ENVIronmentally friendly and efficient methods for extraction of Rare Earth Elements from secondary sources

DELIVERABLE D4.2:
REPORT ON THE PROPOSED PROCEDURES AND TECHNIQUES FOR LAND RECLAMATION

Lead Partner: AGH

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1 EXECUTIVE SUMMARY

The purpose of this deliverable is to report the physical and chemical properties of beneficiation residues after the process of REE production from mining waste. The report objective is to provide information required to choose appropriate way of reclamation of the residues. The research carried out within Task 4.4: Developing the guidelines for land reclamation for the heap of the most promising tailings to be treated to recover REE (Work Package 4) included analyzing samples of residues from previously selected prospective sources. Previous Work Packages identified New Kankberg (Sweden) and Covas (Portugal) tailings as prospective sources for future REE production. Within the WP2 REE concentrates were produced along with beneficiation residues. The residues were delivered to AGH reclamation laboratory. At AGH laboratory chemical, physical and biological analyses were performed aimed at assessing residues usefulness for reclamation purposes.

The samples of New Kankberg and Covas beneficiation residues were delivered to AGH laboratory in November 2016 and February 2017, respectively. They were analyzed for loss on ignition (LOI), specific gravity, pH in water and 1 M KCl, electric conductivity (EC), maximum water holding capacity (WHC), initial moisture, texture, total contents of Al, Na, Mg, K, Ca, Fe, Cr, Ni, Cu, Zn, Cd and Pb as well as contents of C, N and S.

The analyses indicated that the beneficiation residues had disadvantageous physical properties (non-cohesiveness), contained no plant nutrients (or extremely low contents thereof) and had disadvantageous pH. Despite there are several possibilities of their reclamation including direct use of the beneficiation residues as a growing medium for plants (soil substrate).

The New Kankberg beneficiation residues can be used as a backfilling in deep mines or disposed on a surface. They do not contain high levels of toxic metals and have high (alkali) pH. The most disadvantageous properties of the New Kankberg beneficiation residues include their non-cohesiveness, rapid liquefaction and thixotrophy as well as low nutrient contents. Despite these negative properties the New Kankberg beneficiation residues can be stored on a surface and used as a soil substrate in land reclamation. In such a case rapid formation of plant cover is necessary to avoid dust emission from the surface. There are several methods of plant introduction on the disposal facilities of the New Kankberg beneficiation residues. However, the most suitable one is the use of organic amendment such as sewage sludge or municipal waste compost, supply nutrients for plants and enable rapid development of plant cover. The choice of plant species to be used in reclamation should take into consideration local conditions (climate, potential natural plant cover, local plant species etc.).

The Covas beneficiation residues had several negative properties impeding their direct use for reclamation including non-cohesiveness, rapid liquefaction, extremely low pH and high S content (sulphides). In order to alleviate toxic pH the beneficiation process should be supplemented with additional step – neutralization of the residues. Neutralized beneficiation residues can be disposed and used as a soil substrate in land reclamation. The beneficiation residues disposal facilities can be covered with plants and reclaimed either for forestry or nature preservation. Such a way of reclamation requires however, heavy supplementation with essential plant nutrients – in particular N. This may be achieved by using organic amendments (sewage sludge or compost) that will deliver substantial amounts of plant nutrients and will improve physical properties of these materials.

CONTENT

2 INTRODUCTION

Production of Rare Earth Elements (REE) from mining wastes requires their reexploitation and reprocessing. After beneficiation process carried out to obtain concentrate of REE, remain large amounts of residues which characteristics may be changed compared with the initial materials. Large amounts of beneficiation residues need to be properly deposited and the disposal facilities need to be secured and reclaimed. Reclamation possibilities of beneficiation residues depend to the largest extent on their physical and chemical properties, geometry (shape) of disposal facilities and local legal regulations.

Studies carried out in WP1 and WP2 identified mining waste materials potentially useful for REE production as well as technologies to produce REE concentrates from them. The mining wastes from New Kankberg in Sweden and from Covas in Portugal appeared to be the most promising for REE production. Pilot tests of beneficiation processes produced REE concentrates for further processing as well as considerable amount of beneficiation residues that should be safely disposed. In order to assess possibilities of their reclamation, in WP4 assessed were some more important physical and chemical properties of New Kankberg and Covas beneficiation residues. As the materials come from distant places and will be disposed in very distant locations as well as due to their different chemical characteristics the assessment of the usefulness for reclamation processes was done separately for the materials from New Kankberg and Covas.

