

# Design of high-strength backfill for a drift-and-fill mining method at Olympias Mine, Greece

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## Abstract

*Olympias Mine is operated by Hellas Gold S.A., a subsidiary of Eldorado Gold Corporation. The orebody shape and size are suitable for a drift and fill mining method. The mining sequence is overhand and the demand for backfill strengths are generally low except for the initial sill cuts. The design fill strengths are determined from the planned stope exposures to allow for safe extraction of the ore in adjacent drifts and immediately below the initial sill drifts with minimum dilution. Due to the permit constraints imposed on mining at Olympias Mine, after an environmental impact assessment, there is a requirement that the final backfill strength must reach a uniaxial compressive strength (UCS) of 4.0 MPa at 28-day cure age. By developing a suit of mix recipes incorporating superplasticiser admixtures, it was possible to achieve the strength demands and the workability of the backfill. This paper presents the results from comprehensive test work conducted on whole mill tailings and cyclone mill tailings to produce high strength backfill.*

**Keywords:** *drift and fill, backfill plant, cemented fill, test work, rheology, yield stress, mix design, reticulation, superplasticisers, admixtures, uniaxial compressive strength*

## 1 Introduction

Olympias Mine is an underground mine located in Northern Greece in the Chalkidiki Peninsula, about 90 km east from the city of Thessaloniki. Figure 1 indicates the location of Olympias Mine with a description of the lithology. The mine is operated by Hellas Gold S.A., a subsidiary of Eldorado Gold Corporation.

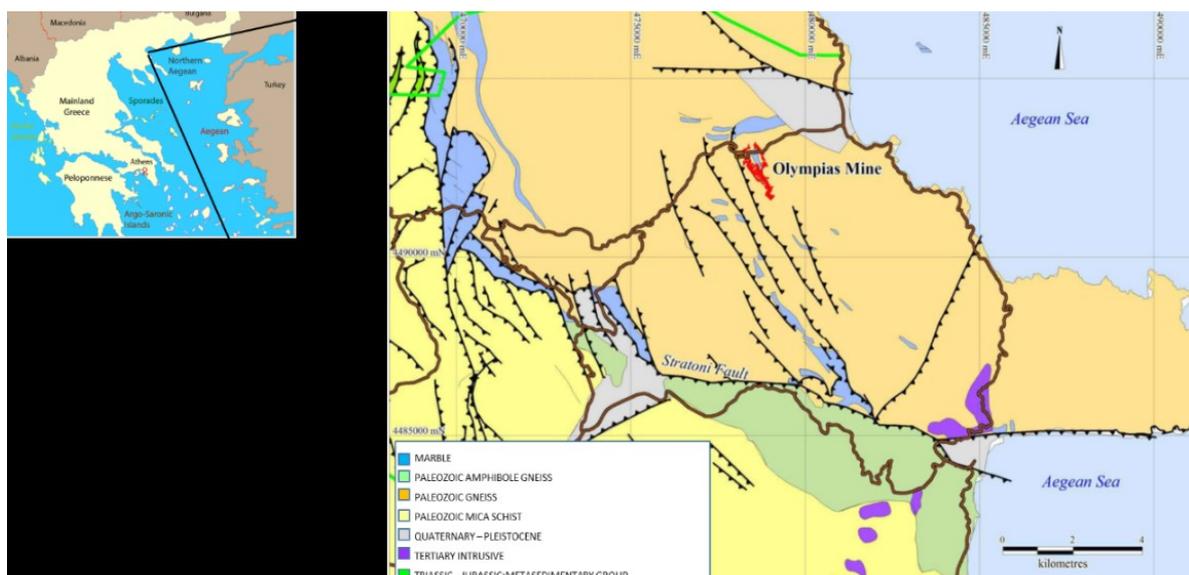


Figure 1 Olympias Mine locality map and geological setting modified after Rhys (2013)

## 1.1 Mineralisation and geology

Mineralisation at the Olympias deposit occurs in lenses of replacement style, manto-like sulphide-dominant mineralisation, siliceous sulphide replacement and breccia mineralisation. Ore lenses occur within and along the contacts of the Olympias marble unit, which is in turn hosted by amphibolite grade biotite-quartz-feldspar gneiss. Mineralisation trends north-northwest and forms several elliptical south-southeast plunging sulphide lenses that elongate parallel to the dominant L2 lineation in the gneiss sequence and to F2 folds. Mineralisation is structurally late in timing and is superimposed on the metamorphic fabrics in the area and in association with an extensional, brittle to semi-brittle fault network that was likely active coevally with a prevalent ore-hosting fault to the south (Rhys 2013).

The mineralisation occurs within two orebodies. The West orebody is approximately 250 m wide and plunges 1,500 m to the southwest. It has been intersected from the surface to a depth of 500 m and is an open down plunge. Its width varies between 5–15 m, with dips averaging 30–35° to the east.

