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The Deliverable D1.8 of the BioMinE Integrated Project is a report entitled:

" State of the Art of Management of Wastewater and Tailings in Processes Relevant to BioMinE"

The level of dissemination of this deliverable is public. A summary is proposed hereafter.

Summary:

This deliverable considers the management of water and waste likely to be generated by leaching metal values from BioMinE resources, especially base metal and gold sulphide concentrates. Because few industrial operations of this type exist so far, important aspects of waste management have been considered as analogous to those of the wider mineral industry. R&D on industrial waste has developed rapidly since the inception of BioMinE. D1.8 has thus been formulated during the project to review recent reports and discuss the current state of the art in relation to BioMinE processes, particularly bioleaching. The deliverable deals primarily with bulk mineral residues and water, and also, where appropriate, with gaseous products and energy. It does not deal with metal recovery itself except in so far as leaching and waste treatment are integrated, more or less, within an overall process flowsheet. The work confirms that mineral dumps and tailings dams continue to represent the best available waste management technology under regulation, when employed with optimum water recycle and void backfill. Additionally, combined uses for mineral wastes with wastes from other industries, yielding practical products, increasingly indicate the potential of integrated routes towards sustainability in mineral and metal production. In particular, tailings might be re-used with ash from power stations or incinerators for controlled low strength materials in the construction industry and with sewage products from the water industry for artificial soil formulations in agriculture and industrial restoration.

Imperial College London

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1. Introduction

Mineral industry waste is normally discarded, at significant cost, to dumps (coarse material) and tailing dams (fine material). The cost is monetary and environmental, under regulation. Efficient management reduces disposal as far as possible, particularly by re-use of mineral matter in backfill of mining voids and recycle of process water – and through improved control of emissions of gases and heat as appropriate. Increasing emphasis is placed on re-utilisation, rather than storage/disposal, of mine waste for the future through innovative solutions and emerging technologies. However, change is slow with conservative mine operators continuing to focus on conventional 'good practice' guidelines. Full sustainability with complete elimination waste, particularly in exposed mineral dumps and dams, remains a distant prospect. Nonetheless, as the cost of disposal increases through regulation, new opportunities for reduction and re-use of mineral waste become possible. In particular, new combinations of mineral wastes with other bulk industrial products such as power station ash and treated sewage sludge can be assessed for application in civil engineering work, agriculture and social amenities.

Deliverable D1.8 centres on the management of bulk wastes likely to be generated by bioleaching metal values from BioMinE resources, especially sulphide flotation concentrates. Resulting wastes have novel technical characteristics, which have been elucidated elsewhere in BioMinE through focussed research and assessed for potential in new products (Deliverable D2.3). By contrast, important aspects of waste management remain largely untested because few relevant pilot or commercial scale bioleach operations exist. However, efficient procedures should reflect those of the wider mineral industry – including rapid developments arising from recent regulatory changes and attendant R&D. Thus, D1.8 was formulated during the lifetime of the BioMinE project to include a review of up-to-date industry-related reports and comment on waste, discuss the current state-of-the-art, and predict practical management procedures for BioMinE processes.

The deliverable deals primarily with bulk mineral residues and water, and also, where appropriate, with gaseous products and energy. It does not deal with metal recovery itself except in so far as leaching and waste treatment are integrated within an overall process flowsheet. One objective is to establish if regulated mineral dumps and tailings dams will, albeit with modification, continue to represent the best available waste management technologies, when employed with optimum water recycle and void backfill. A second objective is to assess whether combined use of mineral wastes with wastes from other industries in new products and applications, especially cemented mixed materials and artificial soil formulations, presages practical routes to improved sustainability through bio-processing in mineral and metal production. A third objective is due consideration of the usefulness and safety of such materials, especially when the materials may contain toxic components otherwise leachable and polluting in the environment.

The approach adopted has involved one partner (Imperial) reviewing recent literature, visiting and/or corresponding with relevant industry (including BioMinE partners and others), collating information and reporting.

2. Literature review

2.1 Rationale

This review considers selected reports (mostly since 2003) on generation, environmental impact, legislation, and management relevant to solid bulk waste materials – and, where appropriate, to water, gas and energy. The treatment is intended to be brief rather than comprehensive, and generally provides one recent reference as an example on each facet of interest, underpinned where appropriate by short un-referenced commentaries on longer established matters. It focuses on issues relevant to BioMinE waste management, for which purpose the review deals partly with wastes from the extractive industries and partly with relevant wastes from other industries. The selection has been based on a recent PhD thesis [1] and on separate searches.

Waste considered here is generally a well-defined large tonnage solid material resulting from localised industrial or municipal activity and having little or no physical or contained value. Mineral bulk waste arises directly from mineral industry processes, e.g., waste rock and process tailings, and from disposal of mineral-derived products, e.g., metallurgical slag, power station ash (particularly pulverised fuel ash, PFA) and construction and demolition products (C&D). Organic bulk waste is mainly sewage sludge from the water industry or municipal green waste. General landfill rubbish is not considered directly, although landfill mining and processing are becoming more feasible [2]. Recycling of significantly distributed or complex products, e.g., automobiles, is also excluded.

Solid waste may be classified (from regulation) as inert, non-hazardous or hazardous, and (from technical character) as of certain volume, particle size distribution and durability (including hardness, porosity and reactivity). By simple management definition, waste is material discarded to the environment, commonly at a cost to landfill. In this context, waste may be strictly unusable (hazardous) or simply surplus to requirements near a locality in question, e.g., too much barren rock for use in underground void stabilisation, too much PFA for use in cement or too little process capability to convert sewage into a safe soil conditioner. Most waste relevant to this review may be considered as surplus material.

Therefore, up-to-date technologies already involving a proportion of a low value bulk material are of interest, as well as innovations possibly leading in future to re-use of the remainder. Emphasis is placed on three main management technologies: void filling in the mineral industry (mine backfill), surface filling in the construction industry (civil engineering fill) especially considering controlled low strength materials, and surface fill and restoration in mining areas (surface regeneration) especially dealing with landscape and artificial soil generation.

Water is mainly considered in this review *inter alia* as an integral part of processing and waste management (and not generally as waste). However, limited separate discussion is given to highlight important aspects of re-use and quality control on discharge. Gases and energy, although similarly integral, have a less direct importance in the present context and are not considered separately.

2.2 Waste generation

2.2.1 Mineral waste

Extractive operations, i.e., exploration, mining, quarrying and processing of minerals, generate large volumes of solid wastes owing to the normally high waste-to-product ratio. These wastes include mining waste (topsoil, overburden, waste rock and mine water); processing waste (coarse process waste and fine tailings/slimes in process water); and metallurgical waste (flue dust/fumes, roasting products, leach residues and/or precipitates, slag) [3].

With regard to processing units [4], comminution, i.e., crushing and grinding to liberate individual mineral phases, is generally followed by concentration, e.g., froth flotation, gravity or magnetic separation, or leaching to separate values from gangue. More than 99% of the original ore may end up as waste, particularly tailings, especially when low-quality ores are processed. Tailings are either produced as a slurry consisting of 15-60% solids (also known as slimes), or as coarse tailings following de-watering, filtration and/or drying. A heap or dump of coarse tailings may also arise from in-place leaching activities. Finished products result primarily from pyrometallurgical processing (smelting) of a flotation concentrate or hydrometallurgical or biohydrometallurgical processing (leaching) of ore or concentrate, leaving behind further quantities of waste as slag or gangue/precipitate.

Wastes generated at different mines vary considerably in their properties because of the different mining and extraction techniques used, and because of differences in the composition of the mined ore. Thus the physical and chemical characteristics of tailings vary according to mineralogical and geochemical compositions; specific gravity of particles; settling behaviour; permeability; consolidation behaviour; rheology/viscosity; pore water chemistry and leaching properties [5]. Tailings particles are generally angular and their grain size is usually in the range of clay to sand, i.e. 1 μm to 1 mm. Dry tailings typically consist of 70-80 wt% sand-sized particles and 20-30 wt% finer clay-sized particles. In general, tailings solids may contain primary ore and gangue minerals; secondary minerals formed during weathering; chemical precipitates formed during and after mineral processing; and chemical precipitates formed after disposal in tailings storage facilities [3]. Analogous comments apply to metallurgical slag. However, the main considerations in management (Section 2.5) are quantity, particle size distribution and reactivity.

As indicated above, mineral products give rise to other bulk wastes as a result of further processing or utilisation. Examples are PFA and incinerator ash, cement kiln dust (CKD) and C&D. PFA, also called fly ash, is finely-divided siliceous or calcareous material captured in large quantities in electrostatic precipitators as a by-product of energy generation at coal fired power stations [6]. The material normally consists of sand/silt-sized particles, often partly fused and spherical in shape, and variable in deleterious components (residual carbon and small concentrations of leachable toxic elements) depending upon the quality of the original coal and the power station process. Ash from municipal or water industry incinerators burning rubbish or sewage solid [7] is similar in production and character, although the intention is generally waste reduction rather than energy generation. The ash is usually relatively less uniform and more seriously contaminated. CKD [8] is a by-product of cement manufacture, an alkaline mixture of fine-grained partially calcined limestone and shale. C&D [9] is a complex waste obtained from old building construction, but usually readily separated into major components, including brick and concrete (relevant to the present review). Mineral derived C&D is often crushed and graded for re-use, although surplus material of all descriptions (particularly silt-sized material) is produced. C&D mineral waste has relatively large range of particle sizes and wide availability in populated regions.

2.2.2 Organic waste

Organic waste or biowaste (biodegradable material) comprises mainly (i) waste products of human food digestion, sent to sewage treatment [10] (ii) surplus food and vegetation, which may be anerobically digested and composted, but is normally sent to landfill [11] (iii) wood products, which may be recycled, burned for energy, or sent to landfill. Municipal sewage is wastewater containing a small proportion of organic material (often less than 1%) of consumer and/or industrial origin. Industrial sewage, separately produced, e.g., in large paper, alcohol and confectionary processing plant, is similar but may contain a greater concentration of organics. Green waste is primarily surplus fruit and vegetation, although the term is also occasionally applied to food more generally and to processed wood, e.g., clean sawdust.