3 PROPOSED PROCEDURES AND TECHNIQUES FOR LAND RECLAMATION FOR NEW KANKERG

3.1 Material reception

The samples were delivered in November 2016 in three plastic bags containing dry material. Each bag was treated as a separate subsample and analyzed separately.

3.2 Analytical methods

The sample was measured for: Loss On Ignition (LOI) by burning the sample in a muffle furnace at 550 °C for 12 h. Specific gravity was measured with pycnometer method. The pH was measured potentiometrically at 5:1 (V:m) ratio in water and 1 M KCl. Electric Conductivity (EC) was measured at 5:1 volume to mass ratio. Maximum water holding capacity (WHC) was determined gravimetrically. Initial moisture of the samples was determined by drying the sample at 105 °C to a constant weight. The texture of samples was measured hydrometrically according to Casagrande method. Atterberg liquid limit was determined with Cassagrande apparatus and plastic limit by rolling out a thread of the fine portion of the material on a flat, non-porous surface according to ASTM Standard D 4318 procedure. Total contents of Al, Na, Mg, K, Ca, Fe, Cr, Ni, Cu, Zn, Cd and Pb were measured with Atomic Absorption Spectrometry after pressure digestion in *aqua regia*. The contents of C, N and S were determined in an elemental analyzer. The N content was measured with Kjeldahl method.

All analyses were done in three subsamples, each in two laboratory replicates.

Pot experiment

In order to check usefulness of the New Kankberg beneficiation residues as a growing medium for plants, a pot experiment with test plants has been established. The New Kankberg beneficiation residues were placed in plastic caps and seeds of a mixture of grasses were sown. All pots were than fertilized with P (27 kg/ha), K (70 kg/ha) and three variants of N fertilization: 1N – 50 kg/ha, 2N– 100 kg/ha, 3N – 150 kg/ha were applied. Samples without any N addition were kept as control (Cont – 0 kg/ha). The pots were placed at 22° C and watered over two weeks. After two weeks of growth the plants were removed from the pots and their biomass was measured.

3.3 Properties of New Kankberg beneficiation residues

Results of previous analyses carried out in WP 1 and WP2 indicated that mineral composition of the New Kankberg tailings is dominated by quartz (ca. 49.5%), followed by muscovite (ca. 39.4%). The tailings contain also kaolin (ca. 5.7%), K-feldspar (3.1%) and albite (2.1%). In their chemical composition dominate silicon and aluminum with relatively high contents of potassium and sodium.

Basic physical properties of New Kankberg beneficiation residues are presented in Table 1. The measured properties had low variability indicating high homogeneity of the residues. The delivered samples were almost absolutely dry. Their water holding capacity was at the level typical for natural soil with loamy and silty texture (ca. 36%). The New Kankberg beneficiation residues were fine textured and contained no skeletal fractions – (diameter > 2mm). The share of sand, silt and clay fractions averaged 16%, 70% and 14%, respectively and the materials were classified as silt loam.

Table 1. Basic physical properties of New Kankberg beneficiation residues – shares of sand, silt and clay fractions, maximum water holding capacity (WHC) and initial moisture. Mean values (n = 3) and standard deviations in parentheses.

Specific gravity	**Sand** (2.00 – 0.05 mm)	**Silt** (0.05 – 0.002 mm)	**Clay** (<0.002 mm)	**WHC**	**Moisture**
g cm^{-3}	(%)	(%)	(%)	(%)	(%)
2.716 (±0.01)	16 (±1.4)	70 (±0.5)	14 (±0.9)	36.0 (±1.2)	0.1 (±0.0)

Despite high content of clay particle the New Kankberg beneficiation residues showed non-cohesive properties as the plastic limit could not be estimated (a thread could not be rolled out). In consequence plasticity index could not be estimated.

Specific gravity was 2.71g cm^{-3} and was typical for those type of rocks. However, bulk density of New Kankberg beneficiation residues will depend on their transport and deposition method. At dry transport and deposition (without compaction) bulk density of these materials approximates 1.04 g cm^{-3} and increases with the compaction level reaching 1.15 g cm^{-3} at light compaction, 1.32 g cm^{-3} at medium compaction and 1.38 g cm^{-3} at heavy compaction. In case of wet transport and storage leading to self-compaction bulk density increases to 1.51 – 1.53 g cm^{-3} . Therefore, the method of New Kankberg transport and deposition will have a strong impact on porosity of the dumped material. At low compaction porosity will vary from 0.58 to 0.61 while at wet transport and deposition will decrease to 0.43 – 0.44.