The East orebody lies some 150 m east of the West orebody, has an anticlinal structure, exhibiting axial thickening, with steeper dips toward the peripheries. It dips an average 25–30° to the southeast. Its width averages 75 m and its average thickness is 7 m. The mineralisation has been traced for 600 m down plunge.

## 1.2 Mining method and production

The ore zones at Olympias Mine are variable in orebody geometry and ground conditions. The ore contacts are well defined and are often irregular on the footwall. The high grades associated with these types of ore dictate selective mining methods in order to maximise ore extraction. The current mining methods include transverse and longitudinal drift and fill (DAF) mined in an overhand (bottom-up) sequence over 20 m high sub-levels.

Conventional mechanised 5 m wide × 5 m high drill and blast and load-haul-dump methods of extraction are employed in both production and development. The current production target is 390,000 tonnes per annum (tpa) which will increase to 430,000 t in 2019 (Figure 2).

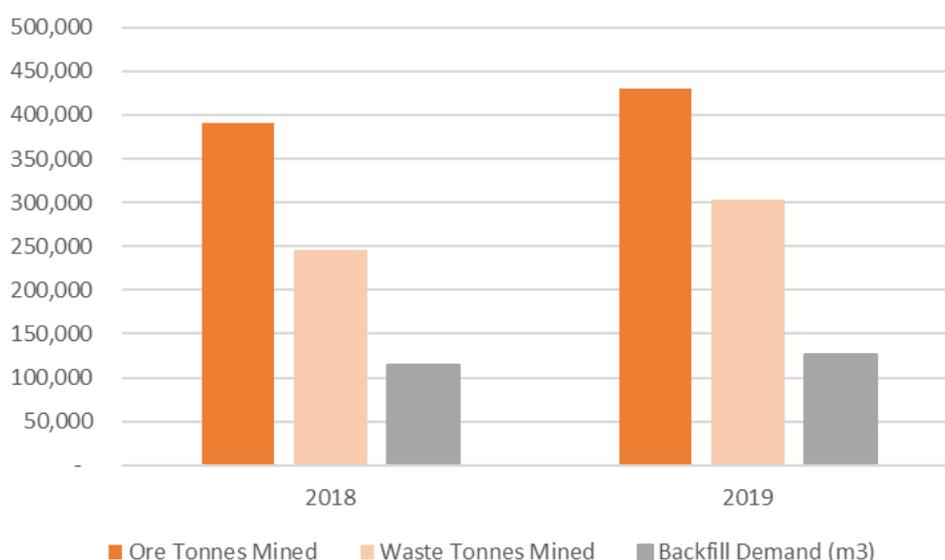


Figure 2 Mine production and backfill schedule

### 1.3 Mining directive

The Olympias Mine mining permit imposed by the Environmental Impact Assessment (EIA) includes the following major items relating to backfill design:

- The backfill must have a final 28-day uniaxial compressive strength (UCS) of 4.0 MPa.
- The backfill must be placed as quickly as possible after the excavation void is formed, and the fill must be in contact with roof rock so that there are no gaps or voids.
- When mining adjacent drifts, the backfill must be placed in the initial drift and reach a minimum UCS strength of 1.0 MPa before the vertical walls are exposed to mine the adjacent drift.

### 1.4 Backfill strength design

Based on conventional engineering design for backfill strength requirements, a nominal UCS of 0.3–0.5 MPa and UCS of 1.0–1.5 MPa will be sufficient for vertical exposures when mining adjacent stopes and for human entry undercut exposures when recovering ore below sill pillars, respectively.

## 2 Backfill system

The backfill plant at Olympias Mine can produce high density fill using both coarse tailings from cycloned tailings and total tailings from the processing plant (Figure 3).



Figure 3 Olympias backfill plant

### 2.1 System rates

The backfill plant has a nominal production capacity of 35 m<sup>3</sup>/h with a peak of 42 m<sup>3</sup>/h cemented backfill at a mix density of 75% $C_w$  solids by weight. The backfill production capacity is governed by the capacity of the positive displacement (PD) pump. The tailings feed (approximately 82% solids w/w) to the backfill mixer is a 40/60 split between feed from disk filters at 20 dry tonnes per hour (dtpH) and 29 dtpH feed from reclaimed tailings. The tailings are mixed with 12.5% cement by solids weight along with process water and superplasticiser admixture in a twin shaft continuous mixer before being pumped underground through a network of boreholes and pipelines.

### 2.2 Reticulation system

The underground reticulation system comprises 5-inch steel pipelines, and friction losses of between 8 kPa/m and 12 kPa/m are expected at the design delivery rate. The current maximum transport distance from surface to underground stopes is 2.6 km in the West Zone and 1.0 km in the East Zone.

The underground pipeline is equipped with inline pressure indicating transducers and a magnetic flow metre (Figure 4).

