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A review of modern paste admixture technology and its effect on cement reduction in paste mix designs

S Arcila Gut *Sika Canada Inc, Canada*

F Erismann *Earth Resource Investment Group, Switzerland*

B Ting *T Engineering, Canada*

Abstract

The number of paste operations has grown since the early application of thickened tailings for backfill in the 1970s. Backfilling underground void stopes with paste is often a competitive backfill option compared to alternatives. Therefore, having suitable tailings is critical for paste backfill. Ideally, a paste system delivers a homogeneous, non-settling fluid with good flowability. Once placed, the paste should generate little bleed water and develop the required strength using the least amount of binder possible. The paste's quality depends on the tailings' properties, like mineralogical composition, related to the ore deposits' geological evolution and formation. For example, epithermal gold systems are formed in a proximal volcanic setting and are triggered by an intense, hot, fluid migration process. This type of deposit has a different mineralogical footprint and alteration surrounding than an orogenic gold deposit, which experienced a different alteration and ore formation history, being formed along major fault zones. These differences, in addition to the required ore comminution processes, are reflected in the tailings produced from a given ore body and, therefore, impact the characteristics of the available tailings material to make a paste backfill product. Modern, state-of-the-art paste backfill admixtures are increasingly used to optimise paste backfill mix designs and to manage problematic tailings properties. This paper outlines the impact of using water-reducing admixtures on the solid content increase and strength gain of paste. Data from 13 different mine sites for three common deposit types – orogenic gold lodes, VMS-SEDEX deposits, and epithermal deposits – have been collected for this study. Special attention is given to the impact of their particle size and their phyllosilicate content on the water-reducing potential and strength.

Keywords: *paste backfill, particle size distribution, mineralogy, admixtures, optimisation*

1 Introduction

The average mined ore grade from underground mines has declined for decades (Calvo et al. 2016). Many mining operations often need to mine ever larger volumes of ore to maintain metal output and economic viability. Backfilling using tailings to produce a paste backfill has been among the key elements enabling efficient mining. Efficient, high throughput paste backfill can reduce stope cycle times and provide the geotechnical stability needed for large underground operations to maximise ore extraction.

In cemented paste backfilling, the use of cement in underground mining has increased significantly in recent years. It is evident when looking at the cement consumption of countries such as Canada and Australia and the portion of cement consumed by the mining industry (Stone 2021). Cement is a significant cost component of an underground mining operation. Furthermore, it is responsible for substantial greenhouse gas emissions during production and transportation (Mahasenan et al. 2003). Hence, the increase in cement consumption is reflected in the increased emission figures of mining companies, mainly reported under scope 3 emissions, as most other CO_2 emissions are related to third-party purchased goods. Mining companies are increasingly investigating modern water-reducing admixture technologies to reduce cement consumption.

With the increasing number of paste backfill operations worldwide, the adoption of water-reducing admixtures has also increased. Reducing water, and thus the water-to-binder ratio, in a cementitious system effectively increases the cured product's strength (Ramachandran et al. 1998). Historically, water-reducing admixtures have been used in the concrete industry since the middle of the last century, and modern high-range water-reducing admixtures have been widely used for the past 40 years (Aitcin & Wilson 2015; Erismann et al. 2016). Today, most concrete applications rely heavily on water-reducing admixtures to improve concrete's fresh- and final-state properties. The science and lessons learned from the concrete industry are making their way into cemented paste applications in mining. Although there are many similarities between concrete and paste, the differences are many. As a paste backfill product is produced directly at the mine site using tailings material from the mined ore body, the resulting paste's quality depends on the tailings' physical and chemical properties. This, in turn, is ultimately guided by the alteration mineralogy within and around the mined ore body and the ore extraction process, which will define the particle size of tailing produced. The main objective of this study is to analyse how the use of admixture improves paste properties and optimises the mix design. The impact of the mineralogy and particle size of the sourced tailings are of key interest.

2 Methodology

The idea of paste optimisation is simple: the water-reducing admixture reduces the water of the paste while compensating for the increase in yield stress resulting from the higher solid content (Silva 2017; Sofra 2017). This process and result are illustrated in Figure 1, where two pictures show a cemented paste with different slump flows, indicating different workability and rheology. Figure 1a shows the reference paste mix with a solid content of around 72%. Figure 1b shows the optimised mix design, with an increased solid content of 75%. Using a customised water-reducing admixture results in increased slump flow and workability, despite an increased paste solid content.

(a) (b)

Figure 1 (a) Paste with a solid content of 72%. (b) Increased flow due to the addition of a water-reducing admixture despite the higher solid content of 75%

In this review, particular attention is given to the mineralogical composition of the tailings, the water-reducing potential when using admixtures, and the strength data at different paste solid contents. The following key metrics were collected:

- The 28-day uniaxial compressive strength (UCS) of the cured paste for a certain cement content: This strength was measured at the mine site using cast paste cylinders cured under controlled conditions at the mine sites. These cylinders were cast following the ASTM international (2022) standard and tested using a compressive soil testing machine following the ASTM international (2006) standard. The UCS in MPa is calculated.

- The granulometry of the tailings: the particle size distribution was measured using the Sympatec HELOS laser diffraction instrument combined with the QUIXEL wet dispersing system. Particles were suspended in distilled water. The analyses were conducted in Sika's research laboratories in Zürich, Switzerland.
- The total solid content of the placed paste: total solids were determined by calculating the difference in weighing a wet paste sample and drying it in an oven under controlled conditions following the ASTM international (2019) standard. The weight loss reflects the amount of water in the sample, and the total solids content can be calculated.
- The per cent solids gain when using admixtures: the total solids gain when using admixtures has been determined based on the workability requirements of the mines. The workability is usually measured by a slump test at the paste plant using an Abrams slump cone. To ensure that the paste remains pumpable while reducing the water, it is necessary to stay within the slump and workability limits of the mine. Alternative to the Abrams slump cone tests, Boger cylinder tests are performed at some mine sites as they can be used to estimate the yield stress of the paste (Pashias et al. 1996).
- The mineralogical composition of the tailings: the mineral composition of the tailings was analysed using the Bruker D8 ADVANCE X-ray diffraction (XRD) machine. The parameters used were a 2θ angle range of 3-65°, a step size of 0.015° and a time/step of 1.0 s. Particular interest was paid to the total percentage of phyllosilicates contained in the tailings and the clay minerals. The analyses were conducted in Sika's research laboratories in Zürich, Switzerland.
- The cement content the mine uses as a percentage of the tailing's total dry weight depends on the backfill operation's strength requirements.

