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Evaluation of paste backfill mixtures consisting of sulphide-rich mill tailings and varying cement contents

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Abstract

Using mill tailings to produce paste backfill is a relatively new technique. The most important way in which paste backfilling is beneficial is through mine reclamation and elimination of adverse environmental effects of the tailings. This article includes discussions on the effectiveness of different paste mixes with varying cement contents and slump values in a paste backfilling operation in a sulphide-rich environment at a copper–zinc underground mine in northeast Turkey. The chemical composition, mineralogy, specific gravity, particle size distribution, and the index rheology tests have been presented. A total of 219 paste samples prepared from mill tailings (tailings samples T1 and T2) were tested at 3, 7, 28, 90, and 180 days for uniaxial compressive strength (UCS). The objective of the study was to determine the rheological properties of the mill tailings with respect to paste production and determine the strength gain of the tailings with the addition of PKC (Portland composite cement)/B-type binder currently used in the pasteplant. Additionally, PKC/A-type binder was chosen to compare the tailings in terms of strength gain. It was found that for high sulphide bearing tailings, neither binder was effective or suitable to provide adequate long-term strength for paste backfilling operations, although paste backfill samples developed high early strength at 28 days of curing. Alternatives such as sulphate-resistant-based binders or desliming of the tailings should be investigated by additional tests for improving paste backfill strength performance.

Keywords: Paste backfill; Particle size distribution; Characterization; Curing; Compressive strength

1. Introduction

The process of mining involves the removal and recovery of economically valuable minerals from the earth's crust. The resulting voids are usually filled with waste materials by a process known as backfilling. Backfilling has long been an integral part of underground mining. The underground placement of backfill is considered to serve three functions, viz. for ground support, underground disposal of tailings, and favourable economics of mining [1–3]. This process significantly reduces the risk of oxidation of the tailings at the ground surface and its environmental effects [4–6]. Waste materials used as backfill material include waste development rock, deslimed and whole mill tailings, quarried and crushed aggregate, and metallurgical process tailings (like slag) [7–9]. Small amounts of cement or other pozzolanic binders are added to the waste material to improve the strength properties of the backfilled areas.

Due to the low operating costs involved and high strength acquisition of paste backfill compared with the other backfilling methods (rock fill and hydraulic fill), the use of paste backfill has steadily increased in recent years [10,11]. Paste backfill consists of total mill tailings, thickened and/or filtered to around 80% by dry weight, to which binder and water are then added to achieve the desired rheological and strength characteristics [12]. The mechanical and rheological characteristics of paste backfill depend on the physical, chemical, and mineralogical properties of the tailings, binder type, and ratio used [13–15].

A mine site was selected to study the paste backfill system for mill tailings of a high-grade copper–zinc underground mine in northeast Turkey. There are two types of mill tailings defined as tailings T1 and T2. T1 is from massive yellow ore, which consists of pyrite and chalcopyrite clasts, up to 20 cm in size, in a sulphide matrix containing less than 10% sphalerite. Tailings T2 is from black ore, which consists of pyrite, chalcopyrite, and sphalerite clasts, from 2 mm to more than

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20 cm in size, in a sulphide matrix containing more than 10% sphalerite of sedimentary textures (notably, graded bedding).

The purpose of this study was to evaluate the influence of mechanical properties of mill tailings and binders currently used on the strength gain of paste backfill. Mill tailings from this mine were sampled (tailings samples T1 and T2) for the preparation of different paste backfill mixtures using different binder types and proportions [16].

2. Material and methods

2.1. Tailings material determination

Mill tailings T1 and T2 were tested in the laboratory for determination of material properties. Both tailings samples were decanted and thoroughly mixed to ensure they were homogenized prior to testing. The laboratory evaluation of the tailings samples consisted of particle size analysis, specific gravity determination, mineralogy, chemical composition, and rheological characterizations. The particle size distribution and colloidal chemistry (governed by chemical/mineralogical composition) determine the material's paste transport characteristics.

2.1.1. Particle size distribution

One of the most important characteristics of any fill material is a well-graded particle size distribution. The distribution has the strongest effect on fill porosity and delivery. In the case of paste backfill, it is the portion of the tailings finer than 20 μm, which seems to have the most pronounced effect on pumpability [17].