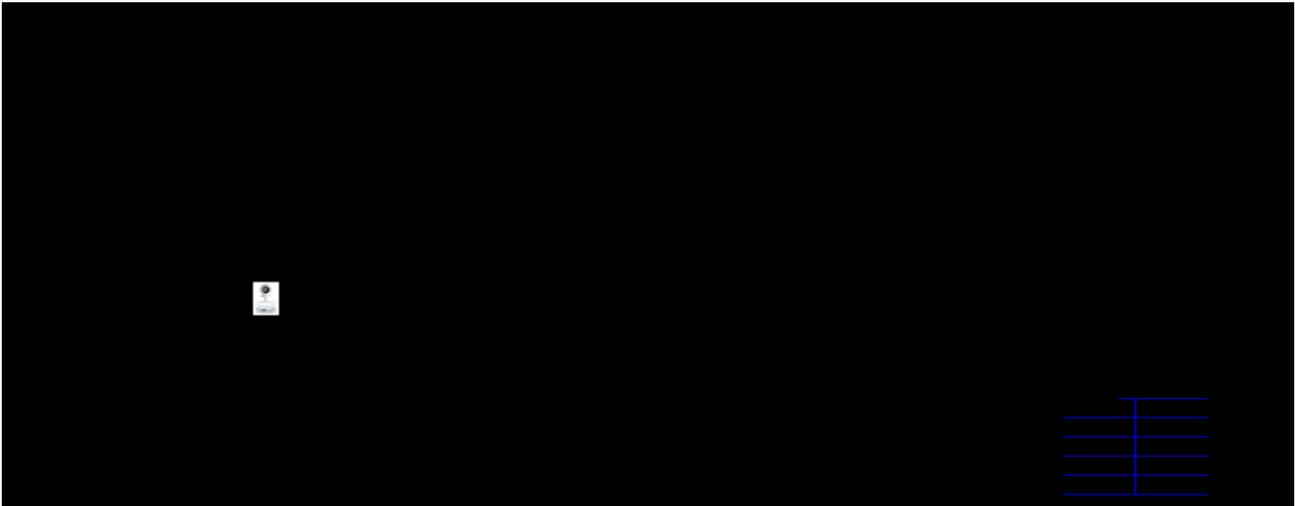


Figure 4 Schematic of backfill reticulation layout

### 3 Mix recipe development

Olympias Mine has conducted an extensive test work program with vigorous analyses of the results in order to determine performance of tailings-based backfill options. A series of high density mix designs were developed aiming at finding out the optimal combination of fill type, cement type and rate, and superplasticiser admixture type and dosage.

Given the requirement to meet the mandated high target strengths, it was clear from the outset that a mix design with high solids concentration and low water cement ratio would be required. This high-density mix would then have to be flowable given the operating conditions and the constraints imposed by the delivery system. The current mining operations are relatively shallow (250 m to 500 m below surface) and the existing reticulation layout has a low aspect ratio of depth to lateral pipeline distance.

Following initial trial mixes, a high density backfill mix with minimal free water was developed. Settling tests for a high-density mix using coarse tailings prepared at 75% $C_w$  solids concentration and 15% cement, indicated less than 2% volume loss. Settling tests for high density mix using total tailings prepared at 75% $C_w$  solids concentration with 12.5% cement yielded less than 0.5% volume loss.

## 4 Material characterisations

### 4.1 Mineralogy

The X-ray diffraction (XRD) analysis indicates that the mineralogy of Olympias tailings is highly variable. Quartz, Calcite, Gypsum, Dolomite, Illite, Muscovite, Pyrite and Kaolinite are the major minerals for the tailings tested (Table 1). The clay minerals Illite and Kaolinite have a strong affinity for water (hydrophile) and can have a negative impact on rheology and strength development of backfill due to colloidal effects. The mineral Muscovite has a planar sheet like structure and can also have an adverse impact on rheology and strength of backfill. The other minerals are considered to be non-detrimental for backfill rheology and strength.

Table 1 X-ray diffraction analysis of full plant tailings

Minerals	Weight % (1)	Weight % (2)	Weight % (3)
Quartz	39.2	32.8	35.6
Calcite	26.8	20.4	15.9
Gypsum	5.9	1.8	4.5
Dolomite	9.6	11.8	13.8
Illite	10.8	3.8	3.3
Muscovite	2.1	7.7	10.2
Pyrite	2.8	4.1	3.3
Kaolinite	0.8	1.2	3.2

### 4.2 Particle size distribution

Particle size distribution (PSD) analysis of the total tailings, cyclone underflow and filtered coarse cyclone tailings were completed by conventional sieving. The PSD results are plotted in Figure 5, which indicates that the full plant tailings have variable PSD with P<sub>80</sub> of 140–170 microns. This can be attributed to the variability of ore types being treated at the process plant. The Olympias total tailings from processing plant contain 30–35% fines passing 20 micron and can be classified as medium tailings, while the tailings from the cyclone underflow can be classified as coarse tailings.

