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INDUSTRIAL BY-PRODUCTS IN ENVIRONMENTAL PROTECTION STRUCTURES IN MINE CONSTRUCTION

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ABSTRACT: UPACMIC (Utilisation of by-products and alternative construction materials in new mine construction LIFE12 ENV/FI/000592) is an EU LIFE funded project aiming to utilize alternative construction materials in new mining facilities and remediating the existing ones. Alternative construction materials meant in this context mean industrial by-products such as gypsum, fiber clay, foundry sand, fly ash, etc. The materials can be used as such or they are refined and mixed with local materials, such as moraine, depending on the purpose of the use and other specific issues. The project started in 2013 and will continue until August 2020. The project coordinator is Ramboll and the associated beneficiaries are Fortum Waste Solutions and Suomen Maastorakentajat. Currently the project has operated in Pyhäsalmi Mine for field tests and in Hitura Mine for piloting cover structure.

Keywords: alternative materials, recycled materials, industrial by-products, lysimeters, cover structure

1. INTRODUCTION

Rapid growth in Finnish mining industry has been a trend in recent years as of the mined ore and number of companies with mining operations in Finland. Profitability is dependent on metal and industrial minerals price development and simultaneously the global mining sector has suffered from a longer period of lower commodity prices. This means that mines have pressures to reduce costs and improve productivity. Especially in Finland, the public debate is focused on environmental and social impacts of the mines and ministry-level action plan for making Finland a leader in the sustainable extractive industry gives pressure for the mining companies to develop best practices for environmental, ecological and social considerations. Continuous improvement actions are related especially to resource efficiency, new technologies for water purification and waste management. (Ruokonen, E. and Temmes, A. 2018). For these issues UPACMIC project tries to find new solutions.

2. FIELD TESTS IN PYHÄSALMI

Field tests were done in Pyhäsalmi Mine, located in Pyhäjärvi in Finland. The mine has produced copper, zinc and pyrite and in 2019 the mine is gradually closing its operations. Lysimeters were implemented in 2016 as 10 m^3 lysimeter structures. Total amount of lysimeters were 10. The objective of the field tests was to study materials in real circumstances. Tested materials were earlier tested in the laboratory. Focus in the lysimeter tests was to complement laboratory studies (water permeability and leaching characteristics) with the seeping water results. When the lysimeters were built, notice was taken especially on the material handling, mixing and compacting. The materials chosen for the lysimeters were the most interesting and potential ones which could be later used in larger scale pilot cover structures.

2.1 Materials and methods

Materials used in the test and material information are presented in Table 1.

Table 1. Total concentrations and material properties of the used construction materials

Material	Al (mg/kg)	Cu (mg/kg)	Fe (mg/kg)	Mn (mg/kg)	Zn (mg/kg)	Ca (mg/kg)	S (mg/kg)	pH (-)	ρ_d (kg/m^3)
Enrichment sand (fine)	7180	680	297000	590	1680	25400	294000	7,0	1870
Enrichment sand (coarse)	6910	720	315000	430	2180	20700	310000	6,7	2380
Ash	52400	120	142000	2430	240	72100	12800	9,5	830
Gypsum	340	13	400	21	20	277000	215000	2,8	1290
Moraine	12800	55	17500	240	63	5040	350	4,8	2300
Inert material	11000	20	20800	190	33	6570	210	7,5	-

Fine and coarse enrichment sand used in the test was sands hails from the enrichment sand basin D of the Pyhäsalmi mine, from the depth of 0...2,5 m. The enrichment sand segregates to finer and coarser material when it is deposited to the basin as very watery material with the help of outlet pipe. The coarser enrichment sand was more homogenous than the finer sand, so the need of homogenisation was lesser with the coarser material. Based on previous studies, the enrichment sand mainly consists of sulfidic minerals (76%) which occurs mainly as pyrite (iron sulfide) and baryte (barium sulfate). Enrichment sand also contains smaller amount (<5%) of pyrrhotite and small quantity (<5%) silicate minerals e.g. plagioclase, quartz and olivine. Enrichment sands contains also some amount of burnt lime, which is added after the enrichment process to prevent the acid generation caused by sulfide minerals. (Räisänen&Bäcknäs, 2016)

Moraine used in the tests was local moraine from the southern part of the mining area. Grains over d60mm were sieved off. Based on the preliminary leaching tests, the moraine might have acid generating properties while the leachate pH was relatively low (4,4 in L/S = 8). However, based on the acid-base accountin (ABA) test results the moraine is non-acid producing.

