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Loop pumping tests of crushed rock mixed with thickened tailings

T Wennberg *LKAB, Sweden*

A Stålnacke *LKAB, Sweden*

A Sellgren *Luleå University of Technology, Sweden*

Abstract

LKAB operates three mines in northern Sweden, where the climate is subarctic with an average temperature of about 0°C. LKAB's long-term overall objective includes feasibility considerations of thickened or filtered tailings combined with waste rock co-disposal covering cyclic economy considerations and landscape forming. At the Kiruna underground mine, about 3.5 Mtonnes of tailings and 12 Mtonnes of waste rock are generated annually. Crushing to less than 30 mm is part of the sorting plant processing, and the rock is deposited in stockpiles while the tailings are pumped conventionally to water-holding impoundments.

The aim is to indicatively test the pipeline pumping of paste-rock mixtures at solids concentrations by weight of over 85% to limit segregation and leakage during deposition in nearby old pit holes. A test was carried out at a paste thickener with direct access to fresh paste, which was mixed in a concrete mixer with crushed rock from the processing. A 38 m long loop with a pipeline inner diameter of 0.075 m was equipped with a concrete type of pump. Unfortunately, a second test in a larger pipe could not be carried out at the planned time. LKAB then had the opportunity to test a laboratory-scale concrete industry device, the sliding pipe rheometer, Sliper, developed to simulate concrete pipeline pumping frictional resistance in a 0.126 m diameter pipeline. Initial loop results with crushed rock particles of up to 10 mm with a rock-to-paste mass ratio R:P of 1.2:1 showed a pressure requirement of about 25 kPa/m at 0.7 m/s for a total solids content of 84% by weight corresponding to 65% by volume and a water content of 19% (Solids density 3000 kg/m^3).

The 10 mm product loop pressure results agreed relatively well with simulated Sliper data scaled to 0.075m from 0.126 m for C_w 85-86% and R:P of up to 2.6:1 at 0.7 m/s. The 30mm Sliper result at 89% indicated a pressure requirement of 14 to 24 kPa/m at 0.7 m/s for R:P of 2.6:1 and 3.5:1, respectively. With a 0.15 m diameter pipeline, a pumping requirement of 20 kPa/m at 84% and 0.7 m/s was also discussed regarding feeding requirements.

The results form the basis for a planned larger-diameter test. Long-term flexibility factors related to tailings availability and clarification of suitable routings and allowed water contents may necessitate that the wider diameter loop test includes a limited once-through pipeline pumping demonstration feeding arrangements. Variations in the rock-to-tailings ratio related to tailings availability and disturbances can be investigated. The system feasibility for filling depressions may cover a concentration span starting from about 75% by weight which means a more stratified flow where the coarsest particles form a sliding bed.

Keywords: *paste-rock pumping, loop test, high concentration, particle stratification*

1 Introduction

LKAB operates three mines in northern Sweden. The mines and concentration facilities are located north of the arctic circle. Scandinavia has an average temperature of about 0° C, with winter temperatures falling to -35 to -40° C during weeklong cold spells. Snow is present from mid-October to mid-May.

Since the early 1990s, LKAB has considered new technologies for handling, transporting and disposing of waste rock and tailings. The potential for the combined integrated pumping of waste rock and tailings with co-disposal in one storage area with a limited footprint was highlighted by Sellgren & Sundqvist (1995). In a once-through pumping facility and a large-scale laboratory loop, co-disposal of waste rock with a particle size of up to 65 mm and tailings of up to 4 mm mixed on a 1:1 mass basis with an even particle size distribution was tested. The tests were up to a solids concentration by weight C_w of around 60% (Sundquist & Sellgren 2004). However, it is still a lot of water. Williams (1998) argued that segregation and washout were key problems when coupled with integrated handling and co-disposal, based on his experiences with coal washery wastes.

Today, LKAB's long-term focus is on feasibility considerations of thickened and/or filtered tailings combined with waste rock co-disposal technologies, including cyclic economy considerations and landscape forming. The goal is to reduce the need for water-holding impoundment structures considering the climatic conditions. In the Kiruna underground mine, approximately 3.5 Mtonnes of tailings and about 12 Mtonnes of waste rock are generated annually. Crushing a portion of the rock to less than 30 mm is part of the processing. It is then deposited in stockpiles. The tailings are pumped conventionally to a water-holding impoundment. Long-term plans to extend the mine include extracting industrial minerals and iron ore at a depth of about 1500 m. Considered alternatives so far also include cut and fill mining. With this, the tailings will also be used for backfilling. Therefore, we must consider the future handling of residual products more broadly.

Wilson et al. (2006) studied mine waste cover systems based on matching a blend of tailings, waste rock and slag to a moraine-like broad and even size distribution with 30% less than 40 µm, average and maximum particle sizes of about 1 mm and 10 mm, respectively. The term paste-rock was used with a small amount of water added to reach a suitable consistency. Wickland (2006) conducted in-depth studies using large-scale cover tests on optimum paste-rock mixture ratios for best packing density. A low porosity was obtained when coarse material dominated the paste-rock or binary mixture because the smaller particles filled the larger particles' void space.

Filtration-based disposal means pumping moderately thickened tailings to a filtration process whereafter the mixture typically becomes "spadable" and therefore not pumpable. Further transportation in conveyor belts or trucks to machine-based receiving facilities for spreading and packing for storage. For co-disposal with crushed waste rock, various approaches for handling after filtering are used or under development to form a homogeneous mixture to fulfil site-specific geotechnical stability criteria. Water reduction in the thickening co-disposal storage chain resulting in "dry-stacking" may not always be directly adaptable in a humid subarctic area with a positive water balance.