Sewage is treated to remove harmful components (particularly pathogens), separate and discharge most of the contained water to the local drainage system and stabilise (minimise) residual sludge for safe re-use or disposal in landfill. Conventional sewage treatment [10] involves primary treatment (physical sedimentation, i.e., settling of solid particles from suspension under gravity), secondary treatment (biological oxidation of dissolved and residual suspended organic particles) and anaerobic digestion (degradation of combined sludge from primary and secondary treatment in the absence of oxygen). The product is digested (stabilised) sludge, a dark-coloured slurry (about 6% solids) or, after centrifuging, a semi-solid gel (about 20% solids). Concentrated industrial liquors may be anaerobically digested directly [12], with process water recycled for re-use. Recent developments have included biological N&P removal, e.g., at the state-of-the-art sewage treatment works at Reading, UK [13], to reduce nutrient concentrations in discharges to river water. Local brewery effluent is used at Reading to create the necessary biological conditions. CHP technology is also included for energy recovery.

2.3 Environmental impact

Despite the efforts of EU member states to minimise disposal, quantities of solid mine waste continue to increase [14]. This waste was recently estimated to amount to about 34%, i.e., 714 million tonnes, of the total waste generated in the EU [15]. Thus, notwithstanding improved mineral and land management, such large quantities indicate that environmental risks and actual impacts on the landscape and drainage systems are likely to continue into the foreseeable future.

For instance, the visual impact of tailings dams and ponds, of which at least 3500 exist worldwide (with more planned), is evident because of their large footprint near many large mining enterprises [4]. Despite continual development of improved guidelines, standards, regulations and management plans, including increasingly complex containment systems [16], there have still been 2-5 major tailings dam failures per annum with serious environmental consequences during the last 30 years. On water quality, acid mine drainage has been described recently as the major problem facing the mining industry worldwide [17]. This creates a huge issue, for instance, in meeting the terms of the Water Frame Work Directive by 2015 (Section 2.4).

Mineral derived wastes e.g., C&D and ash, and organic wastes e.g., municipal and agricultural/forestry products, are grouped differently in the literature [15] but interpolations can nevertheless be made from the data for them each to account for about 20% of the total (most of the remaining 26% being attributable to manufacturing). In these cases, legislation is leading to significant reductions through recycling, e.g., much C&D is now retained as new foundations on site or reused in new building products and, in some areas, essentially all sewage products are returned to the land. However, it is clear that large volumes of these materials remain as waste, with corresponding landfill related impacts.

2.4 Regulation

The products and wastes arising from industrial, commercial and consumer activities are generally subject to legislation and regulation. For instance, products (but not wastes) must be registered under the new REACH provisions unless specifically exempted [18].

For mineral wastes, the key regulation is the Mine Waste Directive, published by the European Commission in 2006 [19], and applying to deleterious materials from the extraction, treatment and storage of mineral resources and the working of quarries. This directive is designed to ‘prevent or minimise potential adverse effects on the environment and resultant risk to health from the management of waste from the extractive industries’; and ‘prevent major accidents or reduce their consequences through measures based on best available techniques (BAT)’. Implications of the directive and BAT are expressed by the EIPPCB [20] and Directive 2008/1/EC concerning integrated pollution prevention and control [21], and supersede earlier requirements on mineral waste. For water, the corresponding measure is the Water Framework Directive published in 2000, requiring Member States to reach good chemical and ecological status in inland and coastal waters by 2015. Progress continues towards meeting this target [22].

Thus, nowadays no extractive industry in the EU may operate without a waste management plan, and no waste facility may operate without a permit issued by the competent authorities, e.g., the UK Environment Agency. The competent authority must satisfy itself that waste facility operators have taken the measures necessary to prevent water and soil contamination, in particular by evaluating leachate generation; preventing leachate generation and preventing surface water or groundwater from being contaminated by the waste; and treating contaminated water and leachate in order to ensure their safe discharge. When placing mine waste into excavation voids at surface or underground for rehabilitation and construction purposes, i.e., as backfill, operators must take appropriate measures to secure the stability of waste, monitor it and prevent soil and water pollution. This may be achieved by careful design procedures and a thorough understanding of the properties of the backfill material and the surrounding environment. The Mine Waste Directive also introduces specific measures, e.g., relating to cyanide concentrations in tailings ponds and the disposal of waste in waters other than those specifically intended for waste disposal.

With regard to mineral-derived waste, legislation continues to develop rapidly. For instance, although PFA (which contains variable small quantities of metals and carbon and gives an alkaline reaction) is formally classified as waste, regulations are not currently enforced pending de-regulation for some purposes [23]. Thus, the material is widely employed as a pozzolanic binder/filler in cement and concrete, among other applications, and has never been shown to pose a significant environmental risk [24]. However, much larger quantities are usually available near power stations than can be marketed, and these can have a large visual impact. Incinerator ash is problematical because of stronger environmental concerns but rubbish incineration is nevertheless becoming more acceptable, for instance in the UK [25]. Regarding mineral C&D, much is now separated and re-cycled in Europe, although recent reports indicate developments are still needed. A major problem remains with silt-sized residues, which are routinely land-filled.

In the case of biodegradable (organic) waste, or biowaste, a full directive is not yet available, but development continues [26]. Similarly, and more generally, the revised Waste Framework Directive, dealing comprehensively with recycling and waste prevention, is awaited, although a final version was reportedly approved by MEP's in June 2008 [27]. In the meantime, many earlier requirements on biodegradable materials are consistent with above-mentioned provisions on BAT and IPPC.

2.5 Solid waste management technology

2.5.1 Mine backfill

The term backfill refers to replacement of unwanted mineral products in underground voids as a means of waste disposal and/or as a structural support. The term is also sometimes used for filling surface excavations (see Section 2.5.3). Backfilling of underground voids is increasingly perceived as an environmentally friendly, as well as a cost saving and mature technology, for permanent management of mine waste [28]. However, the potential for leaching and contamination of surface and groundwater remains [29]. Mine backfill also represents a substantial expenditure, up to 20% of all mining costs [30]. Provision of cement as a binder, when used, can represent some three quarters of the backfill cost.

Four types of mine backfill are recognised: dry backfill, hydraulic backfill, cemented hydraulic backfill and paste backfill. The characteristics of all four are dependent to a greater or lesser extent on mineralogy, cement content, water content and particle size distribution [28]. Thus mineralogy is important because, for instance, quartz and other abrasive minerals may cause wear in backfill lines while sulphides and others may cause cement breakdown. Rounded particles settle faster than flat ones. More cement, finer particles and less water tend to increase compressive strength in-place and reduce permeability and hydraulic conductivity.

Dry backfill generally consists of unclassified sand, waste rock, tailings and smelter slag, often dropped directly into a stope via a small shaft or raise. This type of backfill is suitable for mechanised 'cut and fill' or other methods where structural support is not required [20].

Hydraulic backfill represents the most commonly placed backfill type [30]. The material placed is mainly slurried tailings, dewatered to up to 75-80 wt% solids (about 50 vol%) - the current maximum for effective pumping. To provide efficient drainage and water recovery underground, the slimes fraction is removed during dewatering (and sent to a tailings dam). Hydraulic conductivity in the range 10^{-7}-10^{-4} m/s (corresponding to a grain size of 0.035-4 mm) ensures good drainage from behind a porous constructed barrier [31] for water recovery. The method is relatively economical, consuming approximately 5% of mining costs.

Cemented hydraulic fill [28] has greater compressive strength for greater structural support underground (typically 1 mPa for cut and fill but 5-7 MPa for pillar recovery). Up to 16% cement may be employed to achieve maximum stiffness. The method of emplacement may be by complete hopper mixing and hydraulic emplacement. It may also be by percolation of cement slurry over a previously placed coarser mineral mixture, the fill typically containing a mixture of coarse <150 mm aggregate and fine <10 mm aggregate treated with water and cement slurry in a 1:1.2 wt ratio.

Paste backfill is becoming increasingly widespread in underground mining operations world-wide [32]. The method originated in red mud management (from aluminium production) several decades ago for water recovery and efficient surface mud stacking, eliminating the need for a pond. It has been modified in the last few years for general use in surface and underground waste management, with and without added binder. The fill consists of the total tailings from a mill, i.e., the full particle size distribution of the tailings, thickened or filtered, perhaps with the aid of a flocculant, to a viscous paste containing 75-85% solids. Most of the process water is thus recovered. Residual water is strongly adsorbed onto the particle surfaces (particularly onto the 15% or so of <20 μm particles present) and provides inter-particle lubrication. The paste can thus be pumped (despite its viscosity) with reliable plug flow and remains in place without barriers or drainage facilities [33]. When a hardened product is finally required, some 3-7 wt% cement, PFA or ground smelter slag may be added. As with ordinary cemented hydraulic fill, mentioned above (but with advantage that slimes management is not needed) the product may then be emplaced as secondary ground support pillars underground, thus effectively increasing ore reserves. Pastefill has a high porosity up to 40%, but relatively low hydraulic conductivity, in the range 10^{-6}-10^{-5} m/s, on account of its fines content.

2.5.2 Civil engineering fill (controlled low strength materials)

Engineering fill in the construction industry represents a wide-ranging activity. However, in this review, references are restricted largely to controlled low strength materials (CLSM) - which are categorised as intermediate in supportive strength between stiff soil and concrete. Such materials have been developed for low load bearing applications in civil engineering construction works during the last 20 years, particularly in the USA [34]. CLSM have not been extensively applied in the mining industry but might find increasing application as an alternative backfill with mineral waste or in complementary construction works in the minerals projects.

CLSM were defined in 1994 by the American Concrete Institute (ACI) Committee 229 as self-compacted, cementitious materials used primarily as backfill in lieu of compacted fill. In addition to backfill, they are employed for utility bedding and bridge approaches. Such materials are usually characterised by a spreading criterion in the raw state (e.g., 200 mm under standard conditions), concerned with simple flow and emplacement under gravity, and compressive strength in the range 0.3-2.1 MPa. Within this range the weight of people, cars, other light machinery and even light buildings may be supported (down to the lower 'walkability' limit) and any future excavation is facilitated (up to the upper 'excavatability' limit). Various terms have been applied to CLSM, including flowable fill, unshrinkable fill, controlled density fill, flowable mortar, plastic soil cement, soil cement slurry and K-Krete. Typical compositions are in the range: 5-10% Portland cement, 10-15% PFA and 80-85% fine aggregate (usually 0.075-4.45 mm sand), based on total solids mass. Lime may be used in place of cement. Added water is usually 10-25% of the total raw mix, the upper end of the range being required when finer and/or absorbent minerals are present. Many other materials have been used as part of the CLSM mix including, CKD, foundry sand, recycled glass, limestone screenings, recycled tyres, flue gas desulphurisation gypsum, ground granulated blast furnace slag, bottom ash, reclaimed crushed concrete, wood ash and acid mine drainage sludge. Such materials should be effectively inert from an environmental control viewpoint and may then represent a positive contribution towards resource recycling and resource conservation [35].

