Modular concept of technical solutions for the improvement of the water quality of acid mine water from former open pits

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1 INTRODUCTION

Tertiary brown coal is mined in the German brown coal districts Rheinland (Rhineland), Mitteldeutschland (Central Germany) and Lausitz (Lusatia) since the 19th century. Almost 100 years of mining activity and the dewatering, of loose rocks in former glacial valleys and low-lying areas have influenced the water balance for a long time. In the course of decades a huge lowered funnel-shaped ground water table was formed which exceeds the area of the former open pit. In 1994 an area of 2100 km^2 was influenced. The ground water deficit summed up to 13 billion m^3, including the volume of the mined open pits. With the decline of the brown coal production in the Lausitz-area in 1990 the dewatering was reduced too. This caused problems with the water balance in the influenced area, and environmental friendly and economic solutions have to be found. The final aim is the re-establishment of a stable and self regulating water balance.

Abandoned open pits are naturally filled up with groundwater, if the dewatering of the open pits stops. This is called **self-flooding**. So called "open pit lakes" are formed. The original native water level will be reached after years or even decades in dependence on the hydrological situation in the area. Self flooding causes a rise of the water level in the loose rock and the formed lake, whereby the rise of the water level in rock is faster. For this reason, slides of water saturated slopes can appear, if the slopes a not specially treated. Such slides can easily have volumes up to some million m^3, see fig. 2. Another problem of the self flooding is the quality of the water. The water in the open pit lakes has often high contents of salts, metal-ions and sulphates and becomes acidic. Both, the stability of the slopes and the water quality can restrict the further use the open pit lakes, see Nitsche et al. [2001].
Because of the interactions between slope stability and water quality it is important to apply measure to ensure the quality of water already during the shaping of the open pit lakes to reduce unnecessary costs and to ensure a further use of these open pit lakes. For this reason first the most important measures for the increase of the stability of the slopes will be described to show, how a modular concept with new technical solutions for the improvement of the water quality can be developed already in this stage.

2 STABILIZATION OF SLOPE-SYSTEMS OF OPEN PIT LAKES

Basically, one can differ between soil-mechanical stability and hydro-mechanical stability. For the soil-mechanical stability the safety against sliding and ground failure have to be proofed. For the hydro-mechanical-stability the safety of the shore against waves and the flow of free water have to be proofed. The definition of safety of slopes from JANBU see equation 1 and Buß et al. [2004].

$$\eta = \frac{\sum T_i + \sum H_s}{\sum G_i \cdot \tan \delta_i + \sum H} \tag{1}$$

η – ground- and slope failure safety; G_i – self load of the individual blade, kN/m

H – moments around the sliding circle of loads and forces, not included in G_i, kNm/m

H_S – moments around the sliding circle of loads and forces, which are defined in German standard DIN 4084, kNm/m;

T_i – available resistance of the loose rock in the sliding line of the individual blade, kN/m

δ_i – tangent angle of the individual blade to horizontal, grad

2.1 *Design principles*

The standard mining profile has to be adapted to the required slope profile as far as possible. Therefore the following pre-conditions have to be established:

The stability of the slopes in abandoned open pits has to be proofed under consideration of the hydro-mechanical conditions.

The slopes under the water surface flatten out to an inclination of 1 : 2 due to transverse flows in dependence of the time. For this process it is necessary to have enough free space in front of the slope, see figure 1.

If it is necessary to support the shoreline, the inclination of the slope in the wave-influenced area should not be greater than 1 : 3.

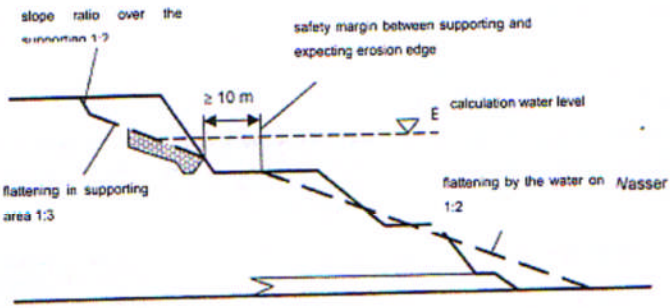


Figure 1: Standard profile in border slope area, LMBV [2001]

2.2 *Stabilization of slopes (shores) of open pit lakes*

The stabilization of slopes and a building ground improvement respectively are necessary, because of the existing slope systems have to be geotechnical stable. The prevention of spontaneous stability loss (land slides) of huge dump areas with the construction of hidden dams is of special interest in the Lausitz-area, see figure 2.