Therefore, we examine the pipeline pumping of paste-rock mixtures at very high solids concentrations as a part of LKAB's long-term development work related to future system integration and flexibility.

2 Hydraulic characterisation

In a review, Pullum (2007) considered high C_w-values of 85-88% and used the term Ultra High Concentration (UHC), referring to low friction loss test results with coarse coal with initial lack of fines for a pump of rotary ram type with valve arrangements (see also Pullum et al. 1996). UHC is where packing can be so close that particles may not reorganise in the pipe, and inter-particle motion is limited. They also observed low friction losses when pumping a broadly sized gravel-sand mixture with about 5% less than 40 µm, d_{50} =2mm and d_{max} =10 mm in a 0.052 m diameter pipe. Low operating velocities of 0.2-0.9 m/s are characteristic of UHC. Pullum et al. (1996) further mention difficulties maintaining stable conditions before reaching the highest concentrations.

In backfilling, the mixture typically contains cement or another binder after thickening and filtration. Pumping with a solids content of up to and over 80-85% by weight includes a binder, friction-reducing additives and sand-gravel-sized particles, or 'aggregates'. Usually, this transportation takes place underground, where potential energy associated with the elevation difference is readily available to complement pumping.

Concrete is pumped at particle concentrations by weight of 90-95%. Self-compaction concretes often flow easily and are included here for comparison. The behaviour is dominated by the cementitious content and friction-reducing additives for a broad size distribution, with sands and rock particles up to about 30 mm in size. Pumping lengths are generally up to 500 m, and the pipeline inner diameters are between 0.1 to 0.15 m; 0.125 m is a common choice.

3 Objectives and scope

The objective is to investigate the system's feasibility of pumping paste-rock mixtures at solids concentrations by weight of about 85% over a limited distance for co-disposal in nearby old pit holes and depressions.

LKAB set up an initial simple test loop with a pipeline inner diameter of 0.075 m for indicative observations and measurements. In the first test, we used rock particles of up to 10 mm. We intended to use 30 mm for a second test after installing a larger pipeline diameter. Unfortunately, the second test could not be carried out in time. We were then offered the opportunity to test a laboratory scale device, the sliding pipe rheometer or 'Sliper', developed to simulate concrete pipeline pumping frictional resistance in a 0.126 m diameter pipeline. The device was tested with the 0.075 m pipe loop testing for the 10 mm mixtures. The two measurement techniques were then evaluated and compared for the two different pipeline diameters. After that, Sliper tests were only carried out for the 30 mm diameter pipe.

4 Set-up of tests

Crushed rock was taken from the sorting plant for dry processing. It was then mixed with tailings from the wet magnetic separation process, where iron ore concentrate is taken out for pellets production. Initially, a 10 mm rock particle mixture was used for the loop pumping test. Then, the Sliper device was used for both crushed products.

4.1 Pipeline loop

The pipeline testing occurred at LKAB Svappavaara operations, where thickened tailings are pumped a short distance to the disposal area. The paste thickener delivers a solid concentration by weight of 65-70%, sufficient for final deposition with no segregation at an average slope of 2.5- 3% (Wennberg et al. 2020). The simple test loop with a pipeline inner diameter of 0.075 m was set up outside for indicative observations and measurements based on a standard Putzmeister concrete pump, as illustrated in Figure 1.

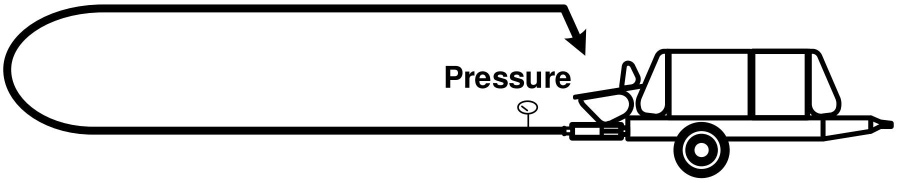

Figure 1 Loop test set up with a 38 m long steel pipeline with smooth rubber bends

Flow rates were based on matching barrel/watch measurements with parallel evaluations for pump stroke volume delivery. The pressure gradient was calculated by dividing the pump discharge pressure by the total length, including a smooth 180° return portion and nominal velocity head at the discharge into the pump sump. Samples were taken for mixture density and particle size distribution measurements.

4.2 The Sliper device

Kasten (2010), at Putzmeister Engineering, developed the laboratory scale device for estimating resistance to concrete pipeline flow. The apparatus, now produced by Schleibinger, is marketed as the sliding pipe rheometer, Sliper. The working principle is to measure the inside resistance to sliding within a 0.126 m diameter Plexiglas pipe (1 in Figure 2) against a corresponding cylindric surface area of a still-standing concrete mixture with a length of 0.45 m, as illustrated in Figure 2.

