State-of-the-Art in Paste Fill Technology in the Mining Industry — A Functional Review

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ABSTRACT

The mining industry has come a long way with paste fill technology. The general level of awareness with paste fill technology has increased significantly in the last ten years due to many paste system implementations, seminars, conferences and publications. To setup a paste fill system has become much easier in some cases where there is a supply of well-drained tailings available from tailings dams. The hydraulic filling method once thought as the backbone of mine filling has been gradually pushed aside by the paste technology.

The technology involved in paste fill making has also steadily improved over the years. Cyclones are increasingly used in some paste fill making processes to partially classify the full tailings to improve either the thickening or filtering operations. The thickener manufacturers are now able to make paste thickeners, which can produce high yield stress (at around 200 Pa) pastes. The vacuum belt filters and the disc filters are used mainly in paste fill making process to increase the final solids concentration of the paste fill. The combined use of cyclones, thickeners and filters has opened up new possibilities in recipe and quality control in paste fill production. Pugmills are an essential part of mixing the various paste fill ingredients. There are many types of pugmills in use and accordingly the degree of mixing achieved and the final consistency of paste fills vary. It is essential to select suitable pugmills to optimise the paste fill rheology and the delivery system.

This paper presents the many developments in the paste fill technology during last ten years. The fundamental principles associated with the paste fill technology are included to give the reader a more comprehensive source of information on paste fill technology. Some suggestions are also made for future directions in paste fill technology research work.

1 INTRODUCTION

The difference between the paste fill used in underground filling and the thickened tailings used in tailings disposal are predominantly in the final consistency of the product. Paste fill is made relatively to a higher solids concentration than thickened tailings. Table 1 summarises the main differences between paste fill, thickened tailings for disposal, and concrete mortar. Except for the cases where a very fine tailings is used to make paste fill, the paste fill flow characteristics are very similar to that of concrete mortar or self levelling concrete. In comparison, due to the very fine nature of the tailings used in most of the thickened tailings disposal schemes, and also due to the presence of considerable amount of clay minerals in the tailings associated, thickened tailings flow characteristic are dominated by particle surface related forces.

2 NEED FOR PASTE BACKFILL TECHNOLOGY

Paste fill is required in underground mining mainly to provide ground support. There are many types of fill available for underground void filling and these can be classified mainly into the following three groups:

- Hydraulic fill including cemented hydraulic fill (HF/CHF).
- Rockfill or aggregates including development waste, quarry produced rocks, process plant coarse rejects, cooled and broken smelter slags (RF) including cemented forms.

- A combination of hydraulic fill and rockfill or aggregates in slurry to paste consistencies (CRF/CAF).

Table 1 Comparison of paste fill, thickened tailings, and concrete mortar

Paste fill	Thickened Tailings	Concrete Mortar
Higher solids concentration	Lower solids concentration	Similar to paste fill in concentration
Filtration is essential to achieve higher solids concentration	Filtration is optional and predominantly thickening process based	Dry ingredients combined
Higher unit cost due to binder addition	Lower unit cost due to very low or no binder addition	Highest unit cost due to larger amount of binder addition
Very little or no moisture loss due to drying or drainage in underground stopes	Sun and wind drying contributes to further thickening	Very little or no moisture loss
Flow rheological parameters important	Depositional rheological parameters important	Flow rheological parameters are important in pumped delivery
Yield stress after short mixing ranging from 200-800 Pa Yield stress after 3-15 minutes of mixing 100-400 Pa	Yield stress just outside the thickener 50-200 Pa Yield stress over the disposal area before resting 25-100 Pa	Yield stress after short mixing ranging from 100-400 Pa Yield stress after long mixing is 100-400 Pa
Plastic viscosity at lower shear rate 1-3 Pa.s Plastic viscosity at higher shear rate 0.3-0.6 Pa.s	Plastic viscosity at lower shear rate 0.1-0.5 Pa.s Plastic viscosity at higher shear rate 0.01-0.03 Pa.s	Plastic viscosity at lower shear rate 1-3 Pa.s Plastic viscosity at higher shear rate 0.3-0.6 Pa.s

The popularity of paste fill is increasing due to many operational advantages associated with the use of paste fill in underground void filling. These advantages are as follows:

- Equal or lower cost in comparison to HF/CHF.
- Minimal or no underground drainage water release after placement.
- Faster strength gain allowing early mining of adjacent stopes.
- Continued reduction in required capital for paste fill plants building.
- Newer and efficient processes available to thicken and filter tailings.