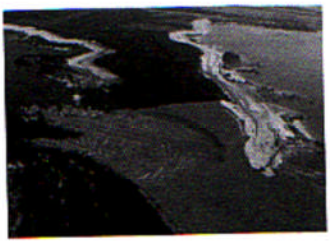


Figure 2: Settlement flow sliding from 06.05.1998, east embankment of Koschen damm

While it is possible to increase the bearing capacity of the loose rock up to a point where a ground failure can be prevented, settlements can be prevented only gradually.

Settlements consist mainly of three parts:

1. Settlement of the entire slope due to its own weight.
2. Settlement, due to static and dynamic loads at the surface, for instance traffic.
3. 3. Settlement due to the rise of ground water.

$$s_g = s_e + s_l + s_{gw} \tag{2}$$

s_g – total settlement (overall settlement); s_e – settlement of the dump due its own weight
s_l – settlement due to static and dynamic loads; s_{gw} – settlement due to rise of groundwater

Almost all applied procedures for the stabilization of the slopes have the aim to reduce the pore volume in the loose rock. Thereby the loose rock is compacted and its tendency to deformation is reduced by applied load or energy. The building ground is homogenized. With deep compaction methods the settlement of the dump due its own weight is done in advance, the settlement due to ground water is reduced and the settlement due to loads is reduced to an acceptable degree, Lersow [2001].
Three main compaction methods have been established over the time, see figure 3 to 5.
With the reduction of the pore volume with deep compaction methods a reduction of the porosity is achieved.

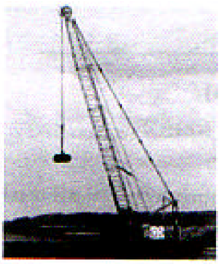


Figure 3: Compaction by falling plate

Figure 4: Compaction by vibration

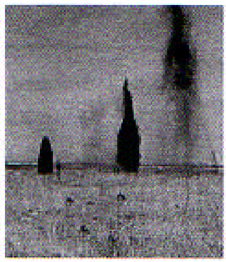


Figure 5: reduction of pore water pressure after compaction by blasting

Furthermore the flow characteristics in the loose rock are changed too. At the same time the acid-potential in the slope is stimulated, and the open pit lake tends to become more acidic. Therefore it is necessary to include alkalization procedures already in this step. Otherwise the costs for the removal of the acidization would be immense. The introduced solution starts at this point.

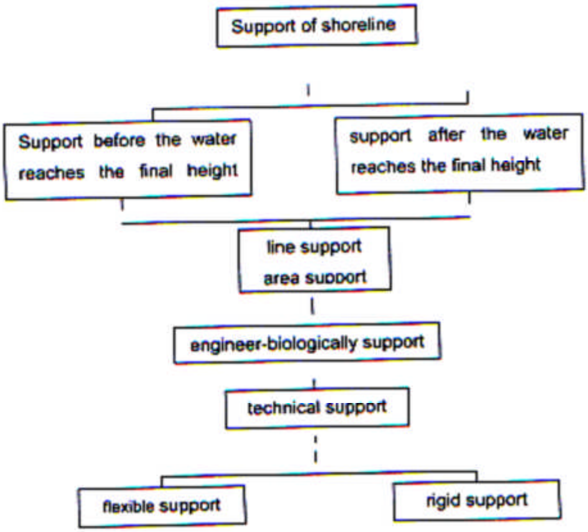
2.3 Support of slopes (shores) of open pit lakes

The support of the shoreline has to be planned according to the following aspects:

- Public safety
- Hydro-mechanic loading

- Nearby objects, which have to be protected
- Landscape planning
- Environmental protection
- Use for water supply, water management
- Economy

Table 1: support of shoreline.



Alkalization methods can be combined with support methods. The introduced solution starts at this point too.

Biologically engineered support

Biologically engineered procedures adapt to the nature conditions. They can be used however only up to a certain limit of loading, see table 2.