The New Kankberg beneficiation residues had alkali pH (ca. 8.9 measured in 1M KCl) and did not contain organic C and N while the S content was relatively high and averaged 0.1 %. (Table 2). Extremely low N content indicated high fertilization need if the material would be deposit on the surface.

Table 2. The pH values, electric conductivity (EC) and the contents of C, N and S in the NewKankberg beneficiation wastes. Mean values (n = 3) and standard deviations in parentheses.

pH in H_2O	**pH in KCl**	**EC**	**C**	**N**	**S**
		µS cm^{-1}	(%)	(%)	(%)
8.7 (±0.0)	8.9 (±0.0)	104 (±7)	0.03 (±0.01)	0.00 (±0.00)	0.1 (±0.01)

Electric conductivity was low (104 µS cm^{-1}) indicating low salinity of the studied materials.

The total concentrations of heavy metals (Cr, Ni, Cu, Zn, Cd and Pb) were low and did not exceed values reported for natural pristine soils (Table 3).

Table 3. Total contents of metals in the New Kankberg beneficiation residues. Mean values and standard deviations.

	Al	Na	Mg	K	Ca	Fe	Cr	Ni	Cu	Zn	Cd	Pb
						$\mu g\ g^{-1}$						
Mean	13279	486	2192	3465	1819	2905	8.0	4.0	6.3	17.3	0.2	15.3
S.D.	2374	102	234	800	76	274	1.2	2.8	0.7	8.9	0.1	2.5

In the pot experiment the grass biomass at 2N fertilization variant (100 kg N ha^{-1}) was 1.44 g and at 3N variant (150 kg N ha^{-1}) was 1.58 g thus was much higher than in control without N addition (0.97 g). However, grass biomass in control soil (0.97 g) was higher than in 1N variant (0.83 g) due to higher root biomass (Fig.1 and Fig 2.)

Fig 1. Shoots of grasses growing on New Kankberg beneficiation wastes fertilized with 0 kg N ha^{-1} (K); 50 kg N ha^{-1} (1); 100 kg N ha^{-1} (2) and 150 kg N ha^{-1} (3).