The complexity of developing admixtures for paste backfill mines not only results from the chemical and physical properties of the tailings, which vary from mine to mine, but also from the cement type, water, and mine-specific requirements characterized by the performance of their equipment like pumps, diameter and length of the pipe, and the overall configuration of the paste reticulation system. For companies producing paste backfill products, several types of admixtures need to be tested and combined to create a customised product that will reduce their cement consumption and address other potential issues such as high pumping pressure, low paste throughput, frequent blockages, transients, and others. As a result, the solid content of the final admixture product may vary, as well as the required dosage. For this study, admixture dosages used were between 1.5-3% by weight of cement and hence, within the economic quantity where the reduced cement quantity would compensate the cost of the admixture volume needed.

There is always an ultimate limit when it comes to water reduction using admixtures. The increase in solid content increases the density of the paste, causing higher interaction between particles. This consequently increases the shear stress, viscosity, and static and dynamic yield stress of the paste at a given solid content. Therefore, prior to testing the admixture in the paste plant, a screening of different technologies of water reducers are tested, and a customised product is formulated depending on the mines' requirements—for example, the retardation of the cement hydration and slump/slump flow retention.

The Boger cylinder and the slump yield stress calculation or Rheometer can be used to get an approximate idea of the yield stress of the paste (Pashias et al. 1996). Figures 2 and 3 show a paste mix design optimisation using admixtures. For the first mix, the total paste solid content is increased from 71% to 77% using a suitable admixture which allowed for a 20% cement reduction while maintaining the 28 days strength requirement. The paste with the increased total solid content shows a higher slump and lower yield stress than the lower solids reference sample over one hour. When looking at the second mix design optimisation, the solid content was increased to 81%, and a cement reduction of more than 35% was achieved. However, this paste only shows reduced yield stress for the first 15 minutes. After this, the paste starts to stiffen significantly. Therefore, this second optimisation, although attractive due to the cement reduction, would not be well suited as it would present a problem due to the rapid stiffening of the paste.

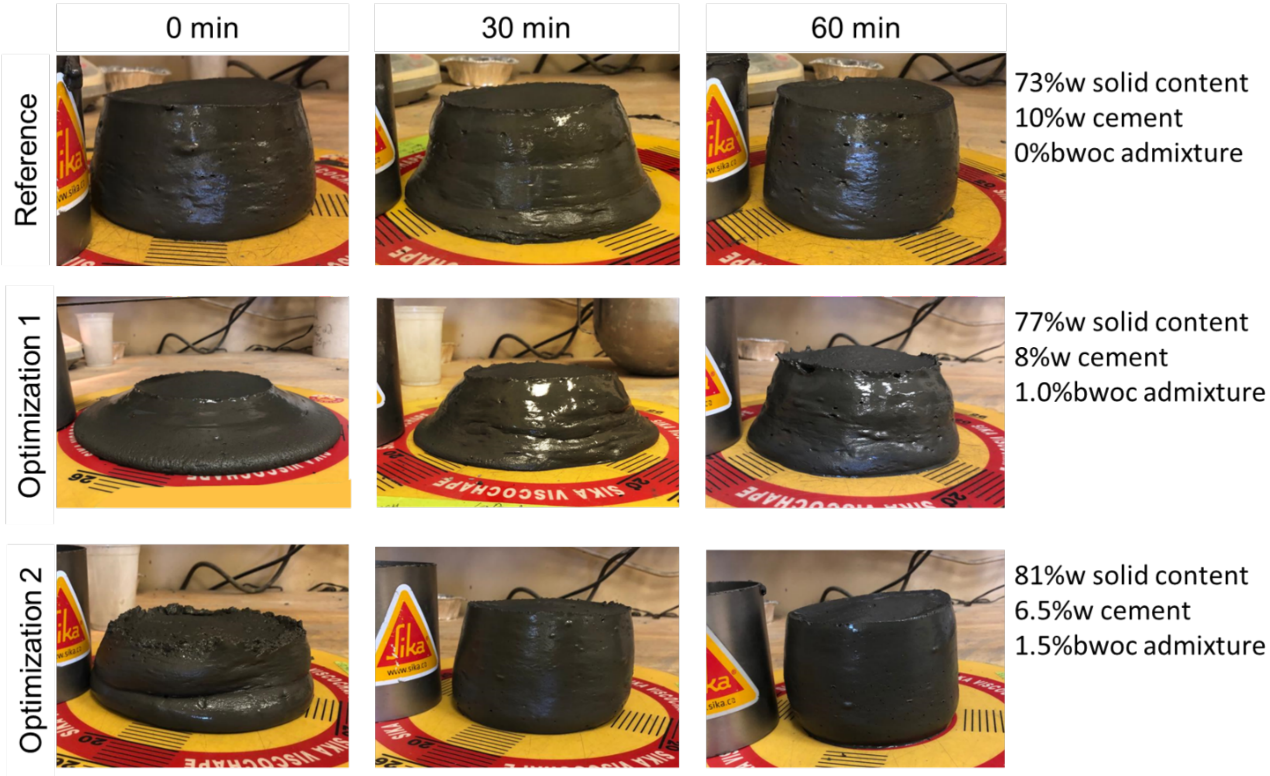

Figure 2 Optimisation of a paste mix design. Images show the slump flow retention comparison for one hour of the reference mix design versus the optimised mix design with 1% and 1.5% by weight (bwoc) of cement of admixture