The tailings were analysed by using a Mastersizer S Ver. 2.15 (Malvern Instruments, UK) particle size analyzer and the results are shown on Fig. 1. The grain size distribution of the two types of tailings is closely similar. Tailings sample T1 was found to have approximately 52 wt.% finer than 20 μm and tailings sample T2 54 wt.%, which indicates that both tailings can be classified as a medium size tailings material [18].

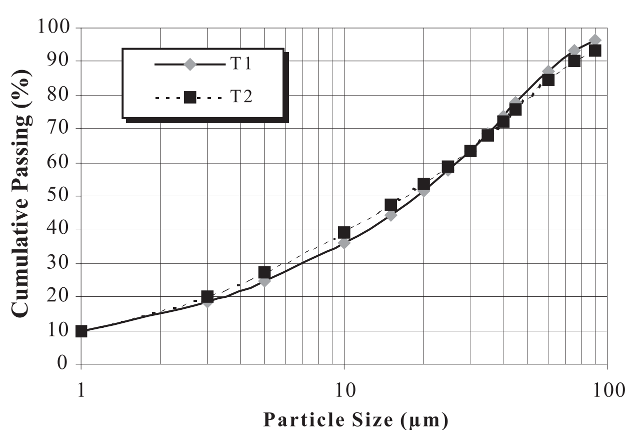

Fig. 1. Particle size distribution of mill tailings T1 and T2.

Table 1
Chemical composition of the mill tailings T1 and T2

Element	Mill tailings T1	Mill tailings T2
MgO	0.45	1.00
Al_2O_3	1.44	3.90
SiO_2	3.26	10.88
CaO	0.74	1.43
Fe_2O_3	57.00	43.67
S^{2-}	2.24	3.68
K_2O	0.14	0.24
Na_2O	0.26	0.22
NiO	0.13	0.17
TiO_2	1.04	0.68
Cr_2O_3	0.04	0.03
Mn_2O_3	0.02	0.10
P_2O_5	0.08	0.13

T1: LOI = 31.55% (sum = 98.39%).
T2: LOI = 27.72% (sum = 93.85%).

2.1.2. Specific gravity

The specific gravity of the tailings was measured using a picnometer. Tailing samples T1 and T2 had a specific gravity of 4.82 and 4.10, respectively.

2.1.3. Chemical composition

The main chemical elements in the two tailings were determined by atomic absorption spectrometry, spectrophotometer (K_2O and Na_2O), and wet chemical analysis (SO_3) and the results are listed in Table 1.

It must be noted that although the compounds are presented as oxides, they may not be present in the tailings as oxides. Tailing T1 is dominated by iron oxide, Fe_2O_3 (57%). Minor quantities of silicon dioxide (SiO_2, 3.26%) and aluminium oxide (Al_2O_3, 1.44%) were detected as well as trace amounts of magnesium, calcium, potassium, sodium, nicelium, titanium, chromium, manganese, and phosphorous oxides (all less than 2%). Tailing T2 is also dominated by Fe_2O_3 (43.67%) and minor quantities of SiO_2 (10.88%) and Al_2O_3 (3.90%), together with trace amounts of magnesium, calcium, potassium, sodium, nicelium, titanium, chromium, manganese, and phosphorous oxides (all less than 2%). The loss on ignition (LOI) values of 31.55% for tailing T1 and 27.72% for tailing T2 are indicative of loss of sulphur, as pyrite is burned off.

2.1.4. Mineralogical composition

The mineralogical composition is determined by X-ray diffraction analysis (XRD), which provides the crystalline mineral assemblage of a sample. The results are summarized in Table 2 as major, moderate, minor, and trace quantities for the phases identified. The relative proportions of the minerals are based on peak height of XRD spectra.

The major mineral identified in tailings T1 and T2 is pyrite. It is common knowledge that sulphide mine tailings generate sulphuric acid in the presence of water and oxygen, which may lead to possible chemical weathering and other consequences. The presence of sulphide minerals within cemented composites as well as the soluble sulphates has a

Table 2
Mineralogical composition of mill tailings T1 and T2

Sample	Crystalline mineral assemblage (relative proportions based on peak height)			
	Major	Moderate	Minor	Trace
T1	pyrite	–	dolomite	sphalerite, barite
T2	pyrite	–	kaolinite, dolomite	barite, sphalerite

Sample	Mineral	Composition
T1	pyrite	FeS_2
	sphalerite	ZnS
	barite	$BaSO_4$
	nantokite	$CuCl_2$
	dolomite	$CaMg(CO_3)_2$
T2	pyrite	FeS_2
	sphalerite	ZnS
	barite	$BaSO_4$
	nantokite	$CuCl_2$
	dolomite	$CaMg(CO_3)_2$
	kaolinite	$Al_2Si_2O_5(OH)_4$

deleterious effect on the strength of paste backfill due to sulphate attack [19,20]. Additionally, dolomite was found as a minor phase in T1, and dolomite and kaolinite in T2. Trace amounts of sphalerite and barite for both samples were also found.