Gypsum used in the test was waste gypsum from Yara fertilizer plant located in Siilinjärvi. Gypsum was stored on top of tarpaulin and covered with tarpaulin.

Ash was moistened fresh fly ash from Oulu Energia energy plant. Ash was moistened in the plant three days before construction to 15,5 % water content when the ash was unloaded from the silo. During the construction the ash was stored in piles on top of the tarpaulin and it was also covered with the tarpaulin. In the lysimeter the ash functioned as a reactive layer, which objective was to change water seeping through the structures.

Lawn topsoil was used as a soil layer in the lysimeter. Soil was built to all test lysimeters despite structures numbers 5 and 8. Grass was planted on top of the soil. Inert material refers to the bottom layer made of gravel and functioning as a filtration layer directing the water through the material. Inert material used is equal to sandy gravel.

2.2 Lysimeter structures

The used vessels are 10 m^3 volume containers, with inner diameter 2.4 m and height 2.2 m (figure 1). Every vessel is equipped with three drainage pipes (surface runoff, lysimeter, bottom of the vessel). The waters are steered to collecting wells. The waters for analyses are steered to lysimeter wells, from where the water is collected for amount and quality checks. (Karjalainen, N., Autiola, M. and Jyrävä, H. 2016.)

Figure 1. Lysimeters in Pyhäsalmi Mine. (Karjalainen, N., Autiola, M. and Jyrävä, H. 2016.)

During the construction, the notice was paid especially to the material workability (compaction amount vs the designed density), used methods and machines. Attention was paid also to dusting as a work safety issue, and material durability during the storaging. (Karjalainen, N., Autiola, M. and Jyrävä, H. 2016.)

The material layer structure and thickness in each lysimeters are presented in Figure 2. Layer composition was selected based on the preliminary laboratory tests (Karjalainen, N. 2016). 5 different top structures were tested for both coarse and fine enrichment sands including reference structures without top structures (lysimeters 5 and 8). Lysimeter 4 represents traditionally used top structure, moraine and soil cover, used in closure of enrichment sand bonds in Pyhäsalmi mine.

