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Research article

Leaching characteristics of encapsulated controlled low-strength materials containing arsenic-bearing waste precipitates from refractory gold bioleaching

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ABSTRACT

We report on the leaching of heavy elements from cemented waste flowable fill, known as controlled low-strength materials (CLSM), for potential mine backfill application. Semi-dynamic tank leaching tests were carried out on laboratory-scale monoliths cured for 28 days and tested over 64 days of leaching with pure de-ionised water as leachant. Mineral processing waste include flotation tailings from a Spanish nickel-copper sulphide concentrate, and two bioleach neutralisation precipitates (from processing at 35 °C and 70 °C) from a South African arsenopyrite concentrate. Encapsulated CLSM formulations were evaluated to assess the reduction in leaching by encapsulating a 'hazardous' CLSM core within a layer of relatively 'inert' CLSM. The effect of each bioleach waste in CLSM core and tailings in CLSM encapsulating medium, are assessed in combination and in addition to CLSM with ordinary silica sand. Results show that replacing silica sand with tailings, both as core and encapsulating matrix, significantly reduced leachability of heavy elements, particularly As (from 0.008–0.190 mg/l to 0.008–0.060 mg/l), Ba (from 0.435–1.540 mg/l to 0.050–0.565 mg/l), and Cr (from 0.006–0.458 mg/l to 0.004–0.229 mg/l), to below the 'Dutch List' of groundwater contamination intervention values. Arsenic leaching was inherently high from both bioleach precipitates but was significantly reduced to below guideline values with encapsulation and replacing silica sand with tailings. Tailings proved to be a valuable encapsulating matrix largely owing to small particle size and lower hydraulic conductivity reducing diffusion transport of heavy elements. Field-scale trials would be necessary to prove this concept of encapsulation in terms of scale and construction practicalities, and further geochemical investigation to optimise leaching performance. Nevertheless, this work substantiates the need for alternative backfill techniques for sustainable management of hazardous finely-sized bulk mineral residues.

1. Introduction

Backfill methods, e.g., hydraulic and cemented paste backfill (CPB), are increasingly perceived as sustainable, environmentally friendly and cost effective technologies, and many modern mining operations incorporate them in their waste management strategy (Marnika et al., 2015; Edraki et al., 2014; Bascetin et al., 2012; Coussy et al., 2012). Dudeney et al. (2013), Chan et al. (2008) and Bouzalakos (2008) summarise the main backfilling methods available for civil and minerals works and their differences with regard to main properties and characteristics. Controlled low-strength materials (CLSM), also known as flowable fill, are included as an additional alternative adopted from the construction industry. CLSM have increased awareness in the construction industry over the past two decades (e.g., Trejo et al., 2004), and despite extensive trials in construction works for civil projects these flowable fills remain untested at mine operations where they might be used in conjunction with conventional mine backfill. On a generic level, backfill technologies all exhibit roughly similar mechanical and permeation properties (Table 1). However, waste pretreatment requirements, binder content, consistency and economics associated with each technology makes CLSM a practical and competitive alternative. In addition, an upper compressive

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Table 1
Summary of main properties and comparison of waste re-use backfill technologies (Bouzalakos, 2008).

Property	Hydraulic backfill	Paste backfill	CLSM
Waste pre-treatment	De-watering, slimes removal	Intensive de-watering	Simple de-watering
Waste particle size	μm–mm	15 wt% <20 μm	μm–mm
Binder content	0–16 wt% cement	3–7 wt% cement	5–10 wt% cement 10–15 wt% fly ash
Water/cement ratio	0.8–1.0	1–8	3–11
Consistency	Slurry, 65–70 wt% solids	Stiff paste, 75–85 wt% solids	'Liquid', 75–90 wt% solids
Product	UCS: 0–7 MPa Porosity: ca. 40% K: 10^{-7}–10^{-4} m/s	UCS: 0.7–2.0 MPa Porosity: ca. 40% K: 10^{-6}–10^{-5} m/s	UCS: 0.5–2.0 MPa Porosity: ca. 40% K: 10^{-7}–10^{-6} m/s
Application	Void filling behind barrier, rockfill cementing	Void filling, structural support	Replacement of compacted fill (construction industry)
Economics	Superficially cheap but needs slimes management	Apparently costly pumping system but increasingly used	Apparently competitive but un-tested in mines

strength limit of ca. 2 MPa creates a CLSM that is excavatable in the future if necessary (ACI 229R, 2006).