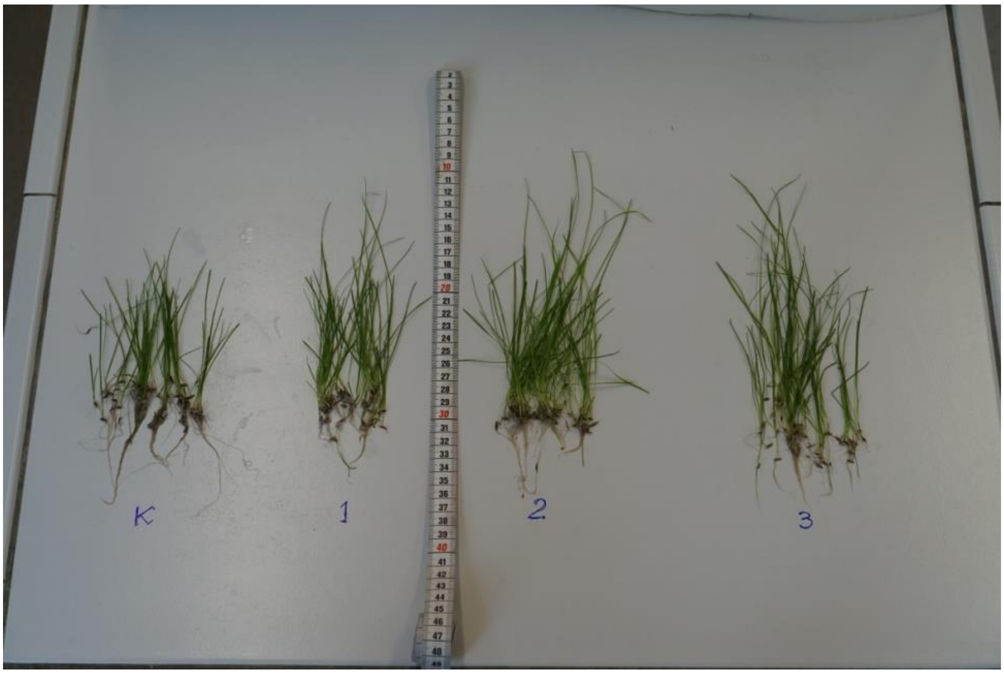

Fig. 2. Length of grasses (shoots and roots) growing on New Kankberg beneficiation wastes fertilized with 0 kg N ha^{-1} (K); 50 kg N ha^{-1} (1); 100 kg N ha^{-1} (2) and 150 kg N ha^{-1} (3).

3.4 Usefulness of the New Kankberg beneficiation residues for reclamation

The laboratory experiments and pot experiment carried out in WP4 enabled assessing usefulness of the New Kankberg beneficiation residues for reclamation.

The residues had advantageous texture of silt loams. Natural soils with such texture usually show good water and air conditions and medium cohesiveness. However, that was not the case for the New Kankberg beneficiation residues. Lack of cohesiveness of the New Kankberg beneficiation residues results apparently from their artificial origin. These materials were produced by grinding ore-bearing rocks therefore they do not have the same properties as natural soil parent materials that emerge due to physical and chemical weathering. In the beneficiation waste materials the finest particles (<0.002 mm) were produced by simple crumbling of rocks and did not have the same properties as naturally occurring clays that contain secondary clay minerals characterized by large sorption capacity and specific area, high values of consistency limits, plasticity index etc. Artificial materials such as tailings, fly ashes often exhibit thixotrophic properties. These materials at certain moisture may rapidly turn their consistency from stiff to liquid when shaken or agitated. Indeed the New Kankberg beneficiation residues tended to flow when shaken and became stiff when allow to settle for certain time. Furthermore upon drying they tended to form a stiff and impermeable surface layer. Thixotrophy of the New Kankberg beneficiation residues is a negative feature excluding possibility of their storage on inclined areas or slopes. Forming of stiff and impermeable surface layer under dry conditions may lead to water deficiency for plants.

The New Kankberg beneficiation residues contained no nitrogen which is an essential nutrient for plants. The residues had no organic matter which is required for proper functioning of soils as an energy source for soil microorganisms. Low contents of plant nutrients are likely to be a limiting factor for growth of plants on the beneficiation residues. Pot experiment indicated a positive reaction of plants to increasing N fertilization (100 – 150 kg/ha). Therefore, during the reclamation of New Kankberg beneficiation residues an initial N fertilization is required. Application of mineral N fertilizer may additionally decrease cohesiveness of the residues. Therefore organic amendments should be preferred.

The total contents of trace elements do not exceed values typical for pristine soils and do not exceed permissible values. Therefore they do not pose and threat for plants and ecosystem functioning.

3.5 Proposed procedures and techniques for reclamation of the New Kankberg beneficiation residues disposal facilities.

Properties of the New Kankberg beneficiation residues enable several ways of their reclamation.

The New Kankberg beneficiation residues are non-toxic and may be used for various purposes. They can be used as back filling in deep mines, as land filling to level off local depressions or be a substrate in reclamation for forestry or nature rehabilitation. However, they should not be used for construction of slopes or deposed on inclined surfaces. The most negative features include non-cohesiveness and rapid liquefaction. In dry state these materials may be a source of dust emission therefore prior to reclamation they should be kept moist.

Since the New Kankberg beneficiation residues are produced from New Kankberg tailings the most suitable way of their disposal is to return them back to the tailings disposal facility they were taken from. Such a tailing disposal facility can be then reclaimed for forestry or nature restoration. Redevelopment of forest or grassland ecosystems on the stored beneficiation residues can be achieved in two ways – covering them with a layer of potentially fertile material (eg. soil) or direct introduction of plants into the dumped residues. The first solution is less suitable as it requires soil removal at a different place as well as transport and spreading of this material on the waste storage facility surface. Since the New Kankberg beneficiation residues are not toxic they can be used as a substrate for *in-situ* soil formation.