The mineralogy analysis shows that sulphide minerals are present, which may lead to acid generation through oxidation of the tailings and ultimately reduce the strength properties of the backfill due to pH and volume changes. To ensure maximum safety for the underground mine workers, the tactic is to use a cemented backfill that is able to stabilize the underground stopes without being affected by the potential long-term strength loss due to chemical deterioration.

2.1.5. Rheological characterizations

In general, a granular material must have at least 15 wt.% of its particles finer than 20 μm to form colloidal properties and remain as a paste. Rheological index tests are used to determine paste-flow properties when transported through a borehole or pipeline [18].

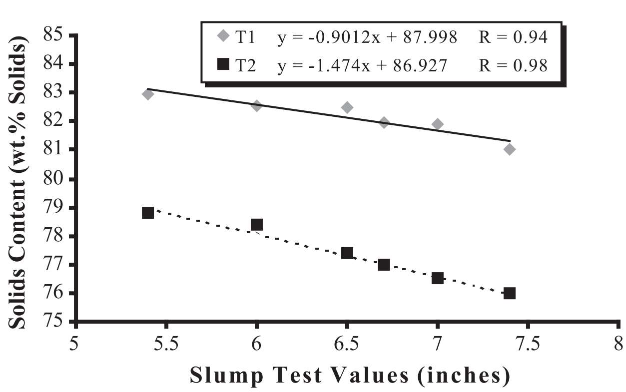

Fig. 2. Solids content versus paste slump for T1 and T2.

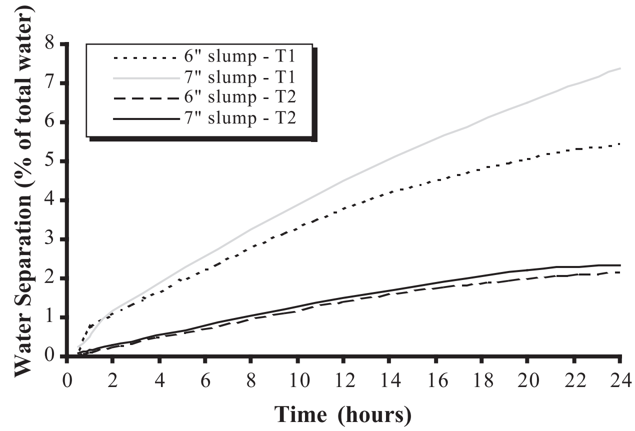

Fig. 3. Water separation versus time for tailings samples T1 and T2.

The index testing consists of a series of water retention, settling, and modified slump cone tests designed to assess the colloidal properties of an uncemented material. Tailings T1 and T2 were mixed at slump consistencies of between 5.4 and 7.4 in., and verified using the 12-in.-high concrete cone test [21]. Slump values corresponding to the solids contents were plotted on a graph to produce relational curves in which slump decreased as solid content increased (Fig. 2). The index test results are summarized on Fig. 3 and Tables 3 and 4.

The solids content of tailings T1 and T2 with a certain slump can be determined using the empirical equations given in Fig. 2. Tailings T1 had a water content approximately 10 wt.%, and tailings T2 approximately 20 wt.%. Water separation tests carried out for both paste samples showed that uncemented tailings T1 bled more water than tailings T2.

Fig. 3 shows results of two water separation tests for the two tailings. Firstly, the water separation of tailings T1 is nearly two times higher than that of tailings T2. Secondly, at 24 h, the difference between 6- and 7-in. slump consistencies of tailing T1 is nearly 10 times higher than that of tailing T2 in terms of water separation. This indicates the change of their rheological characteristics with time.

