Effects of Fine Content, Binder Type and Porosity on Mechanical Properties of Cemented Paste Backfill with Co-Deposition of Tailings Sand and Smelter Slag

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ABSTRACT

Mine backfilling is a process where the underground voids resulted from mining are filled with waste materials. The potential of co-depositing iron sand produced from smelting process with tailings sand was investigated in the present study. Different amounts of iron sand were mixed with the tailings sand to prepare cemented paste backfill (CPB) samples. Two types of binders were used. Uniaxial compression tests were performed for the CPB samples after 28 days of curing. The porosities of the samplers after curing were calculated to correlate the porosity with the uniaxial compression strength, UCS. Results from uniaxial compression tests showed that the amount of iron sand and the type of the binder influences the UCS, as well as content values of fines and porosity. These results demonstrated the possibility for a part of Fe-sand to be deposited together with the tailings sand to increase UCS values for the CPB samples, which will be beneficial for both mining operation and environmental protection.

KEYWORDS: Cemented past backfill, CPB, UCS, porosity, tailings sand, Fe-sand

INTRODUCTION

Mine backfilling is a process where the underground voids resulted from mining are filled with waste materials. The advantages of backfilling include: provide ground support for the surrounding mining structures allowing a safe working environment and maximizing ore recovery from pillars; minimize surface subsidence and decrease deposition of mill tailings on the mine-site surface (Ercikdi et al., 2009; Landriault, 2001; Bayram, et al., 2003). The backfilling methods currently used are hydraulic fill, rock fill, and cemented paste backfill (CPB). The CPB is the most recently developed method and increasingly used by modern mines throughout the world, as it provides higher efficiency of backfilling operation and stability of mines, better support capabilities and a safer working environment (Landriault, 2001; Benzaazoua et al., 2004; Kesimal et al., 2002; Yilmaz et al., 2003). CPB consists of primarily mine tailings, hydraulic binders and water. The purpose of the binder addition is to develop cohesion and strength within pastefill so that the exposed faces can be self-supporting and stable. CPB mix must be designed according to both rheological properties and strength requirement. Laboratory tests measuring values of slump and unconfined compression strength (UCS) are commonly performed for evaluations of rheology and strength properties in order to aid the CPB design. Those tests were carried out by the present study using mining by-products as a part of CPB materials. The by-products are generated from mining and smelting operations of Boliden Group in Sweden.

The Boliden Group (hereafter abbreviated as Boliden) is a metals company that operates mines and smelters in Sweden, as well as other two Nordic countries and Ireland. The mining operation of Boliden in Sweden extracts ores from open-pit and underground mines. The ores are transported to concentrators in or near the mining area, where zinc and copper concentrates are produced. A large part of the concentrates is further refined into metals at one of the Boliden's smelters, the Rönnskär Smelter.

The Smelter is an integrated metallurgy complex, with kaldo and fuming plants to complement its copper production with the recycling of metals from electronic scrap and other secondary materials. Besides the main products, copper, zinc clinker, lead and precious metals, the Smelter produces also some by-products, including sulphuric acid and slags.

One type of the slags is formed mainly by silica sand and iron bound in the copper minerals in the electrical smelting furnace. This slag is then charged in the fuming furnace for the process of Zn fuming. After the fuming, the slag is charged in the settling furnace for a separation of droplets of copper alloy and sulphide from liquid slag. The cleaned slag is subsequently rapidly cooled by water, resulting in a granulated, glassy slag. The flow sheet for the slag processing is presented schematically in Figure 1 (Michael Borell, 2005).

The granulated settling furnace slag contains mainly oxides of iron and silicon of more than 80%. The slag, with its high iron content and being sand-like, was then named as Boliden iron sand. The iron sand contains also trace elements of a total concentration of about 3%, such as Zn, Cu, Ba and Mn. These elements are incorporated in amorphous or glass phases in the Fe sand particles with a very low solubility in water. The results from the laboratory leaching tests have clearly shown that Boliden Iron sand has a very low leachability and can thus be regarded as an inert material.

At the beginning the iron sand was used internally for enlargement of industrial area at Rönnskär. Later application tests demonstrated good heat insulating and draining qualities for the iron sand, making it particularly suitable for road- and ground-constructions in cold climate. Since these tests iron sand has been used as a high quality material for road construction for nearly 40 years in the Skellefteå region in north of Sweden.