The major negative properties of the New Kankberg beneficiation residues are their non-cohesiveness, dust emission in dry state, rapid liquefaction at increasing moisture and extremely low nutrient contents. In order to alleviate these negative features of the New Kankberg beneficiation residues they should be mixed with organic amendments such as sewage sludge, municipal solid waste compost N-enriched peat or bark. Choice of the amendment would depend on local legal regulations and availability. The applied organic amendments should fulfill local environmental requirements in terms of their chemical composition (eg. heavy metal contents) and sanitary requirements. The applied dose of organic fertilizer should contain not less than 100 – 150 kg of total N per ha (preferably even more as only a part of N in the organic amendments is immediately available for plants). Organic amendments are superior to mineral fertilisers due to their high content of both nutrients and organic matter. Application of organic amendments will alleviate negative physical properties of the beneficiation residues by improving porosity as well as water and air availability. This is because the addition of organic amendments will prevent formation of stiff superficial layer upon drying of the residues. Application of organic amendments will create also a stock of essential nutrients for plants.

The method of organic fertilizer application should be adjusted to the way of reclamation. The calculated amount of fertilizer can be spread over the entire area and then mixed with the uppermost part of the waste by plowing down to depth of 25 – 50 cm. Organic fertilization may be also carried out in two stages. In the first stage a part of the organic fertilizer should be spread over the entire area and plowed down to depth of 50 cm and in the second stage the remaining organic fertilizer should be spread over the reclaimed area and plowed down to 10 – 15 cm with ripper or harrow. This method of organic fertilization should be applied is the reclaimed area is to be sown with grasses and herbs. If shrubs and trees are to be planted the organic fertilizer should be applied to planting holes of the tree seedlings. Such application of organic fertilizer will increase the stock of nutrients close to seedlings roots and will restrict the growth of weeds that may compete with the planted target species.

Since the beneficiation residues are prone to compaction the machinery used for agro-technical measures should have as low unit pressure as possible.

The proposed way of the New Kankberg beneficiation residues reclamation does not exclude other ways. As it was mentioned before these residues can be used for backfilling in deep mines, as a landfilling to level off local depressions especially in the landscape affected by mining activities or to form protective layers when compacted.

4 PROPOSED PROCEDURES AND TECHNIQUES FOR LAND RECLAMATION FOR COVAS

4.1 Material reception

The samples were delivered in February 2017 in a single plastic bag containing wet material.

4.2 Analytical methods

The laboratory methods used to assess properties of the Covas beneficiation residues were generally the same as those used for the New Kankberg samples. Briefly, the Covas beneficiation residues were measured for initial moisture by drying at 105 °C to a constant weight, Loss On Ignition (LOI) by burning the sample in a muffle furnace at 550 °C for 12 h and specific gravity with pycnometer method. The pH was measured potentiometrically at 5:1 (V:m) ratio in water and 1 M KCl. Electric Conductivity (EC) was measured at 5:1 volume to mass ratio. Maximum water holding capacity (WHC) was determined gravimetrically. The texture of samples was measured hydrometrically according to Casagrande method. Atterberg liquid limit was determined with Cassagrande apparatus and plastic limit by rolling out a thread of the fine portion of the material on a flat, non-porous surface according to ASTM Standard D 4318 procedure. Total contents of Al, Na, Mg, K, Ca, Fe, Cr, Ni, Cu, Zn, Cd and Pb were measured with Atomic Absorption Spectrometry after pressure digestion in *aqua regia*. The contents of C, N and S were determined in an elemental analyzer. The N content was measured with Kjeldahl method.

The Covas beneficiation residues proved to have low pH, therefore their hydrolytic acidity (Hh) was measured. Briefly, the samples were treated with 1M $Ca(CH3COO)_2$ using 1:2.5 waste/solution ratio. Suspensions were shaken for 1 h, filtered and titrated with 0.1 M NaOH to pH = 8.2.The exchangeable acidity was calculated from the amount of base used and expressed in $cmol_{(+)}kg^{-1}$. However, high S content and in particular high sulphides content may lead to acidification of residues due to oxidation of sulphides. In order to assess potential acidification of the Covas beneficiation residues the waste samples were treated with H_2O_2 to enforce rapid oxidation of sulphides. Subsequently the samples were measured for pH and Hh as described above.

Pot experiment

In order to check usefulness of the New Kankberg beneficiation residues as a growing medium for plants a pot experiment with rye (Secale sp.) has been established. The Covas beneficiation residues were placed in plastic caps and seeds of rye (n = 14 per pot) were sown. All pots were than fertilized with P (32 kg/ha), K (75 kg/ha) and three variants of N fertilization: 1N – 50 kg/ha, 2N– 100 kg/ha, 3N – 150 kg/ha were applied. Samples without any N addition were kept as control 4K – 0 kg/ha). The pots were placed at 22° C and watered over two weeks. After two weeks the growth plants was monitored visually by assessing the number of germinated seeds and height of plants.