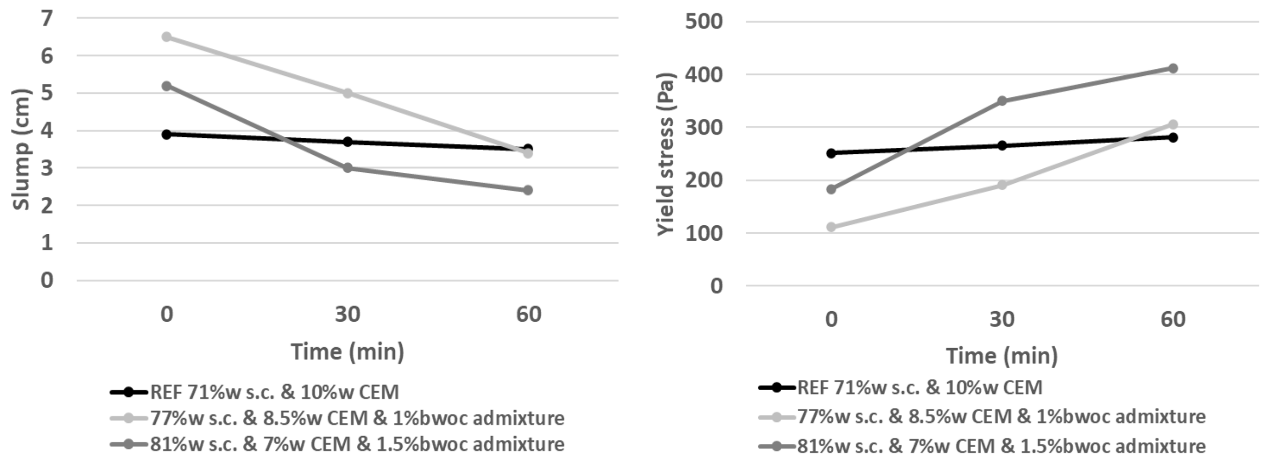

Figure 3 Slump (cm) and yield stress (Pa) results for 1 hour of the reference mix versus the optimised mix designs with 1 and 1.5% by weight of cement (bwoc) of admixture

3 Different deposit types – Different paste backfill

The thirteen mine sites cover a range of three different deposit types. As shown in Figure 4, the deposits are in various world regions. All these mines use continuous paste backfilling as part of their mining method.

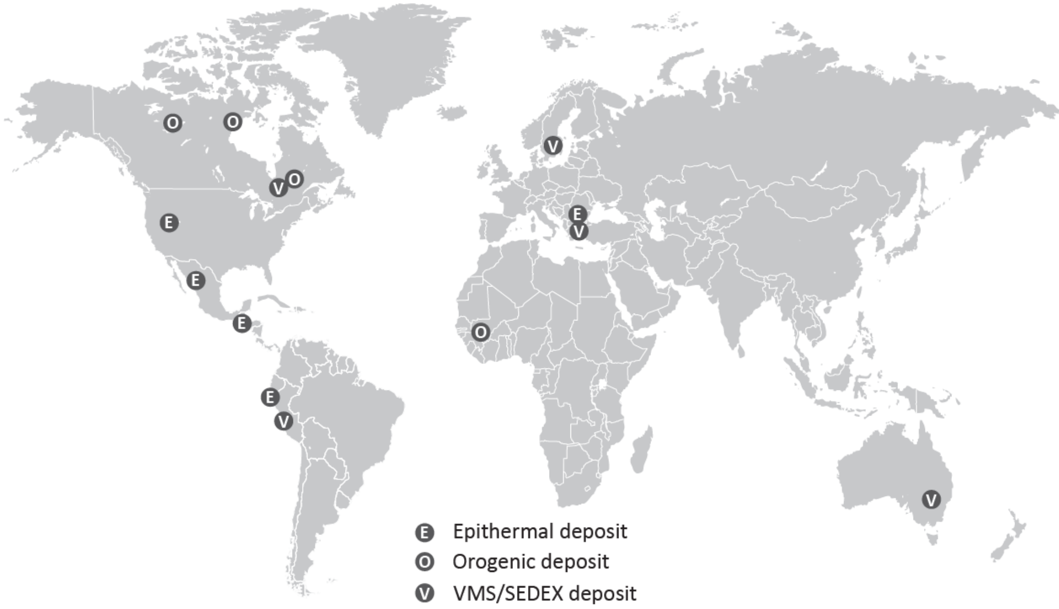

Figure 4 Location of the 13 mines that provide the database for this study

Of the 13 projects, four are in Latin America, five in North America, three in Europe, one in Africa, and one in Australia. The deposits are mined to extract precious metals, such as gold and silver, or industrial metals, such as zinc, lead, and copper. They can be grouped based mainly on the ore deposits' geological evolution and setting, as shown in Figure 5. These deposit groups are:

- **Orogenic gold deposits**: Structurally formed precious metal deposits, often also referred to as orogenic gold lodes, form along major fault zones. Large deposits of this kind are usually related to crustal-scale structures that have triggered extensive fluid flow with mobilisation and deposition of precious metals, typically along specific lithological boundaries.
- **Epithermal gold-silver-base metal deposits:** Ore deposits formed through a direct or indirect link to a volcanic or intrusive source. Large-scale epithermal systems usually form in an extensional geological setting (Hedenquist & Arribas 2000). Intense and focused/concentrated fluid migration, triggered by a cooling magmatic system in its vicinity, is responsible for a complex alteration pattern and ore formation process. The most extreme alterations occur in the top part of such systems, where so-called advanced argillic alteration decomposes the original rock mass into clay-rich lithologies. Furthermore, silica sinter caps are common in these systems, describing a fully leached groundmass where silica is the only remaining mineral. As one progresses further down in the alteration system, more phyllosilicates such as chlorite and sericite make up most of the alteration mineralogy along with clay minerals, but to a lesser extent than higher up in the deposit.
- **Volcanic hosted massive sulfides (VMS) and sedimentary exhalative (SEDEX) deposits** have a direct link to submarine volcanic activity, usually related to an extensional plate tectonic setting (McKibben et al. 1997). Ore formation is strongly influenced by physical cooling and fluid migration through the oceanic crust, leading to a distinct alteration pattern and mineral deposition. As ore formation is usually syn-volcanic, there is a distinct alteration pattern with a strongly altered footwall and a nearly unaltered hanging wall. The mineralisation is often covered with barren submarine sediments.