2.1 Ground Support for Mining and for Stabilising Cavities

Paste fill is required to support hanging walls in dipping orebodies, and also to support the adjacent ore pillars and the crown in vertical open stopes in massive orebodies. Timely filling of underground voids created by ore extraction will enable mining operators to achieve maximum extraction rate, and improved underground working environment. Delays in filling will lead to ground conditions deteriorating and preventing mine operators to continue mining near such areas.

2.2 Tailings Disposal Both in Underground and on Surface

Paste fill technology is used to replace the conventional tailings storage facilities and the associated risks involved with the tailings containments. Thickened tailings disposal facilities are created in increasing numbers all over the world today. From an environmental protection point of view, thickened tailings disposal schemes are preferred to conventional tailings storage facilities. This paper will not address surface thickened tailings disposal technology.

2.3 Co-disposal of Coarser Materials with Finer Waste Materials

Paste fill technology is applicable in implementing co disposal of coarse rejects and finer tailings and creates engineered waste disposal systems, where mineral processing plants are generating both coarser rejects and finer tailings. Elevated landforms and quick consolidation of the waste deposits are the benefits from co disposal schemes. Paste technology is useful to optimise the waste combinations and to minimise drainage water.

3 MATERIAL SOURCES FOR PASTE MAKING

In mining environment, many types of materials are used to make paste fill. The paste fill technology could be adopted to make use of the available materials at a mine site to produce non-draining and flowable paste like fills. The main sources of materials to make paste fill are concentrator tailings, deposited tailings from tailings storage facilities, sand tailings from mineral sand extraction, coarse rejects from heavy medium separation process, granulated slags, quarry produced rockfill, borrow pit produced earth fills. Depending on the source material used to make paste fill, different processes are required to combine them and make flowable paste like fill for underground placement.

3.1 Online Tailings Supply from Mineral Processing Plants

When tailings from a mill or process plant are directly used to make paste fill, it is called on-line paste fill system. There are many paste fill plants around the world making paste fill through on-line production process. Depending on the process involved in making paste fill, on-line paste fill systems make full or total tailings paste fill, partially classified tailings paste fill, or blended tailings paste fill as illustrated in the later sections. Water from the process tailings has to be removed to make paste fill in the on-line systems.

3.2 Reclaimed Tailings from Tailings Storage Facilities

When tailings is excavated from a previously deposited tailings storage facility and used to make paste fill it is called reclaimed tailings paste fill. The reclaimed tailings paste fill is gaining popularity in the recent times mainly due to the following reasons:

- The process involved in paste fill making is simple.
- Modular or mobile paste fill plants are available at lower capital cost.
- Suitable for smaller mining operations.

Tailings extraction from storage facilities, pre-processing the tailings before paste fill making, acidity of the tailings needs special attention in this scheme.

3.3 Sand Tailings from Mineral Sand Extraction, or from Dune Sand

In some cases, either on-line paste fill or reclaimed tailings paste fill may not be possible due to lack of suitable tailings at the site. If sand from a mineral sand extraction scheme or from natural dunes is available, it may be possible to consider making paste fill by adding fines to sand to give adequate flow characteristics.

3.4 Co-disposal Materials from Coal Processing

In many coal processing plants, two types of wastes are generated namely coarse reject and fine tailings. In some base metal mines such waste products are also generated. It is possible to combine these waste products at the required ratios to produce a non-segregating flowable rocky paste for either mine backfilling or waste disposal purposes.

4 TYPES OF PASTE FILL PLANTS

4.1 On-line Paste Fill Plants

There are three types of on-line paste fill plants depending on the process used to make paste fill from the concentrator tailings.

4.1.1 Full tailings paste fill plants

Full tailings paste fill plants use thickeners and filters to achieve water removal from the concentrator tailings. Tailings from concentrators usually comes at lower solids concentration in the range of 20-45% by weight. Concentrator tailings is first thickened in a thickener to achieve higher concentration. Further water reduction of tailings by filtration is usually necessary. In such cases, thickener underflow is filtered to achieve a filter cake of total tailings at higher solids concentration in the range of 75-80% by weight. The total tailings filter cake is combined with binders and makeup water in a paste fill mixer known as pugmill to produce total tailings paste fill.

