Vadose zone monitoring of soil covers for acid generating waste rock at the Ronneburg uranium mining site

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Abstract
The rehabilitation of WISMUT's former Ronneburg uranium mining site involves backfilling of waste rock to the Lichtenberg open pit. The relocation project comprises about 110 million m3 of sulphide-bearing and ARD-generating waste rock which makes it the most important and most cost-intensive single surface restoration project conducted by WISMUT GmbH at the Ronneburg site. The backfilled waste rock has to be covered on an area of about 220 ha to control water infiltration and gas diffusion. Design planning for the final cover placement which is to begin in 2004 had to be based on a comprehensive cost-benefit analysis as well on field tests of alternative cover options which are in compliance with legal requirements. An intensive testing program concerning the vadose zone of soil covers has therefore been started in 2000. To test soil cover designs, WISMUT built three test plots with different cover constructions and an additional reference plot without any cover on top of the waste rock. Each test plot measures 50 x 60 m. Soil water content and soil suction are monitored within and below the cover. Surface runoff, interflow above the sealing layer and infiltration into the waste rock are measured with large-scale lysimeters. Additional meteorological monitoring is included. Pore water can be sampled with suction cups. Boreholes and additional lances were installed to monitor the oxygen flux through the cover. The paper presents an overview of the test area designs, including geotechnical aspects, and the results of the vadose zone measurements since summer 2000. Additional data will be presented from the oxygen measurements and concluding remarks about the cover design of the waste rock at the Ronneburg site will be given.

1. Introduction

Relocation of about 110 million m^3 of sulphide-bearing waste rock into the Lichtenberg open pit mine is the most important and cost-intensive single surface restoration project conducted by WISMUT GmbH at the former Ronneburg uranium mining site. The approach used has been extensively described elsewhere (Jakubick et al. 1997, Hockley et al. 1997, Jahn et al. 2002, Paul 2003).
Following relocation of the Gessenhalde waste pile, mine wastes from the Absetzerhalde (begin in 1995) and the Nordhalde (begin in 1998) dumps are currently placed into different zones (A, B, and C) of the open pit depending on the materials' acid generating potential. Under that scheme, waste material having the highest acid generation potential is to be placed in the deepest zone of the pit below the anticipated flood level within the anoxic zone A. Material with low acid generating potential is to be placed in zone B above the flood level (zone of reduced O_2) while the near surface and therefore relatively oxygen-rich zone C (thickness approx. 10 m) is to be filled with acid consuming waste rock. Placement is in lifts of 1.2 m thickness, with granulated anhydrous lime being added to the material placed in Zone A. The elevated degree of compaction will prevent to a large extent groundwater and gas flow through these wastes (average permeability 10^{-6} m/s to 10^{-8} m/s).
Following completion of the backfill that will be up to 60 m above the initial ground level, a dry cover will be placed on top of the backfilled mine wastes. The area to be covered amounts to about 220 ha. Design planning for the final cover placement which is to begin in 2004 had to be based on a comprehensive cost-benefit analysis as well on field tests of alternative cover options which are in compliance with legal requirements. An intensive testing program concerning the vadose zone of soil covers had therefore been started in 2000. First

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[1] This paper is dedicated to our colleague Bernd Eschrich, who died in October 2002

results of these test works are reported in this paper.

2. Methods

To test the performance of different cover designs under field conditions, four test plots were constructed during spring 2000 on an already contoured area of the Lichtenberg open pit backfill. The test plots have surfaces of 50 x 60 metres each, the average slope inclination is 10 percent.

Three different soil covers (test plots 1 to 3) were constructed using local soil material. Test plot 4 is a reference plot without any soil cover. The lowermost layer of all the cover profiles consists of 0,6 m of so called ZAN-material, which is old cover material of the relocated Absetzerhalde and Nordhalde waste rock dumps. It was separated during the relocation process and is planned to be reused for the final cover construction of the backfilled Lichtenberg open pit.

The vertical profiles of the plots are (Fig.1):

(1) Test plot 1: The ZAN-material (0,6 m, further details in Hoepfner et al 2001) is overlain by a 0.4 m thick low permeable sealing layer, built of a mixture of local glacial till and loess loam and a storage layer (thickness 1.5 m, mixture of loess loam and sand).