More generally, large amounts of industrial waste having a granular nature accumulate every year in all industrial countries. These materials are often unsuitable for use in industry, especially the construction industry, because of their high content of very fine particles, or their poor mechanical properties [36]. CLSM can serve as an excellent means to utilise large quantities of fines without impairing the material properties. Thus, fine aggregate is the major component of standard flowable fill and often accounts for more than two-thirds of the total weight of ingredients.

CLSM are credited with several advantages over conventional backfill, applicable to both surface and underground operations. These advantages include reduced costs arising from the elimination of the need for separate levelling and compaction, faster emplacement and ability to place material efficiently in confined spaces. As mentioned above, the materials also often contain by-product materials, e.g., PFA and foundry sand, thus reducing demand on landfills. They have similarities to cemented paste backfill [37] and might suit similar or complementary applications. Thus, the particle size distribution, cement content and water to cement ratio are comparable. However, important differences are recognised between the two types of fill material, particularly in consistency, i.e., the workability of the fresh mix. Thus, CLSM are free flowing slurries prior to setting while paste backfill with mine waste is viscous and requires a costly pumping system to drive the material to underground mine voids. Expensive de-watering is also required to pre-thicken the tailings [38].

Research has been reported recently on the characteristics and possible applications of CLSM containing modelled mineral waste [39]. In this work, ochreous minewater sludge and an industrial goethite residue have been used as a partial replacement for sand. The study aimed to determine (given suitable spreading distance for free flowability) whether appropriate strength, porosity, hydraulic conductivity and inertness could be achieved. The work indicated that wastes containing high iron and calcium contents, typical of products from hydrometallurgical processing, especially bioleaching, could be beneficially re-formed as CLSM of appropriate compressive strength. The porosity and hydraulic conductivity were also satisfactory. However, forced flow through leach tests indicated that, while most toxic elements were satisfactorily contained in the CLSM matrix, lead and chromium became significantly mobilised. Further work is necessary to reduce the risk of toxic elements leaching, when present, under environmental conditions. Encapsulation and lined, ‘self healing’, monolith structures have been proposed.

Resistance to leaching of hazardous components, from waste materials incorporated in CLSM, into the environment is an important property not commonly assessed, mainly because of the largely inert nature of materials studied. Nevertheless, as above, waste materials may contain significant amounts of contaminants, predominantly heavy metals, which need to be included in experimental protocols, particularly because of the permeable nature of CLSM [34]. Chemical evaluation methods, including leaching tests and determination of acid neutralisation capacity, are especially useful in addressing the solubility and reactivity of contaminants when exposed to different reagents and environments [40]. Chemical evaluation can also give valuable information on the binder in immobilising heavy metals.

2.5.3 Surface regeneration

In this review surface regeneration or reclamation means landscape modification by designed deposition of waste around mining and quarrying areas by surface backfill of excavations and depressions; restoration of soil and vegetative cover; and water retention or drainage. The review does not consider fill and landscaping more generally. The main issues are the appearance, stability and utility of various solid waste deposits, e.g., spoil tips, heaps and dumps, solid/water systems, e.g., tailings dams and ponds containing the waste products of mineral processing, and permanent water bodies, e.g., artificial lakes sometimes formed as end-of-life products of open pit mines and quarries. Because of the shear scale and intricacy of many mining operations, these issues cannot always be fully resolved. For instance, the trained eye can nearly always detect visual evidence of former large-scale mining activity no matter how careful the restoration. However, notwithstanding the dereliction and despoliation of abandoned mines and environs that used to be commonplace, regulation at the turn of the millennium has led, and continues to lead, to an impressive range of waste and water management technologies, e.g., for closure of tailings dams [41], particularly near centres of population. In remoter areas, a more pragmatic approach continues to prevail with large tailings facilities, heaps and leach constructions likely to remain in place indefinitely.

Progressive and end-of-life re-distribution of spoil and solid tailings, with appropriate compaction and drainage for ground stability, is routinely undertaken to provide a shaped landscape, typically with final surface spreading of lime and sewage products to assist re-vegetation [42]. End uses might then be in agriculture, forestry, housing or general amenity.

Tailings dams and ponds are often problematic and frequently represent the most visible sign of a mining activity owing to their large 'footprint'. Tailings dams are large surface impoundments, ranging from a few to thousands of hectares, in which slurried tailings from wet processing are managed. The slurry pumped into tailings dams commonly consist of 20-40 wt% solids, but levels from 5-50 wt% solids have been known. The solids settle out of the slurry after discharge and the dam is, therefore, composed of settled solids and free water. The free fluid is typically returned to the processing plant for re-use, stored in the impoundment for future use, removed by evaporation or it may be discharged into surface water courses, often after undergoing treatment (Section 2.6).

The common practice in dams in the past has been to provide a well engineered structure into which the tailings can be deposited without a great deal of attention being given to closure requirements or issues related to long-term management. Current practices take into account various rehabilitation strategies, such as covering and re-vegetation, required to contribute positively to an area's development, and ensure acceptable closure so that stability and environmental performance criteria are achieved. Recent comprehensive accounts on mine waste and rehabilitation strategies have been published, including work on sustainable improvement in safety of tailings facilities [43]. To assist in the minimisation of risk of future failures, modern mining operators consult a range of guidelines, standards and regulatory documents in order to establish and implement a tailings management plan. The implementation of modern technology reduces the risk associated with the storage of tailings, and mine waste in general. For instance, high-density polyethylene (HDPE) and clay-lined tailings impoundments with complex under-drainage systems are now becoming more popular to protect groundwater and downstream environments from pollution [16].

Best practice techniques for tailings management include thickened tailings disposal, underwater disposal, heap disposal and backfilling, already mentioned for underground application (Section 2.5.1). As underground, surface paste emplacement is becoming generally attractive, although applications of CLSM have yet to make an impact. Separate reviews of paste thickener technology have been published recently, including the notion of eliminating the need for a pond in certain cases through effective stacking of paste [44]. In general for surface operations, applying thickened tailings management requires the use of mechanical equipment to de-water tailings to about 50-75% solids, similar to underground use. The tailings are then spread in layers over the storage area, to allow further dewatering through a combination of drainage and evaporation. This is done by deposition of the de-watered waste material from a central disposal point to form a tailings stack of conical geometry. The formation of such a cone is advantageous as the need for high dam walls is eliminated and the stability of the deposit is enhanced through improved consolidation. In addition, problems associated with steep tailings slopes and the surface 'ponding' of slimes are avoided. Land utilisation is improved as higher tailings densities are achieved compared with conventional tailings dams. As in underground operations, the final stiffness of the product can be increased by adding cement. Some pastes, however, have the useful property of being self-cementing.

Underwater disposal overcomes a problem encountered with sulphidic paste and other tailings reactive in air, albeit at the expense of permanently managing a covering pond, and is considered as the BAT for such mineralogy. Lining and capping (effectively encapsulation) of sulphide paste, which is under trial, may offer an alternative solution. On the downside, thickened tailings operations may be subject to dust generation or even failure due to thixotropic liquefaction of the waste [3]. Moreover, not all mine wastes, particularly tailings, are suited as backfill material because of swelling or shrinkage after emplacement.

Regarding soil cover, fine sized minerals are natural precursors to soil and form the main physical support medium for plant growth in natural soils. Such minerals are available as waste in large quantity (being unsuitable for most applications) and should serve the same purpose in artificial soils. Thus, waste minerals, together with a few percent of organic matter and mineral nutrients (some of which may already be present in the mineral mix) should be re-formable as viable soil. In circumstances where original topsoil has been lost as a result of industrial activities, landscaped mineral wastes may sometimes be re-vegetated simply by spraying with digested sewage sludge and seeding with a 'restoration mix' of grasses and clovers. After a few years stable soil and growth, and appropriate soil microbiology develop spontaneously. Acidity, e.g., from pyrite in the mineral mass, may be controlled with lime.

In addition to providing a green cover on mine wastes in this way, marketable artificial soils are also possible, based on designed formulations and protocols, e.g., BS 3882 in the UK. Thus, R&D [45] indicates that an enhanced product having good texture, water retention and nutrient balance, suitable for sale as a soil material, can be produced by mixing waste quarry fines and green waste composts. This technology is being taken up by the water industry using sewage composts, e.g., via a product called SPC ('sludge phyto-conditioning') which is digested sludge mixed with greenwaste or sawdust and stabilised by using as a medium for growth of ryegrass for a season [46]. The process of phytoremediation mainly involves removal of water and elimination of pathogenic organisms. In addition to providing an excellent general growing medium, this type of product conserves resources. Thus, traditional proprietary composts, e.g., those formulated by the John Innes Foundation, are based less sustainably on loam soil and peat. A different means of conserving resources is to employ permanently stabilised mineral-organic mixes as confined (encapsulated or mononlith emplacements [47]) in place of quarried materials in landscape fill. Both mineral waste and carbon are thus conserved. This type of emplacement awaits full scale field trials.

Many other applications and potential applications of mineral wastes and slags in surface processes have been reported [48]. For instance, waste precipitates, e.g., jarosite [$MFe_3(SO_4)_2(OH)_6$], where M may be Na^+, K^+, NH_4^+ or H_3O^+, and goethite [FeOOH], from the hydrometallurgical extraction of zinc have been used in attempts to produce glass-ceramic materials by vitrification, and to make stabilised/solidified products. Many metallurgical processes produce gypsum [$CaSO_4 \cdot 2H_2O$] during the neutralisation of effluents by the addition of lime/limestone, e.g., bioleaching of sulphide ores and concentrates. In some processes the gypsum may be contaminated with toxic elements, e.g., arsenic from gold extraction, or may be in a relatively pure state. In cases where gypsum is not excessively contaminated, it may potentially be applied in the construction industry, e.g., as plasterboard, cement clinker, or as a supplementary binder.

2.6 Water management technology

Water is central to many mineral processes as an original source of mineral concentrations and as a medium for suspending and dissolving mineral matter in industry (among other attributes). It is also the medium for carrying out a myriad of chemical reactions at low and moderate temperatures. A major biogeochemical example is the existence of limestone and similar deposits, being precipitates from seawater and representing major geological stores of mineral alkalinity employed worldwide in industrial and commercial products. A typical industrial example is the humble flotation process in which a few mass percent of mineral is separated into concentrates in a medium made up largely of water. As is well known, water recycles naturally and is recycled industrially as far as possible on economic grounds, before re-joining meteorological or condensed drainage systems. The main issue, already partly addressed in above paragraphs, is the purity of water entering, recycling in and exiting mineral processes, both environmental and industrial.