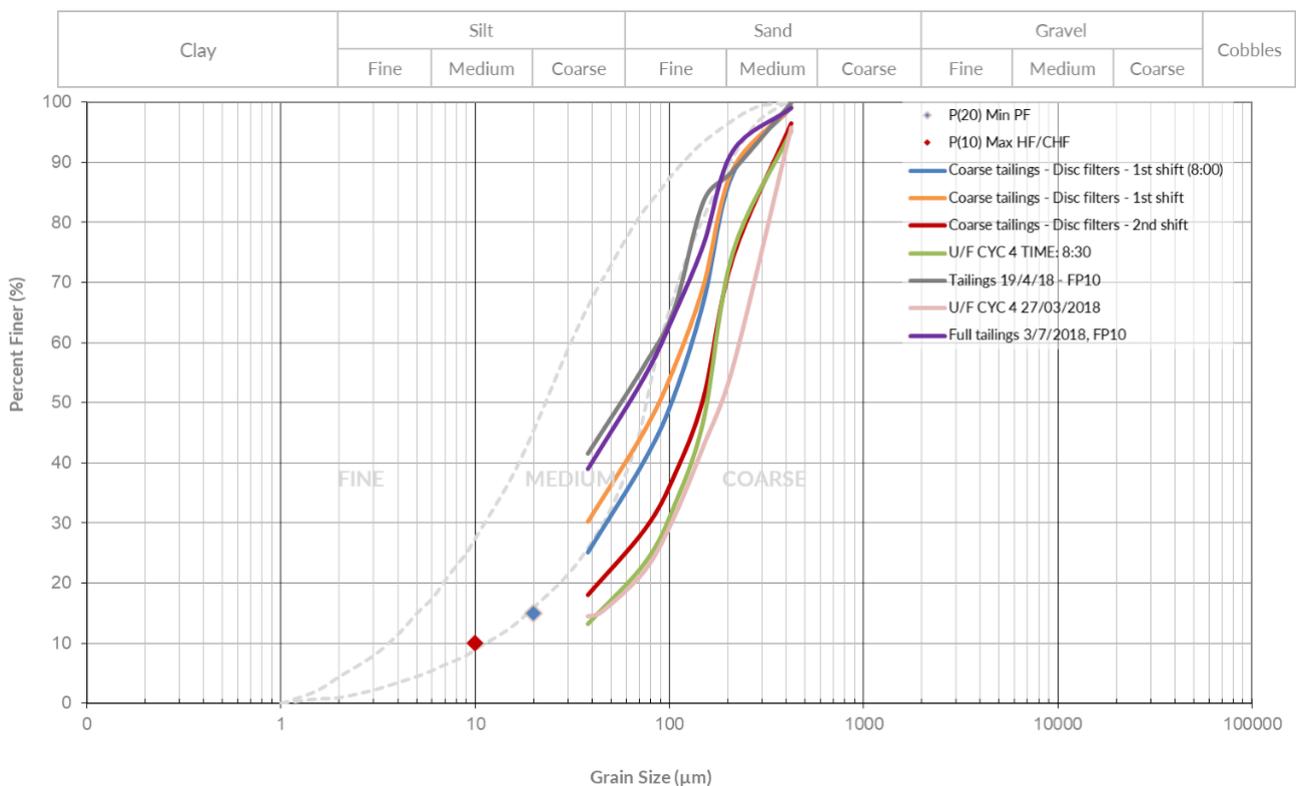


Figure 5 Olympias tailings particle size distribution

### 4.3 Specific Gravity

The specific gravity (SG) of tailings were measured to be between 2.88 and 2.96.

## 4.4 Rheology

Rheological flow characterisation tests were completed using a rotational Viscometer. Yield stress of various backfill mix, containing 12.5% and 15% cement by total dry solids, respectively, and no superplasticiser admixtures, were measured at a range of solids concentrations in order to determine their flow properties (Figure 6). Yield stress is defined as the minimum force required to initiate flow. Static yield stress was determined by using a very slow-moving vane spindle. It should be noted that the optimum yield stress is the maximum yield stress at which the fill will achieve the required target strength and flow to the stope without blocking the reticulation pipeline.