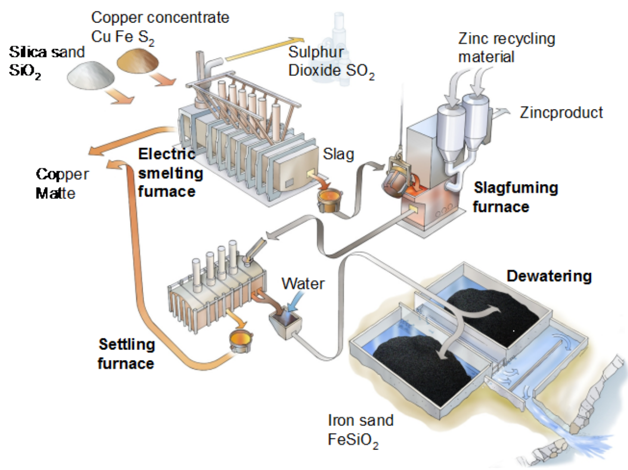

Figure 1. Process flow sheet of Cu settling furnace slag that is granulated to generate the Boliden Iron Sand

In recent years there have been more strict limits prevailing to control environmental properties of industrial by-products for civil engineering applications. Values of the limits include not only metals leaching but also metals concentration. These strict limits have largely decreased volumes of iron sand used in construction in Sweden. One way to avoid deposition of the iron sand is to use it in some of the mining operations carried out by Boliden.

The Garpenberg mine is one of the Bolidens underground mine, where the ore is mined from between 500 to more than 1200m below the ground level. Sublevel stoping is the main mining method, cut-and-fill mining, rill mining and residual mining of sill pillars are also used. The excavated areas are backfilled with waste rocks in early times. Since 2006, CPB has been implemented in Garpenberg Mine as an alternative backfill material using the full tailing together with cement and process water to achieve the 28-days strength values of 0.5-1.5 MPa for different purposes of the fill bodies.

As there is a need to utilize iron sand in Boliden mines. The present work was carried out to investigate the potential for a co-deposition of Fe-sand with tailings in CPB materials to improve the mechanical properties of the CPB for backfill requirements of Boliden mines. CPB samples were prepared in the laboratory using various ratios of Fe-sand to tailings sand from Garpenberg mine and two kinds of binders. The UCS values of the CPB samples were determined after 28 days of curing, as well as the porosities of the samples.

For natural or manmade porous material, it is well known that the UCS tends to diminish with increasing porosity. Many studies have been done on rocks and concrete, as well as soils and fills(Sarda et al., 1993; Palchik, 1999, Berry, 1981; Rozos and Koukis, 1986; O’Rourke and Crespo, 1988; Del Olmo et al., 1996; Popovics, 1987). Ouellet et al. (2008) studied effects of porosity in CPB and found that the strength increase was related to the decrease in porosity during curing. A mixing of relatively coarser iron sand with the Garpenberg tailings sand can result in a modified particle size distribution (PSD) for the filling materials. This modification on PSD may lead to a better gradation of fractions, providing a denser, minimum pore structure and strength improvement. Values of porosity of the CPB samples tested in the present study were thus calculated for clarification of the relation between the porosity and the values of UCS measured. Li-Aubertin model (Ouellet, et al, 2008) linking the two parameters was also employed to present the results for a better understanding of the porosity effects.

2 Materials and Method

2.1 Characterization of the Fe-sand and tailings sand

The tailings sand collected from Garpenberg mine in this study contains about 35 % fines (particles <20 µm). The Boliden Fe-sand, with no any fines content (<20µm), can be classified as very sandy gravel. Contents of moisture were 22.4 % and 2.3%, respectively, in the tailings sand and Fe-sand. The tailings sand consists mainly of quartz, muscovite, pyrite, phlogopite, dolomite, and labradorite (ALS Mineralogy Pty Ltd, 2010). Some data of chemical composition of the Boliden Fe-sand and the tailings sand from Garpenberg mine are shown in Table 1. The pyrite and dolomite are the main sources for the S of 5.5% and C of 4.7%, respectively, in the tailings sand. There are no C and S existing in the Fe sand.