Technical support

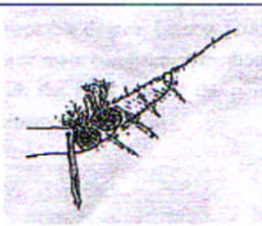
Rigid support

Technical support methods are necessary, if traffic loads or tension loads have to be taken by the ground, or, if a special use is planned, like massive supporting walls, quaysides, sheetpilings.

Flexible support

In contrast to bending hard the bank supporting are insensitive these building methods to settlements. In addition, they are water permeable, so that methods are necessary against rinsing the backfilling out. For this a geo textile is used favourably.

Table 2: Biologically engineered support, LMBV [2001]

Examples	Short characterization
	**Transplant of tack woods:** - Simple form of slope support - Close to nature shore support - Reasonable - Not any or low maintenace - Not any or low resistance against hydromechanical
	**Vegetation fascines:** - Simple form of slope support - Absorbs the wave energie - Close to nature by possible planting - Good filter effect against suffusion - Flexibly with maintenance work **Use:** Reinforcement of hydromechanicaly slight reinforced
	**wood green sill:** - Simple form of slope support - Flexibly - Close to nature by possible planting - Good filter effect against suffusion - Good combination by dead and living shore support **Use:**

3 DEVELOPMENT OF AN ACID OPEN PIT LAKE

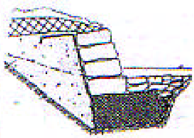
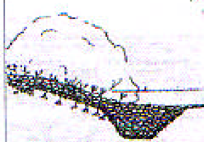
With the end of the brown coal mining in numerous open pits after 1990, extensive safety measures have been carried out at the slopes of abandoned pits to minimize the danger of slides and to improve the geotechnical safety. The flooding of open pits with surface water, the so called **foreign-flooding** from outside, improves the geotechnical safety considerably, because the water level of the lake is often higher, than the water level in the loose rock. But, with the flooding with suitable water from outside the water quality of the lake can be influenced positively.

The main sources for dissolved matter and acids in flooded open pits are the ground water and the dump material, LUA [1996]. The reasons are iron-sulphides in the coal seams and silt

layers on one hand and locally considerable amounts of pyrite and marcasite aggregates ($FeS_{2(S)}$) in brown coal dumps on the other hand.
The sources of dissolved matter and acids and hydro chemical processes, which are important for open pit lakes, are shown in figure 6.

During the flooding of an open pit, the geo-hydraulically gradients and consequently the direction of the flow are temporarily reversed. The groundwater flow from the open pit lake is greater than the groundwater flow into the open pit lake. After reaching the final water level, the main flow of the groundwater is into the open pit lake. If the open pit lake has an

Table 3: Flexible support. LMBV [2001]

Examples	Short characterization	Examples	Short characterization
	**Gabion wall:** Prefabricated baskets from wire or plastics, which is filled in situ with crushed stone. **Advantage:** - hydromechanically and statically favorable - Fast building progress - sowing down possible **Disadvantage:** - to accept formatively everywhere		**Krainer wall:** *Crosswise shifted individual components with crushed stone or soil filling.* **Advantage:** - simple support - earthstatically favorably - Close to nature support possible(wood, sowing down) - With use of precast concrete parts durably.
	**Hand-placed riprap on gravel mats:** Structure of hewed ashlars **Advantage:** - Simple inserting techno-logic - formative positive - durable **Disadvantage:** - With increasing height expensively - difficult material procurement		**Rockfill:** Rockfill or gravelfill on the surfaces which can be secured. **Advantage:** simple support simple building method Employment with variable slope ratios sowing down possible - Durably and economic **Disadvantage:** - With use of timber ele-

	**Stone packing:** Structure of unhewed ashlars or boulder. **Advantage:** - simple and fast inserting - sowing down possible, sowing down - design positively **Disadvantage:** - material procurement - Usually long routes of transportation		**Rockfill in modified form:** Rockfill or stone packing on the surfaces which can be secured. **Advantage:** - simple support - simple building method - Employment with variable slope ratios - sowing down possible - Durably and economic

unfavourable location nearby old dumps and other open pit lakes, acidic groundwater can flow into the flooded new open pit lake.

Abandoned open pits are mostly flooded with water from nearby rivers, to prevent a natural inflow of groundwater into the open pit with all the negative effects on the future lake and to accelerate the flooding process.