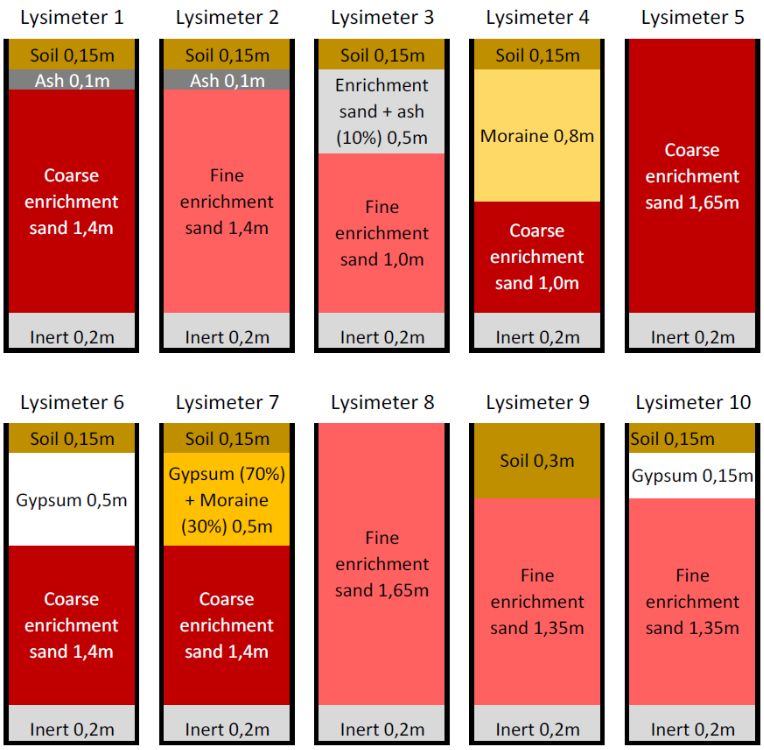

Figure 2. The layer structure of the tested lysimeters in Pyhäsalmi Mine.

2.3 Practical experiences from the test structure construction

During the construction of the test structures, it was found out that compacting the fine enrichment sand is challenging due to its high water content. When considering coverage of the enrichment sand basin, this has no crucial significance other than from the surface levelling and pre-compacting point of view. Other challenging materials were mixes of enrichment sand and ash. Most challenges in the construction caused the mixing of enrichment sand and ash in order to get homogenous mix. When considering this for a large scale constructing, a suitable mixing equipment for this purpose has to be on site. (Karjalainen, N., Autiola, M. and Jyrävä, H. 2016.)

It was also found out that if the water content of the ash is too low, compacting will be difficult and the material remains too loose. Other observations about the materials were that the coarse enrichment sand was easier to compact. Targeted density was not reached with gypsum, but when gypsum was mixed with moraine, compacting work was easy and there were no problems in the mixing work.

Target densities of the materials varied between 80 % ...110 %. Finer enrichment sand compacted above the target, but other materials were somewhat below the set target values, which were determined in the Ramboll Luopioinen environmental R&D geotechnical laboratory. When the density is lower than the set target, the water permeability will increase.

2.4 Sampling from the lysimeters

The bottom wells and lysimeter wells were emptied 2-5 times in month and the seepage water amount was measured. The quality of the seepage water was monitored after 42, 134, 165, 233, 345, 375, 453/459 days. The samples were collected during one-week period from the lysimeter well between emptying. The seepage water amounts varied during the test due to weather conditions. The sampling was carried out by the personnel of Pyhäsalmi Mine.

2.5 Analytics

Lysimeter water samples were analyzed for Al, As, Ba, Cd, Cr, Cu, Fe, Hg, Mn, Mo, Ni, Pb, Sb, Se, V, Zn, Ca, K, Mg, Na and S (µg/l) and also for sulfate, fluoride, chloride and DOC (mg/l). The focus in this study was the leachability of the main components in the enrichment sand Cu, Fe, Zn, S, Ca and sulfate. In addition, pH and conductivity were measured weekly, on average, at the same time when the lysimeter wells were emptied. Samples were analysed in Ahma Ympäristö Oy (present Eurofins Ahma Oy) laboratories in Rovaniemi.

3. RESULTS

The field tests produced large quantity of data of which the most important parameters, selected leachable metals, sulfate, pH and EC, has been analysed in more detailed. The main objective was to compare different top structures for fine and coarse enrichment sands and find the most suitable cover structures for future large-scale piloting.

3.1 Seepage water quality and amount

The seepage water quality was monitored from each lysimeter wells 6-7 times during the follow-up period 23/05/2016-24/08/2017. The amount of seepage water was determined almost every week. The measured average concentrations of selected parameters (SO_4^{2-}, Al, Cu, Fe, Mn, Zn, Ca, S), pH and cumulative seepage water amount and calculated L/S ratio based on cumulative water amount and dry solid amount, including enrichment sand, moraine and by-products in lysimeters, during follow-up period are shown in Table 2. The average concentrations were calculated mg/kg dry matter based on the cumulative seepage water amount and dry solids.

The comparison of main metal leachate concentrations Cu, Zn and Fe calculated per dry solids are shown in Figure 3 for different coarse and fine enrichment sand top structures. The comparison of S, Ca and sulfate calculated per dry solids are shown in Figure 4 for different coarse and fine enrichment sand top structures.

