The Evolution of Paste for Backfill

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Abstract

Paste thickened tailings backfills have undergone a rapid evolution from their first applications in the early 1990's, and with it the industry has seen significant advances in both the technology and the equipment that is needed for the production, transport and placement of paste. In the early years, the production of paste was largely based on "rules of thumb" and industry experience with conventional thickening systems hence paste performance failures were common. Nowadays the production of paste is based on a much improved understanding of the rheology of thickened tailings, and the behaviour of non-Newtonian slurries. This talk will walk through the advances in the science of paste thickening of tailings, and the associated improvements in the equipment used for thickening, mixing, pumping and transport of these materials..

1 Introduction

My first introduction to mine backfills was over 30 years ago as a Ph.D. student studying under Dr. Robert Mitchell at Queens University. Many of you will recognize Dr. Mitchell as an early pioneer in the empirical design of stable backfill exposures. The so-called Mitchell equations are still in use today for both vertical fill exposures, and for undercut sills. During my tenure at Queen's, Bob constructed the first geotechnical centrifuge for physical modelling of backfill exposures and this led a much better understanding of the geomechanics of backfills.

Since that time, my 30+ year career has taken me to all corners of the globe, from Papua New Guinea, to the Arctic in Canada. Like those of you from my generation, I was witness to the introduction of paste thickened tailings for backfill, and to its widespread adoption by the mining industry. The industry acceptance of paste for backfilling is quite remarkable, and in my mind it is the single greatest advance in the technology of mine fills since the Minefill Symposia series started in 1973.

My talk today is intended as somewhat of a history lesson in the evolution of paste backfills, primarily for underground metal mines. While the early history of paste fills is well documented in a number of previous papers and keynote addresses, my presentation will lean more towards the science of paste thickening for backfills. This will lead to a discussion on the evolution of the technologies used in paste plants today.

2 Before There Was Paste

The earliest beginnings of paste thickened tailings for backfilling can be traced to South Africa and Canada in the mid to late 1970's where hydraulic backfill was the backfill of choice. At that time hydraulic fills were the standard, and they had been widely used for over 50 years. With the large scale commercialization of Portland cement in the 1960's, cemented hydraulic fills allowed bulk mining of large open stopes without the need to leave pillars.

Hydraulic fills were relatively cheap because of the availability of mill tailings, they were easy to classify and dewater by cycloning, and they were easy to transport to stopes in small diameter pipelines - typically without pumping. The downside with hydraulic fills, however, was they created huge volumes of dirty decant water for the mine to deal with, and they consumed vast quantities of cement when fill strengths needed to be over about 200 or 300 kPa. As the stopes got larger, and cement costs escalated, binder costs could easily account for 60 to 70% of the cost of the fill.

In the early years of hydraulic fill, before the introduction of more modern grinding and flotation equipment, the particle size distribution of gold mill tailings was quite coarse. Grinds were typically less than 50% passing 74 microns and these materials were ideally suited to hydraulic fills. However by the late 1970's grinds were getting finer and problems arose with percolation rates in the fills which only aggravated the issues of cement consumption.

In South Africa the excess mine water was a major cost issue because the water had to be pumped back to the surface. This led to research on ways to produce hydraulic fills with less free water, but still render them pumpable. The result was the so-called "dense fill" or "high density backfill" that was essentially what we now refer to as thickened tailings. Compared to the 55-65 wt% solids in hydraulic fills, these new fills reached pulp densities in the high 60's and low 70 wt% solids. This reduced the free water by almost 50%.

The two stumbling blocks with these systems were (i) how to dewater the tailings, and (ii) pumping thickened tailings was beyond the capabilities of most pumps in that day. Even with piston pumps the practical limit was thought to be about 1 km of pipe.

The dewatering issue was highlighted in a SAIMM paper which noted "the equipment at present available is either of unsuitable mechanical complexity and size or is relatively untried" (Patchet 1977). By the late 1970's several methods of thickening hydraulic fills were being investigated. Some of the more novel methods included vibrating the sands in the stope after placement, batching in settling tanks and then drawing from bottom of the tank, and centrifuging.

