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Crushed rock-thickened tailings pumping at ultra-high concentrations

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Abstract

At the LKAB underground mines in northern Sweden, crushing a portion of the rock to less than 30 mm is already part of the surface processing and an interesting alternative for co-disposal. Long-term plans may also include use of backfilling which requires flexibility with respect to tailings availability.

The overall objective here is to investigate the system's feasibility of pumping paste-rock mixtures with particle sizes of up to about 30 mm at ultra-high concentrations. Initially, it is a limited distance for co-disposal in nearby old pit holes and depressions. In a wider perspective, it is a possible site-specific complement or alternative to filtration in systems for tailings storage or cut-and-fill mining with paste aggregate.

Indicative tests were carried out in a 94 m long loop with a 0.15 m diameter pipeline for mass rock to paste ratios (R:P) of 1.2:1 up to 4.9:1 at solids concentrations by weight (C_w) of up to 89% corresponding to a water content of 12%. The test was carried out at a paste thickener with direct access to fresh paste and mixed with crushed rock from the processing. A concrete mixer truck was used for the blending before pumping. A laboratory-scale concrete industry device was also used, the sliding pipe rheometer, 'Sliper', developed to simulate concrete pipeline pumping frictional resistance in a 0.126 m diameter pipeline with length 0.5 m adopted vertically. The result agreed well with the pipeline pressure gradients if extrapolated to some larger flow rates. An inverse pipeline diameter dependence on friction losses was confirmed.

The pressure requirement loop results were within 10 to 23 kPa/m for velocities from 0.7 to 1.4 m/s for solids concentrations by weight of 87% to 89% with R:P from 3.8:1 to 4.9:1. The corresponding concentrations by volume were 70 and 74% with water contents of about 15 and 12%, respectively. Solids density 2,900 kg/m^3. At C_w values from 77 to 85% the resulting pressure gradients were from about 3 to 7 kPa/m with water contents exceeding 18%. The R:P values 3.8:1 and 4.9:1 mean that the coarse particles take up 75 to 80% of the volume combining coarse particle related frictional resistance with a near wall viscous contribution through silica flour slurry.

Dependent on the availability of paste and function of the mixing and feeding arrangements a disturbance was simulated for pumping with only coarse particles for fully stratified flow friction loss conditions.

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

1 Introduction

This work is a continuation of an investigation presented at the Paste 2023 conference, Wennberg et al. (2023). LKAB operates three mines in northern Sweden. In the Kiruna underground mine, approximately 3.5 Mt of tailings and about 12 Mt of waste rock are generated annually. Crushing a portion of the rock to less than 30 mm is part of the processing in the sorting plant. It is then deposited in stockpiles. Long-term plans to extend the mine include extracting industrial minerals and iron ore at depth of about 1,500 m. Considered alternatives so far also include cut-and-fill mining. With this, the tailings will also be used for backfilling. Therefore, pumping of paste-rock mixtures at very high solids concentrations are examined as a part of LKAB's long-term development work related to future system integration and flexibility.

2 Characterisation and earlier work

Wilson et al. (2006) introduced the term paste-rock. 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/binary mixture because the smaller particles filled the larger particles' void space.

Wennberg et al. (2023) presented pressure requirement results from tests for a 38 m long loop with a pipeline inner diameter of 0.075 m and equipped with a concrete type of pump. The tests were carried out at a paste thickener with direct access to fresh paste mixed with crushed rock in a concrete mixer. Loop test results with crushed rock particles of up to 10 mm with a mass rock to paste ratio R:P of 2.2:1 showed a pressure requirement of about 25 kPa/m for a total solids content of 84% by weight corresponding to 65% by volume and water content of 19% (solids density 3,000 kg/m^3).

The loop test was complemented with a laboratory-scale concrete industry device, the sliding pipe rheometer, Sliper, developed to simulate concrete pipeline frictional resistance in a 0.126 m diameter pipeline with measurement length 0.5 m adopted vertically. The working principle is based on a Plexiglas pipe with diameter 0.126 m sliding vertically down under the force of adopted weights. The pressure on the still-standing mixture and time are recorded, reproducing the frictional resistance and velocity.