4.3 Properties of Covas beneficiation residues

The texture of the Covas beneficiation residues was similar to the New Kankberg residues – they contained 16% of sand fraction, 67% of silt fraction and 17% of clay fraction (Table 4). However, they consistency limits were typical for non-cohesive materials. The calculated plasticity index was only ca. 1 – 2% indicating that these materials may rapidly change their consistency from stiff to liquid (rapid liquefaction).

Table 4. Basic physical properties of Covas beneficiation residues – shares of sand, silt and clay fractions, maximum water holding capacity (WHC) and initial moisture. Standard deviations of three replicated measurements (when available) in parentheses.

Specific gravity	**Sand** (2.00 – 0.05 mm)	**Silt** (0.05 – 0.002 mm)	**Clay** (<0.002 mm)	**WHC**	**Moisture**
g cm^{-3}	(%)	(%)	(%)	(%)	(%)
2.74 (±0.01)	16	67	17	64.0 (±1.2)	48 (±4.7)

Mineralogical analyses indicated that prior to beneficiation process dominating minerals in the Covas material were muscovite (24.64 %), quartz (17.37 %), calcite (13.94 %) and kaolinite (12.45 %). The material contained also considerable amounts of K-feldsper (5.85 %), arsenopyrite (5,37 %) and albit (5.02 %). However, the delivered samples of the Covas beneficiation residues did not contain any carbonate. Presumably, during technological processes large part of arsenopyrite was decomposed to suphuric acid that in turn was partly neutralized by calcite.

The Covas beneficiation residues had strongly acid pH (3.2 measured in 1M KCl), contained no calcium carbonate and had high S content (0.76%) (Table 5). The hydrolytic acidity was initially 3.2 $cmol_{(+)}$/kg. However, after oxidation with 30% H_2O_2 pH in water decreased to 2.9 and Hh increased to 13.3 $cmol_{(+)}$/kg.

Table 5. The pH values, electric conductivity (EC) and the contents of C, N and S in the NewKankberg beneficiation residues. Mean values (n = 3) and standard deviations in parentheses.

pH in H_2O	pH in KCl	EC	C	N	S
		$\mu S\ cm^{-1}$	(%)	(%)	(%)
3.5 (±0.0)	3.2 (±0.0)	577 (±13)	0.28 (±0.02)	0.48 (±0.01)	0.76 (±0.02)

Table 6. The hydrolytic acidity prior to (Hh_1) and after oxidation (Hh_2) of the Covas beneficiation residues with 30% H_2O_2. The pH in water after the oxidation is also presented.

Hh_1	Hh_2	pH in H_2O
$cmol_{(+)}$/kg		
3.2	13.3	2.9

The Covas beneficiation residues contained more N and C_{org} than the new Kankberg residues (0.47% and 0.29% for N and C_{org} respectively). However, availability of N for plants was low as indicated in the pot experiment. In this experiment increasing N fertilization resulted in improved germination of rye. At 50 kg/ha N only three seeds germinated, at 100 kg/ha N five while at 150 kg/ha N ten out of 14 seeds germinated. The growth of plants was also apparently better at higher N fertilization.