4.1.2 Partially classified tailings paste fill plants

Partially classified tailings paste fill plants use cyclones to remove some fines from the full tailings to give the most desired particle size distribution. The partially classified tailings is filtered to further reduce the water from the cycloned tailings. Depending on the degree of fines removal and the solids concentration achieved for the classified tailings, thickeners may be necessary to further thicken the tailings before filtration. It is possible to achieve higher degree of water removal during filtration due to partial classification prior to filtration. The filter cake may achieve around 85% solids concentration. The partially classified tailings filter cake is combined with binders and makeup water in a paste fill mixer to produce paste fill.

4.1.3 Blended tailings paste fill plants

Blended tailings paste fill plants first separate the full tailings into coarser underflow and finer overflow fractions through cyclone classification. The coarser cyclone underflow fraction of the tailings is filtered to produce damp sand like filter cake at around 85% solids concentration. The finer cyclone overflow fraction of the tailings is thickened in a thickener to over 50% solids concentration. The coarser filter cake, finer thickener underflow, binder, and makeup water are combined in certain ratios to give the best combination regarding the flow characteristics and strength development. It is possible to alter the ratios between the coarser filter cake and the finer thickener underflow to alter the properties of the final paste fill. Blended tailings paste fill is produced at the optimum combination of the ingredients for a particular application.

4.2 Reclaimed Tailings Paste Fill Plants

There are two types of reclaimed tailings paste fill plants available, namely modular plant and mobile plant. There are well known manufacturers making modular paste fill plants. However, it is also possible to design and build these plants to suit the site conditions than buying off the shelf plants. The mobile paste fill plants are not originally manufactured as paste fill plants but converted from other application environments such as road building, soil stabilisation, or concrete making. At present few operations in Australia are using mobile plants to make paste fill, and the paste fill making at these plants is heavily depending on the skill of the operators, as very few control mechanisms are fitted to these plants.

4.3 Concrete Mixing Plants

There are two types of mixing plants available to make concrete like paste using coarse aggregates and fine aggregates or tailings with binder. One is similar to modular paste fill plant explained in Section 3.2 but with provisions to add two or three streams of different materials into a pugmill. The other type is a concrete batching plant without any modification. These plants are used in making concrete like flowable rocky paste fill.

5 PROCESSES INVOLVED IN PASTE FILL MAKING

There are many processes involved in paste fill making such as cyclone classification, thickening, filtration and mixing in a pugmill in on-line paste fill production. Tailings harvesting and transporting, pre-processing, and mixing in a pugmill are the processes involved in a reclaimed tailings paste fill production. Where coarse aggregates are used to make flowable concrete like rocky paste fill, pugmill mixing is the main process involved.

5.1 Cyclone Classification

Cyclones serve two purposes of size classification and water reduction. In partial classification of tailings, the cyclone underflow will carry more fines to ensure at least 20-25% of the underflow tailings is finer than 20 µm. The spigots and the vortex are adjusted to give the desired underflow size distribution. As the underflow tailings includes more and more fines, the solids concentration drops and need further dewatering in filters. In blended tailings paste fill production, the cyclones are set to produce coarser underflow (fully classified similar to HF sizing) with around 12-15% passing 20 µm.

5.2 Thickening

Thickeners are used to thicken partially classified tailings, full tailings, or the finer tailings removed as cyclone overflow in a blended tailings paste fill system. There are many types of thickeners available such as conventional thickeners, high rate thickeners, high compression thickeners, and paste thickeners. Table 2 summarises the different environments in which these thickeners could be used and the nature of the final thickened tailings.