Table 1 Chemical composition of the Boliden Fe sand and tailings from Garpenberg mine

Weight %	Zn	Cu	CaO	SiO_2	Al_2O_3	MgO	Fe	MnO	C	S	Loss on ignition
Fe sand	1.1	0.81	3.6	36	4.1	1.5	36.3				
Tailings sand			15.7	45.2	2.4	9.7	8.0	2.6	4.7	5.5	-12

2.2 Binder and mixing water

There were two types of binders added in the CPB samples. One type of the binders is bascement (CEM II/A-V 52.2N), a type of ordinary Portland cement produced in Sweden blended with fly ash. Another type consisted of 20% of the bascement and 80% of Merit 5000 (hereafter abbreviated as Merit). The Merit is produced by steel industry in Sweden using water granulated blast furnace slag. Specifications of the binders are shown in Table 2.

The water used for the CPB samples was process water from Garpenberg mines containing 720 mg/l sulphate (SO42-) (DIN 4030-1, 1991), which is highly aggressive and can induce strength loss for the CPB due to sulphate attack. Thus sulphate resisting binders, such as bascement and Merit, were required and adopted for the present study.

Table 2 Specification of bascement and Merit 5000 (SSAB Merox AB, 2012)

	Chemical analysis, weight %										Specific surface, cm^2/g	Grain density, g/cm^3
	CaO	SiO_2	MgO	Al_2O_3	TiO_2	Mn_2O_3	FeO	S^{2-}	SO_3	Na_2O		
Bascement	55.8	24.1	2.7	6.4	-	-	-	-	3.5	0.38	4500	3
Merit 5000	31	34	16.5	13	2.4	0.6	0.3	1.3	0.25	0.9	5000	2.9

2.3 Preparation of CPB samples for the laboratory tests

The transportation of CPB through pipelines into underground placement is governed by its rheological properties, which depend strongly on the amount of process water added. The rheological properties of CPB are often difficult to determine accurately and, instead, the simple standard slump test for cement concrete is usually used as a measure of the CPB flowability. The dimensions of the standard slump cone are: top diameter 100mm, bottom diameter 200mm, and height 300mm (Figure 2). The standard slump cone is commonly used for slump tests in industrial sites. The requirement of the Garpenberg mine is the slump height of 195 mm by standard slump cone for the CPBs. However, tests using standard slump cone require a big volume of CPB materials and, thus, mini slump cones became an alternative to use for laboratory tests in many studies (Michael, et al., 2008). A mini slump cone used in this study is shown in Figure 2. The mini slump height equivalent to that required by the Garpenberg mine (195 mm) was 65 mm, calculated by an analytical model proposed by Clayton et al. (2003). Process water was slowly added until the well mixed CPB reached the slump height of 65mm measured by the mini slump cone. The procedure of slump test is described in ASTM, Standard C143-00.

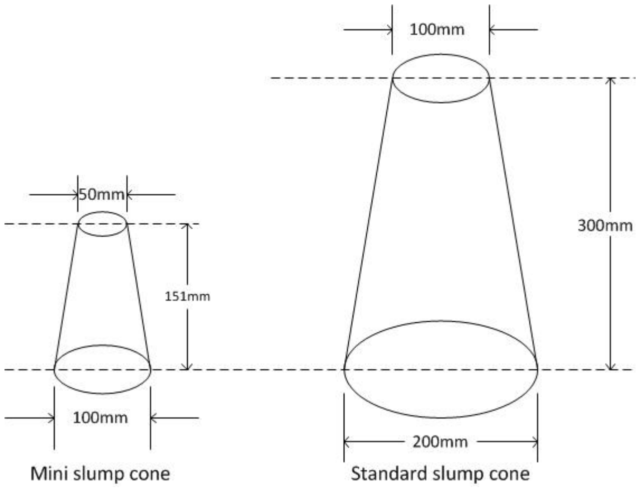

Figure 2 The dimensions of the mini slump cone and the standard slump cone

The CPB mixtures with various mixing ratios and resultant solid contents are shown in Table 3. Each of the samples added only one type of the binders with the amount of 4% by dry weight. The amount of process water was decided by slump test. Fe-sand, the tailings sand, binder and the process water were mixed thoroughly using a hand mixer for about 15 minutes. The mixture was then poured into cylindrical forms of 100 mm diameter and 200 mm height for curing in a period of 28 days under room temperature (Figure 3). The samples were covered with plastic caps to avoid evaporation. The UCS of the samples after cutting for 28 days was measured with the deformation rate of 1mm/minute. For each mixing ratio, three replicates were tested to obtain the averaged UCS value. After the UCS tests, the samples were dried in an oven with 105˚C to measure moisture contents and, then, ground to measure the grain density by using gas pycnometer.