The importance of water purity is encapsulated in the Water Framework Directive, already discussed [22] and, together with air purity, in the Directive on IPPC [21]. The present short review of water management technology focuses on selected purification methodologies. In fact, from a fundamental point of view only six such methodologies are available: evaporation/condensation, precipitation/sedimentation, filtration/osmosis, adsorption/ion exchange, solvent extraction and flotation. Two examples will be given relevant to the present work: the behaviour of iron species in ochreous (iron-rich) mine drainage [49] and removal of arsenic from leach solutions by reverse osmosis [50].

Ochreous minewater is a typical water-polluting product of abandoned coal and metal mines (a similar product arises from many hydrometallurgical processes). As is well established, iron in pyrite dissolves underground as ferrous iron by bacterially catalysed oxidation. Emerging minewater dissolves oxygen from the air, which converts ferrous to ferric iron, and causes precipitation of hydrated iron oxide (ochre). The orange ochre coats surfaces and smothers bottom life in rivers. Actually the process is partially adsorptive (ferrous iron onto surfaces followed by *in situ* oxidation) and partly sedimentary (ochre separating from suspension under gravity once a region of low enough flow is encountered). Great efforts are under way to capture the ochre by one or the other process, clean up the receiving rivers (already successful) and make use of the ochre (still under development).

Reverse osmosis is one of the only techniques available for removing dissolved impurities at low concentration directly from true solution. The process is carried out on a semi-permeable membrane, which preferentially allows passage of water under an imposed hydraulic pressure, while preventing passage of dissolved ions. Thus, arsenic, which is considered toxic in drainage at >50 ppb, exists largely as arsenate anions (oxidation state 6) and can be removed to about this level by reverse osmosis. Care is necessary to avoid reduction to arsenite (oxidation state 5), which forms neutral species (which penetrate the membrane). Use of ion exchange removes arsenic to dinking water levels (10 ppb). Although the work cited is at the research stage, rapid technological developments in reverse osmosis already indicate a range of practical applications, e.g., seawater desalination.

3 Brief case histories

3.1 Rationale

This review outlines selected information relevant to waste management for operations having links to BioMinE. The information has been collated from recent web-site entries, field site visits and discussions with industry staff. No attempt has been made to provide comprehensive information. Wider based considerations on recent advances in waste management (backfill, tailings restoration and surface civil applications) are given in the

Section 2. A more general review of metal deposits in Europe and their potential for metallurgical or biotechnological exploitation has been provided elsewhere [51].

3.2 Boliden Group

The Boliden Group (New Boliden since 2004) has operated numerous mines and tailings facilities since 1924, particularly 29 mines and 4 mills in the Skellefteå region, Sweden, mainly involving complex sulphides of Cu, Zn, Pb and Ag, and/or free gold mineralisation [52]. The Group currently operates a number of mines and tailings facilities in Sweden (e.g., Aitik, Garpenburg) and Ireland (Tara), and smelters in Sweden and Finland (e.g., Ronneskar and Kokkola).

With regard to waste management, the company employs traditional methods of backfilling underground voids with waste rock and also newer pastefill technology in underground stopes, e.g., at Garpenburg and Tara. The company operates conventional tailings ponds adjacent to central concentrators, e.g., the Gillervattnet facility at Boliden town (near Skelleftea). Acid generation from sulphides has posed a problem during production and continues as a risk once useful life is complete. Following structural failure of two of its tailings dams in the last 10 years (Los Frailes, Spain and Aitik, Sweden) the company has adopted state-of-the-art technology (designed according to ICOLD Bulletin 103 recommendations) for a new tailings facility at Hotjarnmagasmet near Boliden, to replace the Gillervattnet pond in 2008. The new design includes permanent water cover to prevent acid generation. The perimeter also has specially designed beaches covered by sand and soil [53].

Additionally, recent field research has been carried out on the feasibility of reclaiming ponds, e.g., Gillervattnet, by new technology progressively covering the tailings with successive layers of power station ash (PFA) and sewage sludge, on which vegetation can be been established. The technology is described in the Boliden Skelleftea Kraft fly ash project 2004 [54].

Field site visits were made on 18/19 September 2007 (Gillervattnet tailings pond and Ronnskar smelter) and 7/8th May 2008 (Gillervattnet tailings pond and Aitik open pit). The company has increased use of waste in building construction, with a large reduction (20%) in landfill. At Aitik underground fill is not relevant but large quantities of waste rock are expected to be suitable as a commercial product in the future to be used in the construction of roads and as a ballast material in cement. Moreover, thanks to an agreement with the Stockholm Municipal Water Works, the mine has assured continuous deliveries of sewage sludge which is used to cover and improve soil on mine reclamation sites. The Aitik pit will eventually become a large lake as an amenity. However, a massive tailings area will remain. The area around the Ronnskar smelter has been extended by means of a foundation of metallurgical slag. Waste heat from the smelter is employed in some 1000 houses. However, hazardous wastes produced have currently to be dealt with by specialist companies rather than being re-interred underground.

3.3 Lundin Mining Corporation

The Lundin Mining Corporation [55] is reported to operate eight mining complexes, including three recently acquired properties of direct interest to BioMinE. They are associated with the Iberian Pyrite Belt: in Spain Aguablanca (Ni/Cu), formerly a Rio Narcea property, and in Portugal Neves Corvo (Cu/Zn) and Aljustrel (Zn/Pb/Ag), both formerly of Eurozinc. Flotation concentrates are transported for smelting.

Aguablanca was the subject of a detailed feasibility study prior to the start of production as an open pit operation in 2005 (MDM report, with KP plan for tailings containment, embedded in the Lundin website). Salient features on waste management are that (i) the flotation tailing solids consist largely of minus 100 µm amphibole, pyroxene, pyrrhotite and limestone, probably with sufficient neutralisation potential to prevent acidification (ii) the tailings can be thickened to >70% solids by mass, probably with the aid of flocculant, and then have suitable 'slump' and slurry rheology for 'paste' disposal (plus significant water recycle) (iii) production of potable water from raw water is feasible on-site. From a site visit on 4th April 2006, it was seen that pastefill is employed successfully in tailings disposal and would probably also be useful in likely future underground workings at the mine.

Neves Corvo has been in production since 1989, primarily as an underground copper mine based on chalcopyrite mineralisation. The operation formerly recovered tin as cassiterite and increasingly produces zinc mainly as sphalerite. The process circuit typically involves mineral liberation at fine sizes, e.g., 80% minus 40-45 µm, for flotation away from predominant silicate and pyrite gangue. Therefore, relatively fine-sized tailings solids containing reactive pyrite are produced. Underground stope voids are backfilled with waste rock, hydraulic fill and pastefill. Older hydraulic fill technology employs quarried sand, tailing cyclone underflow and cement fed to bore holes. The cyclone overflow (slimes) goes to the Cerro do Lobo dam, together with the larger mass of pyritic waste. The dam is operated in sub-aqueous mode to minimize acidification from pyrite oxidation.

Sub-aerial trials have been carried out to minimise pyrite oxidation (and increase tailings capacity) by depositing thickened tailings as pastefill in near-surface layers up to 5 m in depth, followed by appropriate capping. This approach also facilitates progressive concurrent closure of the facility during production. These processes, including use of a deep cone thickener at the site of deposition (a remote corner of the dam), were observed during a site visit on April 5th 2006. It was advised that the pyrite tailings contain about 1% 'locked' copper. With suitable agglomeration, they might form the basis of a viable heap bioleach process. The oxidised iron-rich waste could go to the paste-fill operation (instead of the original pyrite) and thus remove the risk of uncontrolled oxidation in the future.

Aljustrel produced zinc and lead sulphide concentrates containing silver during 1991-3. A site visit on 6th April 2006 was undertaken during a period of extended care and maintenance, and early stages of reconstruction. The visit highlighted a large potential problem from acid mine drainage, at the time running into the existing tailings facility. The management plans to overcome environmental hazards through use of a new tailing pond and paste deposition system. Zn concentrate has been produced at the mine since late 2007 and Pb/Ag concentrate from 2008.

3.4 KGHM Polska Miedz

KGHM [56] was established in 1961 to produce copper and precious metals by means of an integrated operation based on a single large deep sedimentary deposit located in SW Poland. The company presently comprises three mines and associated concentrators (Lubin, Rudna and Polkowice-Sieroszowice), two smelters (Glogow and Legnica), a rolling mill (Cedynia) and a surface waste management system (Zelazny Most Tailings Pond).

The ore, primarily as chalcocite and bornite contained within layered strata of sandstone, shale and brown coal, is mined by a room-and-pillar system. With regard to waste management, mined-out rooms beneath built-up areas are hydraulically backfilled with quarried sand, which is retained behind wooden walls. Other volumes are allowed to fill by natural settlement. Groundwater from the mines is used to facilitate ore comminution and flotation of sulphides during processing and to transport gangue to the tailings pond. Excess of water (the overall water balance being consistently positive) is neutralised and filtered before discharge to the River Odra.

A visit to surface installations on 8th June 2007 emphasised problematic concentrator products, particularly a large volume complex flotation ‘middlings’ containing organic matter. The visit also highlighted issues of waste management, e.g., dust control at the huge Zelazny Most pond (which is significantly elevated above the level of surrounding countryside) and contamination of discharge water (which contains 16-18 g/l soluble salt). The ‘middlings’ cannot be concentrated conventionally much beyond an uneconomic 6% Cu. A proportion might be bioleached using redundant tanks at KGHM but unreasonably large bioreactors would be required to deal with the whole mass. Additionally, a regulatory requirement would probably be made to re-inter the bioleach waste underground. The large area of the tailings pond makes it difficult to see to the opposite side from a position on the embankment, or, because of the wide protective beach, even to open water. The embankment and beach are presently sprayed periodically from the air with bitumen to suppress dusting, but natural and managed re-vegetation, analogous to that already applied at the long closed Gilow pond, is planned for the longer term. With regard to water contamination, the company has investigated mechanical and chemical purification treatments, including reverse osmosis, but concluded that the only economic procedure is staged discharge, matched to the state of flow in the Odra, to avoid unacceptable salination.