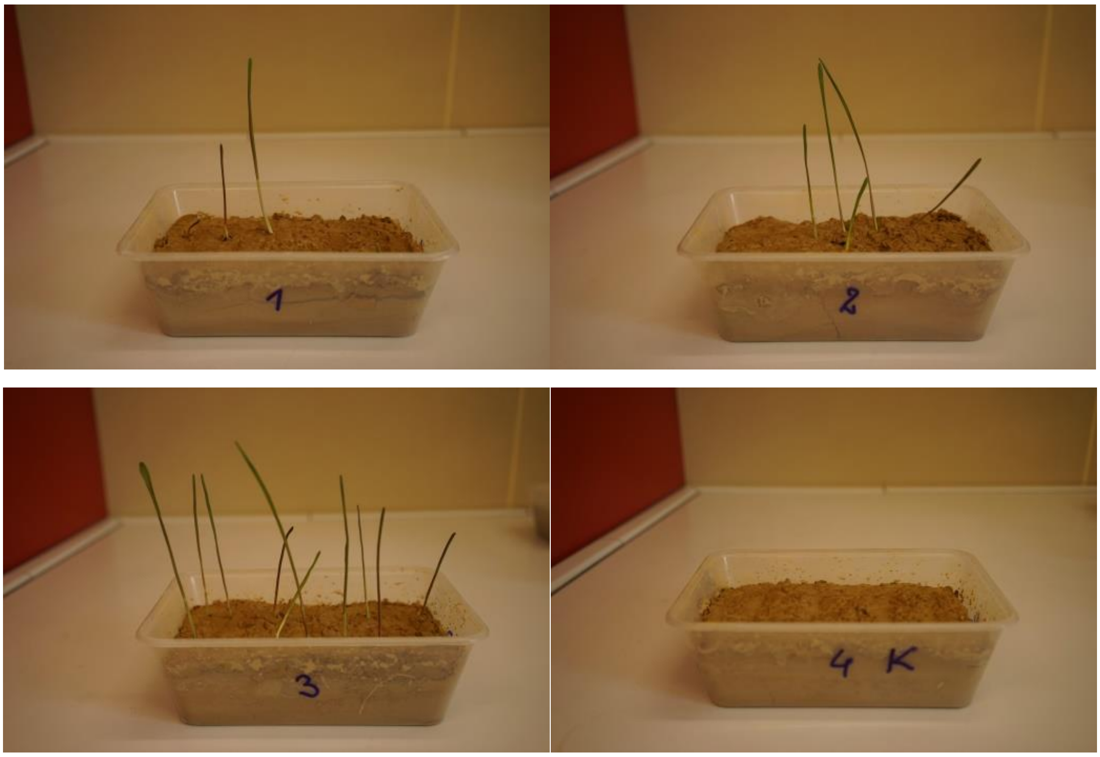

Fig. 2. Growth of rye on the Covas residues fertilized with 0 kg N ha^{-1} (4K); 50 kg N ha^{-1} (1); 100 kg N ha^{-1} (2) and 150 kg N ha^{-1} (3).

The total contents of metals (including heavy metals such as Cu, Zn, Cd and Pb) was low and did not exceed values reported for natural pristine soils (Table 7).

Table 7. Total contents of metals in the Covas beneficiation residues. Mean values and standard deviations.

	Al	**Na**	**Mg**	**K**	**Ca**	**Fe**	**Cr**	**Ni**	**Cu**	**Zn**	**Cd**	**Pb**
	μg g^{-1}											
Mean	29072	213	2348	4656	10947	37162	28.6	13.6	156.0	139.7	0.6	56.2
S.D.	2908.3	38.0	52.7	453.3	259.0	177.5	0.5	0.5	2.9	1.2	0.0	0.4

4.4 Usefulness of the Covas beneficiation residues for reclamation

The laboratory analyses along with pot experiment indicated that the Covas beneficiation residues can be used as a substrate for plants growth. The most important reclamation measures crucial for further steps of reclamation include neutralization of extreme acidity of these materials, supplementation of essential nutrients (in particular N) and improvement of physical properties (thixotrophy and rapid liquefaction).

The Covas beneficiation residues are characterized by extremely low pH and high S content (present as sulphides). The hydrolytic acidity of the unoxidized beneficiation residues was relatively low (3.2 $cmol_{(+)}$/kg) however after oxidation with H_2O_2 it increased to 13.3 $cmol_{(+)}$/kg with concurrent pH decrease to 2.9 (measured in water). Neutralization of this acidity would require ca. 7 kg of $CaCO_3$ or nearly 5 kg of $Ca(OH)_2$ per 1 Mg of the Covas beneficiation residues.

The second negative feature of the Covas beneficiation residues was their non-cohesiveness. The texture of the Covas beneficiation residues was similar to the New Kankberg residues – they contained 16% of sand fraction, 67% of silt fraction and 17% of clay fraction. However, their plasticity index were typical for non-cohesive materials. In consequence these materials may easily undergo liquefaction and exhibit thixotrophic properties.

The content of N in the Covas beneficiation residues was low and the present N was largely unavailable for plants as indicated by very poor germination of rye seeds in control sample. Therefore the residues will require substantial fertilization during the process of reclamation.