Figure 3 CPBs in cylindrical forms

Table 3 CPB recipes with corresponding solid contents using the binder amount of 4% by dry weight

CPB recipes	Fe-sand/ the tailings sand in dry weight

		0:1	0.2:1	0.4:1	0.8:1	1:1	1.2:1
Bascement	Solid content, wt. %	73.5	77	80.4	84.2	84.9	85.2
20% bascement+80% Merit	Solid content, wt. %	72.8	77	82.5	84.1	-	84.9

3 Results and discussion

3.1 Effect of adding Fe-sand on the particle size distribution and gradation of CPB samples

It has been shown that a minimum of 15 weight% of fines (particles <20 µm) is needed for a workable CBP to be transported through pipelines (Landrianult, 1995). Based on the system for tailings classification developed by Golder Paste Technology, the coarse tailings with fines content between 15-35 % can have a higher strength development than the fine tailings (Landrianult, 1995).

Furthermore, the material needs to be well graded with grains of all sizes. The material is well graded if values of curvature coefficient CC (CC = D302/D60*D10) are between 1-3. The material is not uniformly distributed with the uniformity coefficient CU > 5 (CU = D60/D10); when 5<CU <20, the material is somewhat spread out and the material is spread out while 20< CU <200. Values of CC and CU for the tailings sand from Garpenberg mine are 0.71 and 9.1 (Table 3) and these for Boliden Fe-sand are 1 and 2.2, respectively. As the Fe sand possesses more favorable values of both CC and CU than the tailings sand, mixing the Fe-sand and the tailings sand with the dry-weight ratios of 0.2:1, 0.4:1, 0.8:1, 1:1 and 1.2:1 has modified values of fine contents, CC and CU for the CBP raw materials, Table 3, as well as the PSD of the materials, Figure 2,. The data in Table 3 indicate that the Fe sand additions can lead to greater modifications to values of fine contents and CU than to values of CC.

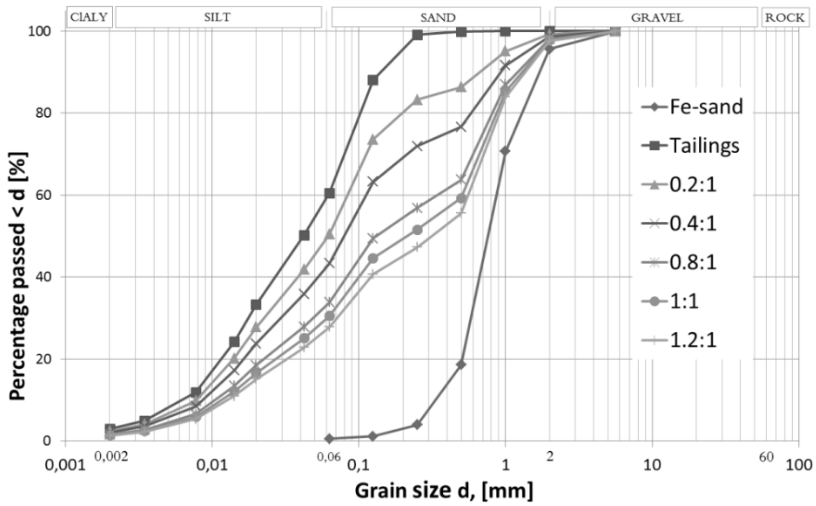

Figure 4 PSD, particle size distribution, of Fe-sand, the tailings sand and the CPB raw materials, mixtures of Fe-sand and tailings sand with dry-weight ratios of 0.2:1, 0.4:1, 0.8:1, 1:1 and 1.2:1