This paper presents an attempt to reduce the leachability of hazardous components by physically encapsulating CLSM containing waste with substantial amounts of heavy elements within a layer of CLSM which is, in large, stable and inert. No pre-treatment operations or alterations to the cement content have been included, and the encapsulated CLSM (ECLSM) structure is not expected to be particularly difficult or costly to construct given the gained environmental benefit. This is largely attributed to the liquid-like consistency of CLSM filling up hard-to-reach voids and requiring no compaction or levelling. Leachability has been evaluated by performing semi-dynamic leaching tests according to EA NEN 7375 (2005). Mineral bioleaching processing wastes (precipitates) have not been previously assessed in any other form of backfill technology. Further, encapsulated CLSM (ECLSM) systems proposed herewith have not been previously considered and provide a novel type of backfill structure to physically immobilise hazardous components. Encapsulation was found to significantly reduce the leachability of certain heavy elements which is indicative of a promising approach.

2. Materials and methods

2.1. Materials

The materials used include binders (i.e., Portland cement and fly ash), mineral processing waste (i.e., flotation tailings and bioleach neutralisation precipitates), silica sand and water.

2.1.1. Binders

A commercially available Portland cement (PC) (Blue Circle CEM-I, Lafarge, UK) and a low-calcium (2.57 wt% CaO), Class F, fly ash (FA) (Drax Power Ltd., North Yorkshire, UK) were used as binders in CLSM formulations. A low-calcium FA has been selected to minimise long-term strength development of CLSM specimens (in addition to controlling bleeding). Physico-chemical properties are presented in Tables 2 and 3, respectively.

2.1.2. Flotation tailings

Tailings (T) were received as bulk samples of dewatered underflow from the flotation plant at the Lundin Mining Corporation Aguablanca open pit operation (Spain). According to Bouzalakos et al. (2013), XRD testing revealed that the material was primarily basic silicate minerals remaining after floating a Ni/Cu concentrate from the crushed and ground sulphide ore. The material also contained significant quantities of pyrrhotite (nominally $Fe_{0.9}S$), but little or no quartz. The identification of phyllosilicates, e.g., micas and chlorites, could potentially explain the high BET

Table 2
Physical properties of materials used in CLSM formulations.

Parameter	FA	SS	PC	T	P35	P70
Water content (wt%)	14.0	–	–	1.00	–	–
pH (slurry)	10.2	7.10	12.6	6.74	2.64	2.93
Specific gravity	1.96	2.37	2.77	2.72	2.44	2.42
BET surface area (m^2/g)	2.65	1.00	1.10	30.2	20.2	21.3
Mean particle size (μm)	31.2	250	10.1	29.1	13.8	27.5
Median particle size (μm)	21.1	380	15.8	17.5	7.37	6.75
% fines (<20 μm)	48.5	–	56.7	53.8	82.7	78.2
LOI (wt%)	6.00	–	1.20	11.4	14.2	15.8

Note: FA = fly ash; SS = silica sand; PC = Portland cement; T = tailings; P35 = bioleach precipitate (35 °C); P70 = bioleach precipitate (70 °C).

Table 3
Elemental analysis of waste materials[a].

Element (mg/g)	T	FA	P35	P70
Ag	0.000160	0.0000400	0.000240	0.000160
Al	29.8	25.9	1.74	2.99
As	0.0146	0.0594	34.5	33.3
Ba	0.104	0.313	0.00450	0.00360
Be	0.000350	0.00363	0.0000900	0.000190
Ca	29.0	18.4	250	295
Cd	0.000170	0.000760	0.00521	0.00541
Co	0.0376	0.0188	0.0805	0.100
Cr	0.0651	0.0405	0.101	0.150
Cu	0.387	0.0654	0.240	0.533
Fe	38.9	27.5	156	143
K	2.75	2.84	0.765	0.229
La	0.00737	0.0338	0.00220	0.00301
Li	0.0165	0.0591	0.0132	0.0122
Mg	24.7	4.79	1.63	1.72
Mn	0.412	0.174	0.0114	0.0238
Mo	0.000200	0.0116	0.00430	0.00500
Na	3.00	2.45	1.69	1.71
Ni	1.28	0.0567	0.544	0.845
P	0.273	2.16	1.06	1.14
Pb	0.00800	0.0372	0.118	0.0164
S	8.05	1.77	204	221
Si	115	510	0.915	1.12
Sr	0.111	0.682	0.315	0.282
Ti	1.54	0.850	0.0318	0.0355
V	0.0182	0.0737	0.00456	0.00620
Zn	0.0175	0.0575	0.138	0.170

Note: FA = fly ash; SS = silica sand; PC = Portland cement; T = tailings; P35 = bioleach precipitate (35 °C); P70 = bioleach precipitate (70 °C).
[a] Digestion with HNO_3, $HClO_4$ and HCl according to Thompson and Wood (1982).