All three groups of deposits are characteristic in their specific alteration patterns that reflect the ore formation processes and deposit evolution. The alteration is strongly influenced by the fluid composition, fluid temperature, and the host rock through which the fluids migrate. In addition, the alteration and ore deposit mineralogy have often been further altered by subsequent metamorphic processes, usually unrelated to the ore-forming processes. Due to this complex interplay and often unique evolution pattern, the mineralogical composition varies greatly from deposit to deposit.

Figure 5 illustrates the generic differences between these deposits. All deposit types have in common that alteration is most intense at the proximal parts of the ore system and then gradually fades out towards more distal portions of the ore deposit, where it usually becomes less and less profitable to mine. However, the alteration history of deposits is often more complex, as "telescoping" alteration processes frequently occur. This process describes the overprinting of early and deep alteration mineralisation patterns with late and shallow alteration mineralisation patterns (Sillitoe 1994).

A mined deposit's alteration footprint, especially the mineral composition within and proximal to the mined ore body, influences any produced paste backfill product. Alteration minerals will form a significant portion of the derived tailings from these deposits, affecting the final characteristics and performance of the final paste.

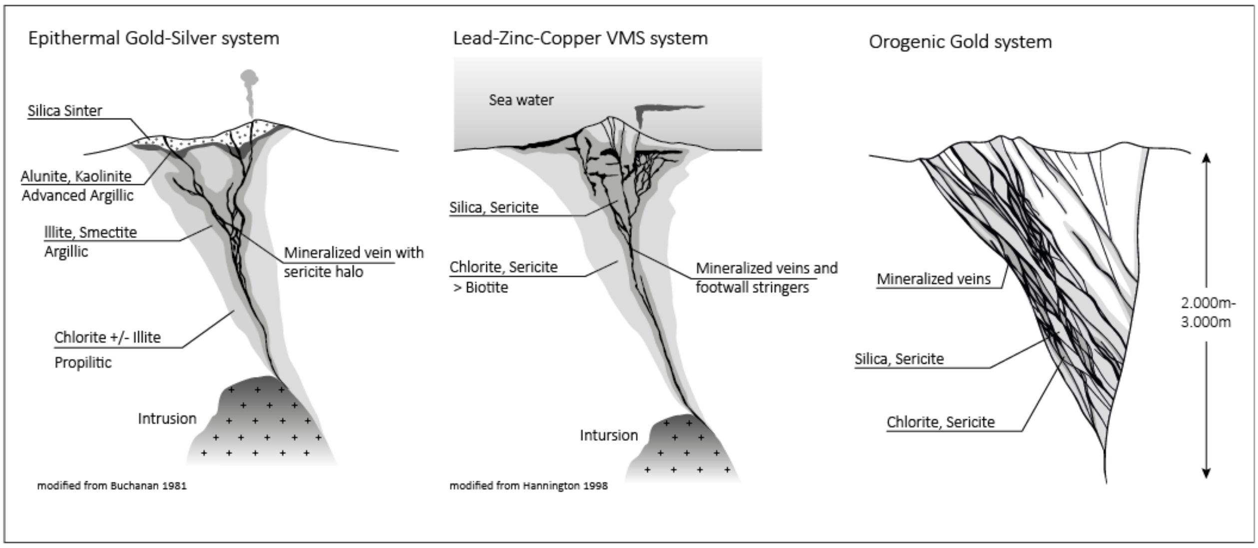

Figure 5 Schematic illustration of the three deposit types used for this study (epithermal, VMS and orogenic gold deposit). Modified from Buchanan (1981) and Hannington et al. (1998)

Table 1 shows the data used for this study. Phyllosilicates are present as precipitations from fluids or as mineral alteration of the host rock by the hydro-/magmatic-fluids during the fluid migration and mineralisation events. Examples of phyllosilicate groups are micas, chlorites and clay minerals. The total phyllosilicates as a percentage of the total tailings mass can indicate the degree of alteration. Some tailings are further enriched in clay minerals, which are extremely fine-grained phyllosilicates (< 2-microns use here, correct terminology µm) produced by weathering and low-temperature, acidic hydrothermal alteration processes. Examples of these clay minerals are illite and kaolinite. These clay minerals are included in the total phyllosilicate content, but their percentage is also listed separately in Table 1. To understand the number of fines in each tailing, the percentage passing the 20-micron fraction is shown for all mines.

To further investigate the impact of the mineralogy and granulometry on the paste's water reduction potential and strength, the total solids content was collected with and without the addition of water-reducing admixtures. It is important to note that these solid contents correspond to pastes, meeting the mine's workability requirements regarding slump and yield stress. This is critical as paste needs to flow by gravity or to be pumpable through the mine's underground distribution system.

The uniaxial compressive strength (UCS) at 28 days was compiled for different solid contents and a specific cement addition. The strength gain measured in percentage for a changing solid content was recorded and analysed in the subsequent data review to compare the data. Several data sets were collected for mines 2, 5, 8 and 9, as listed in Table 1.