The 10 mm product Sliper apparatus pressure requirements agreed relatively well with loop diameter data at concentrations by weight of 85–86% and R:P values of up to 2.6:1, seemingly confirming a laminar flow inverse diameter dependence for pressure requirement. Sliper tests were also carried out for the 30 mm product used in this study. Sliper results at the highest concentration of 89% were uncertain with appearance of blockages.

Concrete is pumped at solids concentration by weight in the range of 90–93% corresponding to 77–80% by volume (C_v). The behaviour is dominated by the cementitious content and friction-reducing additives for broad size distributions, 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.

Self-compacting concretes are often considered to flow easily at concentrations of over 90% and containing about 20% cement, additives, and a water content of 6–8%. Even so, the flow is not considered to be completely homogeneous. A cementitious lubrication layer may develop in the near pipeline wall region as reviewed by for example Feys et al. (2022). The inhomogeneity means that the idealised assumptions of the ordinary rheological Bingham fluid model for friction losses are not fulfilled in the wall region.

Kaplan et al. (2005) therefore formulated a Bingham rheological model for concrete pipeline flow in terms of combined gliding and shearing parameters. Kasten (2010) developed the Sliper apparatus and used the Bingham approach above for the evaluation procedure, including software for pipeline pumping pressure requirements for given concrete flow rates. 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.

Pullum et al. (1996) 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. Low operating velocities of 0.2–0.9 m/s are characteristic of UHC. The Pullum et al. (1996) tests showed an inverse pipeline diameter dependence on friction losses in the 0.15-0.3 m diameter range. In a review, Pullum (2007) considered high C_w values of 85–88% (C_v=65–75%) and expressed that UHC is where packing can be so close that particles may not reorganise in the pipe, and inter-particle motion is limited. He pointed out the strong function of the underlaying carrier fluid rheology and that the mixture in motion is essentially a stratified flow despite the high concentration.

The UHC concept here for crushed rock-thickened tailings pumping at C_w values of 85–89% homogeneity-like behaviour cannot always be expected when pumping the mixture in practice. If the solids concentration for a UHC mixture shrinks, then the flow stratifies with the coarsest particles start sliding along the bottom. In a situation with only coarse particles, the flow becomes fully stratified with a sliding bed. This is another mode of pipeline transportation at moderate solids concentrations with turbulent flow requiring a minimum velocity to avoid particle deposition on the pipeline invert.

3 Objectives and scope

The overall objective is to investigate the system's feasibility of pumping paste-rock mixtures with particle sizes of up to about 30 mm at ultra-high concentrations. Initially, it is a limited distance for co-disposal in nearby old pit holes and depressions. In a wider perspective, it is a possible site-specific complement or alternative to filtration in systems for tailings storage or for cut-and-fill mining with paste aggregate. The aim is to indicatively test how the pressure requirement increases with increasing R:P ratios and solids concentrations by weight from about 75% to nearly 90% in a 0.15 m diameter pipeline loop. A well-known relationship is adopted to simulate only coarse particles pumping with moderate solids content. The Sliper device is used at all tests.

4 Set-up of tests

The test was carried out at a paste thickener with direct access to fresh paste and mixed with crushed rock from the processing. A concrete mixer truck was used for the blending before the loop pumping test (Figure 1).

Figure 1 Filling of concrete mixier truck

The pipeline testing took place 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 0.15 m was setup outside for indicative observations and measurements based on a standard Putzmeister concrete pump, as illustrated in Figure 2.

Figure 2 Loop test set up with a 94 m long steel pipeline with smooth bends

The Sliper devise consists of a 1.5 m long vertical and a 1 m long cylinder that is placed within the pipe. A pipe is sliding down under the force of weight along the still-standing mixture. Pressure and time are registered. With this, frictional resistance and flow rate are reproduced in the 0.126 m diameter pipeline. To induce varying velocities or flow rates various weights are applied.

5 Test evaluations

All particle size distribution results before and after the loop and Sliper tests are shown in Figure 3. R:P denotes the mixture rock to paste dry mass ratio.