Table 2. Average concentrations of seepage water and calculated L/S ratios during the test. 6-7 measurements were conducted from each lysimeters during 459-day follow-up. Dry solids used in calculations includes enrichment sand, moraine and industrial by-products. Inert material and soil are excluded. * Lysimeter 6 well had leaked during the tests. **Calcium was determined only from 3 samples during the test.

Lysimeter no.	SO_4^{2-} (mg/l)	Al (µg/l)	Cu (µg/l)	Fe (µg/l)	Mn (µg/l)	Zn (µg/l)	Ca** (mg/l)	S (mg/l)	pH	Cumulative seepage water (l)	Dry solids (kg)	L/S ratio
1	4986	17,1	2,6	10,5	3573	237,1	456	1638	7,7	995	14153	0,07
2	3229	710,8	2,5	30,0	2827	37,9	513	1134	5,8	780	12733	0,06
3	2786	33,8	12,0	25,6	7740	21,0	603	1054	6,0	1120	14065	0,08
4 (traditional)	3103	42,1	2,0	75,3	146	193,3	404	1076	7,5	1047	14090	0,07
5 (no cover)	**4914**	**72,8**	**4,6**	**24,3**	**2464**	**75,9**	**547**	**1745**	**6,5**	**1169**	**15370**	**0,08**
6*	4692	15,9	5,1	11,9	1065	502,6	357	1533	7,3	739	10930	0,06
7	4104	22,0	5,5	11,8	1377	666,7	570	1725	7,4	1043	14430	0,09
8 (no cover)	**3443**	**2753**	**6,7**	**48,3**	**8717**	**203,4**	**447**	**1366**	**5,2**	**1273**	**15345**	**0,09**
9	2214	1337	5,4	41,7	8509	123,6	501	896	4,9	985	11900	0,10
10	1600	2632	15,6	175	11835	206,0	587	675	4,5	248	13760	0,01

Coarse enrichment sand	(white)
Fine enrichment sand	(grey)