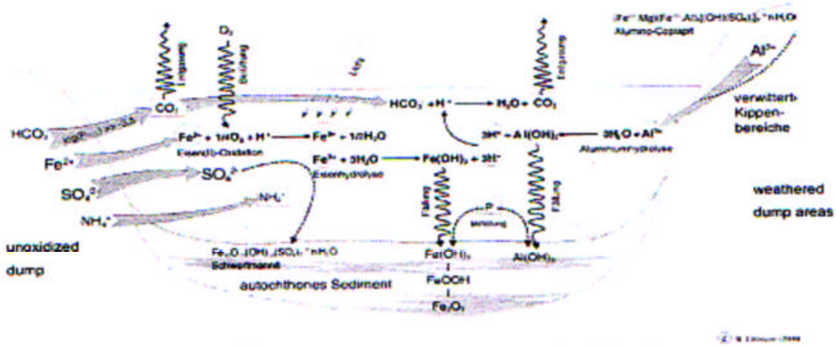


Figure 6: Sources of material and hydraulicchemical processes in sour open pit lakes, © W Ullmann (2000)

4 MODULAR CONCEPT OF TECHNICAL SOLUTIONS FOR SUSTAINABLE ALKALIZATION OF ACID OPEN PIT LAKES

Alkalization measures should start already in the planning phase of the morphological and geotechnical modelling. These measures should be continued or repeated during the flooding and after the flooding, when the open pit lake is given to public or private use. The proposed measures for an alkalization are summarized in figure 7.

The measures include:

Permeable, vegetative cover (alkalization mat), which is especially suited for shorelines, for inorganic and biogenic alkalization, see figure 8.

A procedure for the creation of sources of alkalization in open pit lakes. Thereby the building-in of alkali material in the loose rock can be done by help of vibro displacement. The alkali material is built in as suspension to prevent and sedimentation. With suitable material, like blast furnace residues, gravel columns can also be created, see figure 7 and 9.

The flexibility of all technical measures allows the adaptation / combination of methodical solutions to the given area. Thereby all open pit lake zones, like aquatic zone, semi-terrestrial zone and terrestrial zone, can be included. It is obvious, that the modular concept of the sustainable alkalization coordinates and combines measures for the establishment of the soil mechanical stability, measures for the establishment of the hydro-mechanical stability (deep compaction, support of slopes) and measures for the alkalization.

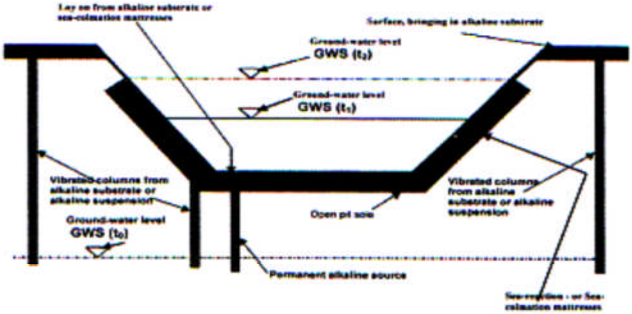


Figure 7: Structure of the modular developed concept, in particular to the alkalization of mining lakes, © Lersow [2004]

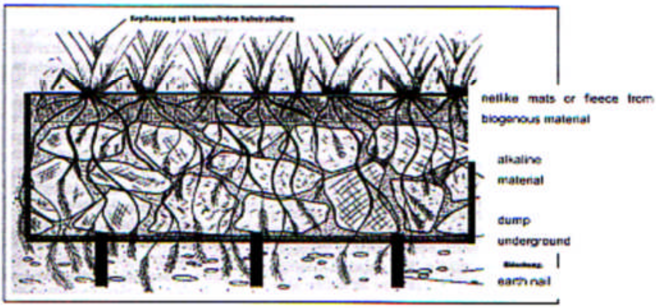


Figure 8: Sea-reaction - and Sea-colmation mats - schematic layout, © Lersow [2003]