Table 2 Summary of thickener performance

Type of Thickener	Nature of Feed Tailings	Nature of Thickened Tailings	Application Environment
Conventional thickeners	Low concentration mill tails	Less than 50% solids	Conventional tailings disposal
High rate thickeners	Low concentration mill tails, partially classified tails or cyclone overflow	Less than 55% solids	Conventional tailings disposal or before filtration for cake
High compression	Low concentration mill tails, partially classified tails or cyclone overflow	Less than 70% solids	Thickened tailings disposal
Steep Cone Thickeners	Low concentration mill tails, partially classified tails or cyclone overflow	Less than 75% solids	Thickened tailings disposal or for mine filling
PPSM	Low concentration mill tails, partially classified tails or cyclone overflow	Less than 75% solids	Thickened tailings disposal or for mine filling

5.3 Filtration

Filtration of tailings is essential to increase the solids concentration of the final paste fill to desirable range. Also filtration of tailings enables the operators to control the final solids concentration of the paste fill by adding makeup water. There are three different types of filters available to filter tailings namely belt filters, disc filters and drum filters. All these filters need vacuum to remove water from the tailings to produce filter cake. The final solids concentration of the filter cake from these filters depends on the nature of the feed tailings, and the details are as shown in Table 3.

Table 3 Summary of filter performance

Filter Type	Nature of Feed Tails	Filter Cake Consistency	Application
Vacuum Belt Filter	Thickened full tails, partially or fully classified tails	80-85% solids	Paste fill making
Vacuum Disc Filter	Thickened full tails, partially or fully classified tails	80-85% solids	Paste fill making
Vacuum Drum Filters	Thickened full tails, partially or fully classified tails	70-80% solids	Concentrate filtration or paste fill making

6 WET PASTE FILL PRODUCTION

6.1 Paste Fill Composition

Paste fill during placement comprised of mineral and binder particles (solids), water (liquid), and very little or no gaseous phase. Some air may be introduced in to paste fill during mixing and the borehole and pipeline reticulation. Basically paste fill at the time of introducing into borehole is a saturated particulate medium with very little shear strength (less than 1 kPa). From geotechnical point of view such a medium could be considered as a heavy liquid.

The particle size distribution of the solids in paste fill varies depending on many site-specific factors including the fineness of grinding achieved in processing the ore. The maximum size of the particles in paste fill is usually smaller than 1 mm, and the minimum size is smaller than 1 µm. From a simplistic point of view, the particle size distribution should ensure a minimum of 15% by mass passing 20 µm size to achieve cohesive paste like flow behaviour during transportation and deposition. However, higher proportion of 20 µm fraction (20%-35%) has been found to give better flow characteristics in some paste fill operations.

The particle size distribution of the solids phase in some paste fill operations is modified through either partial classification or through splitting into coarser and finer fractions and recombining in some optimum ratios. The aim of modifying the particle size distribution is to produce a final deposited paste fill with minimum void ratio that could dilate before achieving shear failure. Dilating fills develop negative pore water pressure and hence more shear resistance before failure. On contrary, contracting fills develop positive pore water pressure and less shear resistance before failure. The contracting fills have the potential to reach liquefaction failure either during a prolonged static loading, or sudden shock loading from blasting or from moving machinery.

6.2 Paste Fill Mixers and the Mixing Process

Paste fill is made by mixing different ingredients specified by a design recipe, in a mechanical mixer commonly known as pugmill. The paste fill ingredients include tailings solids, binder solids, any other admixtures and makeup water. There are different types of paste fill mixers available such as twin axles paddle mixers, twin axles screw mixers, or a rotating drum mixer. These mixers are programmed to mix paste fill either in a batch-processing mode or in a continuous processing mode. After a short stay and mixing in the mixers, paste fill emerge either from the bottom of the mixer, or over a weir used to retain the materials during mixing. Mixing of paste fill is a very important operation in paste fill making, and apparently very little attention has been paid to provide good mixing of the ingredients.

Any paste fill mixer has to perform the following functions:

- Combining many paste fill ingredients into one material stream for handling and transport through the reticulation system.
- Mixing the many ingredients into a homogeneous state in terms of the distribution various paste fill ingredients.

- Mixing the paste fill ingredients for sufficient time to reduce the static yield stress to enable a smaller diameter reticulation system could be used to transport the paste fill. It is a common observation by the authors that the Static yield stress drops with increasing mixing time for non-agglomerated and non-clay tailings.

For a mixer to perform all the above functions, it should have the following capabilities:

- Good mixing mechanism to suit the type of tailings used to make paste fill.
- Sufficiently large mixing chamber that could retain the paste fill ingredients until a homogeneous condition achieved.
- Mechanism to retain the paste fill ingredients in the mixing chamber through reversed paddles and weirs.