By 1976 the South Africans were experimenting with centrifuges for dewatering total tailings streams. At the leading edge of this work was the "Tailspinner" (Wayment 1978) introduced by Joy Manufacturing of Cambridge, Ontario sometime around 1972. Operating at about 1500 to 3000 rpm, this device allowed for the continuous dewatering of a slurry stream from an inlet solids content of about 40 to 60 percent solids by weight, to an outlet solids content of 75 to 85% solids. The device was designed to dewater the entire tailings stream, and the discharge generally contained less than 1% solids. The device was compact and fit in a 4-foot cube which allowed it to be portable. The South African's took this concept to a prototype stage and installed a Tailspinner underground in the Witwatersrand basin.

The Tailspinner could produce a material that was just short of filter cake (e.g. a high yield stress paste) which had to be pneumatically stowed. The biggest disadvantage with the Tailspinner, however, was the throughput was limited to about 15 tonnes per hour. The other disadvantage was that all the dewatering was done underground at the stope in order to avoid having to pump thickened tailings.

By the early 1980's Tailspinner's were in use in Canada at South Porcupine and the Dome Mine in Ontario, marking the first introduction of a form of paste fill in Canada. Like the African's, the Canadians did not believe in pumping paste in the early to late 1980's.

3 The science behind paste rheology

The industry seems to have adopted a rule of thumb that paste must contain more than 15% passing 20 microns. The fines, it is said, make the paste "slippery" so that it can be pumped easier. Even the ACG "*Handbook on Mine Fill*" shows a figure illustrating this. A paste that is deficient in fines (<325 mesh) will typically exhibit much higher pipe friction losses during transport.

I have often wondered who came up with these ideas, and it is probably no coincidence that is also found in concrete technology. It seems that a lot of the early ideas and research into the pumping of pastes are rooted in concrete technology. Some of you may recall that in the very early days paste was not considered to be pumpable (Landriault 1992).

Consider the standard 1/2/3 recipe for concrete mixes which says you add 1 part cement to 2 parts sand and 3 parts gravel. This results in a concrete mix with roughly 15% cement (aka fines) by weight. It should not be a surprise that in concrete transport, the cement is also thought to be responsible for making the pipe walls "slippery" so that it can be pumped.

It should also not be a surprise that the industry adopted the ASTM standard concrete slump cone as a measure of the rheology of a paste mix. Even today most mines design their paste mixes based on a target slump.

One of the earliest researchers into the science of rheology of paste mixes was Neels Verkerk (Verkerk 1988). Thanks to his early work we now recognize that the behaviour of Bingham plastic and non-Newtonian slurries is governed by viscosity and yield stress. Verkerk produced some of the earliest tailings rheograms along with research on pressure gradients at varying flow rates.

Nowadays we understand that the stability and pumpability of a paste mix is dependant on yield stress and viscosity. Up until the mid-1990's these terms were rarely heard in reference to backfills. However in the past 25 years the depth of understanding of the rheology of paste mixes has expanded considerably.

The reality is that the stability and pumpability of a paste mix is complex and is impacted by a number of variables such as the mineralogy of the solids, specific gravity of the solids, particle size distribution, particle shapes, clay content and clay mineralogy, salts or other dissolved chemicals in the carrier fluid, and even the pH or temperature. It is no wonder that early paste mixes were largely designed on trial and error, and even today these mixes are highly sensitive to changes in the ore mineralogy, oxide content, and changes in the mill grind.

4 Making Paste

4.1 Dewatering with hydrocyclones

The cyclone has played a dominant role in both dewatering for hydraulic fills, but also for classifying the material to remove the slimes portion of the tailings.

The idea of using centrifugal forces to separate liquids and solids in a hydrocyclone was first patented in 1891. This first generation of cyclone had a closed apex that allowed intermittent discharge and was the forerunner to present-day de-sanders that are used for separating sand from water in pressurized water systems.

The present day cyclones can be traced back to patents in the 1940's by the Dutch State Mining Company which developed designs for the removal of sand from coal. These patents were licensed to the Dorr Company (the predecessor to Dorr-Oliver) around 1948 who then commercialized the equipment. In 1955 Krebs Engineers started manufacturing their own version that eventually dominated the market. The basic design of the modern day cyclone has not really changed in the 60 years since then.

4.2 Thickening

We could, and others have, filled many keynote addresses talking about the evolution of thickeners, flocculants, and underflow characteristics. In my view the evolution of the thickener has contributed the most to adoption of paste for backfilling. A large number of paste backfill systems today are based solely on paste thickened underflows.