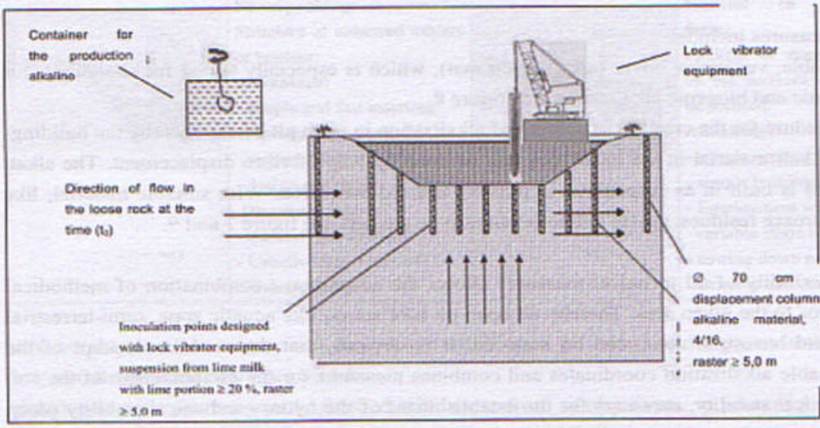


Figure 9: Procedure for the design of sources of the alkalization, © Lersow

5 APPLICATION

Application possibilities can be seen in Figure 10.

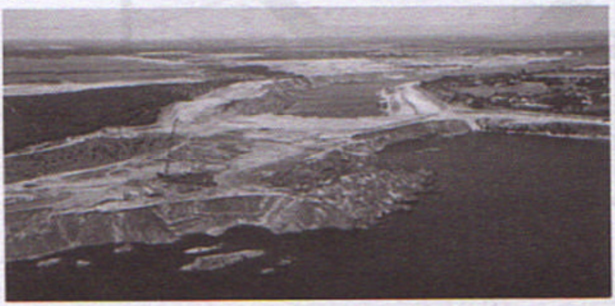


Figure10: Aerial photo of a post mining landscape, in the foreground the mining lake Spreetal, near the city of Hoyerswerda, Saxony

5.1 Characterisation of the location

The building-in of the mats and the placement of the sources of the alkalization require a hydro-geochemical and geotechnical characterization of the initial state of the location, sees fig. 10.

Furthermore, the extension and constitution of the weathering zone has to be characterized at the distinct location. Therefore horizontal holes are drilled into the slopes. First field tests (field eluation tests) are carried out on the obtained samples to determine the general relevance of the delivery of acid drainage water. Furthermore the acidity capacity of the solid material and the immobile water phase has to be determined by column test, for example according to the procedure after Zeien & Bruemmer, 1989. The area behind the weathering zone has to be tested regarding water quality an acidity potential. For the localization of the inflow area from the dump it is necessary to construct ground water measuring points, which fullfill the brown coal quality standards (see Nitsche et al., 1999). These points should be carried out as measuring clusters, which are able to characterize the depth-dependent flow.

For the geotechnical characterization in the inflow area the initial pore water pressures are measured. Therefore pore water pressure tubes (lost tubes, sensors) are built in. These tubes are further used as monitoring elements.

Regarding the entire system "dump inflow area – weathering zone – residual lake" a hydro-geochemical characterization of the initial state of the residual lake sediments und residual lake are necessary. Sulphate reduction- / sulphide formation processes are most important in the process of retaining the acidity at the boundary layer lake sediment / lake, see Nitsche et al.[2001].

5.2 Technological arrangement of a full-scale test

To proof the success of technical alkalization measures and to compare it with others, the full scale test is separated in 4 test areas:

area 1 ⇒ permeable, vegetative cover (alkalization mats)

area 2 ⇒ application of the procedure "sources of alkalization"

area 3 ⇒ application of both measures alkalization mats and sources of alkalization

area 4 ⇒ untreated area

Area 1 ⇒

The sections of the slopes and/or bottom of the open pit treated with alkalization mats should not be smaller than the critical length of 200 m to avoid a flow around the mats. A placement within the full width of the inflow would be desirable. If a considerable flow around appears during the test, special measures should be taken at the border zones (sealing). The mats will be placed up to 2 m under the expected water level. During the flooding, the mats are placed up to 1,50 m over the actual water level of the lake, see figures 7 and 8.

Area 2 ⇒

The sections of the slope and/or the bottom of the open pit, in which sources of alkalization are built in, should cover the full width of the inflow region of the abandoned open pit. The sources of the alkalization are built-in by help of a lock vibrator at least 2 m under the highest possible surface of the inflow. As alkaline additive a suspension of lime-milk with a lime content of ≥ 20 % should be used for the full scale test. With this technique permanent sources of alkalization are created, which can be filled up, if the reactive material is used up. A minimum of 3 rows with a distance ≥ 5 m is intended (advised) across the entire length of the inflow region, see figures 7, 9 and 11. This ensures that sufficient reactive material is available.