Table 3 Particle size parameters of the CPB material

	Fe-sand	Tailings sand	Ratio of Fe-sand/tailing sand in dry weight				
			0.2:1	0.4:1	0.8:1	1:1	1.2:1
Fines content, %	0	33.3	27.8	23.8	18.5	16.7	15.2
C_c ($D_{30}^2/D_{60}*D_{10}$)	1	0.71	0.76	0.97	0.76	0.7	0.88
C_U (D_{60}/D_{10})	2.2	9.1	10.3	11.93	33	46.7	47.3

3.2 Effect of adding Fe-sand in the tailings sand on the strength of CPB samples

Figure 5 shows the uniaxial compression stress-strain curves for the CPB samples after 28 days of curing. Some of geotechnical parameters of the samples are listed in Table 4. Using the tailings sand only, values of UCS for the CPB samples are 0.37 and 0.40 MPa with binder Bascement and the mixture of 20%Bascement+80%Merit, respectively, Table 4. These values are lower than the least strength requirement of 0.5 MPa.

Using the Bascement as binder and the Fe-sand/tailings sand ratio of 0.2:1, the UCS is 0.25 MPa; Table 5, and also lower than the least strength requirement. While increasing the ratios of Fe-sand/tailings sand to the range from 0.4:1 to 1.2:1, values of UCS are all higher than the least requirement and ranged 0.61-0.92 Mpa, Figure 5a. Using mixture of 20%Bascement+80%Merit as the binder has enhanced the effect of Fe-sand addition and increased the UCS to 0.73-1.90 Mpa with the ratios of Fe-sand/tailings sand of 0.2:1-1.2:1, Figure 5b.

These results demonstrate that the compressive strength, UCS, and the modulus of elasticity, E, of the CPB samples are influenced by the amount of Fe-sand added to the tailings sand. Mixing Fe-sand with the tailings sand can have two results: 1) Optimizing PSD that can produce a better packing of CPB structure as the fines filling up the spaces created by coarse grains; 2) Making the CPB samples stiffer, leading to lower elasticity. For the sample with Bascement binder and Fe-sand/tailings sand ratio of 1:1, the CPB reached the maximum strength of 0.92 MPa, due to the best packed structure within CPB sample.

The CPB sample with the mixture of 20% bascement + 80% Merit and Fe-sand/tailings sand ratio of 0.4:1 achieved the maximum strength of 1.90MPa. The sample with the ratio of 0.4:1 may not have the best packed structure, but may possess some other geotechnical parameters more favorable for achieving the highest UCS value, such as the moisture content, W, and degree of saturation, Sr, Table 4.

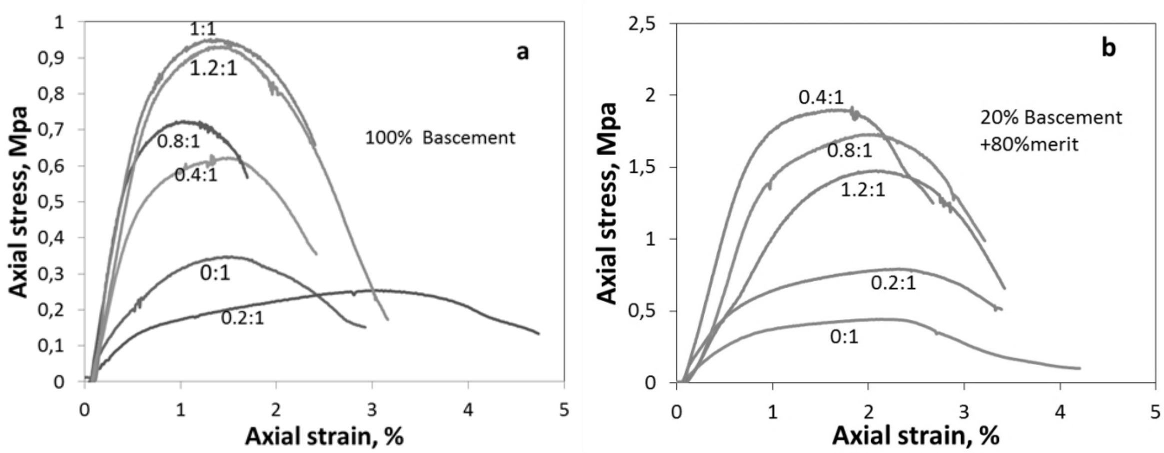

Figure 5 Uniaxial compression stress-strain relationships for (a) CPB samples using bascement as binder, (b) CPB samples using the mixture of 20%bascement+80% Merit as binder. The ratios shown on the curves are Fe-sand/tailings sand in dry weight

