide with irrigation waters quality.

Homogenous blending of limestone to the –4mm waste rock fraction (testpad No 3), further improved the drainage quality. Given the circumneutral pH of leachates, total iron levels remained well below the environmental limits throughout the test (Table 5), whereas for Zn, Mn and Cd, presenting increased solubility even under alkaline conditions, the reduction in dissolution was not significant. However, given the significantly lower volume of leachates produced from test pad No 3, i.e. 48mm (Table 6), as compared to the control testpad (385mm), corresponding to a 88% reduction, a dramatic decrease, ranging from 94% to nearly 100% in the cumulative amount of dissolved metals and sulphate was achieved, as it is seen in Table 6.

No leachates were collected after 1,114 days of testing from testpad No 4, including successive layers of limestone amended –4mm waste rock and coarse +4mm size waste rock material. Zero leachate collection clearly indicates the low permeability of limestone amended cover, and the effectiveness of capillary barriers in inhibiting the infiltration of rainfall waters.

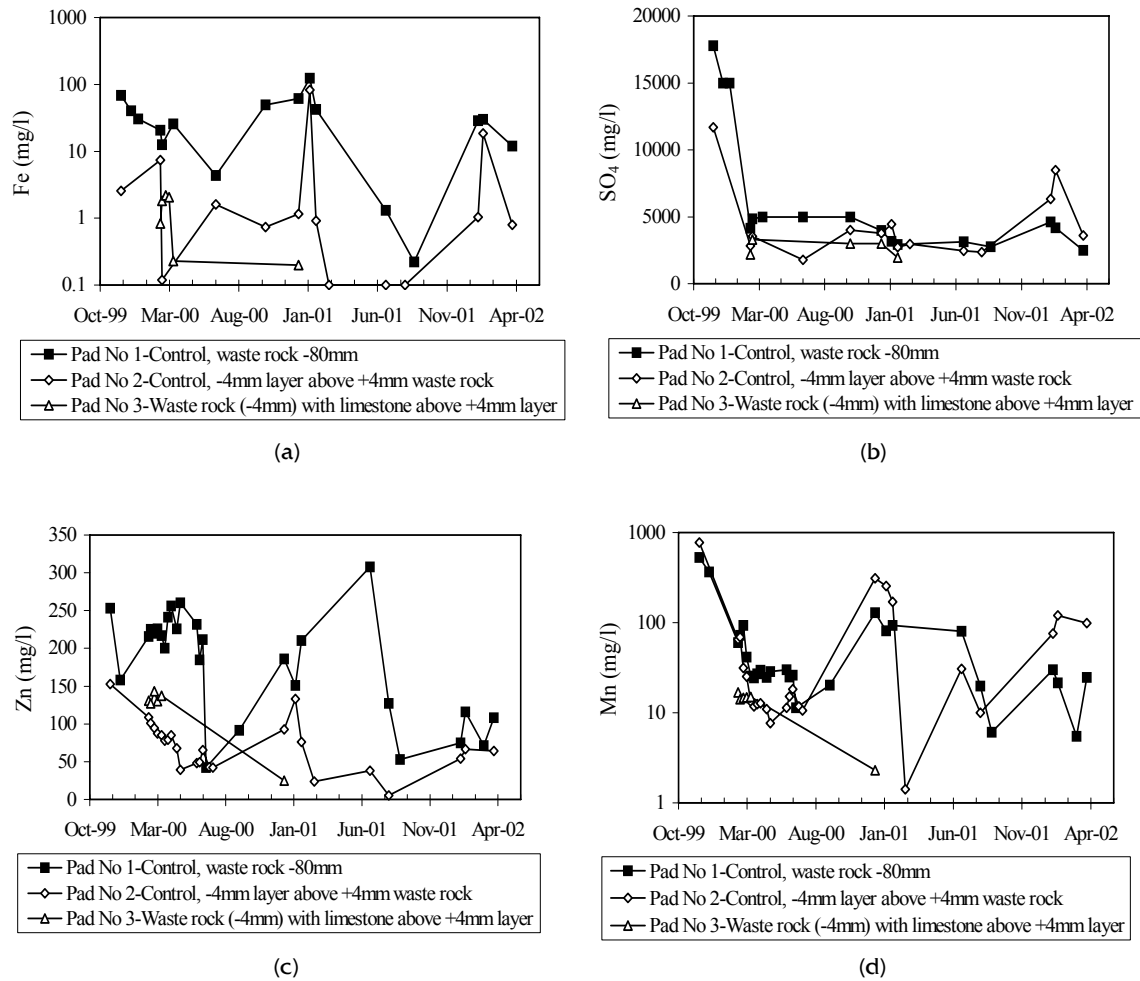


Figure 4. Temporal variation of (a) Fe, (b) SO₄, (c) Zn and (d) Mn concentrations in the testpads leachates

Table 6
 Cumulative amount of metals and sulphate dissolved from the field testpads

Testpad	Description	Drainage (mm)	Cd	Cu	Fe	Mn	Zn	SO ₄
			Amount dissolved (g/m ³ of disposed material)					
No 1	Control, waste rock -80mm	385	0.17	0.37	9.3	30.5	42.5	1583
No 2	Waste rock fraction -4mm above +4mm size material	213	0.07	0.16	0.9	19.9	10.8	652
% reduction (comparison pad No 2 with pad No 1)		44.7	61.4	55.5	90.2	34.8	74.6	58.8
No 3	Waste rock fraction -4mm mixed with limestone above +4mm size material	48	0.008	0.00	0.03	0.3	2.6	82
% reduction (comparison pad No 3 with pad No 1)		87.7	95.4	99.9	99.6	99.0	93.8	94.8

4. CONCLUSIONS

Based on the field scale tests conducted over a period of 1,114 days, the conclusions drawn regarding the effectiveness of the waste rock rehabilitation scheme examined are the following:
 The Stratoni waste rock with a grain size of -80mm (testpad No 1) tested in field scale had a Net Neutralization Potential of -17.9kg CaCO₃/t and was classified as potentially acid generating. During the monitoring period, the volume of leachate produced from the control test pad with no further amendment,