3.5 European Goldfields

European Goldfields Limited [57] has majority holdings in Hellas Gold SA (Greece) and in the Certej Au/Ag project (Romania). Hellas Gold ownership includes three properties in Chalkidiki, Northern Greece (Kassandra Mines): the current Stratoni operation (Zn/Pb/Ag) and two projects - Olympius (Au, Zn, Pb/Ag) and Skourias (Cu/Ag). The deposits were known by the ancient Greeks and those at Stratoni and Olympius have been worked at various times for the last 2000 years or more. The mines are based on complex subduction, fault-zone, mineralisation, including sulphide replacement in carbonates and porphyry intrusion.

Stratoni comprises two deposits: Madem Lakkos (mainly of historical interest) and Mavres Petres. Mavres Petres is currently mined at depth (some 230 m beneath the village of Stratoniki), mainly for sphalerite and silver-bearing galena, which are concentrated by flotation. Gold pyrite/arsenopyrite concentrates have also been marketed since 2006. The mine produces an excess of water, which is neutralised, settled and discharged to the sea. Tailings from flotation (mainly quartz, calcite and pyrite/arsenopyrite) are de-slimed for use in cemented hydraulic backfill. Slurries of fines from de-sliming and mine water neutralisation are filter-pressed, the cake being stacked at surface (Karakoli Dam).

Olympius is presently managed on a care-and-maintenance basis and might be reopened in the near future to produce three flotation concentrates: Au, Pb/Zn and Zn. Surface stockpiles of gold-bearing pyrite/arsenopyrite might also be processed or marketed. During the early 1990’s the owner at that time (TVX Gold), proposed a BIOX process to process the ores, but was refused a ‘social license’ on environmental grounds relating to the toxicity of cyanide (to be used in gold recovery) and arsenic (to be disposed of in tailings). Under Hellas Gold, a flash smelting and matt leaching processing has been proposed (Outotec). Arsenic would be captured in a novel process (as relatively stable scorodite) for disposal. Waste (about 40% of production) would be employed as aggregate and backfill. The company also proposes to market historical dumps of gold-bearing arsenical pyrite.

A visit to the Kassandra mining area with IGME on 1st February 2008 highlighted environmental issues. At Stratoniki public concern continues over the effects of underground blasting at this tectonically active location. Backfill containing up to 13% cement is employed to increase ground stability (at the large cost of some Euro10/tonne). Historical excavations within the Madem Lakkos deposit are also backfilled for stability and mine water management purposes.

3.6 Fairview Gold Mine

Microbiological oxidation of refractory gold sulphide flotation concentrate employed at the Fairview operation in South Africa since 1986 represents the first of eight BIOX processes worldwide [58]. BIOX is designed to liberate gold from sulphide matrices and thus render the metal amenable to cyanidation.

BIOX at Fairview produces two types of waste stream, the residue from bioleaching and the residue from neutralisation of the bioleach liquor. Water from bioleaching cannot be directly recycled for use upstream because cyanide residues, and thiocyanate produced by reaction between sulphur species and cyanide, are increasingly considered as toxic hazards. However, ASTER biodegradation using an activated sludge process or attached growth system is reported to solve this problem [59].

A visit on 3rd November 2006, organised by Mintek, facilitated comparison of laboratory and full scale operation of bioleach technology. The visit highlighted the fact that the above-mentioned waste streams have quite different characteristics and require two large separate tailings ponds.

3.7 Talvivaara Mining Company

Heap bioleaching of large low grade sulphide deposits is exemplified by the Talvivaara Mining Company's new nickel operation coming on stream at Sotkamo, Finland, in late 2008 [60]. The nickel deposits (Kuusilampi and Kolmisoppi) are located in the southern part of the Kainuu schist zone, containing fine-grained disseminations, sulphide breccia and metacarbonate ore. The main mineralisation is of pyrrhotite, pentlandite, pyrite, chalcopyrite and spalerite, together amounting to 21 mass percent of the ore. The operation, similar to many copper heap bioleach operations around the world, involves large scale open pit mining of low grade sulphides and metal dissolution by gravity percolation of acid through stacked aerated heaps of comminuted and agglomerated ore in the presence of indigenous acidophilic bacteria. Unlike copper and gold heap leaches, the metals are to be recovered by a novel method of selective sulphide precipitation (OMG Finland Oy), with intermediate neutralisation and precipitation of iron/gypsum waste. Care has been taken with environmental control but, as with analogous operations elsewhere, large heaps and pits will remain at the end of the mine life, albeit probably restored to lakes and re-vegetated amenities. A tailings pond containing iron contaminated gypsum is also likely to remain.

A visit on 8th May 2008 organised by Skeria facilitated observation of ongoing preparations for mining and processing.

4 Discussion

This section outlines the principles of integrated methodologies for waste management. The principles have been distilled from the literature review and case histories (above), and from experience in the Biomine project. However, the text is presented in a largely self-contained format, without extensive direct reference to the review but with judicious re-statement of key information contained therein. The treatment is exemplified and discussed where feasible through proposed Biomine processes.

4.1 Sustainability

From the perspective of full life cycle analysis, mineral industry activities are far from sustainable and inherently problematic to the environment. As is well documented, most mineral resources are non-renewable and continually depleted through production. In the case of sulphide minerals - of great importance in base and precious metal production - a complementary issue is that oxidation processes (fundamental to processing), additionally deplete the geological store of alkalinity. Thus, pyrite oxidation generates acidity (sulphuric acid and hydrogen sulphate) – in an analogous, but intensified way, to coal oxidation (burning) generating acidic carbon dioxide and aqueous carbonic acid.

Thus the ‘footprint’ of mineral operations is large, typically involving larger excavations, consumption of materials and energy, and volumes of objectionable solid, liquid and/or gaseous waste than can be sustainably managed. Even the valuable products (especially metals), while representing a small proportion of total material mined or quarried, retain through complex containment in finished products or enhanced toxicity the potential to degrade or pollute when finally discarded.

Nonetheless, mineral activities are permitted by regulation, on the basis of societal need, through the principal of ‘best available technology not entailing excessive cost’ (BAT). New processes, e.g., Biomine processes, therefore aim (at least) to minimise environmental damage, while meeting the anticipated economic requirements of regulation, society and the market. Such requirements become more demanding through legislation in response to increasing environmental and socioeconomic expectation. However, process improvements and superior products are expected from successful new operations, while improved waste re-use is facilitated through enhanced funding thresholds, facilitated by high and increasing disposal costs. Even now waste management can account for 10-25% of total costs, sufficient to underpin substantive development work on bulk mineral re-use.

Similar comments apply to other industries producing bulk materials. Relevant examples, considered below, include cement, pulverised fuel ash (PFA) and treated sewage sludge.

4.2 Waste management technologies: underground and surface backfill

Underground backfill is mostly concerned with operating mines, although former mines and natural voids are backfilled when access is available and sufficient need exists for ground stabilisation or additional storage volume. In fact, many former underground excavations remain unfilled because of lack of information or access, leading to the need for customised management against subsidence and gaseous emanation. Underground fill represents one of the few acceptable repositories for significantly toxic material. Even nuclear waste is increasingly considered for storage in this way, sometimes with special excavations, taking particular account of containment (especially regarding structural stability and rock permeability) and security of access.

Traditional hydraulic fill and newer pastefill are the main methods of filling underground voids, with pastefill becoming increasingly important. Voids are sometimes partially filled with loose material, including gravel and rock, aided by use of mining machinery. Sand-sized and finer materials are typically transported hydraulically in slurry pipelines and generally require simple constructions underground, e.g., hoardings, for material retention and drainage. This drainage may necessitate preliminary desliming, with the slimes (or clay-sized fraction) going to a tailings dam. Unlike simple hydraulic fill, pastefill employs the whole particle size fraction and contained water, although intensive (expensive) preliminary dewatering is required to produce a suitable paste. Being relatively viscous, the paste also requires greater pumping energy. Much of the material backfilled underground is additionally solidified with Portland cement or pozzolanic ash, e.g., PFA. Addition of cement or PFA can follow emplacement as slurry (hydraulic fill) or be part of the initial mix (pastefill). Solidification increases the possible proportion of fill and provides structural support against subsidence of surface strata. Structural support represents a bona-fide re-use beyond simple disposal.

Table 1 gives an outline comparison of techniques used and proposed for underground cemented fill. The category of controlled low strength materials (CLSM) is included, although presently used almost exclusively in surface civil engineering. It can be seen that all are soft materials in construction terms, all having unconfined compressive strength (UCS) much less than the 10-80 mPa normally needed in building elevations. Conversely they are still stable under substantial compression, particularly in confined spaces and lightly loaded foundations (and therefore subject to less stringent building regulation). They are also relatively porous and lightweight.

Table 1. Comparison of technologies for mineral waste re-use in cemented constructions

Property	Hydraulic fill	Pastefill	CLSM*
Pre-treatment	Dewatering and de-sliming	Intensive dewatering	Simple dewatering
Amendment	0-16% cement	3-7% cement plus possible other binder	5-10, 10-15, 80-85% cement, PFA and sand
Consistency	Slurry, 65-70% solids	Stiff paste, 75-85% solids	Self-levelling 'liquid', 75-90% solids
Product character	UCS** 0-5 mPa and voidage 0.7	UCS** 0.5-3.0 mPa and voidage 0.4	UCS** 0.5-2.0 mPa and voidage 0.3
Economics	Inexpensive method underground if slimes go to tailings dam	Costly dewatering and pumping but increasingly used	Complementary method, untested in underground mines

*Controlled low strength material. **Unconfined compressive strength

Cemented pastefill and CLSM have complementary properties and different possible applications underground. For instance, owing to its stiff consistency, pastefill would be preferable in room and pillar constructions. Thus, hardened pastefill can provide secondary pillars (after initial mining) so that valuable material in the primary pillars can be accessed. Conversely, as a result of its characteristic of free spreading at high solids content before setting (resulting from its particular formulation with cement, PFA and sand), CLSM is preferably used under gravity flow. Thus it can be used to fill complex volumes at particular horizons without specific emplacement or compaction.

Surface backfill is a province of both mineral and civil engineering. In mineral applications surface backfill is exemplified by recovery of open cast workings, landscaping of former mine tips and remediation of tailings dams. Wastes from mining and processing are mainly employed. Additionally, downstream materials such as PFA or metallurgical wastes can be applied. In civil projects backfill is characterised by general landscaping and embankment construction prior to surface re-development. Quarried materials are typically employed but also construction and demolition waste (when not retained on site as foundations for new buildings). Fine-sized material, particularly silt, has few uses and continues to be land-filled. Many examples exist of successive application, e.g., backfilling of an open pit mine followed by construction of housing or light industry. Fewer historical tips and excavations in populated areas of the EU require action nowadays, many tips having already been re-vegetated and excavations used for municipal or other landfill.