4 Results

4.1 Optimisation of paste mix design through water-reducing admixtures

This study aims to investigate if there are differences in the water-reducing potential of chemical admixtures when used with tailings from different deposit types. As an increase in solid content strongly impacts the 28 days cured strength of the paste (Erismann & Hansson 2021), compressive strength is a key metric considered in this thesis. Figures 6a and b show a strong correlation between a paste's strength and solid content or water-to-binder ratio. Data from many different paste plants worldwide are displayed in grey. Data points for the pastes specifically analysed in this study are marked black. The UCS increases significantly when a total paste solid content of about 70% and a water-to-cement ratio of about 5 is reached. Below these values, the correlation between strength and total solids for a given cement content is poor.

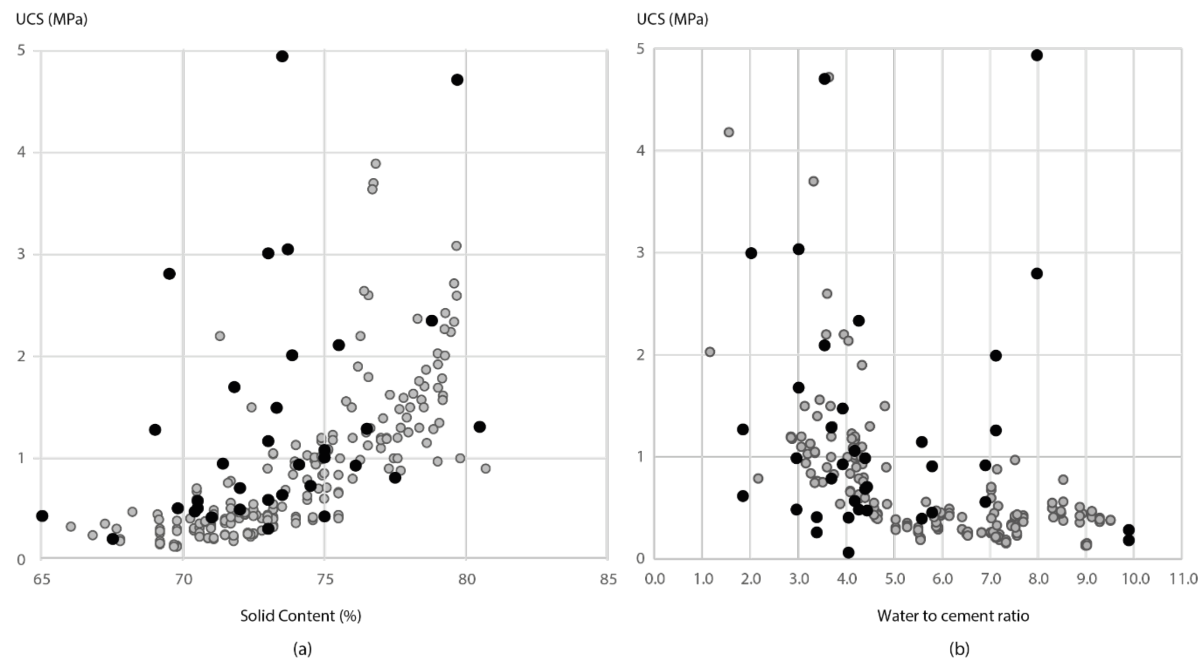

Figure 6 (a) The solid content and (b) the water-to-cement ratio, both plotted against the uniaxial compressive strength (UCS) for a large number of mine sites (grey dots) and projects which are part of this study (black dots). Modified from Erismann & Hansson (2021)

Figure 7a shows the correlation between the cement content and the strength achieved at 28 days for two sets of samples: one with admixtures and thus with higher solid content, and the other without using admixtures and thus with lower solid content. There is a clear trend towards a higher strength gain for higher cement contents when admixtures are used. In other words, the cement reduction potential for mixes with higher cement contents is greater than those with low cement contents. For example, a strength target of 1.5 MPa can be reached using 12% cement or with 6% cement and a suitable admixture. Figure 7b illustrates that achieving higher strength is more difficult for the epithermal deposit group. This group displays poor strength results for different cement contents compared to the other deposit groups. The VMS/SEDEX deposits show the highest strengths for a given cement content. Orogenic deposits show intermediate strength results.

Table 1 Recorded data from the 13 studied mining projects

Deposit type	Mine #	Total Phyllosilicates (%)	Clays (%)	Mass passing 20 µm (%)	Paste solids without admixture (%)	Paste solids with admixture (%)	Solid content gain (%)	Cement content (%)	28 days UCS without admixture (MPa)	28 days UCS with admixture (MPa)	Strength gain (%)
Sedex/VMS	Mine 1	17,3	3,3	56	73	76	3,0	12,5	3,00	5,20	73
	Mine 2.1	16,8	14,1	43	71	73	2,0	5,0	0,41	1,16	182
	Mine 2.1	16,8	14,1	43	71	73	1,9	7,0	0,94	1,49	58
	Mine 2.3	16,8	14,1	43	72	74	1,9	9,0	1,69	3,04	80
	Mine 3	14,5	0	39	69	74	4,8	4,0	1,27	2,00	57
	Mine 4	17	0	18	72	75	3,0	6,0	0,70	1,00	43
	Mine 5.1	18,6	-	-	70	79	9,0	6,0	0,50	2,34	368
	Mine 5.2	18,6	-	-	71	74	3,6	4,0	0,57	0,93	62
Orogenic	Mine 6	24,4	0	52	70	76	5,7	4,6	0,47	0,92	96
	Mine 7	34,4	10,7	50	68	73	5,5	3,0	0,20	0,30	50
	Mine 8.1	22,7	0	45	73	75	2,0	7,0	0,58	1,07	84
	Mine 8.2	22,7	-	45	74	77	3,0	7,0	0,63	1,28	103
	Mine 9.1	7,2	0	35	78	81	3,0	5,0	0,80	1,30	63
	Mine 9.2	7,2	-	31	76	80	4,2	12,0	2,10	4,70	124
Epithermal	Mine 10	28,7	25,3	67	72	75	2,5	6,0	0,49	0,72	47
	Mine 11	13,1	13,1	57	70	74	4,0	7,0	0,27	0,48	76
	Mine 12	12,9	-	54	71	75	4,5	8,0	0,50	1,00	100
	Mine 13	22,5	6,4	52	63	65	1,6	12,0	0,28	0,43	55
	Mine 14	13,9	4,4	36	61	75	14,0	4,0	0,08	0,42	425