(2) Test plot 2 is build only with the ZAN-material (thickness 1 metre) above the waste rock.

(3) Test plot 3 has a 1 m-storage layer of local loess loam on top of the 0.6-m-ZAN-material.

All the test plots were instrumented with lysimeters and nests of vadose zone instruments (Fig. 2).

To measure the percolation into the waste rock, lysimeters with an area of 50 m^2 are located in the waste rock material 0.6 metre below the cover. Surface runoff and interflow above the sealing layer, on top of the ZAN-Layer and above the waste rock are measured for the entire field. The measuring devices are tipping buckets and flumes. Suspended sediment is collected in runoff traps

Field-testing of the vadose zone includes soil water content, soil suction and temperature. Water content is measured using time domain reflectometry probes. Soil suction is detected with tensiometers. To detect soil suction up to the wilting point, so-called equitensiometers are used. Pore water can be sampled with suction cups.

To monitor the oxygen flux through the cover, at the centre of each of the test plots a borehole was instrumented with temperature probes and sampling ports. The boreholes reach down into the waste rock to depths of 50 to 60 m. Additionally gas lances were installed in the soil cover and the upper part of the waste rock for air sampling in shallow depths. The oxygen measurements in the soil air are carried out using a portable field device, controls were performed in the laboratory.

A meteorological monitoring station is located in the testing area, to measure all relevant meteorological parameters such as temperature, humidity and solar radiation. The precipitation is measured with two rain gauges, one in a surface pit and one at one metre height.

All hydrological data are stored in data loggers. The remote loggers are connected via modem (GSM) with the WISMUT database.

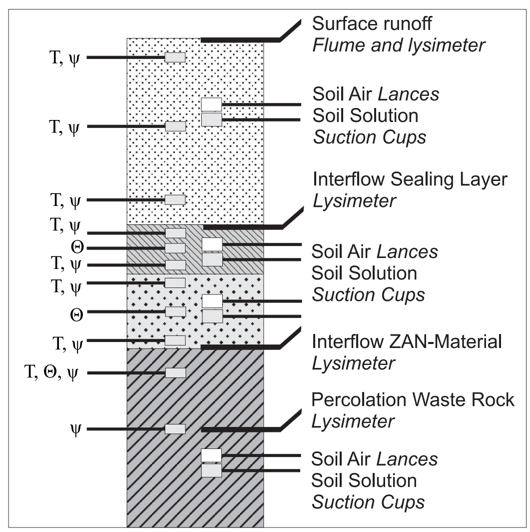

Fig. 2: Schematics of the instrumentation of the vadose zone of test plot 1 (water content θ, soil suction ψ and temperature T)

3. Results

Monitoring of the vadose zone of the soil covers and the waste rock yields important results for the assessment of the cover effectiveness. The results are used to validate the conceptual design of the cover types, to test the hydrological field performance and to provide the essential input data for calculating the oxygen flux into the waste rock. Additionally, the data of the field program are used to calibrate water balance models such as HELP and HYDRUS-2D.

3.1 Hydrology

As expected, the three cover designs show significant differences in their water balances and especially in their percolation rates. The percolation rate of test plot 1 is significantly smaller than that of the test plots 2 and 3. Nevertheless during the winter of 2000/2001 all test plots showed higher percolation rates which were higher than originally predicted by hydrological models (10 % for test plot 1, 15 % for test plot 3, and 20 % for test plot 2). As a reason for that behaviour it is believed that there was an inflow from the upstream area into the lysimeters. As a consequence in 2001 the lysimeter areas of all the test plots have been separated by ditches with HDPE membranes. Because of these disturbances of the measured water balance, no final percolation rate or water balance can be reported here.

Two examples of the hydrological results of the vadose zone monitoring are shown in Fig. 3 and 4.

The high resolution data recording with tipping buckets gives an impression of the dynamics of lateral and vertical water flow through the soil covers. In autumn, after the matrix has reached saturation, distinct rain events cause single peaks of drainage with a forerunning interflow and a slower vertical percolation into the waste rock. The fast response of the drainage gives some indication, that part of the water flow is preferentially oriented towards macropores. This is supported by measurements of the hydraulic conductivity of the soil surface, which shows an increase up to 1 x 10^{-4} m/s for the two years old cover (Hoepfner et al 2002).