Pastefill of surface constructions in the mineral field can be seen in new methods of progressive regeneration of tailing dams. Thus, tailings are pumped to a tailings dam and intensively de-watered there with the aid of flocculants or polyelectrolytes (the water being returned to the process plant), prior to emplacement as a paste layer 1-2 m in thickness under shallow water. The emplacement is covered and compacted with stable run-of-mine rock to a further depth of 1-2 m. The solid phase of the tailings can even be finely divided pyrite, or other reactive mineral mass, provided it has high solids content (say, 80% solids by mass, 50% by volume) and is effectively sealed by water and the rock cap. The tailings may or may not be cemented.

In a complementary way, use of CLSM (always cemented) can be discussed in terms of near-surface pipe bedding, in which pipe runs are laid flat on a cemented base before full incarceration in CLSM material. The resulting emplacement is competent enough to carry vehicles and generally protect the pipe-work but soft enough to be readily excavated if necessary. Many different examples exist. For the future, the sand component might be replaced with process tailings in a mining area, thus giving rise to possible classification in regulatory terms as recovery operation.

4.3 Waste management technologies: soil conditioners and artificial soils

Large scale spreading of digested sewage sludge and partly composted products as an agricultural or reclamation amendment/conditioner is well established internationally, although use of raw sewage in increasingly prohibited on H&S grounds. The products may be simply spread or incorporated into the topsoil by injection or back-hoeing, with or without addition of lime and fertiliser. Thus, farm field soils are texturally improved and nutrient-balanced for crops. Mineral mass is not spread in this way. However, old mineral tailings dams or tips are similarly covered with sewage products to augment natural re-vegetation, improve environmental appearance and provide amenities.

In contrast to in-place soil conditioning, whole or artificial soils can be formulated from more fully composted organic materials and recovered mineral mass and marketed on a smaller scale as more generally tradable commodities. They are designed to comply with protocols (e.g., EUSOILS, BS 3882, on texture, particle size distribution and ion exchange capacity), categorising premium or general purpose soils. The detailed compositions of organic and mineral components are not a primary issue for the protocols, but may be important on grounds of durability or toxicity. Thus, most mineral mixtures in natural and artificial soils provide an essentially stable anchor for plant roots, while holding air, water and nutrients and participating reversibly in adsorption and ion exchange processes underpinning biological processes. However, a few minerals from underground are detrimentally active, e.g., pyrite, which oxidises under ambient conditions and may acidify the soil with release of toxic trace elements. Ageing or washing procedures employed for contaminated soils from former industrial sites might be applied to render artificial soils compliant.

In other words, assuming insignificant toxicity, viable whole or artificial soils can be founded on mineral and organic components similar to those of natural soils. Such artificial soils are analogous to traditional proprietary composts but with loam and peat replaced by minerals from the minerals industry and by organics, sewage products and green waste, from the water industry and municipalities. In the sense of the recovery principles mentioned earlier, they can replace loam, which is in short supply, and peat, which is increasingly preserved.

The minerals are selected fines from quarrying, mining or mineral processing, or impounding reservoir sludge and potable water treatment waste from the water industry. Building and landscaping developments short of topsoil, garden centres and other speciality markets are especially targeted. Distribution of artificial growing media is currently limited but subject to intensive research and marketing development. For instance, a new low cost type of composted sewage termed SPC was first publicised in the UK for use in artificial soil in 2003. For SPC production, digested sewage sludge is typically mixed with green waste and used as a growth medium for grass for a season. The resulting product is essentially free of pathogens and odour (phyto-conditioned) and suitably reduced in water content, thus yielding a free flowing, safe, material which, when suitably mixed with minerals, forms an excellent growing medium for site reclamation and smaller-scale consumer products.

4.4 Integrated waste management

Waste material from mining and processing activity typically represents >75% of the total mineral mass produced. This mass cannot be wholly returned to excavation voids because of reduced effective density (mined material typically occupies 1.8 times the original volume in-place), reduced space (subsidence may reduce void volume) and adverse economics (excessive cost may be associated with less accessible voids). In accordance with the mine waste directive (2006/21/EC) and BAT, a proportion of these wastes might be employed in backfill operations. Typically, 30-50% waste is backfilled. Much of the remainder is stored permanently at surface, i.e., disposed of, in mineral dumps or tailings dams.

To reduce non-sustainable disposal, schemes of integrated waste management (IWM) can be proposed, particularly for new operations where novel designs are more practical. In IWM, backfill of mined solids is maximised and excess is utilised in additional designed applications in combination with other bulk materials of little or no value likely to be available in a mining area. Opportunities are primarily aimed at a mine locality in question because transport of bulk materials usually becomes prohibitively costly beyond a radius of 10-20 miles. The main bulk materials targeted would be industrial ash or dust (activated with cement or lime) and sewage sludge (pre-treated to remove pathogenic organisms). Both types of material are produced in substantial quantity near enough to many industrialised areas where mining or processing activity occurs. For instance, mixtures of mine waste with pulverised fuel ash and cement might become foundations in civil engineering construction or with treated sewage sludge could provide artificial soil in industrial restoration projects.

Despite their wide use, cement, lime and PFA are themselves problematic materials, reflecting different issues encountered in mineral waste management. Cement is an important commodity, based on large scale excavation and processing of limestone and clay. It has a large carbon and energy footprint arising from the mining procedures and from the intense heating required to expel water and carbon dioxide from the raw materials. The use of fossil fuels for heating leads to additional expulsion of carbon dioxide and the heat generated is typically difficult to re-use. The procedure leads to a large volume waste, kiln dust. The valuable product, cement clinker, once ground to a fine powder for bagging, represents a risk from dust and alkaline reaction. The overall procedure is therefore both expensive and environmentally unfriendly. However, the market for cement is huge, including the general construction industry, and its many applications lead to refined logistics for ready transport and safe delivery over relatively large distances. Largely similar comments apply to lime. PFA is presently classified as waste, but exhibits pozzolanic properties analogous to cement and has similar markets. It is associated with energy production rather than consumption and, from the technical viewpoint, has the advantages of imparting enhanced flowability in hydraulic cements and producing relatively great late-stage unconfined compressive strength. However, as a by-product of the energy industry, it has low priority and poorer quality control. Thus, huge stockpiles of sub-grade material of variable quality accumulate near coal fired power plants. Although a waste, regulations controlling PFA use in the construction industry are not currently enforced (while a new EU protocol goes through the various stages towards publication, probably late in 2009). Similar comments can be applied to ash from municipal and water industry incinerators, although in these cases less or no energy is obtainable (because of lower calorific value and greater water content), a greater risk of pollution exists from possible gaseous emissions, e.g., of dioxins, and leaching, e.g., of heavy metals, and regulation is generally more problematic. Red gypsum and quenched metallurgical slag are related materials, which have all been included in cemented formulations.

Organic products based on sewage treatment (sedimentation, biooxidation, anaerobic digestion and composting) and green waste, are also widely used. Although still regarded as a source of pollution in some EU regions, such products are increasingly seen as valuable assets for soil conditioning and plant nutrition. In the EU essentially all sewage is treated at least partially and, in some regions (particularly in parts of the UK), essentially all the sludge products are recycled to land. However, because continuing developments in sludge treatment and regulatory limits on the frequency of spreading on particular fields, sludge is likely to remain available for new applications.

All being well, IWM could deal simultaneously with the management problems of several bulk materials. However, integration of waste streams is ideally considered at an early stage of design because of likely variability of conditions from one location to another (especially regarding availability and suitability of other industry waste) and difficulties encountered in making substantive changes once an operation has become established. Legislation also requires that a product re-formulated from mineral and other waste should meet strict criteria so as not itself to be classified as waste. Ideally it should replace virgin material that would otherwise have to be mined or quarried for a specific purpose. It would then need to exhibit all of the significant characteristics of the virgin material and function overall at least as well without detriment to the environment. In fact, it is generally required that the environment be enhanced by its application, not least through conservation of raw materials. A recovery operation must additionally accommodate the complex logistics likely to be involved and be economic, or at least economically marginal, in comparison with the combined costs of alternative virgin material production and waste disposal to landfill. Moreover, successful planning for a new product implies public acceptability.

From the literature review and consultations, it is clear that application of IWM with minerals is currently limited. A number of ‘partial’ applications exist, sometimes augmented by pragmatic approaches to regulation applied in remote mining areas having small populations, but the full idea remains novel. However, appropriate regulatory pathways have been worked out, notably the ‘recovery product’ route employed in the UK. This route is exemplified for Biomine bioleaching and waste management below.

4.5 BioMinE bioleaching

In the context of BioMinE, bioleaching implies direct incongruous oxidative dissolution of sulphide minerals in stirred tanks in the presence of microbial catalysts, such as *Acidithiobacillus ferrooxidans* (Figure 1). Sulphide flotation concentrates are employed. The complementary method of heap leaching of sulphide ores is not considered.

Relevant sulphide concentrates are produced from selective froth flotation of finely ground sulphide ores – a long established technology, traditionally a preliminary to refining at a smelter. Particle sizes suited to flotation are mostly less than 100 µm, i.e., are of fine sand, silt and clay sizes, which provide the required slurry in process water. Perhaps 5-10% of the ground material is floated as concentrate. The concentrate consists of valuable metal sulphides and the reject is gangue minerals not responsive to flotation. The sulphides contain base metals, particularly Cu, Ni, Co, Pb, Zn and/or precious components, i.e., Au, Ag, Pt group metals. They may also contain variable concentrations of toxic heavy elements of little or no economic value, e.g., As, Cd, Hg, Bi, and traces of flotation chemicals, e.g. xanthates. The 90-95% gangue residue from flotation is mostly mixed silicate gangue and/or barren pyritic minerals, which are managed as waste. Bulk waste management primarily employs tailings dams, rather than rock dumps. This is because of the fine particle sizes involved. Coarser material generated in upstream mining and process pre-treatment units is managed separately. The physical form and mineral composition of bioleach feed and upstream waste are thus analogous to materials routinely encountered in the mineral industry. However, most other issues, including waste characteristics and management are distinctive.