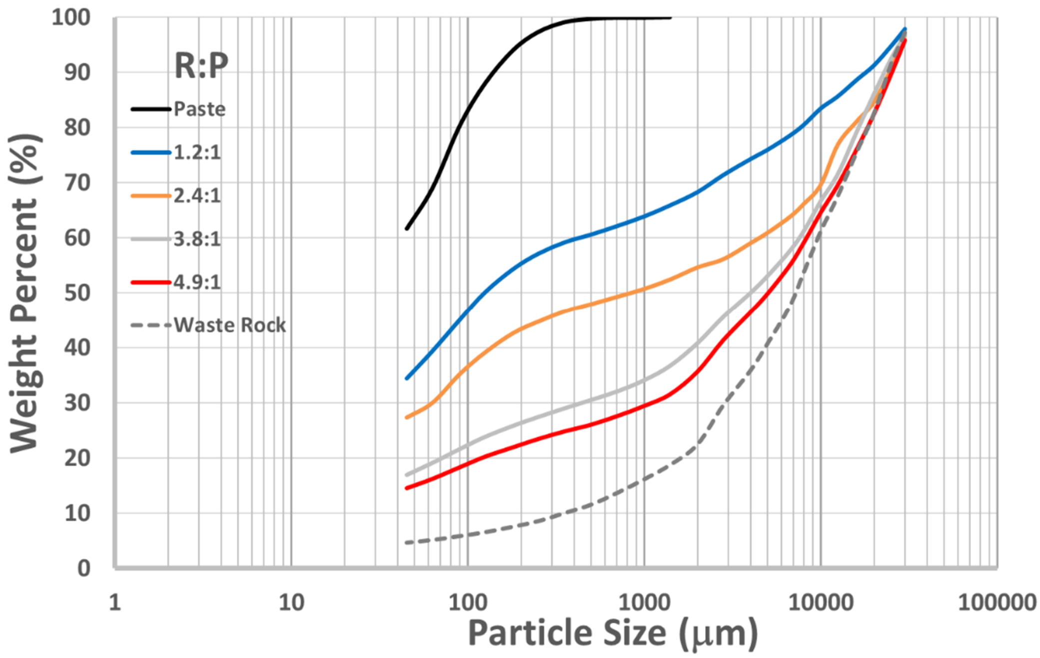

Figure 3 Particle size distributions for the crushed rock-tailings mixtures used in the 30 mm tests

Numerous failures occurred initially with complete clogged pipelines. In the last 25% of the total length of about 94 m, pipeline sections had to be dismantled and replaced with spared pipelines. It was very time consuming to break up the blockages inside the dismantled pipelines (Figure 4).

Figure 4 Blockage in pipelines

A procedure from concrete pumping was then adopted. A portion of the paste slurry was first delivered and introduced in the loop as a paste buffer before the rock-paste mixture was introduced. In this way, the paste prevents the coarser particles from separating from the mixture. The pump cyclic valve opening and closing push the mixture forward where the coarsest particles keep moving relative to the paste and smaller particles. In this way, blockages develop by mechanical 'dry' friction between coarse particles and the pipeline wall.

The pumping tests were based on a normal thickened tailings solids concentration by weight of 68%. Solids density 2,900 kg/m^3. However, the value was down to 60–63% because of a processing plant disturbance. Flow rates were adjusted due to the slight reduction in pump delivery cylinder stroke volume. Flow rates were based on evaluations for pump stroke volume delivery. The pressure gradient was calculated by dividing the pump discharge pressure by the total length, including bends. Bends losses corresponding to about 4 m equivalent length following concrete experiences. In addition, the velocity head at the discharge into the pump sump was considered. Thus, the about 94 m loop had an equivalent length of 98 m which was used to evaluate the friction loss pressure gradient. Samples were taken for mixture density and particle size distribution measurements.

The evaluated test results in terms of the pressure gradient (kPa/m) versus flow rate (m^3/h) and velocity (m/s) are given in Figure 5, together with the solids concentrations by weight C_w and the R:P dry mass ratio.