Monitoring of the sealing layer from test plot 1 shows a distinct seasonal variation of the water content and tension in that material because of the upward hydraulic gradients in the storage layer in summer. This effect depends on the capillary conductivity of the storage and sealing layers. With higher evaporation and transpiration rates at the upper boundary of the cover system in the future this seasonal drying will be increasing low.

It is not clear today, if the tension will cause shrinkage cracks as it was documented from the waste disposal site at Hamburg-Georgswerder (Melchior and Miehlich 1994) which would result in a significant increase of the hydraulic conductivity of the sealing layer.

3.2 Gas flux

Oxygenation of the backfilled open pit is both by the aquatic pathway (dissolved oxygen) as well as by the atmospheric pathway (gas diffusion and/or gas transport processes due to atmospheric pressure variations, known as "barometric pumping").

Construction of a cover system on top of the contoured surface of the Lichtenberg open pit will minimise both infiltration of precipitation and oxygenation and will consequently diminish contaminant concentrations and loads which might penetrate into ground and/or surface waters. In conjunction with the final cover, the effectiveness of the acid-consuming C-zone material in the pit plays a crucial role in inhibiting additional acid generation. This will be accomplished by oxygen consumption through sulphide oxidation and the neutralisation of the acid produced by acid-buffering carbonate material.

To assess the performance of cover systems in conjunction with C-zone material in terms of oxygen reduction, measurement results for test plot 2 and test plot 3 are presented as examples below. Table 1 shows oxygen data from boreholes sunk into the pit backfill recorded during the period from May 2001 to October 2002. Following significant initial variations in concentration when measurements began in August 2000, measurement results tended to stabilise by May 2001 and remained more consistent ever since. The results show that test plot 2 and test plot 3 exhibit significant oxygen levels in boreholes only at upper measuring points. In test plot 2, significant levels of oxygen occur only down to a depth of about 2 m (at 2 m approx. 5 % O_2 max.) and in test plot 3 only down to a depth of approx. 1 m (approx. 5 % O_2 max.). Oxygen concentrations peak during dry summer months when soil moisture levels are low. During winter and spring of 2002, stagnant water prevented sampling at measuring points in the upper 2 m of test plot 2. During that period, maximum concentrations of up to 6 % O_2 were found in a depth of approx. 3.5 m (Fig. 5). Levels of 0.1 to 0.3 occasionally recorded at greater depths are near the detection limit of the oxygen measuring device and therefore of no importance.

Table 1. Oxygen data recorded from boreholes during the period May 2001 to October 2002 for test plots 2 and 3.

Depth	Test plot 2 (%O_2)			Test plot 3 (%O_2)		
(m)	Min	Max	Ø	Min	Max	Ø
-0.90	0.0	17.7	5.1	0.0	4.4	0.6
-1.90	0.0	4.9	0.3	0.0	0.5	0.1
-3.40	0.0	6.1	0.4	0.0	0.3	0.07
-4.90	0.0	0.8	0.09	0.0	0.9	0.11
-6.40	0.0	0.8	0.06	0.0	0.3	0.04
-7.90	0.0	0.7	0.05	0.0	0.2	0.04
-12.15	0.0	0.4	0.04	0.0	0.2	0.05
-17.65	0.0	0.2	0.04	0.0	0.2	0.04
-24.15	0.0	0.2	0.04	0.0	0.2	0.04
-30.65	0.0	0.2	0.03	0.0	0.2	0.05
-37.15	0.0	0.3	0.06	0.0	0.2	0.04
-43.65	0.1	0.1	0.09	0.0	0.2	0.04
-50.15	0.0	0.3	0.06	0.0	0.2	0.05
-57.15	0.0	0.2	0.05	0.1	0.1	0.10

Depth data in column 1 are referenced to the top edge of backfilled waste rock.

Oxygen data recorded from gas lances during the period May 2001 to October 2002 are summarised in Table 2.