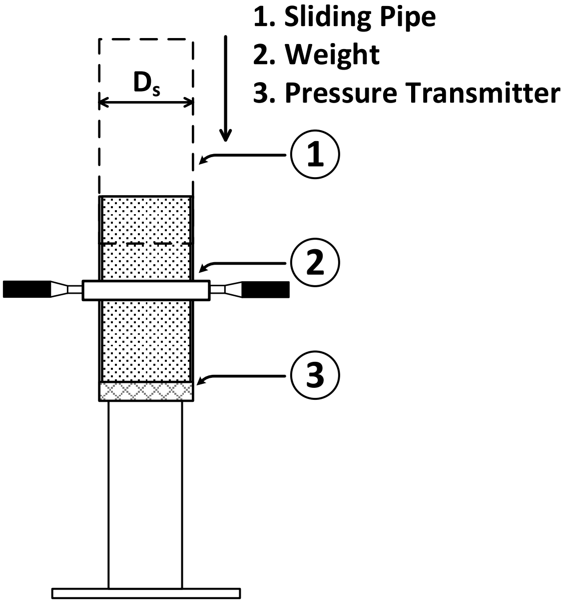

Figure 2 Illustration of the sliding pipe rheometer, Sliper, based on the brochure from Schleibinger GmbH

When the Plexiglas pipe with diameter D_s is sliding down under the force of adopted weights (2 in Figure 2), the pressure of the still-standing mixture and time are recorded, reproducing the frictional resistance and velocity. The flexible weights on the handles modify the speed, thus representing the flow rate.

5 Test evaluations

All particle size distribution results before and after the loop and Sliper tests are shown in Figures 3 and 4. R:P denotes the mixture rock-to-paste (R:P) dry mass ratio. The 10 mm pumping test values in Figure 3 are based on a normal thickened tailings solids concentration by weight of 68%. During the 10 and 30 mm Sliper tests, the value was down to 62% due to a processing plant disturbance. Therefore, the R:P are not identical for the pipeline and Sliper tests. When we compared the 10 mm data for pumping, we adjusted the Sliper R:P values.

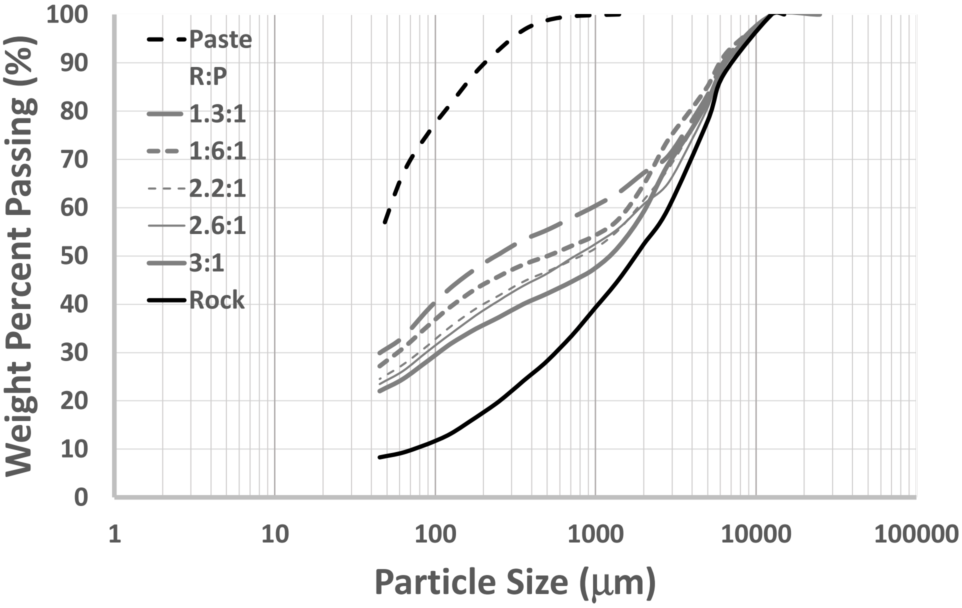

Figure 3 Particle size distributions for the crushed rock-tailings mixtures used in the 10mm tests

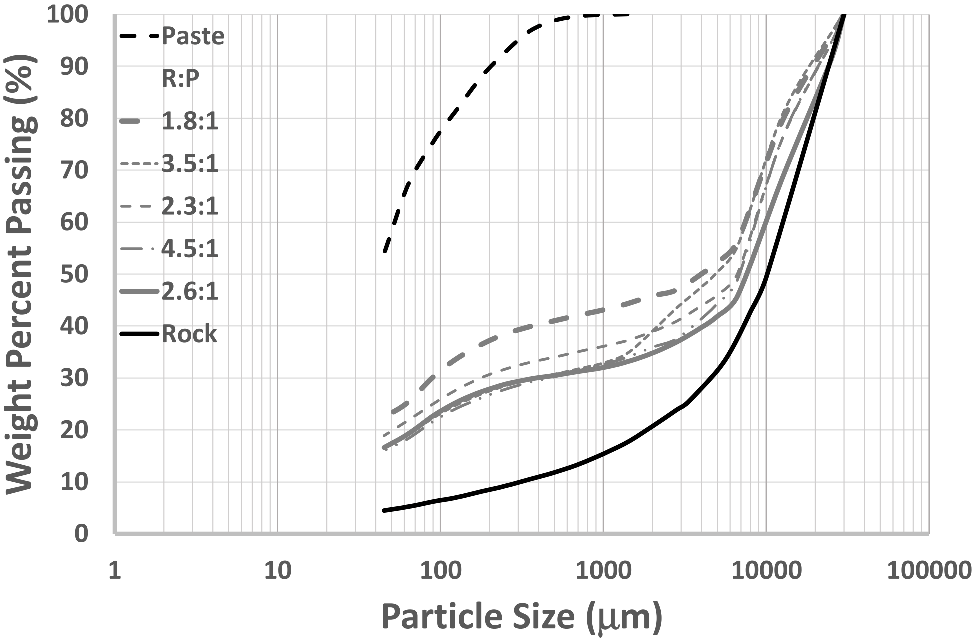

Figure 4 Particle size distributions for the crushed rock-tailings mixtures used in the 30mm tests

5.1 Loop test

Figure 5 outlines our evaluated test results in terms of the pressure gradient (kPa/m) versus flow rate (m^3/h) and velocity (m/s), together with the solids concentrations by weight C_w and the R:P dry mass ratio. Flow rates were adjusted due to the slight reduction in pump delivery cylinder stroke volume. For gradients of interest, measured velocities were rounded off to 0.5 and 0.9 m/s, with 0.7 m/s used in upcoming comparisons.