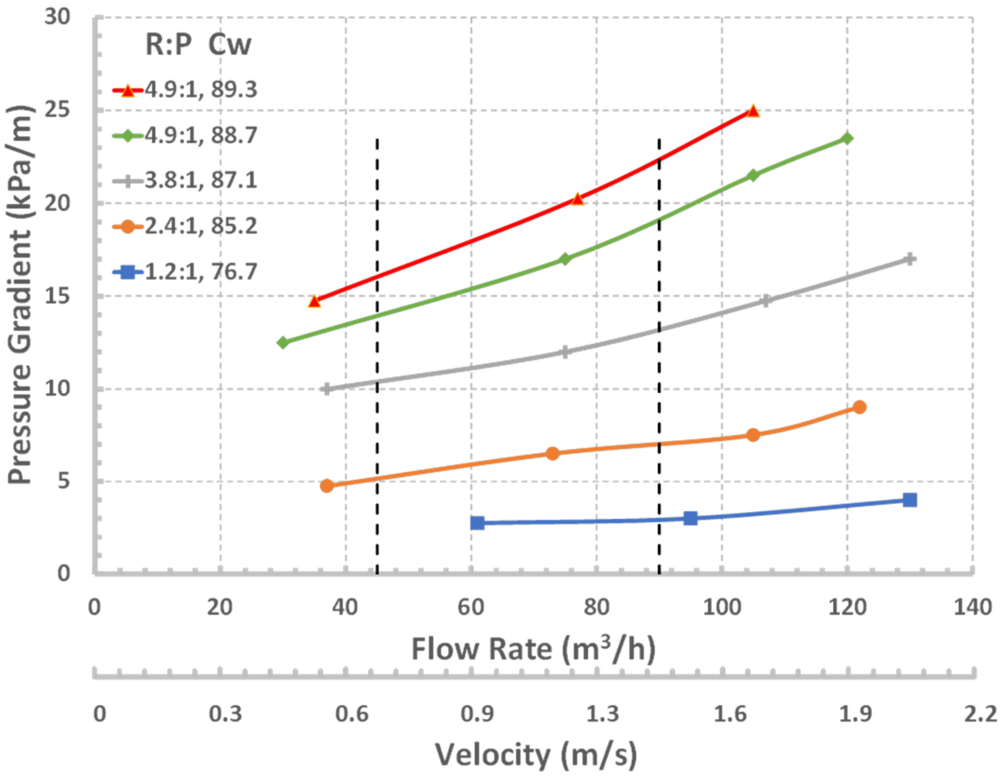

Figure 5 Pressure gradient versus flow rate and velocity. The dotted lines represent velocities of 0.7 and 1.4 m/s

The results in Figure 5 are listed in detail in Table 1.

Table 1 Summary of measured pressure gradients in kPa/m and the corresponding concentrations and R:P ratios at 0.7 and 1.4 m/s

C_w %	76.2	85.2	87.1	88.7	89.3
R:P	1.2:1	2.4:1	3.8:1	4.9:1	4.9:1
kPa/m-0.7 m/s	2.7	5.0	10.4	14.4	16.5
kPa/m-1.4 m/s	3.0	7.2	14.0	20.2	23.4

6 Discussion and outlook

Figure 6 summarises the evaluated test results in terms of pressure gradient versus C_w and C_v. It is impossible to fully distinguish the increase in pressure requirement with C_w from the effect of increasing values of R:P. The increase in pressure requirement is a combination of the effect of R:P and the increase at already very high concentrations.