For non-clay, non-agglomerated tailings, a mixing time of 30-45 seconds has been found to produce well-mixed paste fill. Such a well-mixed paste fill with 200-400 Pa static yield stress at the mixer could easily be distributed through reticulation system. The static yield stress has been found to drop continuously as during the transport through the reticulation system. Table 4 summarises a typical variation in the rheological parameters of a specific paste fill during transport from the mixer to underground stope due to additional shearing and mixing.

Table 4 Typical variation of rheology during transport of a paste fill made of non-clay, non-agglomerated tailings

Location	Static Yield Stress (Pa)	Plastic Viscosity at Shear rate < 50 sec-1 (Pa)	Standard Slump (mm)	Time of Mixing (sec)
At the mixer exit	400	1.2	175	30
At the bottom of a borehole	300	1.2	200	180
At the underground stope	250	1.2	225	600

Mixing is the most important part in a paste fill production system, and it is prudent to provide adequately designed paste fill mixers to achieve the desired degree of mixing which would result in a smaller reticulation system. With reclaimed tailings paste fill systems, agglomeration of the tailings solids in the feed tailings is an important factor to be considered in the design of paste fill mixer and the overall plant. The tailings agglomerates have to be crushed before and during the mixing to achieve reasonably homogeneous paste fill. If tailings agglomerates present in the paste fill at the mixer discharge, they may gradually break in the reticulation system and result in increased stiffness of the paste fill in the underground reticulation system. Tailings agglomerates in a paste fill may also contribute to reticulation system failure due to line blockages.

6.3 Paste Fill Placement Rate

The first priority in designing paste fill is to ensure trouble free reticulation to underground stopes. To achieve the required filling rate to sustain the designed mine production rate, uninterrupted fill placement is necessary.

A simple relationship could be derived between the mine production rate and the required fill placement rate as given in Equation 1.

The required average daily fill placement rate in dry tonnes is given by Equation 1.

$$QF_{wd} = \frac{P_a . F_p . \gamma_d . R_p}{(3.65). G_s . M_a . E_p} \qquad (1)$$

Where:

QF_{wd}	=	The required daily fill placement rate (tonnes/day)
P_a	=	Mine production per anum (tonnes)
F_p	=	Percentage of void need to be filled
γ_d	=	Dry unit weight of paste fill in stope (tonnes/m^3)
R_p	=	Rate of peak fill demand / rate of average fill demand
G_s	=	Specific gravity of ore
C_a	=	Concentrator availability to process ore (%)
E_p	=	Paste fill system efficiency or availability (%)

The hourly volumetric fill flow rate through the reticulation system is given by Equation 2.

$$QF_{vh} = \frac{QF_{wd}.100}{(24).C_w.\gamma_w} = \frac{(1.142).P_a.F_p.\gamma_d.R_p}{C_w.\gamma_w.G_s.M_a.E_p} \quad (2)$$

Where:

QF_{vh}	=	hourly filling rate m^3/h
C_w	=	Solids concentration of paste fill (%)
γ_w	=	Pulp density of paste fill (tonnes/m^3)

The head loss in the reticulation system of internal diameter of D (m) is given in Equation 3.

$$h_f = \frac{(4).\tau_B}{D} + \frac{QF_{vh}.\eta_B}{(28.125).\pi.D^4} \quad (3)$$

Where:

h_f	=	Head loss in the reticulation system in kPa/m
D	=	Internal diameter of the reticulation system (m)
τ_B	=	Bingham yield stress from intercept of flow curve (Pa)
η_B	=	Bingham plastic viscosity (Pa.s)

The above calculation based on assumed Bingham model is adequate to choose appropriate reticulation system based on the mining rate and the required filling demand. There are alternate viscosity models such as “Power Law” or “Herschel Buckley” models also available to design reticulation systems for paste fill. It is important to design paste fill reticulation system with adequate flow velocity to avoid deposition of paste fill in the pipe. If the flow velocity is too small there are possibilities for the pipeline get scaled up.

7 EXPERIMENTAL TECHNIQUES

There are many testing methods available to test the quality of paste fill from the very simple slump test to the most advanced rheological testing. It is the authors’ experience that, simple test procedures are adequate to control the quality of paste fill.