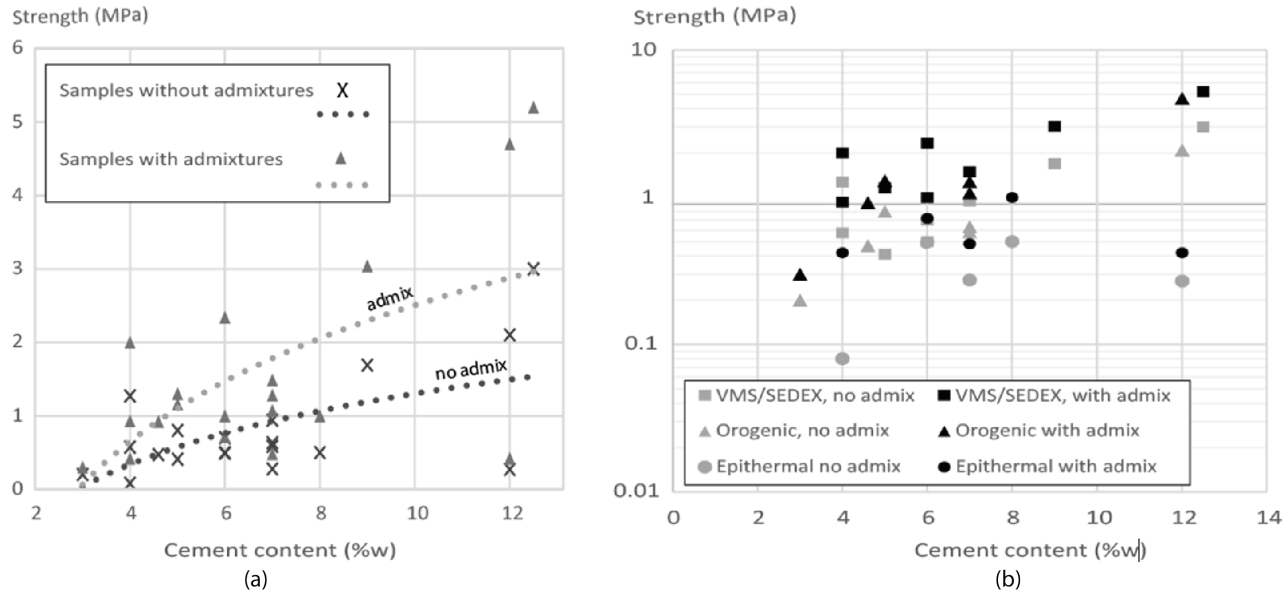

Figure 7 (a) Cement content versus strength relationship and (b) the same relationship by deposit type in logarithmic scale

4.2 Impact of granulometry and mineralogy on water reduction potential and cement reduction

The granulometry of the paste, characterised by the particle sieve curve, is influenced by the nature of the ore deposit and the concentration processes or comminution used for metal liberation. Therefore, tailing's particle size distribution is important when designing a paste. Figure 8a presents the particle size distribution curves for the different projects and their variations. The thirteen deposits cover a broad range of individual tailings particle size distribution. One way to measure the total fines in the tailings is the fraction passing 20 microns. The epithermal group deposits contain the highest fraction below 20 microns. The VMS/SEDEX group deposits, as the orogenic group deposits, show an overall coarser particle size distribution. The VMS/SEDEX with the lowest fraction below 20 microns showed the highest compressive strengths when using admixtures. The epithermal with the higher total fines had the lowest compressive strengths (Figure 7b).