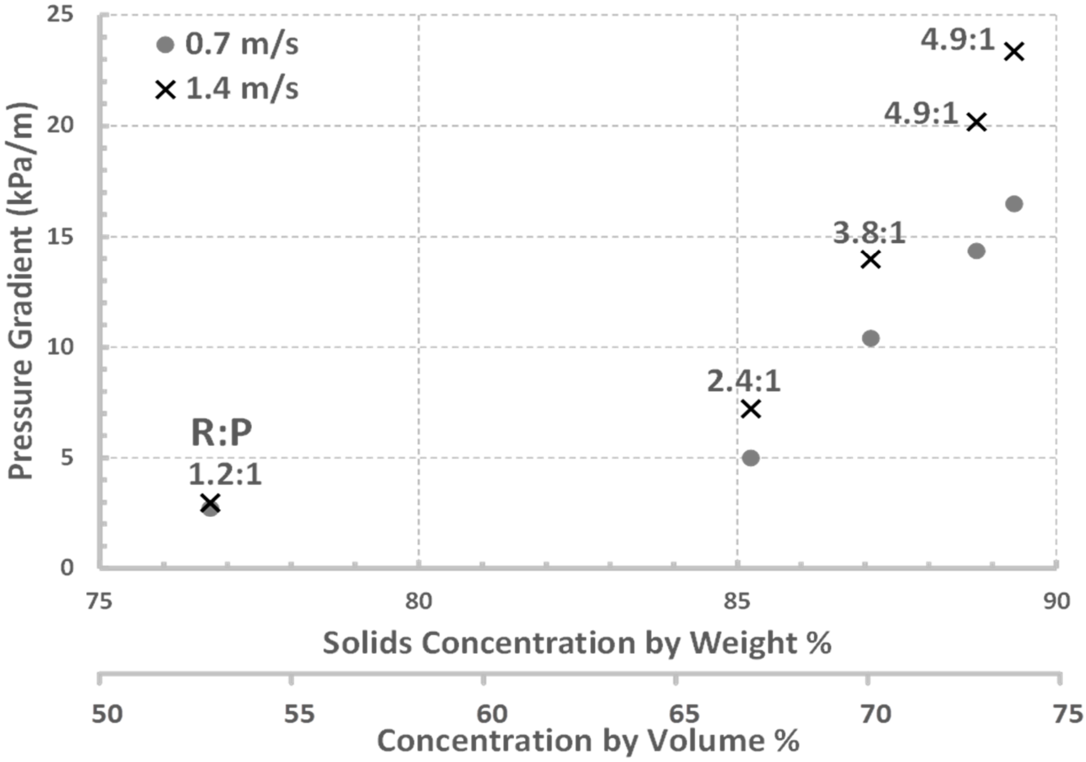

Figure 6 Evaluated pumping pressure gradients versus the solids concentration by weight and volume, pipeline diameter 0.150 m

The results for solids concentrations by weight of 87% to 89% with R:P from 3.8:1 to 4.9:1 were within 10 to 23 kPa/m for velocities from 0.7 to 1.4 m/s. The corresponding concentrations by volume were 70 and 74% with water contents of about 15 and 12%, respectively. At C_w values from 77 to 85% the resulting pressure gradients were from about 3 to 7 kPa/m with water contents exceeding 18%. In backfilling, binders and friction-reducing additives are used. Here a flocculent is only added to the thickening process preceding the paste pumping. The R:P values 3.8:1 and 4.9:1 mean that the coarse particles take up 75 to 80% of the volume combining coarse particle related frictional resistance with a near wall viscous contribution through silica flour slurry.

6.1 Sliper

It follows from the description that the Sliper testing procedure is well established for concrete products. Figure 7 outlines the pumping results from Figure 5 including Sliper results in terms of pressure gradient versus flow rate and velocity (dotted lines). The Sliper measurements were carried out with mixtures directly taken out from the loop tests.