Table 4 Geotechnical parameters of CPB samples after 28 days of curing

Binder type	Fe-sand/Tailings sand ratio in dry weight	W (%) (water content)	Sr (%) (degree of saturation)	n (porosity)	E (MPa) (modulus of elasticity)	UCS (MPa)

Bascemnt	0:1	26.3	98	0.44	44	0.37
	0.2:1	29.8	100	0.44	29	0.25
	0.4:1	19.8	99	0.38	105	0.61
	0.8:1	15.6	96	0.34	181	0.73
	1:1	14.4	98	0.32	181	0.92
	1.2:1	14.4	99	0.31	133	0.88
20%Bascement +80%Merit	0:1	34.4	100	0.47	64	0.40
	0.2:1	25.8	98	0.43	91	0.73
	0.4:1	19.5	100	0.37	250	1.90
	0.8:1	16.2	100	0.33	147	1.71
	1.2:1	15.0	100	0.32	119	1.42

It was found in an early laboratory investigation that the maximum strength (UCS) can be obtained for the backfill samples containing fines of 47-53 weight% (Fall et al., 2004). Another laboratory study with different tailings samples demonstrated that the UCS had a 1.38- to 1.52-fold increasing with decreasing the fines contents to 15-20% (Bayram, et al., 2003), which are rather similar to the result obtained by the present work. As shown in Tables 3 and 4, the CPB samples have acquired the maximum UCS with fines content of 16.7% and 23.8% using, respectively, Bascement and mixture of 20% Bascement+80% Merit as the binder, demonstrating that binder type and chemistry can also strongly influence the UCS acquisitions for the CPB samples, besides the fines contents and some other geotechnical parameters.

3.3 Effects of binder type and chemistry on the strength of CPB samples

Results in Tables 3 and 4 are plotted in Figure 6, showing that, with fines contents of 18.5-23.8%, the values of UCS acquired for the CBP samples solidified by the mixture of 20% Bascement+80% Merit are considerably higher than the CBP samples solidified by the Bascement. The result from another laboratory work preparing the CPB samples with different binders, Figure 7, demonstrated that, while the fine contents ranged from 35 to 60%, significantly higher values of UCS could be obtained for the CBP samples employing slag blended cement than those for the samples only employing blended cements (Belem et al., 2008).

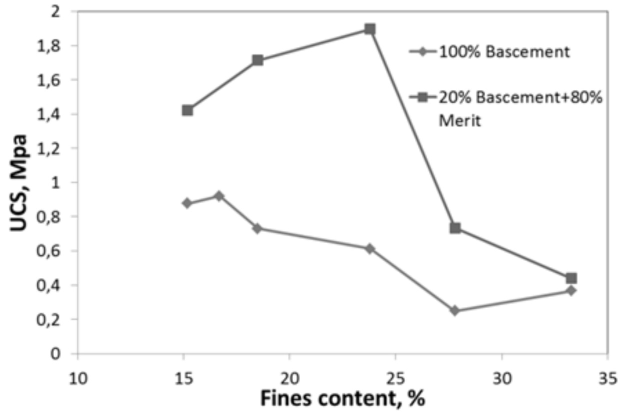

Figure 6 UCS variation as a function of fines contents in the CPB samples solidified by Bascement and mixture of 20% Bascement+80% Merit as the binders in the present study

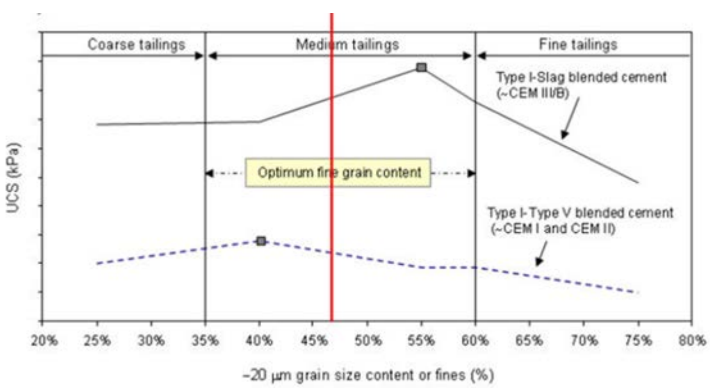

Figure 7 UCS variation as a function of fines contents in tailings solidified by two types of binders (adapted from Belem et al., 2008)