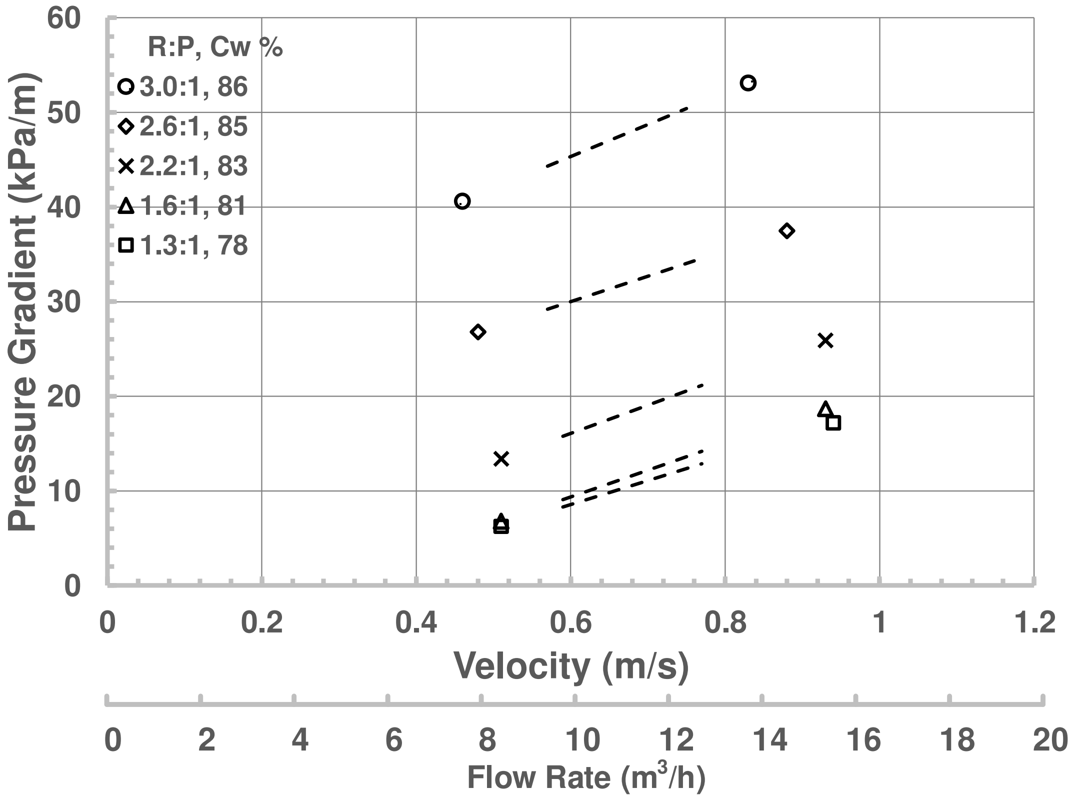

Figure 5 Measured pipeline pressure gradients versus flow rate and velocity. Pipeline diameter 0.075 m

The dependence of the pressure gradient on the flow rate or velocity in Figure 5 is only just perceptible; at lower velocities, a yield-like behaviour may occur or may result in a stratified flow with tendencies of a sliding bed at the lowest solids concentrations. Figure 6 outlines the evaluated test results in terms of pressure gradient versus the solids concentrations by weight C_w and volume C_v.