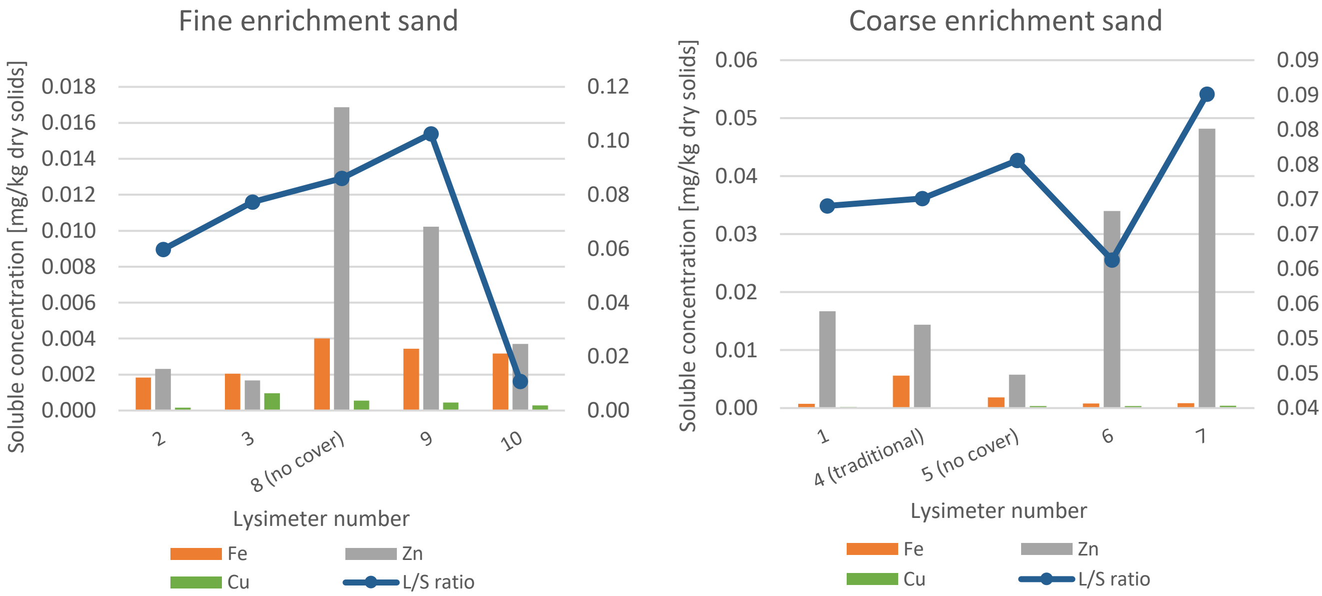

Figure 3. Average soluble Fe, Zn and Cu concentrations from different top structures in comparison with dry solids content (mg/kg dry). Values are calculated by using average metal concentrations, dry solids content and amount of seepage water shown in Table 1.

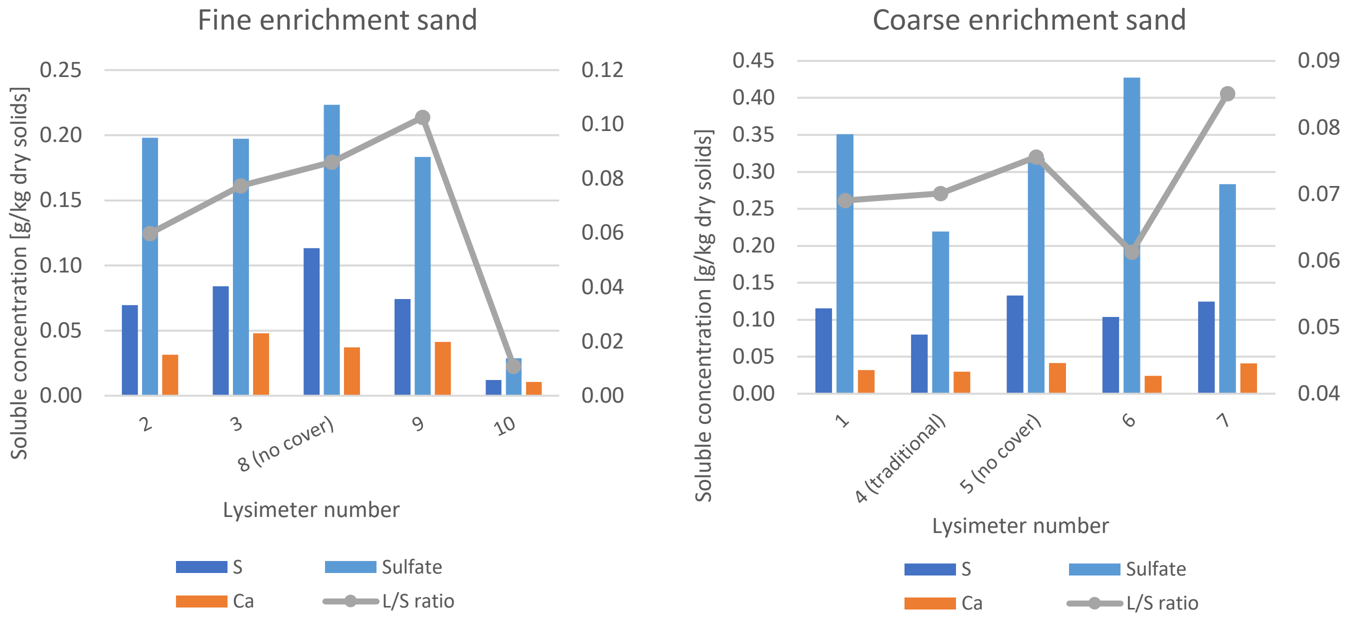

Figure 4. Average soluble concentrations of sulfur, sulfate and calcium from different top structures in comparison with dry solids content (g/kg dry). Values are calculated by using average metal concentrations, dry solids content and amount of seepage water shown in table 1.