Mostafa Benzaazoua et al. investigated influences of chemical factors on performance of CPB materials prepared using mine tailings with different sulphur contents (Mostafa Benzaazoua et al. 2002). Their results indicate a direct relation between the binder hydration and the tailings sulphur content. The CPB samples prepared by the authors with tailings of low and medium sulphur grades containing S of 5-16% have developed lower UCS values with the cement binder formed by blending ordinary and sulphate-resistant Portland cement. However, these tailings have acquired higher values of UCS while using the binder formed by blending the cement and blast furnace slag with ratio of 30:70.

The Merit and Bascement possessed similar properties as the blast furnace slag and the Portland cements used in the studies performed by Mostafa Benzaazoua et al. (Mostafa Benzaazoua et al. 2002) and Belem et al. (Belem et al., 2008). The tailings sand of the present study contained S of

5.5%, Table 1. Thus, due largely to the tailings sand with this low sulphur grade, the higher strength acquisition has been achieved by using the mixture of 20% Bascement+80% Merit as the binder, rather than by the Bascement, which is in a rather good agreement with the results of Mostafa Benzaazoua et al. (Mostafa Benzaazoua et al. 2002) and Belem et al. (Belem et al., 2008).

3.4 The influence of porosity of CPB samples on UCS

Table 4 shows the calculated porosity (n) of the CPBs after 28 days of curing. The calculation was done using moisture content, bulk density and grain density of the samples. Porosity is one of the key microstructural characteristics and may influence many geotechnical properties including uniaxial compression strength. It is well known that the uniaxial compression failure strength tends to diminish with an increase of the voids within a material (Li and Aubertin, 2003). Some predictive models of mechanical strength have been developed based on the total porosity (n) (Bal'shin, 1949; Rzhevsky and Novik, 1971). Li and Aubertin (2003) proposed a general relationship between porosity and uniaxial strength, including both compressive and tensile strength, for engineering materials, and this is later modified by Ouellet et. al. (2008) for compressive strength:

$$\frac{(C_0)_n}{(C_0)_{max}} = 1 - \sin^{x1}\left(\frac{\pi}{2}\frac{\langle n-n_{min}\rangle}{n_c-n_{min}}\right)$$

(1)

Where (C0)n is the evaluated UCS for porosity n, nc is the material critical porosity when the UCS becomes almost nil, (C)max is UCS at the minimum porosity (nmin), x1 is the fitting material parameter, and ⟨ ⟩ are Macauley brackets ($\langle y\rangle = 0.5(y + |y|)$).

Many researchers have measured values for the minimum porosity (Mabes et al., 1977; Bussiere, 1993; Aubertin et al., 1996) and the value of nmin has been reported as close to 0.25. The maximum UCS, (C0)max , corresponding to the nmin is estimated at 4.080 MPa in the literature (Amaratunga and Hein, 1997; Cayouettem, 2003; Brackebusch, 1994). Ouellet et al. (2008) have made a comparison between the UCS values versus porosity predicted using Modified Li-Aubertin model and measured UCS values for the CPB samples solidified using three types of binders. As observed in Figure 8, the measured UCS values are rather close to those predicted by the model and the types of binders seems to have less influence than the porosity.

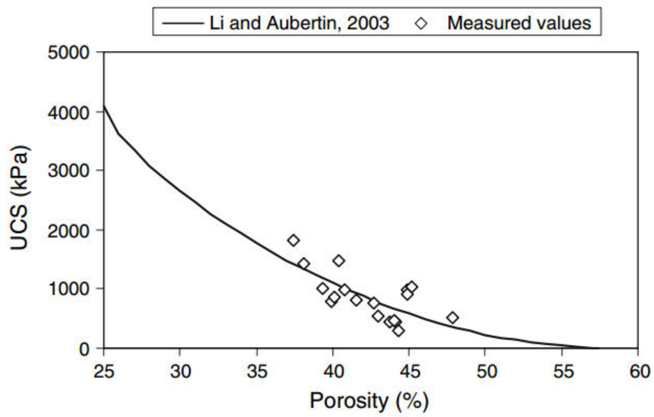

Figure 8: Comparison between the UCS values versus porosity predicted using Modified Li-Aubertin model and measured UCS values for the CPB samples solidified using three types of binders. (adapted from Ouellet, et al, 2008)