The beginnings of the modern thickener started in 1906 when John Dorr patented the first continuous thickener with a circular tank and a set of rakes. Since that beginning the basic thickener design has seen significant advancements to increase throughput, and to push the operating limits in terms of solids concentrations and yield stresses. Some of the more significant improvements include flocculant chemistry, rake designs, feed wells and feed dilution, dewatering pickets, shear thinning, re-injection of underflow to improve bed movement, tank designs and tank geometries, and modern computerized instrumentation and control systems. Numerical modelling of the beds has resulted in significant performance improvements, and structural modelling of the tanks and rakes has allowed these facilities to reach today's enormous sizes of 90m diameter and more.

Nowadays we have a range of thickeners designed to meet different needs. Conventional thickeners for thickening tailings for the production of tailings slurries typically have underflows with 50-55% solids and 20-30 Pa yield stress. High rate thickeners generally have an increased bed height to increase self-consolidation and produce underflows in the 55-60% solids range and 30-100 Pa yield stress. Paste thickeners have much deeper beds (hence the reference to “deep cone” and “deep bed” etc) and are designed to produce an underflow material in the paste range of yield stresses (>100 Pa). Both high rate and paste thickeners have the capability of producing underflow in the paste range of yield stresses.

The origins of modern paste thickening units date to the late 1970’s and early 1980’s when the alumina industry was looking for ways to dewater bauxite residues to improve water recycling and to allow “dry stacking” of red muds. Both Alcoa and Alcan developed technologies that were the forerunners to today’s paste thickener units. The first of these units were constructed by Alcoa at Pinjarra in Western Australia in 1985, and Alcan had other units underway in Jamaica and Quebec. In 1996 Alcan signed a technology sharing agreement with Eimco to bring this technology to non-alumina industries and the rest is history.

By all accounts there are some 300 or more paste thickeners installed worldwide, operating at close to 100 mine sites. Not all of these are for backfilling as many of them produce thickened tailings for surface disposal. However there are even more high rate or high compression thickeners in use, and these are typically dedicated to surface disposal of thickened tailings.

5 Transporting Paste

As I have already noted, the rapid advancement of paste was largely due to our understanding of concrete rheology and transport at the time. This impacted the evolution of paste in two ways, one was the mix design, and the second was the design of the distribution system.

Inco was one of the first to investigate the connection between the rheology of concrete and the pumpability of high density tailings and paste mixes (Landriault and Goard, 1987). As Landriault notes: “any granular material could be pumped like concrete if it was mixed with a sufficient quantity of a suitably fine material”. Inco’s research focused on the variation in pressure losses over a range of fines contents, and not surprisingly, the lowest pipe pressures were noted in materials with 10-14% fines, and 14-19% water content – just like concrete.

About the same time the South Africans were realizing that it was far easier to distribute paste mixes by gravity than it was to push it with pumps. In an effort to reduce pipe friction, the South Africans tried adding crushed aggregate to the paste mixes. Flow loop testing showed that mixes with crushed rock exhibited lower pipe friction losses than paste mixes based on tailings alone. This seems kind of counter-intuitive, but again, drawing on the concrete experience, the coarse fraction was thought to create a plug flow in the pipeline whereas the fines were meant to lubricate the inside of the pipe. The Bad Grund mine in Germany was took advantage of this when they started up in 1988 as did many early paste systems in South Africa.

Verkerk (1988) discovered the conundrum in that, in laminar flow conditions, increasing the coarse fraction of whole tailings mixes results in increasing yield stresses and increasing pressure gradients. This behaviour was thought to be the result of the coarse fraction sinking to the bottom of the pipe and creating a sliding bed regime. However, in the non-Newtonian range the opposite is true and pressure losses go down as the coarse fraction is increased. Apart from the plug flow behaviour noted previously, another explanation was that the coarse fraction displaced water hence increasing the water content in the carrier media concentrated along the edges of the plug flow thus lowering the frictional resistance. Thus it was shown that, in order to reduce pipe friction losses, the carrier media must have a measurable yield stress.

Early attempts to pump thickened whole tailings with positive displacement pumps did not end well. In most cases the pumps failed prematurely due to excessive wear on a number of parts including poppet valves and valve seats, and blockages in internal passages (Patchet, 1977). This led to an industry acceptance that paste could not be pumped. Landriault (1992) noted that Inco used gravity flow exclusively, and by 1994 Fred Brackebusch suggested that the maximum distance a paste can practically be pumped is about 1 km. By 1998 Fred had changed his mind and suggested the limit was now 3 km. Thompson (1972) provides an even earlier benchmark noting that the maximum capability of a double piston positive displacement pump was 1750 hp (1.3 MW) operating at under 2,000 psi (13.8 MPa).