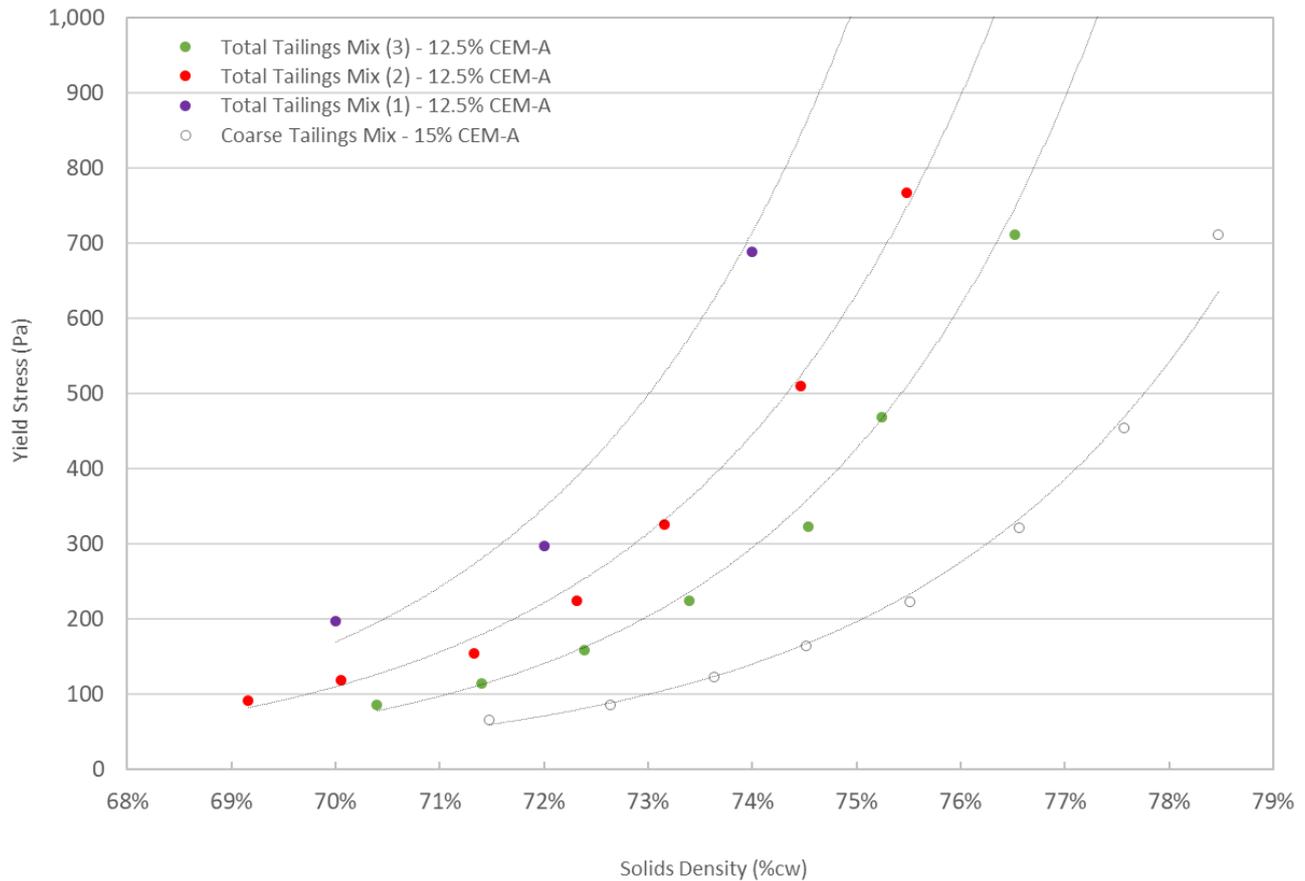


Figure 6 Yield stress profile for total tailings and coarse tailings backfill

Figure 6 indicates that particle sizing of tailings has a significant impact on the yield stress profiles of backfill. The results confirm that fill with coarse tailings has better flow characteristics.

## 5 Results and analysis

### 5.1 Testing overview

The required weight of cement, tailings and water for each batch were measured and combined at the target constant solids concentration of 75% $C_w$  and mixed intensively for five minutes using a hand-held spiral concrete mortar mixer. A reference yield stress measurement was then taken using a rotational viscometer. When this reference yield stress was higher than 300 Pa, superplasticiser admixture was added to improve the flowability of the mix for pumping.

The cement content was defined as the ratio of dry weight of cement to the total dry weight of the mix. The superplasticiser dosage was expressed as percentage of admixture by weight of cement (% $_{bwoc}$ ). The mixtures were prepared using two CEM II 42.5 grade cements from different suppliers (CEM-A and CEM-B) and a fixed

solids mass concentration of 75% $C_w$ . The fill mixtures were proportioned with different superplasticiser dosages to reach targeted yield stress.

Olympias Mine has established a state-of-the-art laboratory facility and all tests, with the exception of XRD, were completed onsite. Strength tests were conducted on 70 mm diameter and 140 mm length cylinder samples. Samples were cured in a humidity room for the planned cure age and tested in a controlled load mode using a 10 t compression press.