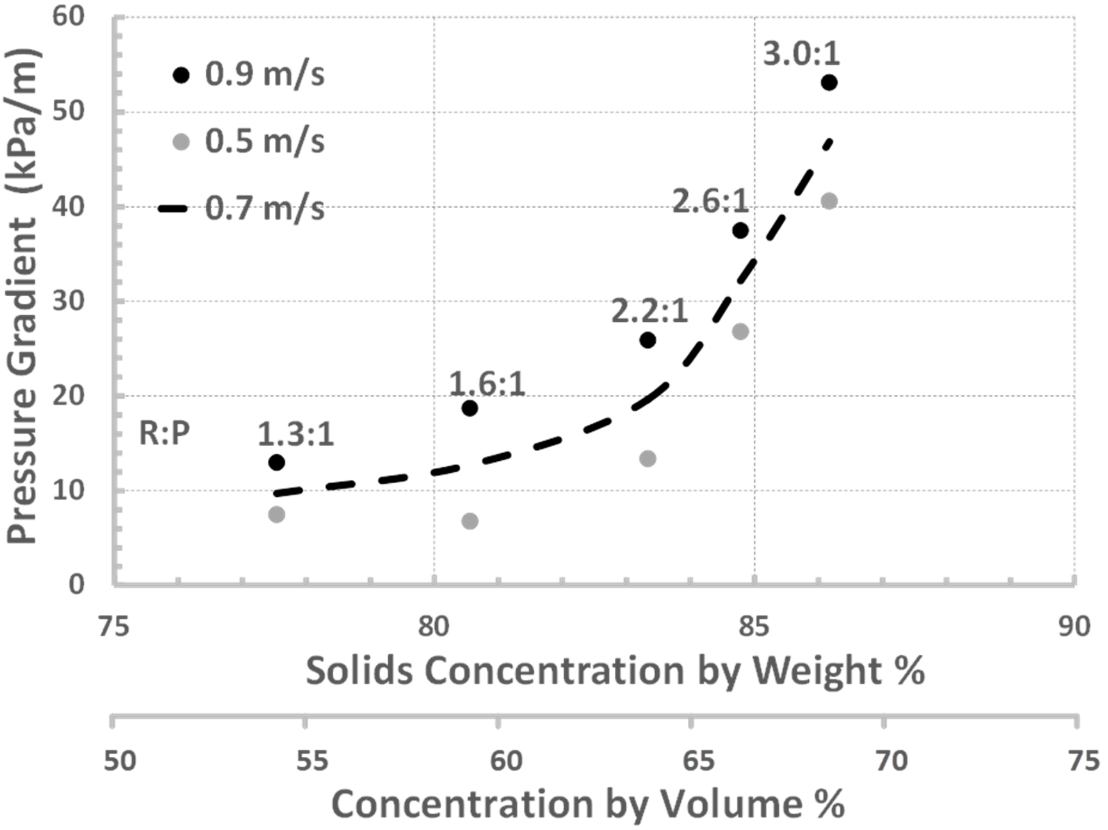

Figure 6 Measured pressure gradients versus the solids concentration by mass and volume. Pipeline diameter 0.075m

It follows from Figure 6 that the pressure requirement or pipeline friction losses increase up to concentrations by weight of about 84% (C_v= 65%) for a required gradient of about 25 kPa/m at 0.7 m/s. The increase in gradient from 25 to 45 kPa from 84 to 86% shows a dramatic dependence on the total solids content and the R:P. From how the tests were conducted, it is impossible to fully distinguish the increase in pressure requirement with solids concentration from the effect of increasing portions of rock 1.3 at C_w 78% to nearly 3 at 86%. In Figure 6, a concentration limit of about 84% was reached, after which the pressure requirement increased exponentially.

5.2 Sliper tests

Kaplan et al. (2005) formulated a Bingham rheological model for concrete pipeline flow in terms of combined gliding and shearing parameters. Kasten (2010) presented an evaluation procedure, including software for pipeline pumping pressure requirements for given concrete flow rates, together with full-scale pipe loop confirmations. The evaluation procedure for a given solids concentration starts with fitting measured pressures and flow rates, with a measuring length of 0.45 m, in a straight line corresponding to a value A on the vertical axis, as illustrated in Figure 7. B_s is the slope of the line h·Pa/m^3, with the flow rate Q_s in m^3/h on the horizontal axis (Kasten 2010).

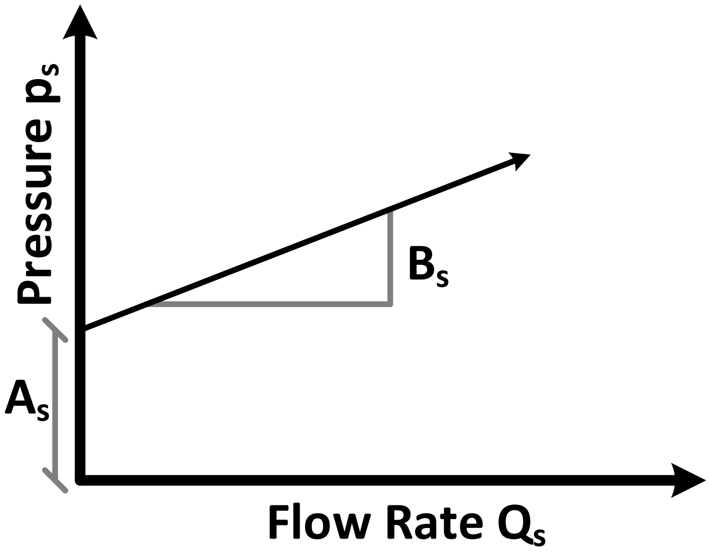

Figure 7 Sliper evaluation input parameters, after Kasten (2010)

Further comparisons and confirmations by Mechtcherine et al. (2014) and Secrieru et al. (2017), for example, verified the feasibility of Sliper testing for a large variety of concrete products and different pipeline diameters. Their parameterisations, based on A_s (Pa) and B_s ($h \cdot Pa/m^3$) for yield stress and near pipeline wall viscous transfers, respectively, are adjusted here to the pressure p_s related to the actual Sliper test length L_s=0.45 m

$$p_s=(1/L_S)\cdot(A_s+B_s\cdot Q_s)= (1/0.45)\cdot(A_s+B_s\cdot Q_s) = (A_s'+B_s'\cdot Q_s) \quad (1)$$

where A_s'= 2.22·A_s and B_s'=2.22·B_s. Following the parameterisations given by the references above, a pipeline size scaling parameter can be introduced by D_s/D in Eq.1 for other pipeline diameters D and flow rates Q corresponding to a full-size application for a frictional resistance pressure requirement p in a pipeline system with total length L.

$$p= L\cdot(D_s/D)\cdot(A_s'+(D_s/D)^{2}\cdot B_s'\cdot Q) \quad (2)$$

5.2.1 Results

Sliper test preliminary results following the Figure 7 procedure in terms of Eq.1 are shown in Figure 8. They represent the different mixtures used in the pipeline loop test for the 10 mm product.