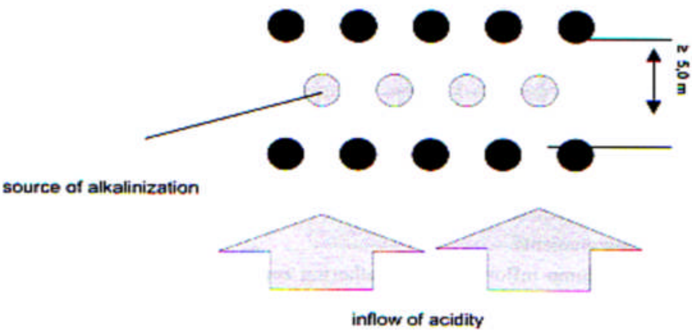


Figure 11: sources of alkalinization

Area 3 ⇒

See descriptions for area 1 and area 2, see fig. 10.

Further elements of the modular concept, like melioration of shorelines and/or open pit bottom with neutral substrate [in dry open pits before flooding] should not be discussed here.

6 MONITORINGS AND INTERPRETATION OF THE FULL-SCALE TEST

Essential aspects of the full scale test are the monitoring (measurements) and the interpretation, which bases on a hydro-geochemical transport model.

6.1 Accompanying monitoring

The measurement of the hydraulic conditions (standpipe water level) in dependence of the time and the determination of the hydro-chemical state of the inflow (quality) are carried out at the dump ground water measuring points in the inflow area. The adjacent residue lake is tested in different depths. For the test of the inflow after the passage of the treatment area, special testing systems with pressure compensation are used. The "geotechnical" monitoring is carried out with the built in pressure tubes in the inflow region (see chapter 5.1). The time-dependent measurements can identify blockages. After the finish of the full scale test and the consumption of the reactive material of the alkalization mats, the material is geochemical tested (sequential extraction, ESEM). A first interpretation of the test results compares the balance of the different technical measures and the untreated area.

6.2 Proof of the increase of the sulphate reduction- / sulphide accumulation rates in the residual sediment

In addition to the time-related monitoring of the hydro-chemical behaviour of the residual lake, the following tests are made, to evaluate the acidity minimizing process in the residual lake sediment (the sulphate reduction- / sulphide formation):

a) Determination of the chemical bond of the sulphur

b) Isotopic tests on the dissolved sulphate

c) Microbiological test.

During identification of the chemical bond of the sulphur, the increase of the AVS-fraction is very important. Because of the minimal amount of substance, the determination is very difficult.

Isotopic tests on the dissolved sulphate are very important in relation to the time. With the sulphate reaction, the amount of dissolved sulphur is reduced and the relation of ^{34}S : ^{32}S at the dissolved residual sulphate is changed.

These tests are especially important, if the sulphate content in the inflow differs.

Microbiological tests determine the increase of the germ number of sulphate reducing bacteria (SRB) and its robustness / ability for activation.

The robustness and the ability for activation are closely connected with the conversion rates. Furthermore selective SRB germ numbers a determined with the MPN method.

6.3 Interpretation with a hydro-geochemical transport model

A modelling of the hydro-geochemical transport process must follow the comparison of the balance, see 6.1. The modelling consists of:

a) Identification of the hydraulic parameters of the flow model

b) Establishment of the transport model

Parameter identification of flow model

For the identification of the parameters (k_f value, porosity) of the flow model, all available information has to be used. The number of available ground water measuring point is often limited. For this reason it is necessary to use grain size analyses too.

The determination of the insitu-permeability in the inflow region is done with the "Slug and Bail" test at the groundwater measuring points. A displacement body or compressed air (N_2) (no material filling) is used to guarantee, that no chemical reactions take place at the measuring points. Although these tests give only limited results, they are the only possibility to determine the insitu-permeability. Because of a disturbance of the test conditions, pumping tests are not possible.

Regarding the consideration of grain size analysis for the description of the hydraulic conditions, good results have been get for brown coal dumps in East Germany with procedures according to Kaubisch (1986) or Kaubisch and Fischer (1985) or Beyer (1964). The Kaubisch method focuses on substrates, which cannot be tested with the Beyer-method (pelite content > 10 %).