7.1 Slump Testing – Standard Slump Cone (300 mm high)

Standard slump test has been adopted from the concrete industry by the paste fill industry. A 300 mm high truncated cone with 200 mm ID base and 100 mm ID top is filled with paste fill, ensuring no air is included while filling. The slump cone is lifted slowly allowing the paste to slump and flow. The height through which the top of the paste slumped (to the nearest 5 mm) is known as the slump for the paste fill. Most of the paste fill produced at various plants have slump values between 150-250 mm, at the mixer discharge point and may increase in slump range to 175-275 mm at the underground discharge point. The standard slump values can be correlated to static yield stress and several empirical correlations available to relate these two quantities.

7.2 Slump Testing – Mini Slump Cone (150 mm high)

Mini slump cone testing uses a slump cone of 150 mm high, 100 mm base and 50 mm top and would require less than 1 litre of paste fill to do a test in comparison to 4-5 litres of paste fill required by the standards slump test. The mini slump values could be correlated with the standards slump values or with the static yield stress. Most of the paste fill would have 60-120 mm mini slump at the paste fill mixer, and 75-135 mm slump at underground discharge point.

7.3 Slump Testing – Cylinder Mould 200 mm or 100 mm

A modified slump test using cylindrical moulds of 200 mm high and 200 mm ID base or 100 mm high and 100 mm ID base could be used to test the paste fill consistency. The cylinder slump values could be correlated to either standard slump or static yield stress. Cylinder moulds could be easily obtained by cutting appropriately sized pipes. This is a very simple and useful test.

7.4 Flow Cone Testing

Flow cone test is similar to the Marsh Flow Cone test used in the drilling industry, but the out flow of paste is directed through a pipe section of 30 mm ID and 150 mm long, attached to the cone. The time taken to empty 1 litre of paste is used to judge the flowability of the paste fill. Flow cone testing is a dynamic test, and the paste fill collected at the paste mixer may not flow through the cone if the mixing is too short. It is the authors experience that further mixing of paste fill enable it to flow through the cone easily. A flow time of 5-15 sec has been recorded at one paste fill production plant. Flow cone test is easy to perform and ideally suited for quality control procedures. The flow time could be correlated to slump values or yield stress.

7.5 Flow Table

There are two types of flow table test available. One test used a truncated standard slump cone of 200 mm high and the other test used a smaller ring of 50 mm high and 100 mm base. In both the tests some impact energy is given to the paste to induce flow and the spread of paste after certain number of drops of the table is noted as the flowability of the paste fill. This test is not in common use.

7.6 Rotational Viscometers and Viscosity Testing

There are many models of rotational viscometers are available to measure paste fill viscosity parameters. The three commonly used equipments in the mining industry are Haake, Bohlin and Brookfield.

7.6.1 Haake rotational viscometer

A Haake viscometer with a shear vane attachment is used in many paste fill operations to measure the static yield stress of paste fill. With special attachments, it is possible to obtain data on the flow curve for paste fill, and estimate the dynamic yield stress and plastic viscosity for paste fill. These rheological parameters could be used to design the paste fill reticulation system and to predict the expected pressure head loss in the reticulation system. It is extremely important to obtain the actual pressure head loss from operating paste fill systems to check the predicted head loss against the actual head loss in the system.

7.6.2 Bohlin rotational viscometer

A Bohlin viscometer is similar to the Haake viscometer, but uses cylindrical bob instead of a shear vane. The Bohlin viscometer is suitable to produce good quality flow curve of paste fill. Rheological parameters such as dynamic yield stress and plastic viscosity could be reliably estimated using the Bohlin viscometer test. Shear rate up to around 250 s^{-1} is achievable in this instrument and special testing techniques necessary to eliminate the slippage during testing.

7.6.3 Brookfield rotational viscometer

Brookfield viscometer testing is similar to the Bohlin test and suitable to generate flow curves for paste fill.

7.6.4 Field vane shear or cylinder shear tests

The author has developed these two tests to measure the static and dynamic yield stresses in the field using a hand held vane shear instrument. The vanes of varying sizes ranging from 100 mm OD, 150 mm high to 50 mm OD, 100 mm high could be used in a 10 litre bucket. The cylinder shear test is carried out using a 100 mm OD, 150 mm high cylinder with appropriate surface texture to avoid slippage. The field vane could measure yield stresses in a range from as low as 100 Pa to as high as 5000 Pa, which other rotational viscometers could not handle.