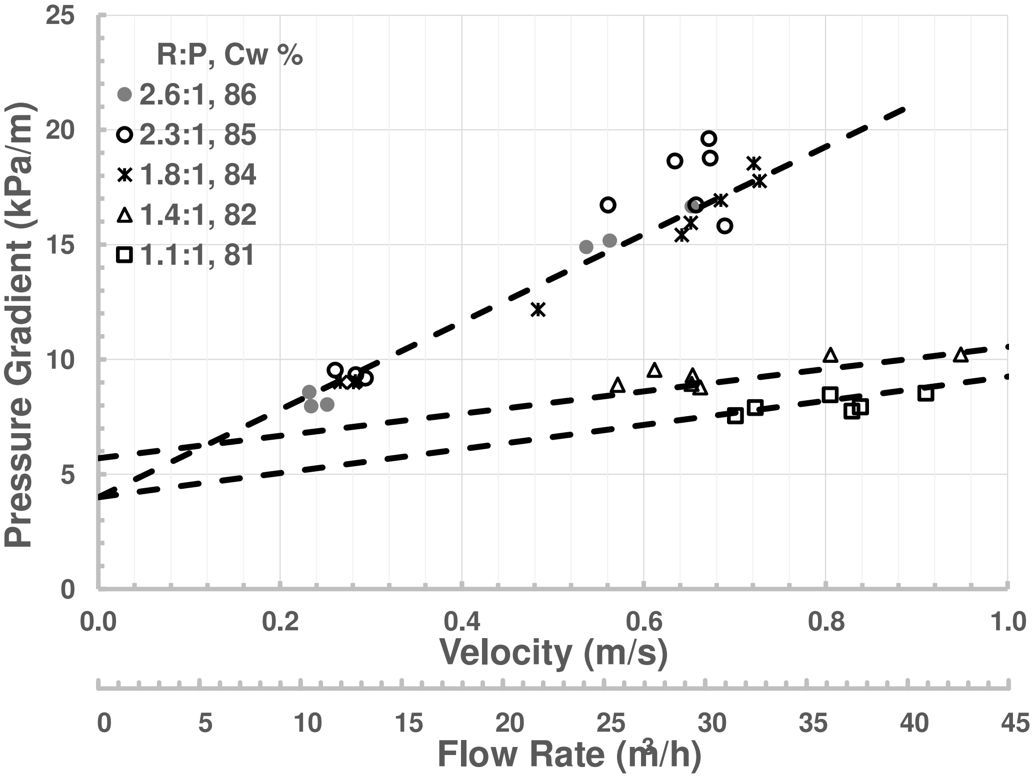

Figure 8 Comparison of pressure requirement versus flow rate for the 10 mm products evaluated from Sliper measurements and evaluations. Diameter 0.126 m

Results from concentrations by weight from 81 to 84% and R:P from 1.1:1 to 2.6:1 are represented by three lines in Figure 8. It follows that upper-line data are gathered in a group and do not follow the substantial increase seen in Figures 5 and 6 for 84 to 86%. The Sliper evaluation procedure is described in detail for the lowest line in Figure 8, with A' evaluated to 4 kPa with B'= 0.117. A velocity of 0.7 m/s in the 0.126 m diameter Sliper pipeline corresponds to a flow rate Q_s of 31.4 m^3/h. With this flow rate, the lowest line crossing in Figure 8 corresponds to a pressure gradient of 7.7 kPa/m, as seen on the vertical axis. Scaling to the smaller pipeline diameter D= 0.075 m in the loop test at a velocity of 0.7 m/s corresponds to a flow rate of 11.1 m^3/h. Insertion of these values in Eq. 2 means $(0.126/0.075)\cdot(4+(0.126/0.075)^{2}\cdot 0.117\cdot 11.1)$= 13 kPa/m in the 0.075 m diameter pipeline.

This procedure was repeated for the central and upper lines with (A'=5.7,B'=0.108) and (A'=4,B'=0.425), respectively, the latter representing R:P= 2.6:1 and 86%. The crossings for 31.4 m^3/h correspond to 9.1 and 17.3 kPa/m, respectively. Repeated adoption of Eq.2 results in scaled pressure requirements of 15.3 and 29.2 kPa/m for the central and upper lines, respectively. These values and the earlier 13 kPa/m are now inserted for comparison with the pipeline loop results in Figure 5, outlined in Figure 9. We could not obtain identical R:P values with the pipeline data, considering the processing plant disturbance during the Sliper test. Furthermore, we could not test the pipeline result for the lowest concentration (78%) with Sliper due to some leakage.