The contents of metals were higher than in the beneficiation residues from New Kankberg however did not exceed values typical for natural soils therefore there is no danger of heavy metal pollution caused by the Covas beneficiation residues.

4.5 Proposed procedures and techniques for reclamation of the Covas beneficiation residues disposal facilities.

Since the Covas beneficiation residues are produced from old, reclaimed tailings the most suitable way of their storage is to return them back to the tailings storage facilities they were taken from. After returning the residues to the storage facilities they can reclaimed for forestry or nature restoration. However, a crucial step for their reclamation is appropriate neutralization of their extreme acidity. Calculated amounts of $CaCO_3$ or $Ca(OH)_2$ required to entirely neutralize their acidity are large. Therefore, the best way of neutralization would be to add neutralizer at the end of beneficiation process or alternatively as the first reclamation measure. Including neutralization into the beneficiation process (as the final step) seems to be the best option. The neutralized beneficiation residues will have neutral pH and elevated Ca content, and this will limit or entirely exclude their negative impact on the environment (eg. acid water drainage). Neutralization of the residues as the first reclamation step would require intensive field works and the neutralized layer would be relatively thin, leaving the extremely acid residues in deeper layers and thus posing potential thread to the environment if not appropriately isolated.

Aside pH other physical and chemical properties of the Covas beneficiation residues are similar to those from New Kankberg. The most negative properties include non-cohesiveness, rapid liquefaction and low nutrient contents. Therefore the proposed reclamation methods are generally similar.

In order to alleviate negative features of the Covas beneficiation residues they should be mixed with organic amendments such as sewage sludge or municipal solid waste compost or N-enriched bark. Choice of the amendment should depend on local legal regulations and availability and the chosen amendment should fulfill local environmental requirements in terms of their chemical composition (eg. heavy metal contents) and sanitary requirements. As in the pot experiment the best results were obtained at N dose 150 kg/ha we suggest that the applied dose of organic fertilizer should contain at least this amount of N per ha or preferably even more to create a stock of these element for future plant nutrition. Application of organic amendments will alleviate negative physical properties of the beneficiation residues by improving porosity, water availability and aeration. Application of organic amendments will supply the plants not only with N but will also create a stock of other essential plant nutrients.

As in the case of the New Kankberg beneficiation residues the method of organic fertilizer application should be adjusted to the way of reclamation. If the waste storage facility is to be reclaimed for grassland the organic amendment should be applied at the entire surface and plowed down to the depth of ca. 25 – 50 cm. If shrubs and trees are to be planted the organic fertilizer may be applied to planting holes of the tree seedlings in order to limit growth of weeds that may compete with the planted target species. The machinery used for agro-technical measures should have as low unit pressure as possible in order to avoid compaction of the beneficiation residues.

Detailed choice of plant species to be used in biological reclamation of the Covas beneficiation residues their spacing, fertilization etc. should be designed taking into consideration local environmental conditions (potential plant cover, climate conditions, mean annual temperature), legal regulations and planned future use of the reclaimed waste storage area.

5 CONCLUSIONS

The laboratory analyses of the New Kankberg and Covas beneficiation residues indicated that these materials are usefull for land reclamation and can be treated as a soil substrate. However, these materials have several neagative properties that impede their reclamation. These features include non-cohesivity, rapid liquefaction, thixotrophy and extremely low nutrient contens. The Covas beneficiation residues additionally are extremely acid and contain high levels of S in sulphides form that may be oxidized leading to even stronger acidification.

The best option for the residues treatment and reclamation seems to be their return to the disposal facilities they were taken from and subsequent reclamation for nature rehabilitation or forestry.

Due to high acidity the reclamation of the Covas beneficiation residues should include their neutralization. For the best results this step should be done at the end of beneficiation process and the dose of neutralizer should be calculated taking into consideration not only the present acidity but also acidity that may arise from oxidation of suplhides present in the residues.

The best way of the beneficiation waste reclamation is their fertilization with organic amendments (eg. sewage sludge or compost). Application of organic amendments can accelerate initial reclamation and lead to rapid development of self-sustaining ecosystems. Readily decomposable organic compounds contained in the amendments may provide immediate nutritional effects, whereas stable, less decomposable compounds may create a stock of essential nutrients and provide long-lasting effects. Application of organic amendments will improve also the physical properties of the residues limiting their sensitivity to water and wind erosion.