Figure 1 gives a generalised flowsheet of basic relationships between direct bioleaching, water management and waste treatment in proposed Biomine options for base metals (especially copper and/or nickel) and gold from sulphide flotation concentrates. For clarity it excludes the option of indirect bioleaching, e.g., production of ferric ion by biooxidation of pyrite for use as a reagent for separate Zn/Pb sulphide leaching. Similarly, it excludes details of inputs (mentioned above), configurations of unit operations and outputs. The general term 'extraction' is used to represent the configurations of particular processes, e.g., selective precipitation (Ni), solvent extraction/electrowinning (Cu) and cyanidation (Au). The products (designated Cu/Ni and Au) are variable depending upon details of process design. Possibilities are refined copper cathode, precipitated nickel hydroxide and impure gold (the Ni and Au products to be refined at a smelter).

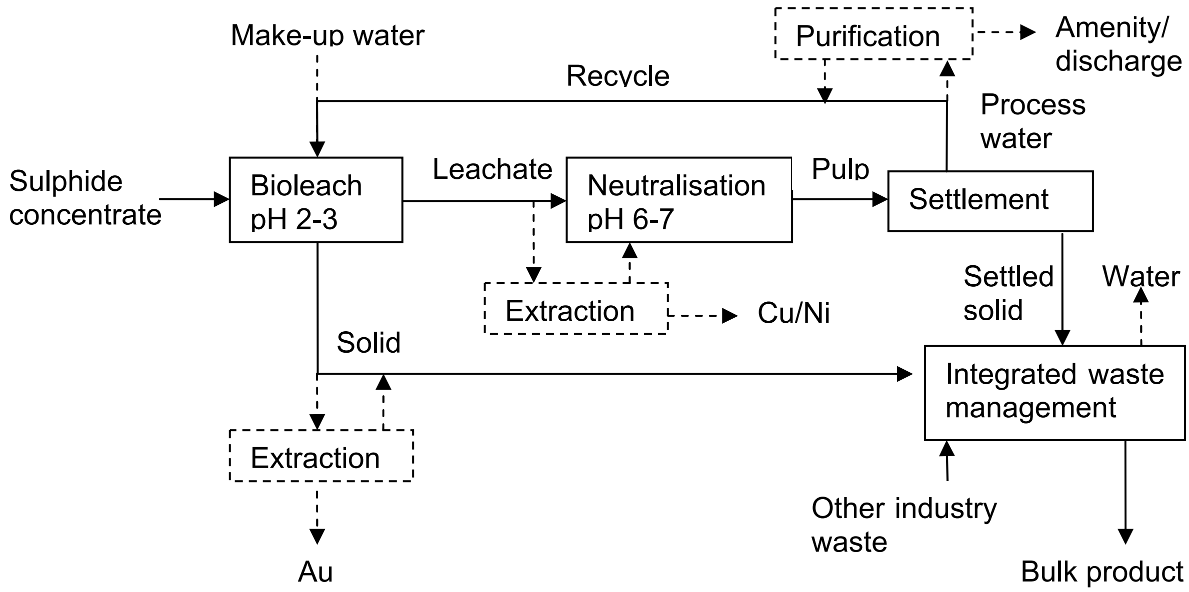

Figure 1. Generalised flowsheet of metals bioleach, water management and waste treatment processes

Regarding water management, the flowsheet shows alternative possibilities of total water recycle or partial recycle and 'make-up', with or without integral purification linked to amenity use or discharge. Water make-up is relevant for a process with negative water balance, e.g., less water from sedimentation and recycling than needed in the process. Discharge or amenity use are options when the balance is positive (more available than required for recycling to the process). Water purification may then be appropriate. Chemical precipitation, filtration and reverse osmosis are examples of unit operations used in such purification.

Long-established practice is thus employed through dewatering and recycling water within the process, as far as feasible. A traditional dewatering route is by gravity settlement and decantation using a tailings pond, although mechanical centrifuging and/or filtration might be employed. Water balance and pulp density (proportion of solid to water) vary substantially from one mineral process, and from one part of a process, to another. However, the water contents and settled densities are relatively steady in tailings ponds. The water content in settled solids, although much lower than in pulp, is still likely to be substantial and may be in excess of that needed in integrated waste management. Further water removal is therefore indicated (Figure 1).

The figure shows the formation of two main types of solid residue - a ferrihydrite/gypsum-rich precipitate from limestone neutralisation of barren bioleach liquor and a mineral-rich residue from bioleaching. Both might be modified by different metal extraction procedures (mainly solvent extraction/electrowinning for copper, carbonate or hydroxide precipitation for nickel and cyanidation/carbon absorption for gold,). The waste solids would ideally be treated together with imported local materials (other industry waste) to yield a marketable bulk product. The flowsheet shows this integrated waste management as essentially a ‘pipe end’ procedure. However, the various bioleach and waste management processes are likely to be mutually interactive to a greater or lesser extent and therefore subject to optimisation to achieve the best overall technical and economic outcome.

For instance, settlement conditions are designed to take account of particle size effects: bioleaching benefits from fine particle sizes (through fine grinding) while separation of solid from water (through gravity sedimentation) is more efficient with larger particles, with consequent effects on water content going through to waste treatment. Mineralogy is also an important consideration: some minerals, e.g., silica sand and many aluminosilicates, form individual free-settling particles, while finer-sized hydrous oxides, like ferrihydrite, may sediment very slowly. Sedimentation may be further retarded by solids forming colloid or gel structures in water, e.g., montmorillonite and other smectite phases. Such variables can be optimised using material balances and other data, once detailed site-related feasibility studies have been carried out.

4.6 BioMinE waste management

Figure 2 expands on the IWM unit shown in Figure 1. Figure 2 focuses on plausible inputs, proportions for water recycle and examples of re-use products, variously destined for mine backfill, agriculture (or restoration) and civil engineering construction. As outlined earlier, inputs of solids and water are partially separated or dewatered by decantation to facilitate water recycle and/or discharge (some 70-80% of the total water in the system) and to increase the solids content of waste to about 70-80% by mass (40-50% by volume). Thus, some 20-30% by mass of the waste is water.

With reference to Section 4.4, industry products potentially useful in admixture with tailings are exemplified by industrial mineral matter (cement, cement kiln dust, lime metallurgical slag, waste gypsum, power station ash and incinerator ash) for backfill and organics (various formulations of sewage sludge, e.g., anaerobically digested sludge with green waste) for soils. Contaminated soil and subsoil from former industrial sites might also be of interest. Representative compositions are given in the scheme for formulated soils, and cemented products (pastefill and controlled low strength materials), which are considered below.

Gaseous emissions and losses of heat to the surroundings are not considered in the figure. They are likely to be quite small for BioMinE because, although upstream energy inputs can be quite large, e.g., in ore crushing and grinding, most relevant processes (including waste management) occur in the condensed phase at or near ambient temperature. Thermophilic bioleaching, one unit carried out at elevated temperature (about 70º C), should generate sufficient heat from the biooxidation and employ efficient heat exchange and recovery technology. Emissions and losses associated with the production of sewage products, cement, coal fired power station ash, and related products may also be substantial.

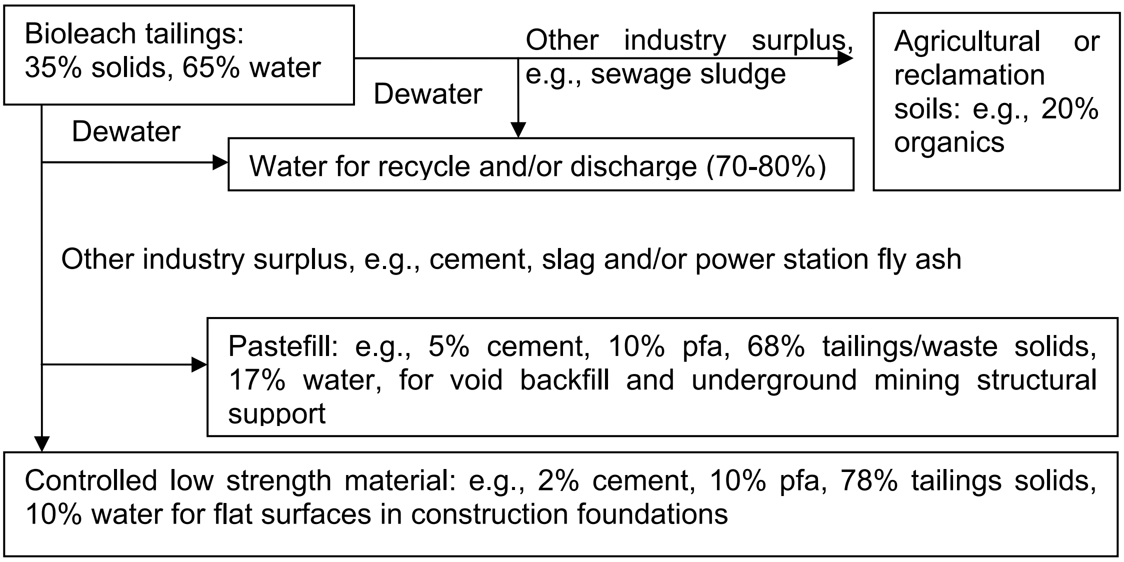

Figure 2. Scheme of integrated waste management

With regard to the application of bioleach tailings to underground or surface cemented pastefill, and possible complementary application to CLSM, the main developments are likely to involve relatively straightforward inclusion of BioMinE tailings (subject to feasibility) within larger volumes of flotation tailings. Some material might be used in special applications such as cemented blocks. However, the possible impact of mineralogical variability needs further consideration. Although many rock-forming minerals and precipitates are expected to be stable in cemented formulations, some components (and breakdown products) are associated with a risk of product disintegration or contaminant leaching. For instance, clay minerals sometimes swell under moist conditions giving rise to cracking, e.g., in flat emplacements or cemented blocks, under the prevailing alkaline conditions, and sulphide oxidation products may contain substantial concentrations of arsenic, e.g., leachate from bioleaching of pyritic gold concentrate, and could give rise to groundwater pollution. Special controls, e.g., constructed wetlands to protect groundwater, would then become appropriate.