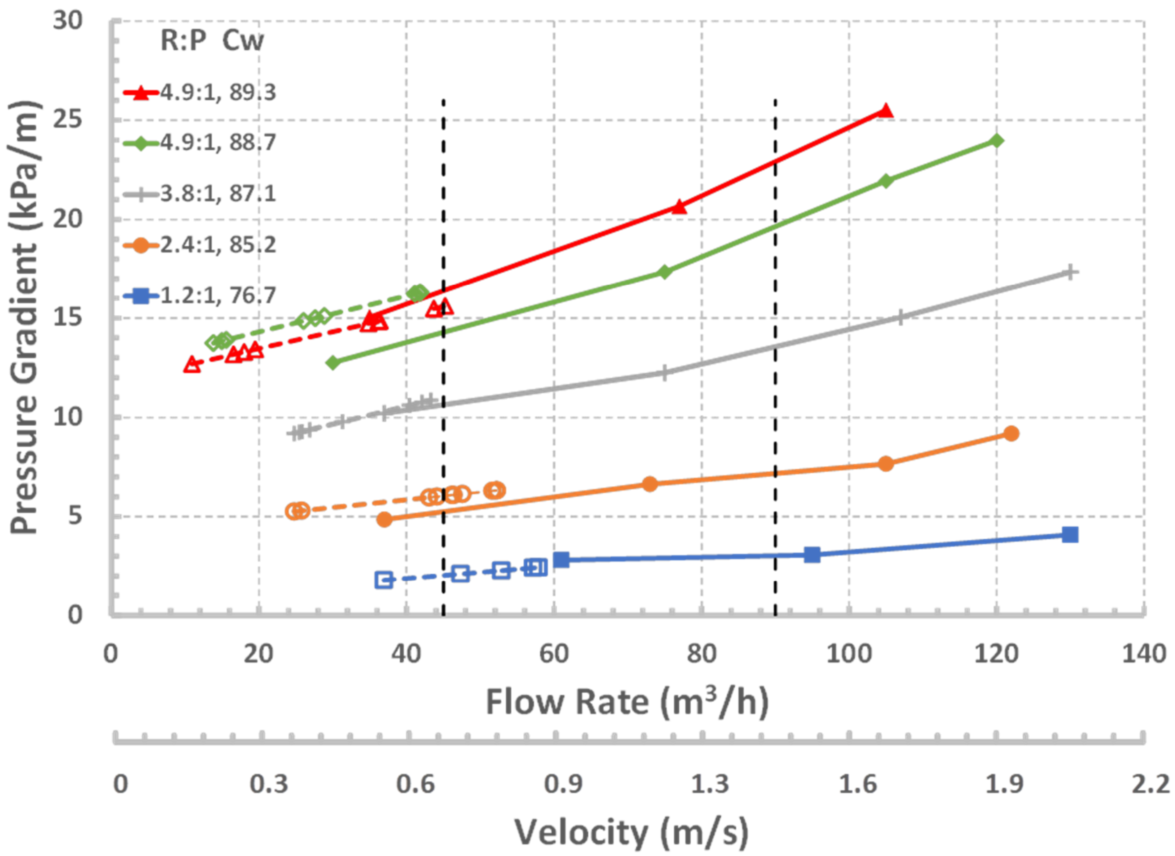

Figure 7 **Pressure gradient versus flow rate and velocity including comparisons with Sliper results at lower flow rates (dotted lines). Vertical dotted lines represent velocities of 0.7 and 1.4 m/s**

It follows from Figure 7 how the Sliper results relatively well represents the pipeline pressure gradients if extrapolated to some larger flow rates. Measured values covered only limited part of the tested pump domain. With additional weights during the measurements, a larger domain would have been covered. We were not able to relate any disorder or confusion of the 88.7% C_w result overestimating the pipeline data.

The feasibility of the Sliper results is interesting because the apparatus is here applied for a mixture with a fine particle content of silica flour while the method developed and validated for concrete containing about 20% of cementitious material and various additives. An inverse pipeline diameter dependence on friction losses was confirmed also for the R:P values 3.8:1 and 4.9:1 which means that the coarse particles take up 75 to 80% of the volume.

6.2 Paste feeding disturbance simulation

Depending on the availability of paste and the function of the mixing and feeding arrangements in a once-through application, coarse particles only must be considered. Coarse particle pipeline friction loss relationships are normally related to narrowly graded products from loop tests where circulation has been limited to avoid particle rounding and generation of fine particles. Coarse particle slurry pumping may mean a fully stratified flow with a sliding bed. Formulas are related to coarse products with d_{50} exceeding 1–2 mm and up to large rock of 50–100 mm and C_v values of up to about 30%. In dealing with fully stratified flows approximated to reasonable accuracy, an expression from Wilson & Addie (1995) has been generalised by Matoušek et al. (2020) for a sliding bed of crushed granite rock in a steel pipe (Equation 1).

$$\frac{i_m - i_f}{C_{vd}\left(S_s - S_f\right)} = 2\mu_s\left(\frac{V_{sm}}{V_m}\right)^{0.25} \quad (1)$$

where:

i_m = the hydraulic gradient of the mixture in m water per m pipe.

i_f = the corresponding for the carrying fluid.

S_f = the relative density (density ratio) of the carrying fluid fine particle portion for particles smaller than 0.04 mm here taken as the water value 1 due to the small portion of fine particles.

C_{vd} = the solids concentration by volume and S_s the solids density ratio here 2.9.

V_m = the pipeline velocity and μ_s=0.48 is the friction coefficient.

V_{sm} = the deposition limit velocity.

The deposition limit velocity V_{sm} is a suitable reference for very coarse stratified slurry flows. Note that the relationship is considered for only deposit free flows i.e. for velocities larger than V_{sm} and a safety factor. V_{sm} can be obtained via d_{50} and D with a diagram or the corresponding formula, see for example Visintainer et al. (2023). The normally large particles in this study represent a situation where V_{sm} decreases for increasing particle sizes. It is so because larger particles are more exposed to the main flow in the pipeline section. Calculated V_{sm} values for a variety of coarse narrowly graded particles are seen in Table 2 for a 0.15 m diameter pipeline.