Table 2. Oxygen data recorded by gas lances in test plot 2 and test plot 3 during the period May 2001 to October 2002

Test plot 2 (% O_2)			
Depth (cm)	Min	Max	mean
+30 (ZAN)	12.2	19.7	17.5
-100 (waste rock)	0.0	10.3	5.1
-200 (waste rock)	0.0	0.5	0.1
Test plot 3 (% O_2)			
Depth (cm)	Min	Max	mean
+70 (storage layer)	18.2	20.9	19.5
+30 (ZAN)	10.9	20.4	18.7
-100 (waste rock)	0.0	2.5	0.2
-200 (waste rock)	0.0	0.3	0.1

In test plot 2, oxygen data from the ZAN layer were almost equal to atmospheric levels (approx. 20 % O_2 max.) and slightly diminished during wet periods (approx. 12 % O_2 min.). Oxygen in upper zone of backfilled waste rock (1 m) showed significant levels only during dry periods from August to October 2001/2002 (approx. 20 % max.). During that period, there is a marked drop in soil moisture content (Fig. 6).

In test plot 3, oxygen concentrations were also at atmospheric levels (approx. 20 % max.) in storage and ZAN layers alike. Oxygen levels recorded in upper zone of backfilled waste rock (1 m) were lower than in test plot 2 with a maximum of about 2.5 %).

In order to evaluate the performance of the C-zone as it currently exists in conjunction with cover test plots in respect of long-term behaviour, a number of model calculations were performed which allow to extrapolate recorded data to conditions which are more typical of long-term cover conditions (extreme climatic conditions, rooting depth variations, etc.) (Hockley et al, 2002). Modelling results for test plot 2 using the most conservative cover design (1 m ZAN layer) reveal that the oxygen level in the upper part of the C zone (above 3 m) will be reduced also under very dry climatic conditions and when the full rooting depth is attained.
All results of oxygen measurements obtained to date as well as long-term predictions have indicated that the C zone of 10 m depth, in combination with any of the tested cover designs, will provide a sufficiently effective oxygen barrier.

4. Discussion

Following weighing of cover-related short and long term costs it was found that higher construction costs for the various cover options will not be offset by cost savings in the long term water treatment (Paul et al 2003). As a consequence of pit flooding, even a costly multiple cover including an impermeable layer as it is represented at test plot 1 will only insignificantly impact on concentrations and loads at ground water spill over points. As a result of comprehensive studies and investigations, a combined cover of cohesive soil material from on-site excavation (ZAN) overlain by a 0.4 m thick storage layer to restore natural soil functions for revegetation was derived and submitted for approval. Together with hydraulic measures, this approach is to meet any requirement in terms of radiology, water protection, stability, erosion protection, and reuse.
Cover test work has to be continued for at least one to two vegetation periods to corroborate the assumptions which were integrated into the systems approach.

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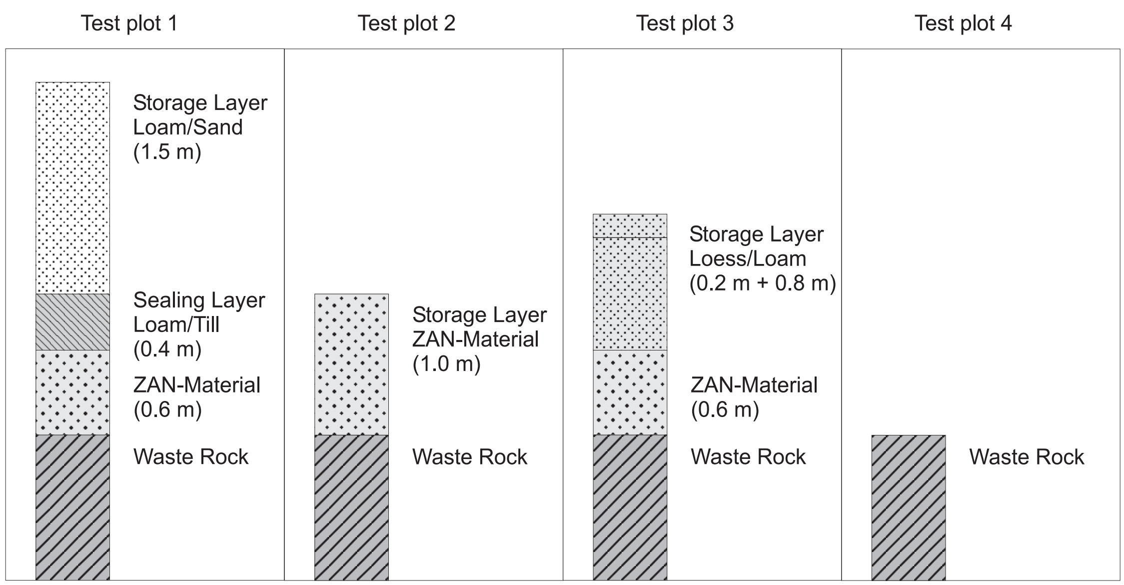