The identification of the actual parameter is done with the finally generated parameter flow model. A minimization of the model error is done by variations of the model parameters within a given range. The basis is the time dependent development of the groundwater level and pore water pressure in the inflow region of test area. The transport model PCGEOFIM (Sames & Boy, 1997) is often used, because it was especially developed for brown coal sites in East Germany. The code includes automatic parameter identification and the implementation of the hydro-chemical reaction tool PHREEQC (Parkhurst & Appelo, 1999). In combination with other software codes, the use of the universal code UCODE (Peoter & Hill, 1998) is proposed for the model calibration.

Transport model

The hydro-geochemical system is very complex. The conventional modelling uses equation 3.

$$\underbrace{div(D \cdot grad\, c}_{\text{dispersiv transport}} - \underbrace{v_a \cdot c}_{\text{konvektiv transport}}) - \underbrace{\lambda \cdot c \cdot R}_{\text{degradation}} = \overbrace{\overline{R}}^{\text{retardation}} \frac{\partial c}{\partial t} - \underbrace{q}_{\text{sources/sinks}} \qquad \text{Eq. 3}$$

Beside the physical transport phenomena (convection, hydrodynamic dispersion), the hydro-chemical transport phenomena are only described by degradation- and reaction terms. Furthermore these formulations are non-reactive, because no real interactions between different transported species are taken into account, which means it is only suitable for cases with one substance.

Consequently, it is necessary to include a term which describes the reactive part for the given complex hydro-geochemical situation. This implementation of the geochemical interactions for the solution of the transport equation is given, if a hydro-geochemical model, like PHREEQC, is used. Thereby a transport equation will be solved for every transported species. The changes as a result of the interaction of source-/ sink term (q), calculated by the hydro-chemical reaction tool, are considered in the transport equation.

Since the mid 90ies different codes are available which use this procedure MINTRAN - Walter et al. [1994]; MULTRA - Brand [1996]; PCGEOFIM - to IBGW[2000] see also Hoth [2003]; PH3TD - Prommer et al. [2002] and further the open source software PHAST - Parkhurst et al. [2002]).

The modelling of a specific location starts with a 1D reactive transport modelling with PHREEQC on basis of the established flow model. In this step, the hydro-geochemical understanding is deepened to identify the relevant reaction mechanisms, which have to be considered in the final 2D reactive transport modelling.

The main questions, which have to be answered by the large scale test, are:

- with which buffer systems,
- with which temporal course and
- with which efficiency the delay / minimization of the acidity inflow takes place.

Thereby these questions focus on the processes of the exchange-buffering and siderite formation. Furthermore the process of the sulphate reduction / Sulphide creation at the boundary layer lake sediment / residual lake will be included.

7 SUMMARY

With the decline of the brown coal production in the Lausitz-area in 1990 the dewatering was reduced too. This caused problems with the water balance in the influenced area, and environmental friendly and economic solutions have to be found. The final aim is the re-establishment of a stable and self regulating water balance.

The main sources for dissolved matter and acids in flooded open pits are the ground water and the dump material. The reasons are Iron-sulphides in the coal seams and silt layers on one hand and locally considerable amounts of pyrite and marcasite aggregates ($FeS_{2(s)}$) in brown coal dumps on the other hand.

The modular concept – as new technical solution for the improvement of the water quality of acid water in open pit lakes – emphasises the necessity of the implementation of alkalization measure of the water already during the improvement or establishment of the soil-mechanical stability and hydro-mechanical stability.

Creative solutions are available especially in combination with the compaction by vibration and support of slopes.

The measures include:

Permeable, vegetative cover (alkalization mat), which is especially suited for shorelines, for inorganic and biogenic alkalization, see figure 8.

A procedure for the creation of sources of alkalization in open pit lakes. Thereby the building-in of alkali material in the loose rock can be done by help of vibro displacement. The alkali material is built in as suspension to prevent and sedimentation. With suitable material, like blast furnace residues, gravel columns can also be created, see figure 7 and 9.

Adapted to the given location, alkalization measures can be planned for the distinct open pit lake, which lead to a long lasting alkalization of the acid water. For an optimal adaptation of the alkalizations measure, the initial state must be hydro-chemical /geotechnical characterized. The applied measure have been described as well as the accompanying monitoring for the proof of the sulphate reduction / sulphide accumulation rates in the residual lake sediment and the hydro-chemical transport processes.

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