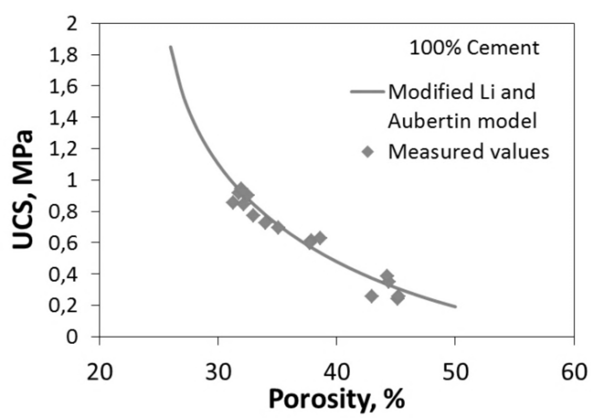

Figure 9: Comparison between the UCS values versus porosity predicted using Modified Li-Aubertin model and measured UCS values for the CPB samples solidified using bascement as binder in the present study.

Figure 9 compares the UCS values versus porosity predicted using Modified Li-Aubertin model with the UCS values measured for the CPB samples solidified using bascement as the binder in the present study. It is shown that the predicted UCS values agree rather well with the measured ones. While using mixture of 20% bascement and 80% Merit as the binder the measured UCS values also agree with the predicted ones, Figure 10, expect for the values of porosity around 37%, where the measured UCS values are higher than the model predictions. The reason for this disagreement may be investigated in later studies.

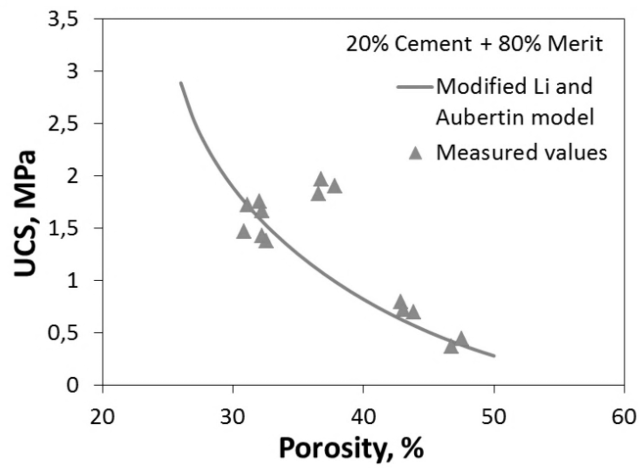

Figure 10: Comparison between the UCS values versus porosity predicted using Modified Li-Aubertin model and measured UCS values for the CPB samples solidified using mixture of 20% Bascement+80% Merit as binder in the present study.

4 Conclusions

1. Laboratory tests have been conducted to investigate the potential to co-deposit Fe-sand with the tailings sand as backfill material in Garpenberg mine in Sweden. Measurements of uniaxial compression strengths showed that parts of Fe-sand can be deposited together with the tailings sand as backfill materials with increased strength, by which the mining operations can become more environmentally friendly and cost effective.
2. The strength depends on both the amount of Fe-sand mixed with the tailings sand the binder types. When only using bascement as the binder, the maximum strength achieved was 0.92MPa with Fe-sand/tailings sand ratio of 1:1. While adopting mixture of 20% bascement and 80% Merit as the binder, the maximum strength was 1.92 MPa with Fe-sand/tailings sand ratio of 0.4:1.
3. Comparison between the UCS estimated by modified Li-Aubertin model and the measured UCS values showed a strong influence of porosity on the strength values for the CPB samples solidified by using bascement. While using mixture of 20% bascement and 80% Merit as the binder the measured UCS values were higher than the model predictions for the values of porosity around 37%, indicating a strong effect of binder type on the measured UCS values around the porosity. The UCS measurements and predictions agree well for other values of the porosity.

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Editor's note. This paper may be referred to, in other articles, as:
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