Fig. 1: Cover designs of field test plots Lichtenberg

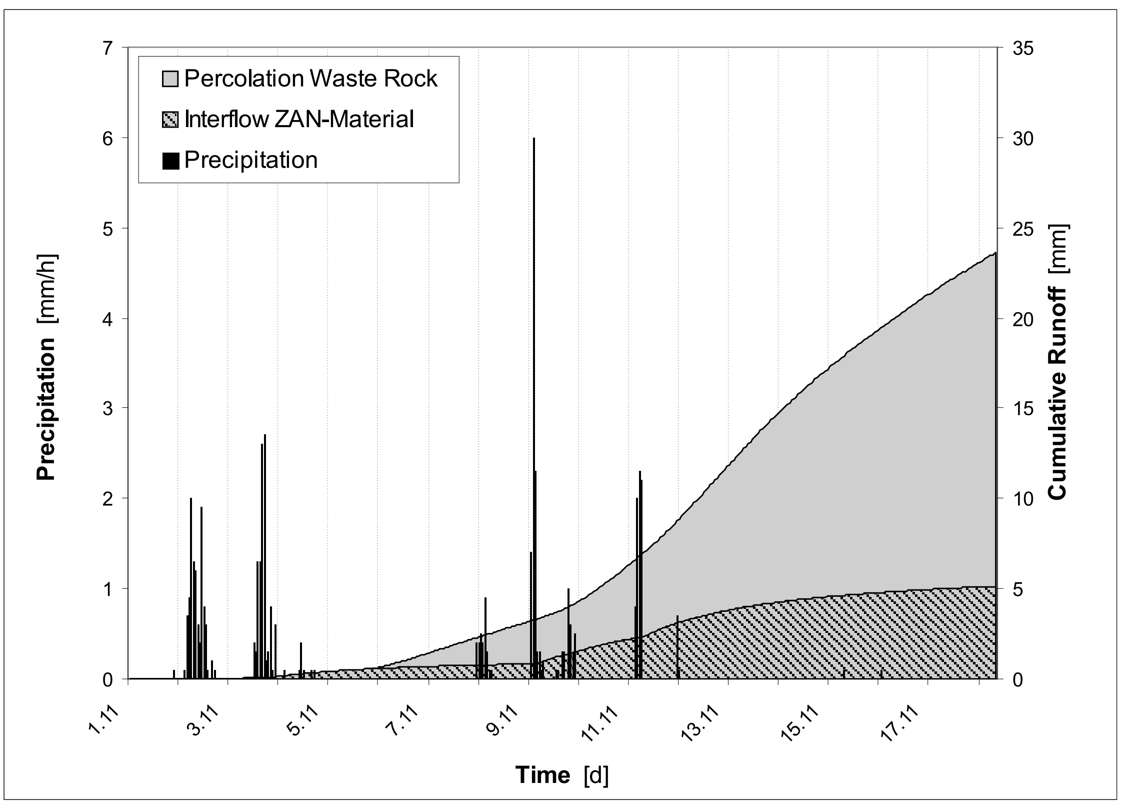

Fig. 3: Precipitation, interflow and percolation at test plot 2, November 2002.