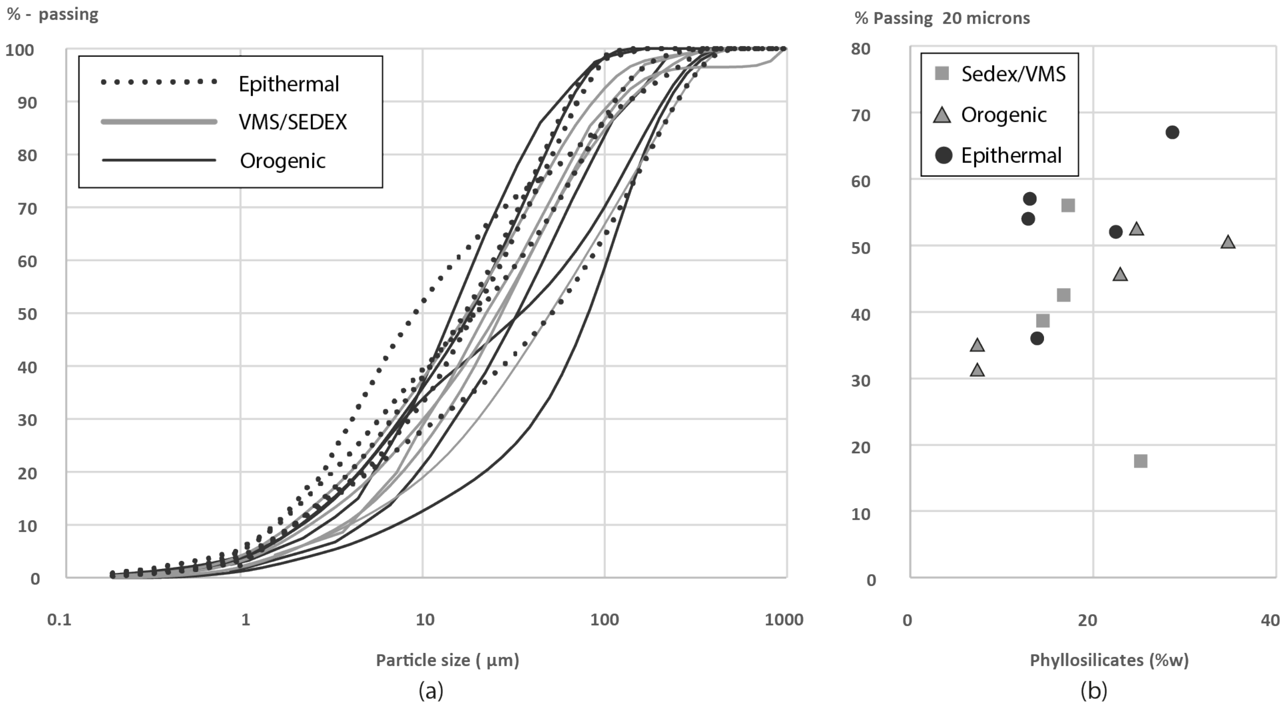

Figure 8 (a) Granulometry and (b) phyllosilicates content versus %-passing 20 microns of the different mine sites

The total fines in the tailings correlate well with the contents of phyllosilicates identified in the tailing, as shown in Figure 8b. It is known that fine minerals like phyllosilicates (micas, chlorites, and clay minerals) influence the water demand, workability, pumpability and strength of cementitious materials, such as concrete, mortars, as well as paste and thickened, uncemented tailings (Palma et al. 2016). Hence, in Figure 9, special attention is paid to the phyllosilicate content (micas & chlorites + clays) and the clay-mineral content of the tailings studied. Epithermal systems have the lowest portion of phyllosilicates, with a median value of 14%w. The VMS/SEDEX deposit mines follow with 17%w. The highest are the orogenic deposit mines, with 24%w. However, a substantial portion of the phyllosilicates in the epithermal deposits is clay minerals, such as kaolinite and illite. In four of five of the studied epithermal mines, clay minerals were identified in the range of 4-25%w. Two of the five VMS/SEDEX tailings had some clay minerals (3.3%W, 14.1%w). The only orogenic mine which contained clays is due to exposure of the tailing to surface weathering since the mines' closure. Clay minerals have a particularly fine grain size, confirming the high fine content of the epithermal deposit observed in Figure 8a.

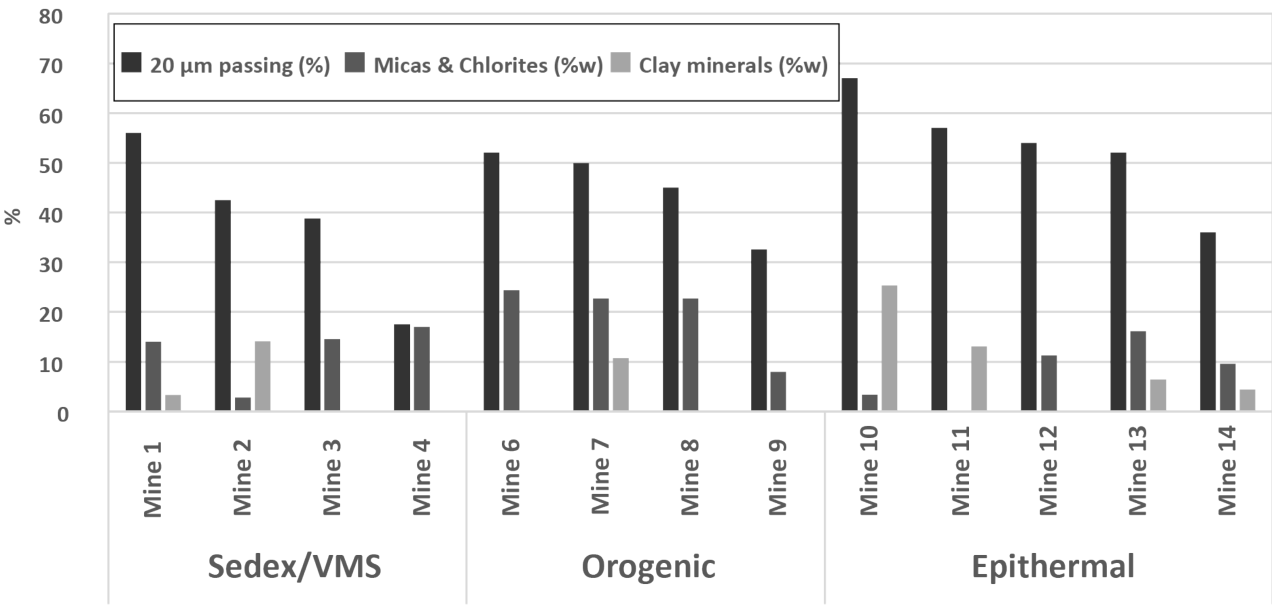

Figure 9 Total fines, micas and chlorites, and clay minerals content for the different deposit types

As the total fines content correlates well with the total phyllosilicate content, Figure 10a shows an exponential decline of the 28-day compressive strength when increasing the % fines normalised by the % cement used. Figure 10b indicates that there seems to be no correlation between the amount of fines contained in a paste and the ability to improve the relative strengths when reducing the water-to-binder ratio using admixtures. All samples obtained a strength gain between 50 -150% using admixtures.