Landscape spreading together with un-composted digested sewage products near the site of production is an option in principle. Such activity would be similar to, and perhaps integral with, well-established landscaping of larger mineral tips or surface covering of tailings dams using upstream tailings. Most minerals expected to be present (as indicated above) should be essentially insoluble and inactive, except for providing a rooting medium and possibly plant nutrients. Additionally, ferrihydrite and clay minerals present should facilitate beneficial ion exchange of nutrients while strongly adsorbing traces of toxic metals. Residues from simple base metal bioleaching should be acceptable in soil amendments, but those from gold processing, which are likely to contain relatively large concentrations of arsenic and toxic process products from cyanidation, will be prohibited. Formulations of whole soil products with BioMinE waste (though still subject to toxicity constraints) provide a promising complement. The smaller scale of operation and the potential flexibility of unit operations in constructed plant afford enhanced control of processes and product quality. In particular, blending to meet textural and particle size requirements is facilitated and impurity reduction or immobilisation can be undertaken, if necessary, to meet regulatory requirements. For example, soil washing and other methods of remediation, mentioned previously, might become relevant. To achieve compliance with soil protocols, especially regarding particle size distribution and texture, a proportion of pyrite-free upstream tailings could be included (*cf* landscaping above).

Assuming the absence of significant toxicity, a plausible scenario for artificial soil production is simple mixing of the BioMinE mineral phase with SPC-like compost in the volume ratio 80:20 (overall water content about 10%). Such a ratio has been shown in analogous studies with impounding reservoir sludge to yield good quality soil, the open texture of the organic phase facilitating ready rooting and effective drainage. For restoration purposes, some 3000 m^3/ha artificial soil would be needed for a cover of 30 cm depth, although other components, e.g., lime or mineral in place, might reduce this proportion. Soil organisms, already present in the compost, should soon establish a viable ecosystem for longer term stabilisation of the soil structure. For smaller scale applications, 25 L bags of artificial soil would be appropriate. In this case the soil might be pre-sterilised, if necessary. Anticipated regulatory and economic features regarding application of artificial soils containing mineral tailings can be interpreted from EU directives, compost quality protocols and present practice in similar industrial applications. In principle, the methodology forms a viable basis in particular situations. However, details of feasible pathways need to await the results of developing EU legislation on waste re-use and site specific proposals from BioMinE.

From the forgoing discussion, four groups or types of wastes from flotation may be identified, based on mineralogy:

(i) un-reactive gangue minerals (e.g., sand),
(ii) reactive flotation tailings (e.g., reject pyrite),
(iii) un-reactive bioleach residues (e.g., simple base metal mineral waste) and
(iv) reactive bioleach liquors (e.g., cyanide and thiocyanate from gold processing).

It can be argued that all four groups apply, with suitable safeguards, to underground and surface pastefill. Un-reactive gangue and bioleach residues apply in principle to CLSM. Reactive gangue might also apply to CLSM if effective encapsulation procedures can be developed. For surface applications, analogous logic applies to soil conditioners and artificial soils, although encapsulation will not then be an option.

Table 2 outlines salient characteristics of three EU mining locations with examples of mineralogical impacts relevant to BioMinE (*cf* Figure 2). It can be seen that the Lundin (1) and Boliden (2) operations are based primarily on igneous geology while KGHM (3) is sedimentary. All three are dominated by silicon minerals, variable in content and composition (e.g., increasing quartz from Columns 1 to 3), but likely to be similarly stable in cemented products (finer sizes may require different proportions of cement, water and/or PFA). All are carbonate rich, which should preclude any need for imported limestone - although other mines without carbonates might require added lime or limestone to facilitate cementation. All contain sulphide minerals, also variable in content and composition, but likely to result in similar bioleach waste - one stream containing gangue and a second stream (from leachate neutralisation) containing ferrihydrite/gypsum - perhaps with significant toxic content. Ferrihydrite and gypsum have both been shown to benefit cementation and soil formulations. In particular, ferrihydrite increases UCS and strongly adsorbs traces of toxic ions. The mineral also strongly adsorbs phosphate (of interest in soil nutrition). However, as a product of chemical and microbiological processing, BioMinE waste would be subject to particularly close scrutiny on toxicity, possibly resulting in a requirement for re-interment underground.

Table 2. Characteristics relevant to waste management at three Biomine locations

1. Lundin (Aguablanca): open pit	2. Boliden (several mines): underground	3. KGHM (several mines): undergound
Geology: complex gabbro breccia ; some limestone hydrothermally altered; up to 20% massive sulphide	Geology: complex magmatic; hydrothermal alteration; massive suphide	Geology: sandstone, shale, mudstone, limestone, dolomite
Mineralogy: complex silicates (no quartz) carbonates, pyrrhotite	Mineralogy: complex silicates, quartz, pyrite, complex sulphides	Mineralogy: quartz, silicates, carbonates (minor sulphide)
Value: flotation concentrates Ni, Cu, PMG	Value: flotation concentrates Cu, Zn, Pb, Ag, Au	Value: flotation concentrates Cu, Ag
Tailing: diopside, albite, anorthsosite, actinolite, chlinochlore, carbonates, pyrrhotite (overall neutral)	Tailing : micas, amphiboles, phyllosilicates, feldspars, quartz, pyrite, minor arsenopyrite (overall neutral)	Tailing: limestone, shale, dolomite, mudstone, sand, minor sulphides (overall neutral)
New tailings dam: pastefill	Established dams with extensive reclamation, e.g., Skelleftea (effluent treatment and partial surface restoration using PFA and sewage sludge).	Long established dams. Some closed with perimeter surface restoration to amenity. Current Zelazny Most dam has intermittent effluent treatment and bitumen spray stabilisation.
Expected bioleach waste: iron-rich primary/secondary bioleach underflow and neutralisation residues from flotation concentrate	Expected bioleach waste: iron-rich primary/secondary bioleach underflow and neutralisation residues (with possible arsenic) from flotation concentrate	Expected bioleach waste: iron-rich primary/secondary bioleach underflow and neutralisation residues (with possible carbon) from flotation middlings

Although detailed BioMinE waste management research has only been carried out on Aquablanca so far, and considerable differences evidently exist between 1-3 in material composition, the mineralogical characteristics at all three locations are seen to be consistent with the groups of waste (i)-(iv) from bioleaching: Type (i) for Aquablanca, and any one of Types (i)-(iv) for Boliden and KGHM (depending on particular level of any toxic content). There seems to be no fundamental reason why the IWM components (Figure 2) should not be applied. Thus, the notion of a simple group of methods and technologies having strong generic characteristics despite material complexities, and being applicable to different locations, might be substantiated - at least on mineralogical grounds.

In common with many mines, all three operations in Table 2 have concerns over sustainable waste management, albeit presently underpinned by pragmatic regulation, and could benefit from improved application of IWM in the future. For successful IWM, access to waste management facilities is evidently an important pre-requisite, particularly underground and/or surface space at a mine/process site in question - if such is where a bioleach operation is to be established. At Boliden (Sweden) and KGHM (Poland), different underground workings, surface dams and smelters are in principle available within small areas controlled by the companies. The range of IWM options (Figure 2) is thus possible in principle, subject to site specific constraints. One such constraint might be a regulatory requirement to place chemical process waste underground, well away from contact with sensitive environmental areas. However, bioleaching might also be carried out elsewhere because sulphide concentrates, having much greater contained value per unit mass than the original ore, are typically transportable over significant distances. In the case of Aguablanca (situated in a relatively isolated location in SW Spain), only a tailings dam will be available near the mine until underground work starts in some years' time. In this case, a bioleach operation could in principle be established at a nearby underground operation on the Iberian pyrite belt or at a location nearer to complementary waste sources where the integrated product might best be accepted and applied.

5. Conclusions and recommendations

A review of the state-of-the-art of management of wastewater and tailings in processes relevant to BioMinE has been carried out. Resulting advances within the frame of BioMinE have been general and specific information about likely scenarios for waste or surplus material management in any future application of bioleaching of sulphide flotation concentrates. In addition to the current deliverable, short specific inputs have been made to project deliverables on life cycle analysis (D1.6) and technology implementation (D5.4). More generally, the relatively new approach of integrated waste management has been highlighted, thus facilitating wider comment on future priorities in waste management beyond BioMinE.

With regard to objectives, it is clear that mineral dumps and dams remain the best available technology for managing mine and process waste, although evidence accumulates of improved sustainability through different forms of containment and re-use. Thus, rock dumps are increasingly shaped and stabilised to suit new surface construction and amenity, and tailings ponds are progressively replaced with pastefill and/or covered from their banks with complementary surplus materials such as pozzolanic ash and stabilised sewage (and re-vegetated). Water is increasingly conserved or purified prior to discharge. However, full integrated waste management, with use of surplus materials from other industries local to a mining operation, remains in its infancy. Thus, 'waste' continues to be largely a 'pipe end' matter rather than an interdependent part of an overall combined process, or indeed of an overall life cycle. Thus, formulation of new products from combined 'wastes' of different contiguous industries remains rare, and their potential usefulness and safety are mostly untested.

Of course, environment, safety and cost are underlying issues moderating progress in any new mineral initiative, with industrial conservatism, insufficiently sensitive regulation and under-developed R&D all implicated. To make advances in integrated waste management (albeit from a low base) consistent general recommendations are therefore that (i) local interested industries should positively emphasise production of 'waste' suited to combination in new products for specific markets (even if at marginally increased overall cost) (ii) a protocol describing a new product and its applications should be formulated in collaboration with the regulator (so as to make use of the recovery principle and avoid classification as waste) and (iii) effective safety should be confirmed concurrently via focused R&D, particularly related to fitness for purpose and containment of any aqueous or gaseous toxicity through designed speciation and appropriate lining or encapsulation (thus eliminating migratory pathways). Details are largely site-specific.

At the time of writing (September 2008), no definite plan is in place to further develop the small-scale BioMinE pilot schemes, so site specific information is unavailable. Nonetheless, outline recommendations on integrated waste management for the next stage of continuous site-based pilot scale work can be made based on principles mentioned above and technical work carried out. As has been seen, biohydrometallurgical leaching of sulphide concentrate leads to two types of unwanted material: insoluble bioleach tailings (similar to flotation tailings) and process precipitates rich in hydrated iron oxide (similar to hydrometallurgical jarosite precipitates). By analogy with available industrial flowsheets, the likely differences in composition and (possibly) pH would indicate use of separate tailings ponds or separate underground deposition (to avoid complications with return process water). In fact bioleach tailings would probably join the larger mass of flotation tailings.

However, if taken together with suitable water management, the combined solids could be divided, subject to technical characteristics and need, between cemented pastefill for underground structural support, non-cemented pastefill for tailings pond regeneration, controlled low strength material with PFA for surface or underground foundations/services and, together with sewage products, artificial soil formulation. If toxic leaching, e.g., of Cr, is an issue, cemented underground deposition (or controlled landfill) would be preferred until effective containment can been established through research. It is recommended that study of these processes should be included in any new sulphide concentrate bioleach development, with particular importance being attached to simultaneous optimisation of metal and waste product recovery.

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