7.7 Tube Viscometer

They are many types of tube viscometers available to obtain reliable rheological parameters of paste fill. The flow resistance is measured when paste is forced to flow through calibrated tubes to generate the flow curve. The driving heads necessary to sustain the flow through tubes are given by air pressure, piston load or gravity head. The driving head is varied and the corresponding flow rate or shearing rate is recorded to generate the flow curve. It is easy to construct tube viscometers at site and use the gravity to drive the flow. The author has constructed and used two tube viscometers with 150 mm ID, 1500 mm high and 300 mm ID, 3000 mm high slurry tanks to test thickener underflow and paste fill. PVC pipes could be used to make the slurry tank, with copper or stainless steel tubes of 10 mm to 50 mm ID for flow measurements.

7.8 Pump Loop Testing

Pump loop testing is very expensive carry out, and only justifiable in larger paste fill plant construction projects. Pump loop testing could be used to confirm the rheological measurements recorded from other laboratory tests, and also to check the predicted friction head loss based on laboratory tests.

7.9 Paste Mixer Power Draw as an Indicator of Paste Consistency

The power consumption at the paste fill mixer is an indication of the paste fill consistency and many experienced paste fill plant operators rely on this indicator to judge the quality of paste fill being produced. If careful record is kept on the mixer power draw, slump, yield stress, it could be evident that the mixer power draw follow similar exponential variation demonstrated by static yield stress against the % solids concentration of paste fill. This relationship could be used to detect any wrong trends in the mixer power draw and take appropriate remedial action during paste fill production.

8 CURED PASTE FILL MASSES AND THEIR PERFORMANCES

8.1 Fill Mass Exposure Performance

Cured paste fill masses in underground voids should remain stable during exposures. Fill masses are exposed either along the vertical faces during mining adjacent ore pillars or from below while mining ore below the fill masses. Each of the above exposure condition would impose different stability condition and forces on the fill mass. The paste fill has to be designed to withstand all the expected stress conditions created by exposure. There are semi-empirical calculation methods available to estimate the required fill strength under these conditions. The most popular semi-empirical methods are limit equilibrium method by

Mitchell and 3D arching derived from Terzaghi's 2D arching theory (Kuganathan, 2005). Numerical modelling also could be used to analyse fill mass stability problems under various exposure conditions.

Fill masses are exposed at various curing times based on many mining related conditions such as mining rate, size and shape of orebody, mining method used, and the filling rate. It is essential that the fill mass has achieved the necessary strength to withstand the stress conditions at exposure. The competency of a fill mass is assessed by the unconfined compressive strength (UCS) of the fill at the time of exposure. Based on the geometry of the fill mass and the exposure conditions, paste fill may need to develop UCS of 200-2000 kPa to be stable. It has been a common observation that the paste fill masses underground achieve higher strength than the laboratory samples with the same binder content.

8.2 Paste Fill Retaining Walls

There are many types of paste fill retaining walls ranging from a simple development waste bund to fully engineered fibre reinforced shotcrete walls. Some mines build a hybrid fill retaining wall comprised of development waste bund and shotcrete. Some mines have used fill fences constructed of steel cables, wire meshes, and geofabrics.

Many paste fill retaining walls failed in the recent past and released paste fill into mine drives. Such releases of fill into mine drives could cause disruptions to mine production and in some cases has the potential to cause injuries or fatalities. The paste fill retaining walls have to be designed to withstand the maximum expected pressure under a particular mining environment based on the following factors such as fill placement rate, rate of strength development in the fill mass, any dynamic loading conditions, and the strength of fill plug in the access drive. It is possible to compute the expected maximum paste fill pressure on fill retaining wall through numerical modelling or spread sheet based calculation models.

It is prudent to use instrumentation at few strategic locations behind fill retaining walls and monitor the actual fill pressures acting at those locations. Such information from instrumented paste filling operation would help to calibrate the models used to predict paste fill pressures on retaining walls.