The variations in seepage water amounts between different top structures showed remarkable variations during the test. Especially lysimeters 2, 6 and 10 had lower seepage water amount (248-780 l) compared to rest of the lysimeters (985-1273 l). Lysimeter 6 emptying valve had leaked during the test. L/S ratios of lysimeters varied at the end of the test between 0,01-0,1. The average pH of lysimeters varied between 4,5-7,7 during the test.

The average metal concentrations (Table 2) measured from fine enrichment sand lysimeters 2, 3 and 9 were mainly lower in covered structures compared to uncovered enrichment lysimeter 8. Lysimeter 10 had higher Mn, Zn, Cu and Fe concentrations compared to uncovered structures. The Fe, Cu, Zn, S, Ca and sulfate concentrations were calculated to mg/kg dry (Figures 3 and 4) for comparison leachability from the dry solids. The comparison showed, that ash cover in lysimeters 2 and 3 seems to be effective to reduce leachability of most metals as well as sulfur and sulfate compared to uncovered structure. The calculated metal and sulfur compound amounts were relatively lower from lysimeter 10 due to almost 10 times lower seepage water amount. Therefore, the calculated concentrations showed in the Figures 3 and 4 are not directly comparable.

The average metal concentrations (Table 2) measured from covered coarse enrichment sand lysimeters 1, 4, 6 and 7 had more variations compared to uncovered enrichment lysimeter 8. Leachability of Al, Fe and S were lower with covered structures. However, the leachability of Zn was remarkably lower with uncovered structure which seemed to be illogical. Comparison of metal leachability form covered coarse enrichment sand structures (Figure 3) the Cu leachability was low for all tested structures; Zn leachability was lowest for ash cover structure (lysimeter 1) and traditional structure (lysimeter 4).

Based on the results, the coarser enrichment sand seems to have different leaching properties compared to fine enrichment sand. The weathering of the coarse and fine sands might have effect on the leaching properties.

3.2 pH-measurements

pH was measured from each lysimeters weekly on average. The measurement results are shown in the Figure 5.