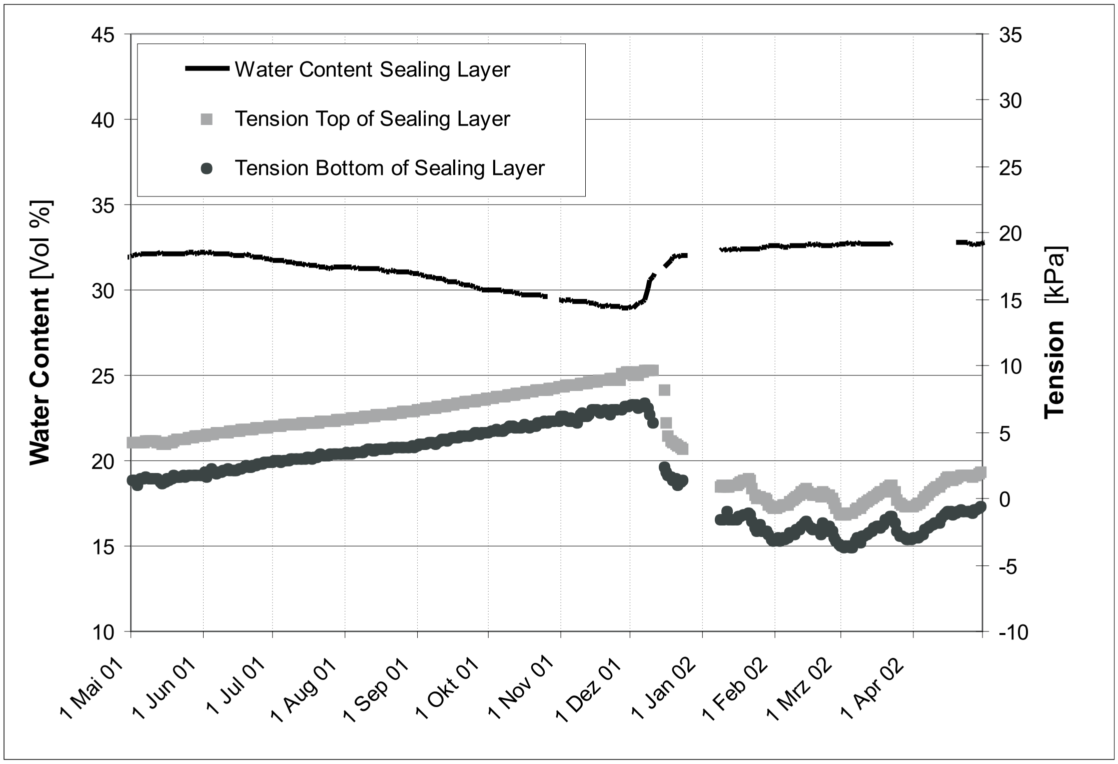

Fig. 4: Soil water content and tension in the sealing layer, test plot 1.