8.3 The Role of Pore Water Pressure

The role of pore water during exposure of a well cured paste fill mass depends on the following factors:

- Degree of saturation of the paste fill mass.
- The tendency of the fill mass to dilate or contract.
- Any additional loading imposed due to stope closure, adjacent blasting activity, or moving equipment over the fill mass.

If the particle size distribution of the paste fill is optimised and sufficient amount of binder added, the paste fill mass should behave very competently and the chances of pore water induced failures are very remote. On contrary, the following factors may contribute towards pore water related failure in a paste fill masses including liquefaction:

- Poor or non-optimal particle size distribution with large amount of fines.
- Larger void ratio of the in-situ paste fill mass due to poor grading.
- Slower strength development in paste fill mass due to active chemicals in tailings.
- Higher degree of saturation at the time of exposure.
- Faster filling rate.
- Dynamic loading from blasting.

8.4 Consolidation in Paste Fill

There are different opinions amongst the investigators regarding the influence of consolidation in the strength development in cemented paste fill masses. Depending on many site specific conditions such as vertical filling rate, size of the underground void, particle size distribution, final solids concentration, the amount of binders in paste fill, and the rate of strength development the influence of consolidation on paste fill could be significant or negligible. The following are the two extreme conditions with respect to the effects of consolidation on cemented paste fill masses.

The long-term consolidation may be minimal in a cemented paste fill (Case A) with the following attributes:

- Optimised particle size distribution that results in dilating fill.
- Relatively non-reactive and non-clay tailings.
- Faster strength development.
- Moderate to lower vertical filling rate in underground stopes.

The consolidation may influence the strength development and subsequent behaviour of a cemented paste fill (Case B) with the following attributes:

- Non-optimised particle size distribution with contractive tendency during shear.
- Reactive or clay minerals in tailings.
- Slower strength development.
- Faster vertical filling rate in underground stopes.

The effects of consolidation may not be an issue and can be ignored in Case A whereas the consolidation may be considered in Case B. It needs further investigation to understand the effects of consolidation on the behaviour of cemented paste fill masses.

8.5 Liquefaction in Paste Fill

Many investigators published on this topic and the readers are asked to refer to these publications for additional information. If paste fill is designed to be dilative, the liquefaction in a well cured paste fill mass may be a very remote possibility. However, liquefaction is possible in paste fill masses with the following attributes:

- Loss of strength due to reactive tailings and ground water action.
- Larger initial void ratio with contractive behaviour during shear.
- High degree of saturation.

Liquefaction in paste fill masses could be avoided by prudent design practices such as:

- Particle size optimisation to give minimum void ratio fill.
- Selection of binders to suit the mineralogy of the tailings and process water.
- Allowing for minimum required strength of over 100 kPa.
- Engineered retaining walls to support the liquefied fill.
- High binder content plugs to cover access drives.

9 FUTURE DEVELOPMENT

Paste fill technology is spreading fast in the mining and civil waste disposal environments. Many investigators are continuously working on various aspects of paste fill technology from all over the world. At present the paste fill technology is implemented based on many semi empirical methods and experience. However, the author believes that many theoretical developments will be made in the future to give more predictive tool in paste fill technology. Paste fill technology may be adopted by thickened tailings disposal system designers to produce high yield stress paste for disposal, with the development of new placement methods based on conveyor belts to transport high yield stress paste. The filtration may be necessary to improve the stiffness of thickened tailings.

The use of alternate binders in cemented paste fill will increase with the associated cost savings. Iron blast furnace slag, geopolymers, other chemical or biological binders may find the way into paste fill technology in the future. Paste fill mixing technology will improve with the increased understanding of the significance of good mixing of paste fill to achieve better flow regimes and smaller reticulation system. Rheological parameters may be obtainable from well-instrumented paste fill mixers.

More mines will try to add aggregates into paste fill and try to deliver it to underground through boreholes and pipeline. More collaboration between concrete technology and paste fill technology will be seen in the future to produce and deliver aggregate added paste or rocky pastfill.

10 CONCLUSIONS

An attempt has been made to present the current state of the paste fill technology in this paper. Due to space limit, detailed presentation of many issues was not possible. However, reasonable amount of information has been given to help the mining industry to understand paste fill technology from this paper. The information presented in this paper and in the previous two papers by the author would give a good introduction to paste fill technology.

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