## 5.2 Influence of fill type

Mix trials comparing the strength performance of coarse tailings mix and total tailings mix was prepared at the same solid concentration of 75% $C_w$  and 15% cement. The strength results indicate that UCS of coarse tailings mix is marginally (~4%) higher than UCS of total tailings mix at 28-day cure age. The small increase in coarse tailings fill strength can be attributed to the relatively low fines content, making the cement more effective. This is to be expected because the two fill types use the same water cement ratio and the use of superplasticiser admixtures in both mixes disperses cement particles by a deflocculating effect – thereby reducing yield stress, increasing packing density and allowing effective cement hydration. It is also noted that the drained solids density of coarse tails mix will be marginally higher due to the loss of drainage water.

The use of admixture reduced the yield stress of total tailings mix from 920–64 Pa and the yield stress of coarse tails mix from 230–40 Pa. The test results indicate that, when using admixtures, there is essentially no difference between the strength of total tailings mix and coarse tailings mix mixed at the same water cement ratio when using superplasticiser admixtures (Figure 7).

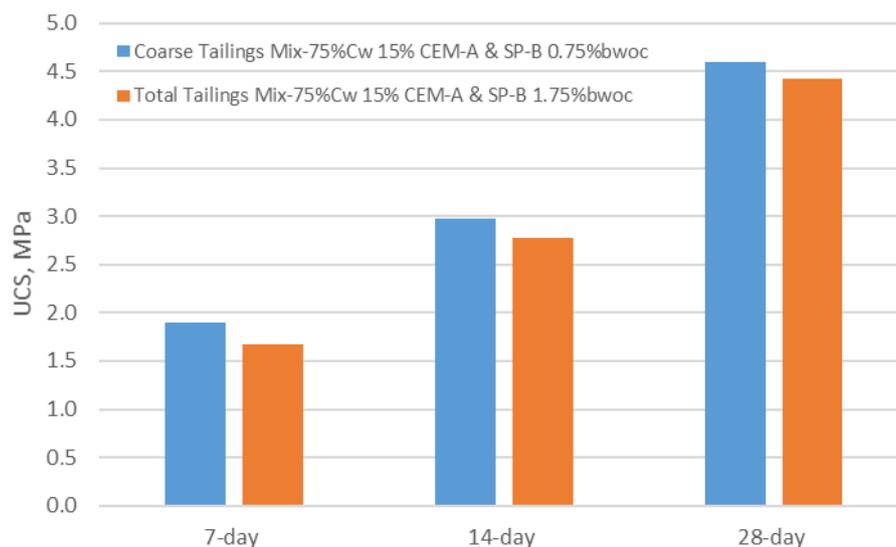


Figure 7 Strength comparison of coarse tailings mix, and total tailings mix

## 5.3 Influence of cement type

Total tailings mix tests mixed at constant solids concentration of 75% $C_w$  and 12.5% cement prepared at a nominal 100 Pa yield stress using superplasticiser admixture indicates that the UCS of CEM-B appears to be approximately 10–15% higher than UCS of CEM-A at 28-day cure age (Figure 8).

It should be noted that the optimal cement type will be the one that delivers the mandated 4.0 MPa UCS at 28-day cure age and at the lowest cost per cubic metre of fill placed. Further test work and firm long-term prices for cement supply delivered to mine site will provide selection of the optimal cement type at Olympias Mine.

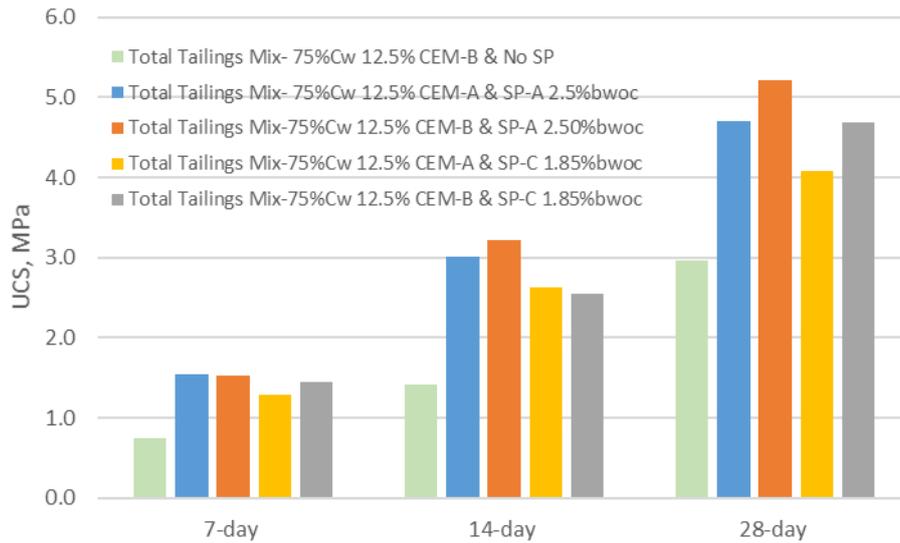


Figure 8 Uniaxial compressive strength of backfill versus cement type

### 5.4 Influence of admixtures

A series of mixes were prepared to determine the performance of three different admixtures (SP-A, SP-B, SP-C) on the rheology and strength of fill. The effect of admixtures on the yield stress of fill is shown in Figure 9. As expected, the admixture dosage rate had a direct impact on the resulting yield stress of the mix. Figure 9 shows that the use of admixtures reduces the yield stress of mixes approximately by an order of magnitude. This is due to the dispersion of cement and tailings particles through the deflocculating effect of admixtures.