Table 3
Rheological index testing of uncemented tailings T1

Paste fill type	Time period (h)	Solids (wt.%)	Weight of separated water (g)	Water separation (% of total water)	Water retention (% of total water)
6-in. slump	0.5	82.550	1.50	0.18	17.27
	1.0	82.550	6.00	0.73	16.72
	2.0	82.550	8.90	1.09	16.36
	24.0	82.550	44.55	5.47	11.98
7-in. slump	0.5	81.875	2.10	0.25	17.88
	1.0	81.875	4.40	0.52	17.61
	2.0	81.875	9.90	1.18	16.95
	24.0	81.875	61.30	7.36	10.77

Table 4
Rheological index testing of uncemented mill tailing T2

Paste fill type	Time period (h)	Solids (wt.%)	Weight of separated water (g)	Water separation (% of total water)	Water retention (% of total water)
6-in.	0.5	78.375	0.35	0.03	21.60
slump	1.0	78.375	1.05	0.11	21.52
	2.0	78.375	2.39	0.25	21.38
	24.0	78.375	19.09	2.15	19.48
7-in.	0.5	76.540	0.75	0.07	23.39
slump	1.0	76.540	1.47	0.15	23.31
	2.0	76.540	2.77	0.29	23.17
	24.0	76.540	22.13	2.34	21.12

2.2. Binder type

Portland cement and other cementitious materials are commonly added to the backfill to increase its support potential. The Turkish Portland composite cements (PKC) [22] were used for tailing samples T1 and T2 at various binder contents. The chemical composition of PKC is given in Table 5. The plant is currently using PKC/B-type cement due to the relatively lower cost. In this study, binder types PKC/A and PKC/B were chosen to compare tailings T1 and T2 in terms of strength gain.

2.3. Paste backfill mixture preparation

The required constituents of the paste batch were measured in accordance with the predetermined paste recipe. Tailings and cement were weighed and mixed with a measured volume of water in a 4.73-l bucket. The paste was thoroughly mixed by a Hobart A 200 model mixer until a smooth consistency was reached, taking about 3 min. The paste was then placed in the slump cone in one-third length increments, each being tamped 25 times with a small rod. Finally, the slump was measured.

Following the slump tests, specimens were cast using plastic cylinder forms with a diameter of 4 in. and a height of 8 in. for uniaxial compressive strength (UCS) testing. Seven holes with 2 mm diameter were drilled into the bottom of the cylinder to allow bleed water drainage. The paste was placed in the cylinder in one-third volume increments and compacted as mentioned above. The slump of the paste backfill mixes varied from 6.0 to 7.0 in. with corresponding tailings concentrations from 83 to 76 wt.%. After pouring the different mixtures into the cylinders, they were sealed and cured in a humidity chamber maintained at approximately 95% at 25 °C (this is similar to underground mine conditions) for periods of 3, 7, 28, 90, and 180 days. Three cylinders were cast for each cement content.

Immediately prior to testing, compressed air was injected into the holes to force the sample cylinder out of the plastic form. The length and the weight of the samples were measured and recorded. The two ends of the samples were ground into smooth parallel surfaces for UCS testing.

2.4. Desliming of the tailings

Additional work has been conducted to observe the effects of particles finer than 20 μm on strength. Therefore, 12 cylinders were cast using the PKC/B-type binder for the backfill samples T1 and T2. Cement content, slump value, and curing period were kept constant, that is, 5 wt.%, 6.5 in., and 28 days, respectively. The tailings samples T1 and T2 have an average of 52 and 54 wt.% particles finer than 20 μm, respectively. They were reduced to 15 and 20 wt.% particles finer than 20 μm by using appropriate sedimentation times for the material suspended in water (Stokes law).

2.5. Uniaxial compressive strength tests

A total of 219 paste backfill samples were tested for UCS tests at 7, 14, 28, 90, and 180 days of curing period, the average of three results per sample being taken for each curing period.

Binder dosages of 3%, 3.5%, 4%, 4.5%, 5%, 5.5%, 6%, 6.5%, and 7% by dry weight were chosen for tailings T1 and T2 for the manufacture of the various mixtures of paste backfill, using PKC/B-type cement for 28 day UCS tests. In addition, another set of cylinders was also prepared for comparison to investigate the long-term (90 and 180 days) strength change of the paste backfill samples. For this purpose, the binder content and slump values were fixed at 5 wt.% and 6.5 in., respectively. The primary objective of the strength-testing program was to compare the strength gain of the backfill samples T1 and T2.