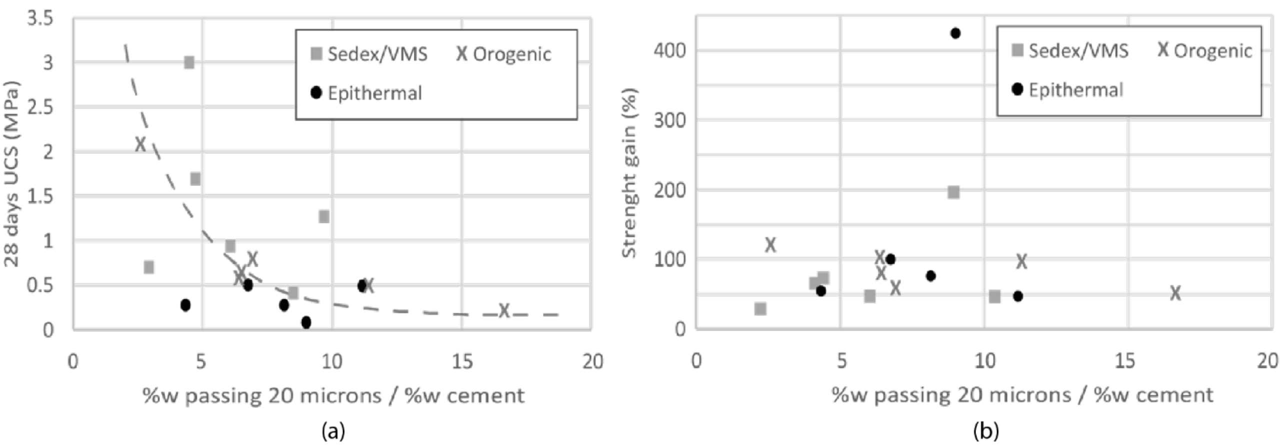

Figure 10 (a) Ratio of the %- passing 20 microns normalised by the %w cement versus the 28 days strength by deposit type. (b) %-passing 20 micros normalised by the %w cement compared to the % strength gain by deposit type

5 Discussion

As described by Erismann & Hansson (2021) and others, the strength of the cured paste and the solid content are strongly correlated. This is also the case for the projects discussed in this study. Strength gain is particularly pronounced once a paste solid content above 70% is reached. The data of this study shows that tailings from epithermal deposits often show large proportions of clay minerals. Such fine-grained phyllosilicates are reflected in the tailings' granulometry, which tends to have a large portion of fines. The epithermal systems included in this study show this characteristic. These fine-grained deposits thus tend to have the lowest paste solid content. This is mainly due to the small particle size, which increases the specific surface area of the tailing. Therefore, these fine epithermal tailings require large quantities of water to achieve a workable paste product that is pumpable through the mine's reticulation system. This results in low initial compressive strength. A higher compressive strength is obtained with the coarser deposit types requiring lower water contents, such as orogenic deposits and coarser VMS/SEDEX deposits.

The reason why the particle size distribution of epithermal deposits leans towards finer fractions compared to orogenic and VMS/SEDEX deposits can be explained by the specific alteration features of epithermal systems. The higher clay mineral content and, therefore, larger fine content in epithermal deposits result from rapid geological processes forming this deposit. Alteration around epithermal gold/silver deposits is derived from acid fluids that strongly affect the rock column. Acid leaching and mixing of hydrothermal fluids with meteoric groundwater are responsible for the intense alteration and leaching processes. The most extreme alterations occur in the top part of such systems. The so-called advanced argillic alteration decomposes the original rock mass into clay-rich lithologies containing large amounts of kaolinite and illite. A fine-grained paste will result if these clay-altered sections are mined as part of the mineralised ore body.

Due to their rapid formation in geological terms, epithermal deposits also, are often refractory. The reason is the intergrowth of ore minerals with gangue minerals such as pyrite and arsenopyrite. Grinding the rock to very fine particle sizes is required to liberate the minerals of interest. Such fine grinding and the presence of clay and phyllosilicate minerals are reflected in the large fines portion of those tailings. This directly affects the water demands of such tailing to produce a pumpable paste. Orogenic deposits contain the highest content of phyllosilicates, although no clay minerals, making them the second finest and second most water-requiring deposit type. Last, the VMS/SEDEDEX shows the coarsest particle size.

The total fines content of the pastes seems to have little impact on the relative strength gain of a given paste. Admixtures seem to have an equal effect on relative strength gain for all deposit types, although at different initial strength levels. This relative strength gain is vital for paste optimisation studies as it directly impacts the cement reduction potential for a given paste.

Although the admixture details and discussion are not part of this study, the admixtures used for the thirteen different deposits all had extensive screening and product customisation trials associated with them. Admixture adaption to the specific mineralogical characteristics is vital to select a cost-performing admixture that will allow for significant cement reduction. This is particularly true when large volumes of clay minerals are present, as in many epithermal systems.

6 Conclusion

The two primary purposes for using water-reducing admixtures are modifying the rheology of a paste to improve flow properties while increasing compressive strength and reducing the cement requirement of the paste. Using customised admixtures, it is possible to increase the solid content of pastes. To achieve this, one needs to have the water requirements of minerals in mind. Fine-grained minerals, such as phyllosilicates and clays, demand higher water due to their high specific area. They are particularly important for the paste rheology and the solid content of a given paste. Using suitable admixtures, a considerable quantity of water can be reduced from the paste while increasing the compressive strength and maintaining similar rheological properties, even with challenging, clay-rich deposits.

This study shows that pastes derived from epithermal deposits are particularly complex, fine-grained and clay-rich due to their heavy degree of alteration. The additional grinding requirements due to refractory ore signature further enhance the large fine volumes. Fine-grained in nature, epithermal deposits need large amounts of water to produce a workable paste which results in initially lower uniaxial compressive strength compared to the two other coarser deposits investigated (VMS &SEDEX / orogenic deposits). This implies that the tailings containing a high fraction of fines and clays will require a higher cement content to achieve the target strength. However, this study shows that the solids increase when using admixtures leads to significant strength gains for all deposit types in the order of 50% to 150% depending on the cement content and deposit type. On average, each 2% solids increase translates to a 50% strength gain for a given cement content. This provides an opportunity for a significant cement reduction of 20-50% and improved paste mix designs from a cost performance and environmental perspective.

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