Table 2 Deposition velocity V_{sm} for a span of coarse particles in a 0.15 m diameter pipeline. Narrowly graded particles with no fines. Solids density ratio 2.9. Friction coefficient, μ_s= 0.48 (Equation 1)

d_{50} mm	1	5	10	20	30
V_{sm} m/s	2.7	1.86	1.56	1.32	1.19

Note that Equation 1 does not show any direct diameter dependence because the first term i_f can be neglected for the high-pressure gradients discussed here. In addition, the effect of D through V_{sm} is small because V_{sm}/V is normally slightly less than 1 and raised with 0.25 in Equation 1, i.e. the term is close to 1.

Equation 1 for coarse particle stratified flow is now used in a simulation where it is assumed that the feeding of paste stops for the pumping at 0.9 m/s of the 87.1% mixture with a R:P of 3.8:1 (Figure 5). This ratio means that only about 20% of the solids is paste. The d_{50} for the rock is 10 mm (Figure 3) and the corresponding deposition velocity 1.56 m/s from Table 2 here rounded off with a safety factor to 1.7 m/s. The coarse particle pumping is assumed to take place at the upper value. Equation 1 has been used for about 30% by volume. Calculated values for the comparison are gathered in Table 3. The velocity 0.9 m/s for the 87.1% mixture was chosen for demonstration purposes because it matches the dry tonnage to have a difference equal to the lost paste.

Table 3 Comparison of operating conditions of a C_w = 87.1% mixture at 0.9 m/s with the corresponding case for only coarse particle slurry operating at C_w = 55.4% and 1.7 m/s. D= 0.15 m

C_w%	**C_v%**	**S_m**	**V m/s**	**m³/h**	**kPa/m**	**t/h**	**kW/m**
87.1	70	2.33	0.9	57.5	11.3	117	0.18
55.4	30	1.57	1.7	108	5.4	93	0.16

It follows from Table 3 how the velocity requirement for pumping only the coarse particle at 1.7 m/s corresponds to a pressure requirement of 5.4 kPa/m with Equation 1 applied for C_w= 55.4% (C_v=30%). It is about half of the requirement for the 87.1% operating at 11.3 kPa/m and 0.9 m/s. The pressure requirement to overcome the horizontal pipeline friction losses is about 10% lower for the situation with only coarse particles at a lower capacity, 93 t/h. Note that a permanent pumping here with the rock-paste mixture at moderate or low solids concentrations would require a velocity of about 3 m/s to avoid deposition of particles. This is related to that particles in the 0.4 to 0.8 mm size range may determine the minimum operating velocity for wide particle size distributions, Matoušek et al. (2020).

7 Conclusion

The overall objective here is to investigate the system's feasibility of pumping paste-rock mixtures with particle sizes of up to about 30 mm at ultra-high concentrations by weight of up to nearly 90%. Initially, it is a limited distance for co-disposal in nearby old pit holes and depressions. In a wider perspective it is a possible site-specific complement or alternative to filtration in systems for tailings storage or for cut-and-fill mining with paste aggregate. The indicative testing results of pipeline pumping of paste-rock mixtures are summarised as follows:

- The results for solids concentrations by weight of 87% to 89% with R:P from 3.8:1 to 4.9:1 were within 10 to 23 kPa/m for velocities from 0.7 to 1.4 m/s. The corresponding concentrations by volume were 70 and 74% with water contents of about 15 and 12%, respectively. At C_w values from 77 to 85% the resulting pressure gradients were from about 3 to 7 kPa/m with water contents exceeding 18%. In backfilling binders and friction-reducing additives are used. In the thickening process here only a flocculent is added preceding the paste pumping. The R:P values 3.8:1 and 4.9:1 mean that the coarse particles take up 75 to 80% of the volume combining coarse particle related frictional resistance with a near wall viscous contribution through silica flour slurry.
- The concrete industry Sliper rheometer device with a diameter of 0.126 m complemented the loop tests. The apparatus pressure requirements agreed well with the pipeline pressure gradients if extrapolated to some larger flow rates. An inverse pipeline diameter dependence on friction losses was confirmed bearing in mind that pumping only coarse particles is weakly dependent on the diameter.
- The dependence on the availability of paste and the function of the mixing and feeding arrangements are demonstrated in an example. Flows with only coarse particles are evaluated with a fully stratified flow friction loss relationship. The pressure requirement was slightly higher with the 87.1% mixture with a R:P of 3.8:1 at 0.9 m/s than for only the coarse particles at C_w 55.4% and 1.7 m/s.
- The results here form the basis for the planning of a once-through pipeline pumping demonstration including mixing and feeding arrangements.