3. Results and discussions

As shown in Fig. 4, the maximum value of UCS for T1 at 28 days obtained with the four slump consistencies was always proportional to the binder proportion. However, it

Table 5
Chemical composition of the Turkish PKCs

Cement type	SiO_2	Insoluble residue	Soluble SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	LOI	Total	Undetermined	Free CaO	Additives	
													Min.	Max.
PKC/A 32.5-R	27.12	12.59	14.53	7.05	3.49	53.93	1.34	2.28	3.56	98.77	1.23	0.59	6	20
PKC/B 32.5-R	32.87	26.38	6.49	8.91	3.83	44.02	1.41	1.99	4.06	97.09	2.91	0.26	21	35

was difficult to correlate the strength gain with slump consistency because changes in slump correspond to very minor changes in the strength acquisition. A comparison of the mixes with 4 wt.% binder indicates a maximum strength of 0.52 MPa for 6-in. slump. With 6 wt.% binder, the maximum strength of 0.97 MPa was for 7-in. slump. In addition, paste backfill samples with 7-in. slump value developed a higher strength gain than samples with other slump values. It is also known that if there is an excess of fines and slimes in the mix in relation to the amount of water, then the increased wetted area presented by the fines and slimes leaves less free water for cement hydration. With a mixture containing 7 wt.% binder content, cylinders cast with 7-in. slump developed the highest strength (1.4 MPa) compared to other cylinders. This arises because this amount of water (18.13 wt.%) is needed in the 7 wt.% binder for binder hydration. In many cases, an adequate UCS for a backfill in a typical mine is 0.7–2 MPa [5].

Fig. 5 shows the variation of the UCS at various binder contents for tailings T2. The overall trend of the curves indicates the difference in the mode of binder hydration at the different slump values. It was possible to correlate the strength gain with particular slump value. A comparison of the UCS test results showed a substantial difference in strength gain associated with 1-in. change in the slump. The strength gain increased when the slump value was reduced. With 7 wt.% cement, the strength reduced from 0.81 to 0.61 MPa when the slump value was increased from 6 to 7 in. This corresponds to a 25% decrease in the strength for a 1-in. increase in slump. The mix with 6-in. slump produced higher strengths than those achieved for other slump values when binder content is higher than 4.5 wt.%. At 28 days of curing, the UCS of the 6-in. slump reached a value of 0.81 MPa. However, the UCS of the backfill sample T2 with 7-in. slump was much lower than that achieved for the backfill sample T1 at the same slump. This could be explained by the water retention of the backfill sample T2 being about 49% higher than that of backfill sample T1 (21.12 versus 10.77 wt.%) after 24 h.

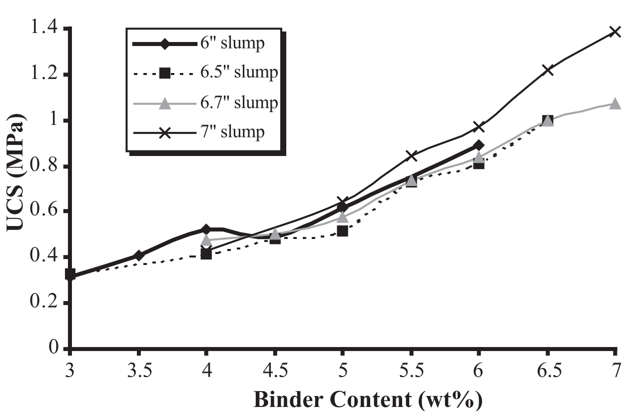

Fig. 4. UCS test results for the paste backfill sample T1 at 28 days.

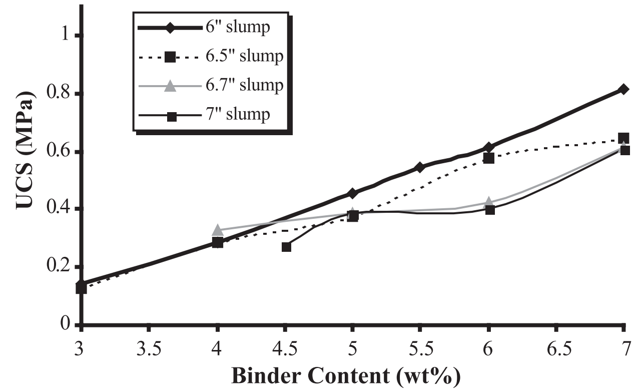

Fig. 5. UCS test results for the paste backfill sample T2 at 28 days.