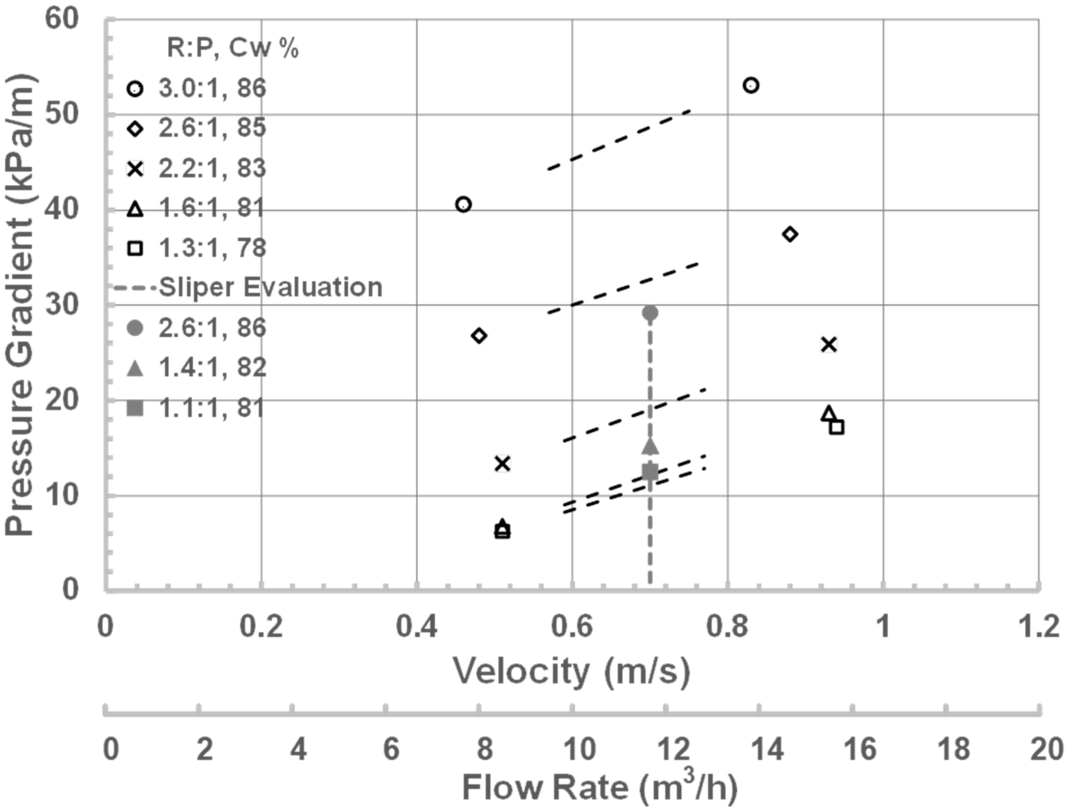

Figure 9 **Comparison at 0.7 m/s of scaled Sliper results from Figure 8 with measured pipeline pressure gradients versus flow rate and velocity (Figure 5). Pipeline diameter 0.075 m**

In Figure 9, a comparison at adjacent pipeline concentrations (85 and 86%) could be made at an identical R:P of 2.6:1, showing a scaled Sliper result of about 29 kPa/m, which was at an upper practical limit both for the pipeline and Sliper tests (Figures 6 and 8). The scaled Sliper results of about 15 and 13 kPa/m in Figure 9 were coupled to pipeline concentrations of 83 and 81%, respectively, with variations in R:P of 2.2:1 and 1.6:1. The corresponding Sliper test evaluations at 82 and 81% were for lower content of coarse solids, 1.4:1 and 1.1:1, respectively.

It follows from the comparisons in Figure 9 that the Sliper testing method (diameter 0.126 m) and evaluation procedure for scaling to an arbitrary pipeline diameter, well-represented measured gradients at 85% and R:P of 2.6:1 at 0.7 m/s from the pipeline loop test with diameter 0.075 m. The 30 mm Sliper results are shown in Figure 10.