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References

Feys, D, Shutter, GD, Fataei, S, Martys, NS & Mechtcherine, V 2022, 'Pumping of concretes: understanding a common placement method with lots of challenges', *Cement and Concrete Research,* vol. 154, pp. 1–17.

Kaplan, D, Larrard, F & Sedran, T 2005, 'Design of concrete pumping circuits', *ACI Materials Journal*, vol. 102, no. 2, pp. 110–117.

Kasten, K 2010, *Gleitrohr Rheometer, Ein Verfahren zur Bestimmung der von Flieseigenshaften Dickstoffen in Rohrleitungen* (The Sliding Pipe Rheometer, Flow Characteristics of Highly Viscous Materials), PhD thesis, Technische Universität, Dresden.

Matoušek, V, Visintainer, R, Furlan, J & Sellgren, A 2020, 'Pipe-size scale-up of frictional head loss in settling-slurry flows using predictive models: experimental validation', *ASME Fluids Engineering Division Summer Meeting,* The American Society of Mechanical Engineers, Houston.

Mechtcherine, V, Nerella, V & Kasten, K 2014, 'Testing pumpability of concrete using Sliding Pipe Rheometer', *Construction and Building Materials*, vol. 53, no. 28, pp. 312–323, https://doi.org/10.1016/j.conbuildmat.2013.11.037

Pullum, L 2007, 'Pipelining tailings, pastes and backfill', in R Jewell & AB Fourie (eds), *Paste 2007: Proceedings of the Tenth International Seminar on Paste and Thickened Tailings*, Australian Centre for Geomechanics, Perth, pp. 113–127.

Pullum, L, McCarthy, D & Longworth, N 1996, 'Operating experiences with a rotary ram slurry pump to transport ultrahigh concentration coarse suspensions', *BHR Group Conference Series Publication*, vol. 20, pp. 657–672.

Secrieru, E, Fataei, S, Schröfl, C & Mechtcherine, V 2017, ´Study on concrete pumpability combining different laboratory tools and linkage to rheology', *Construction and Building Materials*, vol. 144, pp. 451–461. https://doi.org/10.1016/j.conbuildmat.2017.03.199

Visintainer, R, Matousek, V, Pullum, L & Sellgren, A 2023, 'Introduction', *Slurry Transport Using Centrifugal Pumps*, 4th edn, Springer Nature Switzerland, Cham.

Wennberg, T, Stalnacke, A & Sellgren, A 2020, 'Commission and operation experiences of two thickened tailings facilities', in H Quelopana (ed.), *Paste 2020: 23rd International Conference on Paste, Thickened and Filtered Tailings*, Gecamin Publications, Santiago, https://doi.org/10.36487/ACG_repo/2052_32

Wennberg, T, Stålnacke, A & Sellgren, A 2023, 'Loop pumping tests of crushed rock mixed with thickened tailings', in GW Wilson, NA Beier, DC Sego, AB Fourie & D Reid (eds), Paste 2023: Proceedings of the 25th International Conference on Paste, Thickened and Filtered Tailings, University of Alberta, Edmonton, and Australian Centre for Geomechanics, Perth, pp. 554–566, https://doi.org/10.36487/ACG_repo/2355_41

Wickland, BE 2006, *Volume Change and Permeability of Mixtures of Waste Rock and Fine Tailings*, PhD thesis, University of British Columbia, Vancouver.

Wilson, C & Addie, G 1995, 'Coarse-particle pipeline transport: effect of particle degradation on friction'*, Proceedings of the 8th International Freight Pipeline Society Symposium,* University of Pittsburg, Pittsburg, pp. 151–156.

Wilson, GW, Miskolczi, J, Dagenais, AM, Smith, Q, Lanteigne, L, Hulett, L & Landriault, D 2006, 'The Application of 'Paste Rock' for Cover Systems in Mine Waste Management', in R Jewell, S Lawson & P Newman (eds), *Paste 2006: Proceedings of the Ninth International Seminar on Paste and Thickened Tailings*, Australian Centre for Geomechanics, Perth, pp. 209–219, https://doi.org/10.36487/ACG_repo/663_18