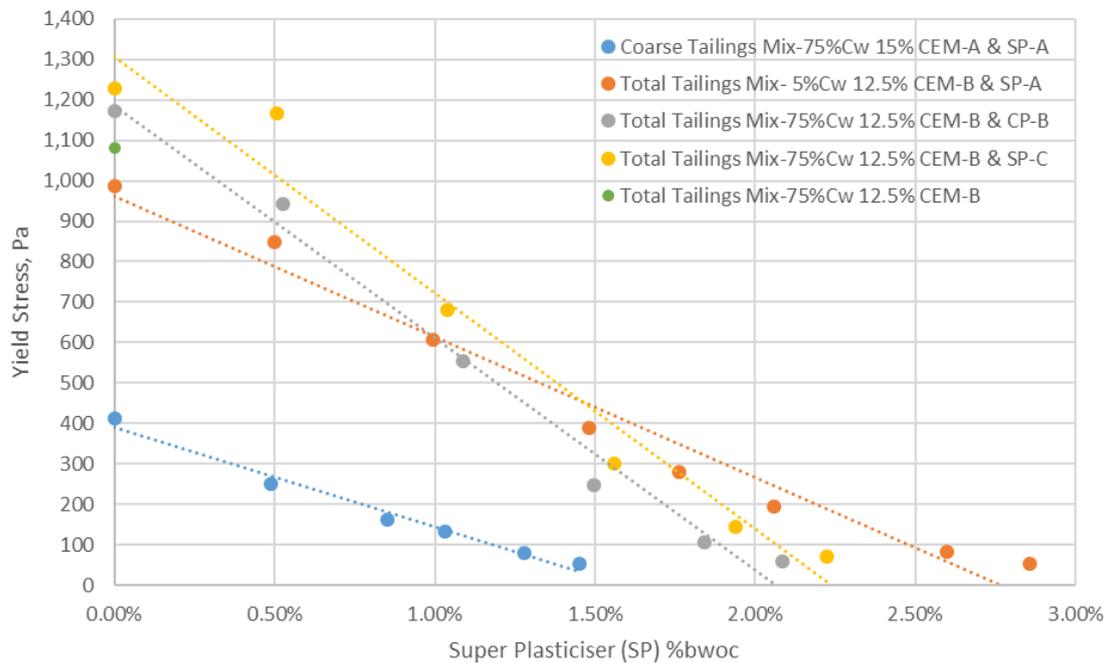


Figure 9 Effect of admixtures on yield stress of coarse tailings and total tailings mix

It is also noted that despite using the same water cement ratio, the yield stress of the coarse tailings mix is less than half of the yield stress of total tailings mix. The mix with finer particle sizing has a higher surface area and a higher affinity for water (hydrophilic) due to their colloidal effect. Finer particles have higher interparticle contacts and hence higher yield stress.

Strength test results for total tailings fill mixed at a constant 75% $C_w$  solids concentration with 12.5% cement indicate that when equivalent doses of superplasticiser admixtures are used to make the mix with a nominal 50–70 Pa yield stress, there is only a small difference in 28-day UCS performance of the fill when using different admixtures (Figure 10). Similar UCS performance is to be expected because the water cement ratio is the same for all mixes and use of admixtures disperses the cement particles, reduces yield stress and improves the packing density and the strength. The results therefore indicate that selecting the optimal admixture can be based on the unit price and admixture dosage. Preliminary economic analysis indicates that that SP-A appears to be the most cost-effective superplasticiser admixture (Figure 11).