Two types of cement, namely PKC/A and PKC/B, were also compared to observe any difference in strength gain at 6.5-in. slump value and 5 wt.% binder content. As shown in Fig. 6, all sets of test cylinders except for the backfill sample T2 with PKC/A-type cement had declining strengths after 90 days of curing. This would mean that there was some degradation of strength over time. The strength gain of the backfill sample T1 was almost the same for PKC/A- as for PKC/B-type binders after 3 and 7 days of curing. At 28 days, the backfill sample T1 with A-type binder produced strengths approximately 15% more than that of the backfill sample T1 with B-type binder. Moreover, backfill sample T2 with A-type cement produced strengths approximately 8% more than that of the backfill sample T2 with B-type cement. The test results to 90 days showed that as time passes, the difference in strength gain between the A- and B-type binder was widening. Although the strength for paste backfill samples T1 were generally increased between 28 and 90 days of curing, declining strengths were observed between 90 and 180 days of curing. Strength losses between the 90th and 180th days for the backfill samples T1 were about 55% and 20% for PKC/A- and PKC/B-type binders, respectively. Likewise, the backfill samples T2 with PKC/B-type binder showed a 2.3% decrease in strength between the 90th and 180th days. However, the backfill samples T2 with PKC/A-type binder, in contrast, showed a 7% increase in strength between the 90th and 180th days. The reason

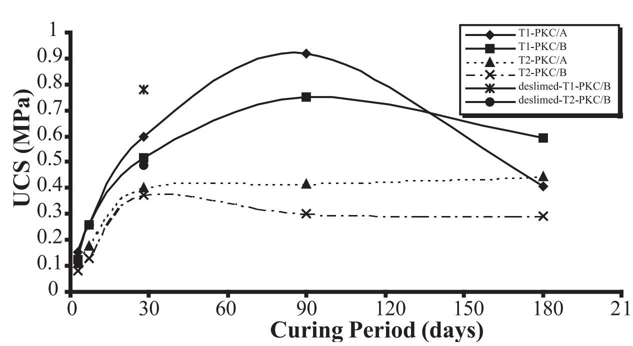

Fig. 6. The UCS test results for PKC/A- and PKC/B-type binder comparison—5 wt.% at 5-in. slump.

behind strength differences between PKC/A- and PKC/B-type binders lay in their additives. The A-type cement has a lower amount of additives (pozzolanic products) than the B-type cement (Table 5). The strength loss observed in these samples up to 180 days of curing is presumed to be mainly due to the sulphate attack in view of the composition of the mill tailings with a relatively high sulphide content. However, this phenomenon warrants further detailed investigation to confirm or to elucidate the reason for the loss of strength in the long term.

Desliming of the backfill sample T1 with 5 wt.% binder and 6.5-in. slump has allowed for average increases of 52% and 38% in the strength for those containing 20 and 15 wt.% particles finer than 20 μm, respectively. The same tests with the backfill sample T2 produced 31% and 21% increases in the strength for those with 20 and 15 wt.% particles finer than 20 μm, respectively. The work indicated that desliming of the tailings would be beneficial to improve paste quality and cost reduction.

4. Conclusions

Two binder types were used to produce paste backfill mixtures with two different sulphide-rich tailings of similar particle size from one Turkish hard-rock mine. Tailings T2 contained more silicate minerals than tailings T1. Rheological tests showed that uncemented samples T1 bled more water than T2. Water separation of T1 was nearly three times as high as T2. As a result, tailings sample T2 resulted in a lower strength gain due to more water retention.

Tailings sample T2, although similar in sizing and composition to the tailings sample T1, produced a somewhat lower strength. Although both paste backfill samples have resulted in a high early-strength development, after 28 days of curing, sample T2 has gradually lost strength. One reason for the lower UCS of sample T2 could be its higher water retention. Although sample T1 produced an increase in the strength between 3 and 90 days, some degradation of strength was observed between 90 and 180 days. This could be related to sulphate attack and needs to be further investigated.

Consequently, neither PKC/A- nor PKC/B binder-types are suitable for providing adequate long-term strength for paste backfilling operations involving high-sulphide minerals. The presence of sulphide-rich compounds causes deterioration in the hardened paste matrix due to sulphate attacks. Therefore, alternative binders including pozzolanic products, such as fly ash and blast furnace slags, should be investigated for their effect on long-term strength of paste backfill materials containing the tailings T1 and T2. Desliming of the tailings should be investigated by additional tests for improving paste backfill strength performance.

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