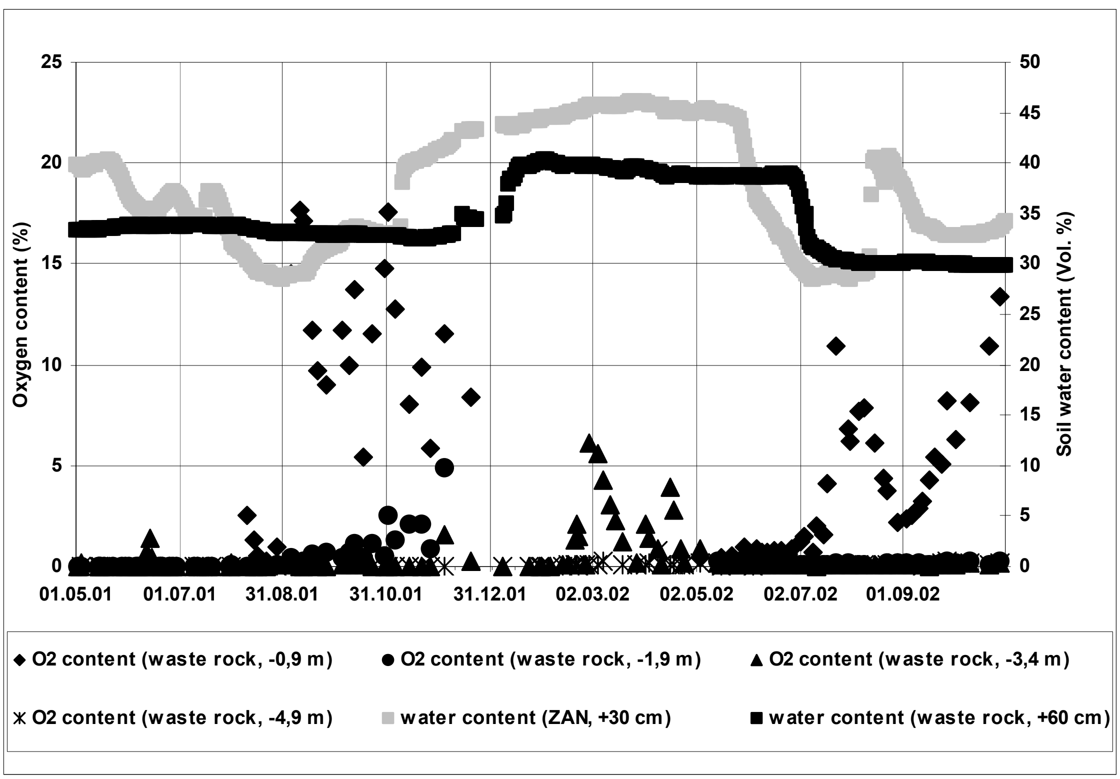

Fig.5: Test plot 2 – Oxygen content measured in the uppermost sampling parts of the borehole (waste rock material) and the soil water content measured in the cover and the waste rock material

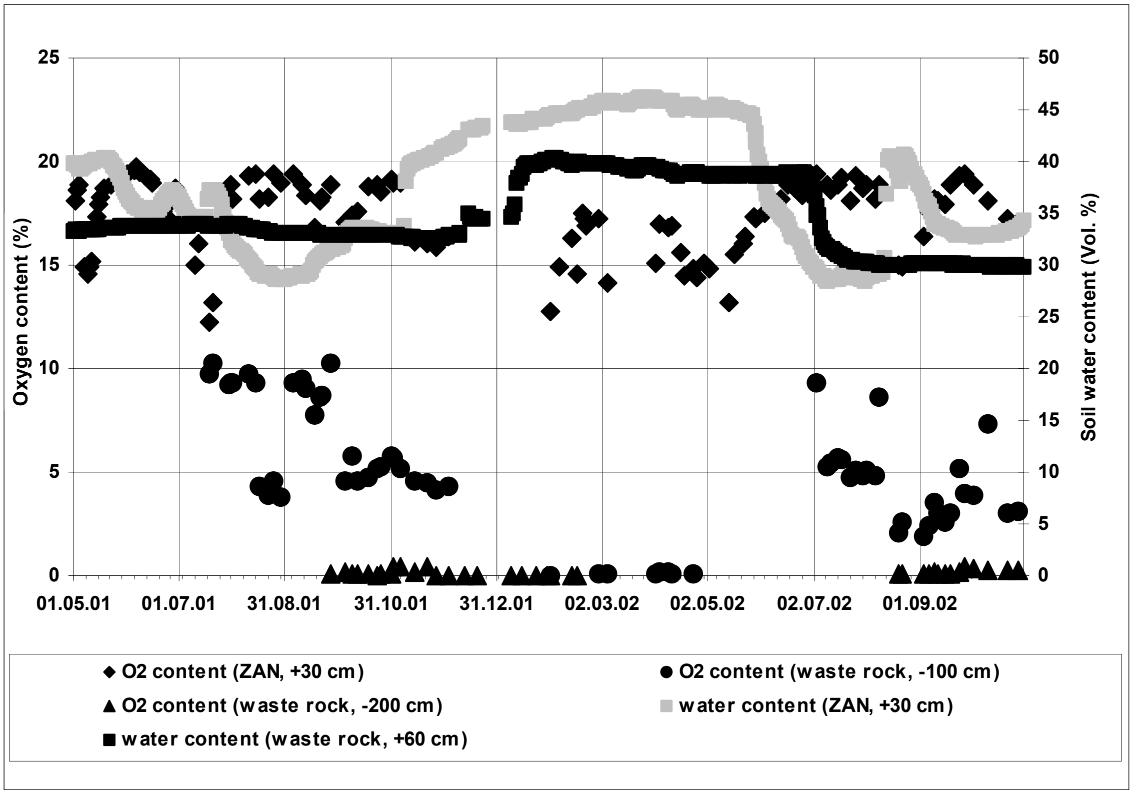

Fig. 6: Test plot 2 - Oxygen content measured in the ground to air lances in the cover and the waste rock material