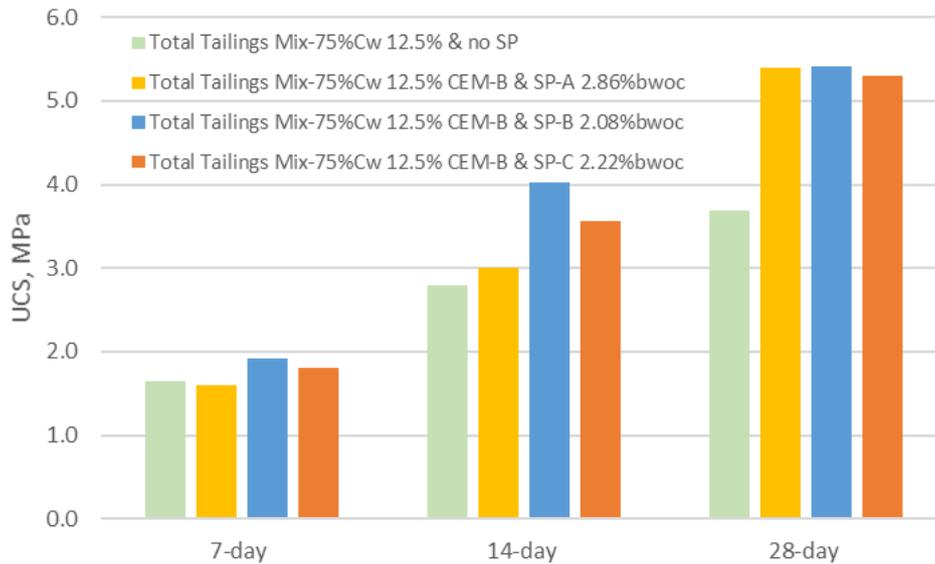


Figure 10 Effect of admixture on uniaxial compressive strength (UCS) of total tailings mix

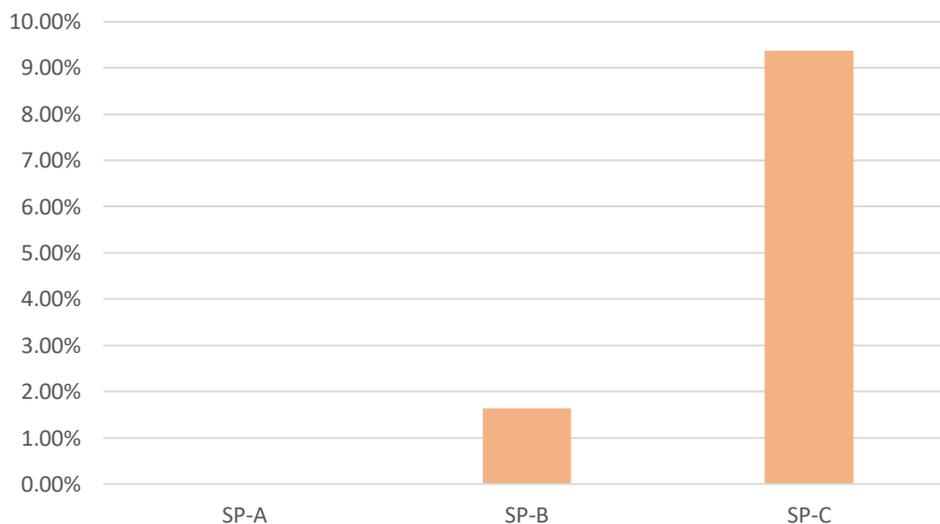


Figure 11 Relative cost of admixtures for total tailings fill

## 5.5 Conclusions

Olympias Mine has completed an extensive laboratory test work program in order to screen and identify a suitable fill type, cement type and superplasticiser admixture type and dosage.

Preliminary test work results presented in this paper indicate that:

- Unless superplasticiser admixtures are used, the required flow properties are not achieved for the high-density fills tested.

- Use of admixture reduces the yield stress of the mixes tested by an order of magnitude.
- Backfill mixes without superplasticiser admixtures do not achieve the required target UCS of 4.0 MPa at 28-day cure age.
- Use of admixtures improves the 28-day UCS by 30%.
- The total tailings backfill mixes prepared at solids concentration of 75% $C_w$  and 12.5% cement achieved the required flow properties and the target UCS of 4.0 MPa at 28-day cure age with a superplasticiser admixture use of 2.0–3.0% $_{bwoc}$ .
- The coarse tailings backfill mixes prepared at solids concentration of 75% $C_w$  and 15% cement achieved the required flow properties and the target UCS of 4.0 MPa at 28-day cure age with a superplasticiser admixture use of 0.75–1.5% $_{bwoc}$ .
- There is very little difference between the 28-day UCS of total tailings backfill and coarse tailings backfill when mixed at 75% $C_w$  with 15% cement when a superplasticiser admixture is used.
- The cement type CEM-B appears to be relatively better performing compared to CEM-A.
- Superplasticiser admixture SP-A appears to be the most cost-effective superplasticiser.

## 6 Concluding remarks

Through an extensive test work program that is still ongoing, Olympias Mine has identified preliminary high density backfill mixes that meet the mandated strength and flow properties albeit at very high cement rates and when using superplasticiser admixtures.

The mix optimisation test work is continuing and there is a possibility of further strength optimisation by using alternative binders such as slag-based cement or using pozzolanic materials such as fly ash and slag. However, the real opportunity at Olympias Mine is to critically review the mandated target strengths and apply for a permit variation to adopt the industry best practice method of determining stope, and schedule specific target design strengths, and adjust the mix design to suit the requirements.

The mandated target UCS is very high and is not aligned with the prevailing mining conditions at the mine. Adopting more realistic strength design based on the planned stope exposures is paramount for ensuring the long-term economic viability of Olympias Mine.

## Acknowledgements

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## Reference

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