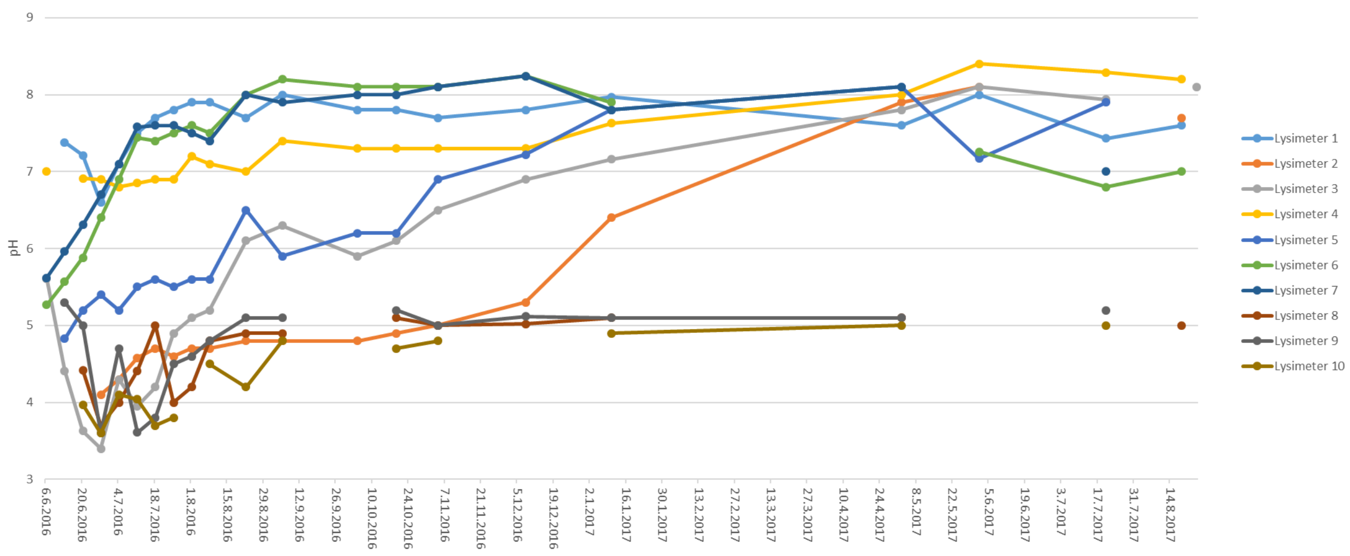

Figure 5. pH measurements from the seepage waters from different lysimeters during 6.6.2016-24.8.2017.

The pH results show, that lysimeters 1, 4, 5, 6 and 7 with coarse enrichment sand have averagely higher pH than lysimeters 2,3,8,9 and 10 with finer enrichment sand. Even the coarse enrichment sand with no cover (lysimeter 5) has increasing pH during the test. Finer enrichment sand with no cover, only soil cover or with soil and gypsum cover (lysimeters 8, 9 and 10) had lower pH during the test. The finer enrichment sand with ash cover (lysimeters 2 and 3) had increasing pH during the test. The ash addition with both enrichment sands seemed to have positive effect on pH.

The variations between fine and coarse enrichment sands are not clear. Based on the initial material tests (Table 1) both enrichment sands had neutral pH (6,7-7,0). During the test however, it seems that finer enrichment sand is more sensitive to acidification and lower pH values were measured from the lysimeters 8, 9 and 10, which had no alkaline ash cover layer. Higher of increasing pH values were measured during the test for lysimeters 2 and 3 with ash cover layer.

Uncovered coarser enrichment sand (lysimeter 5) had increasing pH during the test. Lysimeters 6 and 7, with gypsum and soil cover, had increasing pH during the first two months of the test and the pH values remained neutral during the rest of the test. The ash cover layer in lysimeter 1 seemed to keep the pH neutral during the test. Similar pH results were measured also from the traditional cover layer (lysimeter 4)

3.3 EC measurements

Electrical conductivity was measured from each lysimeters weekly on average. The measurement results are shown in the Figure 6.