corresponded to 20% of the precipitation received. The leachates collected had pH ranging from acidic to alkaline, i.e. pH: 3.5–7.6, indicative of the occurrence of acid generation and neutralisation reactions, as well as preferential pathways of water flow. Zinc, manganese and cadmium were the major contaminants encountered in the waste rock drainage, consistently exceeding the regulated limits for industrial effluents discharge.

The separation of the –4mm waste rock fraction and its placement as a lower permeability cover layer above the coarse size material (testpad No 2), reduced in half the volume of drainage collected. The quality of the drainage was also improved; however, zinc, manganese and cadmium concentrations remained above the environmental limits.

Homogeneous blending of the –4mm waste rock fraction with 14 weight per cent limestone and its placement above the coarse material (testpad No 3) reduced further the volume of drainage produced to only 2.4% of precipitation. The addition of limestone increased the Net Neutralization Potential of the composite material to positive values, i.e. 34.8kg CaCO₃/t and the drainage produced from the test pad remained neutral to alkaline throughout the test period.

The placement of successive layers of homogeneously mixed –4mm waste rock fraction with limestone and coarse waste rock fraction (testpad No 4) proved to be the most effective configuration in terms of preventing water infiltration. In the specific testpad, no drainage was yet reported after 1,114 days of monitoring.

During the current period, the pilot scale application is still in progress to monitor the long-term performance of the examined rehabilitation scheme in preventing acid generation from Stratonis sulphidic waste rock piles, during operation and in the post closure period. The application of technique to a full scale involves many engineering aspects and a technical and economical study should be performed. For the technique to be interesting, the unit cost should be comparable to other methods of acid rock drainage control. Based on the cost data of the testpads construction, the separation of the –4mm waste rock fraction and its homogeneous mixing with limestone would increase the cost of the disposal workings by 2€/m², whereas the cost of conventional low permeability covers applied for the rehabilitation of sulphidic wastes currently amounts to 5–6€/m².

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