Even though the basic operating principle of these pumps has not changed much since the mid to late 1990's, they have undergone significant improvements in the range of operating pressures, available power, and wear-life of the components. Many positive displacement pumps are now capable of pressures of 20 to 30 MPa flow rates in excess of 200 m3/hr.

The final hurdle in getting these systems to work was the distribution piping itself. There were some hard lessons learned here, but again the concrete industry had been through the same learning curve. A number of operations such as Lucky Friday, and even Inco, learned that dropping paste vertically down an empty shaft pipe was a recipe for disaster. The momentum and forces involved were beyond the capability of pipe steel and mounting hardware in those days and blowouts were common. It was quickly learned that it was much safer to operate paste systems with a full pipe but this required much more elaborate control systems and flushing mechanisms.

The next lesson was how to pump the material without plugging the pipe. In this instance it was quickly learned that rheology was the key and that most systems could be designed for an ideal yield stress (slump) that would prevent excessive pressures, reduce pipe wear, and prevent cavitation.

6 Paste Goes Mainstream

Once all the bugs were worked out it did not take paste long to become the backfill of choice. By late 1994 there were several plants in operation in Canada, and by the year 2000 there were some 22 plants in operation (Landriault, 2000). My best guess is that over 150 paste plants have now been built but not all are operating. The Golder files contain some 50 paste plants that have been built, and since about 2000 the industry has been adding about 5 new plants per year.

In Canada and Australia, paste quickly replaced cemented rockfill as the backfill of choice because it could achieve the compressive strengths needed in large blasthole stoping operations. In other parts of the world (especially Peru) it replaced hydraulic fills. In Nevada it took until 2010 before regulators could be convinced that cyanide tails could be used as paste for backfill in an operating mine and Barrick commissioned the first plant in 2012.

A brief timeline of the chronology of some of the major milestones in the evolution of paste is given in Table 1.

Table 1 Chronology of events in the evolution of paste

Year	Event
1985	First Alcoa superthickener at Pinjarra in Western Australia
1988	First paste plant in the US at Lucky Friday
1994	First paste plant in Canada at Inco Garson
1996	Alcan-Eimco technology sharing agreement First DCT's sold outside the alumina industry
1997	Golder Pastec formed
1997	First paste plant in Australia at Henty
1998	First paste plant in Brazil at Cariaba
1998	First plant built by Pastec at Cannington, Australia

2000	22 paste plants operating
2006	Over 40 paste plants operating
2012	First paste plant in Nevada at Barrick Goldstrike

The rapid adoption of paste is ideally illustrated in the proceedings for previous Minefill Symposia. Table 2 is a summary of paste backfill related papers in the proceedings since the Symposia series started in 1973.

Table 2 Paste related papers presented in previous Minefill Symposia

Symposia	Paste Related Papers
1973 – Mount Isa	0
1978 - Sudbury	0
1983 - Montreal	0
1989 - Sweden	2
1993 - South Africa	2
1998 - Brisbane	12
2001 - Seattle	11
2004 - Bejiing	11
2007 - Montreal	13
2011 - Cape Town	10
2013 - Perth	22

The first Minefill Symposia papers to refer to "paste" backfill were published in the 1989 proceedings. One of these papers addressed the liquefaction potential of paste for backfill at the Dome mine in Canada which, at the time, was viewed as a key risk with implementation. The other paper by Dave Landriault compared the convergence resistance of a variety of backfill types including paste fills.

In 1999 the Australian Center for Geomechanics premiered the first annual symposia for "*Paste and Thickened Tailings*" and it has been a valuable forum for the sharing of this rapidly evolving science (Boger 2011). While this symposia series is targeted more towards surface disposal, and technology, it does draw papers related to mine backfilling. In 2010 it attracted a record 12 papers related to paste for backfill, therein documenting what would appear to be a peak in the startup of new paste plants.

7 Conclusions

It is hard to believe that paste backfills have been successful for more than 30 years thanks to the many innovations in rheology and equipment. The benefits speak for themselves.

Acknowledgement

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