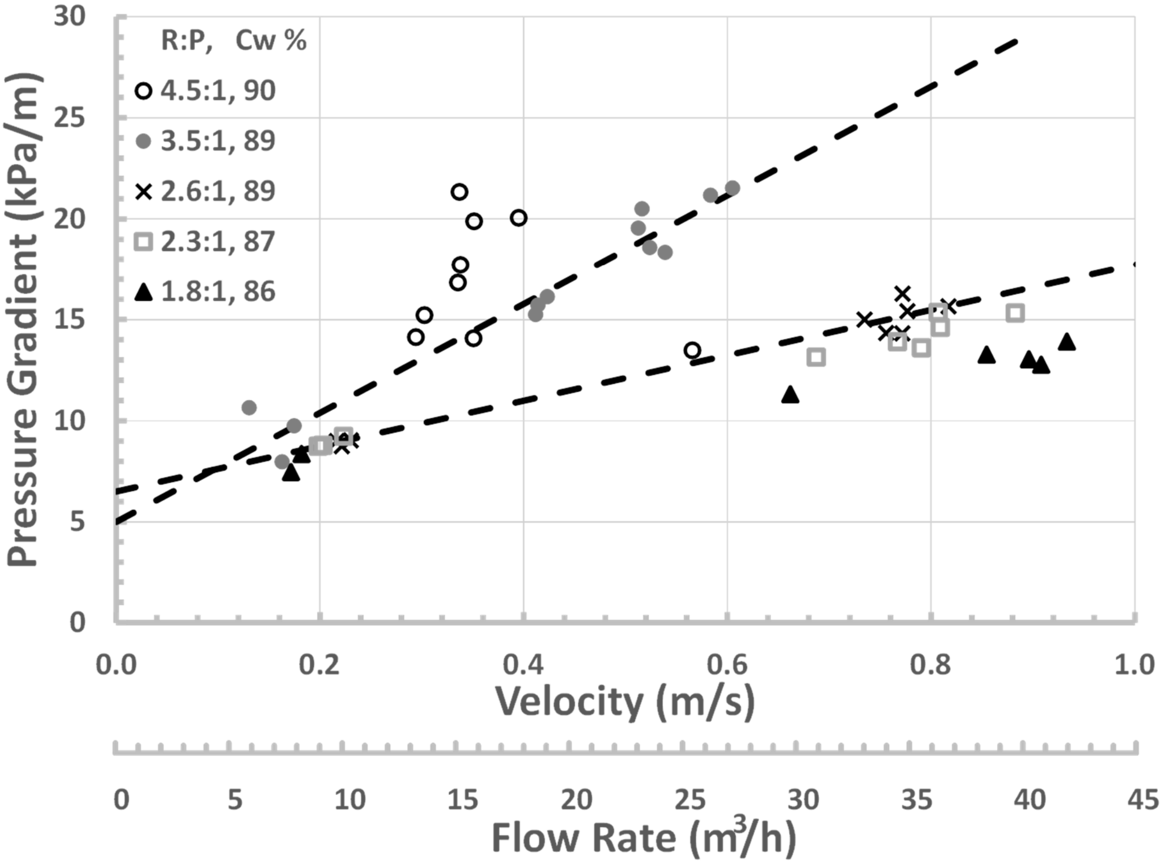

Figure 10 **Comparison of pressure requirement against flow rate for the 30 mm product evaluated from Sliper measurements. Diameter 0.126 m**

With the highest concentration approaching C_w 90% and an R:P value of 4.5:1, the data in Figure 10 were too spread out and, thus, were disregarded. We also were unable to pump the mixture. Otherwise, a similar pattern as in Figure 8 can be seen, albeit with an increase in C_w of about 5% compared to the 10mm product in the 5-25 kPa/m gradient span. The lines in Figure 10 represent a constant C_w of about 89% and a significant difference for R:P from 2.6:1 to 3.5:1. The pressure requirements at 31.4 m^3/h (0.7 m/s) were estimated to be about 14 and 24 kPa/m, respectively. Detailed evaluations at these high concentrations are, of course, uncertain. Assume conceptually that an average value rounded off to 20 kPa/m is directly adopted to a 0.15 m pipeline bearing in mind that predominantly coarse particles tend to reduce the friction loss dependence on pipeline diameter. Furthermore, assuming we are pumping at 0.7 m/s with C_w limited to 84%, the corresponding capacity is about 85 dry tonnes per h or 0.7 Mtonnes annually.

6 Discussion and outlook

Particles with sizes larger than one-third of the pipeline diameter may jam it and should be avoided. However, with the crushed product up to 30 mm, the length of individual particles may exceed the measure, and a pipeline diameter of about 0.15 m is required. Therefore, pipeline loop tests with diameters 0.15 or 0.20 m are the next planned step. In this case, mixing with a concrete mixer truck is considered, following testing conducted by Wickland & Wilson (2005). However, an application with a 0.15 m diameter pipeline for 85 dry tonnes per h requires large-scale concrete-related mixing and feeding installations.

Long-term plans for extending the Kiruna mine include extracting industrial minerals and iron ore at a depth of 1000-1500 m. Conceptually considered alternatives so far also include cut and fill mining. With this, tailings are also to be used for backfilling. However, tailings for backfilling may not be needed continuously, so future handling of residual products must be considered with flexibility.

The results here form the basis for a planned larger-diameter test. Long-term flexibility factors related to tailings availability, clarification of suitable routings, and allowed water contents may require the larger diameter loop test to include a once-through pipeline pumping demonstration, including feeding arrangements. Variations in the rock-to-tailings ratio related to tailings availability and disturbances in the feeding can be investigated. With lower solids concentration allowed, the work should include system feasibility considerations for filling depressions assuming a span starting from C_w of 75-80%. This would mean a more stratified flow where the coarsest particles form a sliding bed.

7 Conclusions

The pipeline pumping of paste-rock mixtures was indicatively tested for solids concentrations by weight of 80 up to 90% to limit segregation and leakage during deposition in nearby old pit holes. The test was carried out at a paste thickener with direct access to fresh paste mixed with crushed rock from the processing in a concrete mixer. The 38 m long loop with a pipeline inner diameter of 0.075 m was equipped with a concrete type of pump.

- Test results with crushed rock particles of up to 10 mm with a rock-to-tailings mass ratio R:P of 2.2:1 showed a pressure requirement of about 25 kPa/m at 0.7 m/s for a total solids content of 84% by weight corresponding to 65% by volume and water content 19% (Solids density 3000 kg/m^3). With further increases from 84 to 87% and R:P ratios of 2.2:1 to 3.1:1, the gradients increased significantly from 25 to 45 kPa/m at 0.7 m/s. However, given how the tests were carried out, we could not fully distinguish the dependence on Cw and R:P.
- The concrete industry Sliper rheometer device, with a diameter of 0.126 m developed for concrete pipeline pumpability, complemented the loop tests. The 10 mm product apparatus pressure requirements agreed relatively well with loop diameter data from 85 to 86% and R:P values of up to 2.6:1, confirming a laminar flow inverse diameter dependence for pressure requirement.
- The 30 mm product tests were only with the Sliper device. An increase in R:P from 2.6:1 to 3.5:1 for a constant C_w of 89% meant nearly doubling the pressure requirement from 14 to 24 kPa/m at 0.7 m/s. A pipeline diameter larger than 0.126 m may be required for the 30 mm product due to the risk of a jammed pipeline section. With a 0.15 m diameter pipeline, a pumping requirement of about 20 kPa/m was conceptually evaluated from the Sliper data.
- The results here form the basis for a planned larger-diameter test. Long-term flexibility factors related to tailings availability, clarification of suitable routings, and allowed water contents may require the larger diameter loop test to include a once-through pipeline pumping demonstration, including feeding arrangements.

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