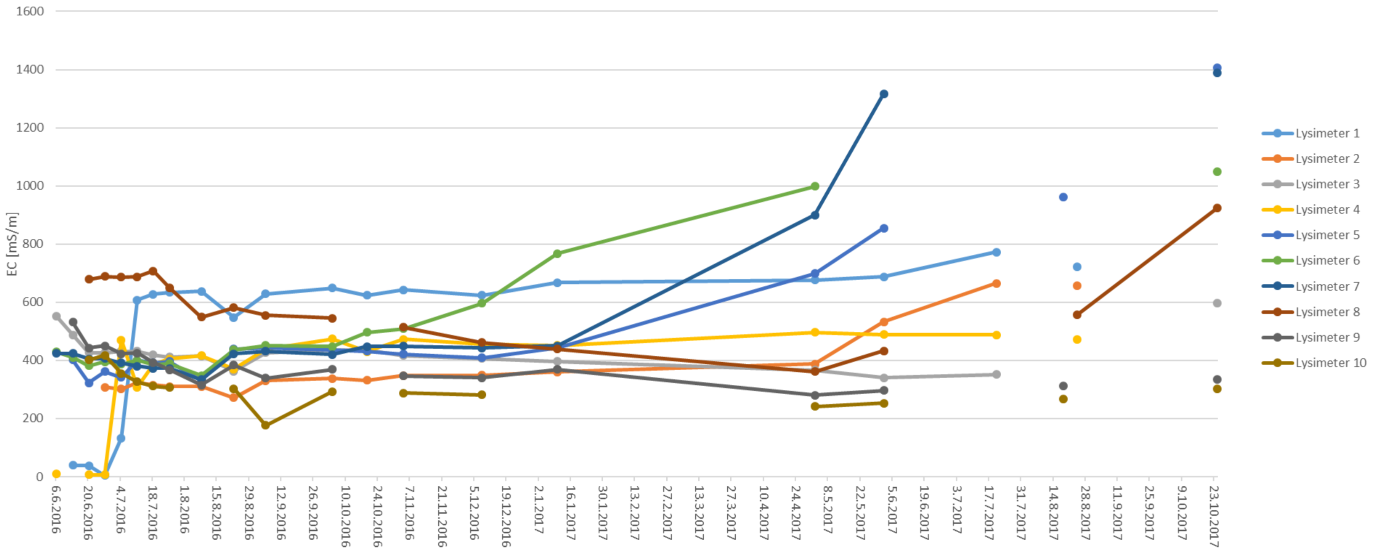

Figure 6. Electrical conductivity of the seepage waters from different lysimeters during 6.6.2016-23.10.2017.

The EC of finer enrichment sand with cover (lysimeter 2, 3, 9 and10) seemed to remain quite stable around one year. During the final months of the measurement clear increasing of EC could be detected with uncovered fine enrichment sand (lysimeter 8) as well as ash covered enrichment sand (lysimeter 2 and 3). No remarkable increase could be detected in lysimeters 9 and 10.

The EC measured from coarser enrichment sand with ash cover (lysimeter 1) and traditional cover (lysimeter 4) showed increase after first month of the test and then remained quite stable through the test. The gypsum cover structures (lysimeters 6 and 7) as well as uncovered structure (lysimeter 5) showed significant increasing of EC after half year of the test.

3.4 Uncertainty estimation of the results

The results achieved from the lysimeters contains certain uncertainties. The analytical results represent only concentrations from short time period of the tests. The sampling could have been improved by taking samples from longer period of time and mixing them to one sample to represent for example the whole month average. The accuracy of calculated soluble concentrations per dry solids could have been able to increase this way.

The coarse and fine enrichment sand seemed to have different leaching properties. Finer enrichment sand seemed to be more sensitive for acidification than coarser sand. The initial amount of burnt lime which had added after the enrichment process was unknown and it might have affected on the results, if coarser sand had more neutralising potential in the beginning of the tests. The weathering speed of the enrichment sands might have also affected on the results. The coarser enrichment sand lysimeters showed increasing of EC in the end of the testing, which might indicate the increase of metal leachability. The pH of these lysimeters showed no decreasing however. The longer follow-up period and closer material testing after the tests might have been beneficial to show the weathering conditions of enrichment sands.

4. CONCLUSIONS

The lysimeter testing carried out in Pyhäsalmi showed some promising results for utilization of industrial wastes in mine cover structures. Especially use of fly ash in cover structures of acid generating enrichment sand seemed to lower the leachability of metals and hold the pH level of leachates near neutral with both tested enrichment sand grades. Compared to the traditional moraine cover structure the use of fly ash has potential in material savings in. In this testing 0,1m thick fly ash cover layer gave similar or even better leachability results with coarser enrichment sand compared to 0,8m thick moraine layer.

However, the use of industrial waste materials in cover layers of different type of mine tailings or enrichment sands needs to be verified case by case. The industrial waste (e.g. fly ash) quality as well as the mine waste composition may variate a lot and the compatibility of different materials needs to be verified.

UPACMIC project continues with large scale construction in Hitura Mine, which is located in Nivala, Finland ~65 kms from Pyhäsalmi Mine. Fortum Waste Solutions has used fibre clay in the cover structure of enrichment sand basins. In addition, reactive dam has been constructed as a reference structure for mobile water treatment plant for the comparison of these two different water treatment methods. Later this year Suomen Maastorakentajat will test alternative materials in Hitura Mine, in bottom structure and in reactive dam structure, which is meant to filtrate harmful substances from the mining area waters.

UPACMIC project continues at least until August 2020, see the project websites: http://projektit.ramboll.fi/life/upacmic/index_eng.htm

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