J. S. Afr. Inst. Min. Metall., vol. 92, no. 1.
Jan. 1992. pp. 27–34.

The performance of backfill pipelines

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SYNOPSIS

The hydraulic transportation of relatively dense slurries for backfill purposes is typically carried through vertical and horizontal pipelines under gravity.

Wear in backfill pipelines has become such a major problem that it is now one of the main reasons for the relatively slow build-up of placed backfill in spite of encouraging performance results in the gold-mining industry.

This paper describes tests on pipeline wear that were carried out on classified tailings from the backfill plant at Vaal Reefs East.

The testwork was carried out under various conditions of slurry relative density, slurry velocity, and pipeline diameter.

Empirical relationships are presented for each transportation and pipeline parameter evaluated and, finally, overall relationships between pipeline conditions and transportation parameters are proposed.

SAMEVATTING

Die hidrouliese vervoer van relatief digte flodder vir terugvuldoeleindes word gewoonlik met vertikale en horisontale pypleidings onder swaartekrag gedoen.

Slytasie in terugvulpypleidings het so 'n groot probleem geword dat dit nou een van die hoofredes is vir die betreklik stadige opbou van aangebringde terugvulsel, ten spyte van bemoedigende resultate in die goudmynbedryf.

Pypleidingslytasietoetse is uitgevoer waartydens 'n geklassifiseerde uitskot van die terugvulaanleg by Vaal Reefs-Oos vervoer is. Die toetswerk is in verskillende toestande van relatiewe flodderdigtheid, floddersnelheid en pypleidingdiameter uitgevoer.

Empiriese verhoudings word aangegee vir elke vervoer- en pypleidingdiameter wat geëvalueer is, en laastens word geheelverhoudings tussen pypleidingtoestande en vervoerparameters voorgestel.

INTRODUCTION

Backfilling is the process in which very fine metallurgically milled waste material is transported back underground as a void filler and support medium. Most backfill operations in the gold and uranium mines on the Witwatersrand utilize cycloned (classified) tailings. This system involves the removal of the finer particle fraction and the thickening of the remaining size fraction (the cyclone underflow) to produce a relatively free-draining and self-supporting backfill material. The reasons and benefits of backfill have been discussed in detail by Spearing[1] and are mainly associated with improvements in mine safety.

The cyclone underflow is typically pumped from the preparation plant to the mine shaft-head storage silo, from where it is introduced to a vertical pipeline. The mixture is transported under gravity to the required mining level, and then transported horizontally under the action of the static head provided by the vertical column. For backfilling to be carried out timeously within the mining cycle, a specific volume of backfill must be transported per hour. This varies, depending on the mine, from 15 to 25 m^3/h and results in mixture velocities through a typical pipeline of between 2 and 8 m/s. These high velocities, together with the inherent abrasive nature of the solid particles and corrosion, lead to rapid wearing of the backfill pipelines.

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 SA ISSN 0038—223X/3.00+0.00. Paper received 6th May, 1991. Modified paper received 14th October, 1991.

To achieve the most effective performance and lifespan from a backfill system, it is necessary to understand all the operating parameters and to match them. Little work has been carried out on wear in pipelines transporting classified tailings at volume concentrations between 36 and 46 per cent. This paper addresses this need for relevant data on pipeline wear in the backfill industry on gold and uranium mines, and should assist in the design of complete backfill-distribution systems.

BASIC RELATIONSHIPS AND DEFINITIONS

Relative abrasivity[2] applies to the ability of solids to remove material from a test sample in relation to the ability of other solids to remove material from the same type of sample, e.g. mild steel.

Relative density of a slurry mixture is the ratio of the mass of given volume of backfill to the mass of an equal volume of water. The calculation of relative density is explained later.

Slurry lifetime[2] is defined as the time that the solids in a slurry have been recirculated through a closed-loop pipeline.

Particle degradation is the decrease in both the size and the sharpness of the particles being recirculated through a closed-loop pipeline.

Mean free path is the mean distance that a molecule, or in this case a particle, moves between two successive collisions between either particle/particle or particle/wall.

Erosive wear is the process of material removal that occurs when a pipe wall is subjected to repeated particle impacts, resulting eventually in the breaking loose of material from the pipe wall. The impact angle[3] on the pipe wall can be between 0 and 90 degrees.

Abrasive wear is the process of material removal by a particle moving nearly tangentially along the material surface, and is essentially a sliding process. The particle sliding on the pipe surface is restrained by the surrounding particles, which also supply loading to the particle on the pipe surface[3].

Abrasivity refers to the ability of particles to remove material from a pipe wall. Abrasivity is determined by particle characteristics such as size, shape, sharpness, hardness, and density[4].

APPARATUS

The pipeline tests were carried out on a closed-loop pipeline facility based at the University of Cape Town. The closed-loop pipeline is shown schematically in Fig. 1 and consists of a slurry reservoir, a centrifugal pump, instrumentation, the test pipeline, and heat exchangers.

Slurry Reservoir

This is a galvanized-iron tank of 1,8 m^3 capacity. The slurry in the tank is kept suspended by two mixer blades that rotate at approximately 30 r/min for the duration of a test. The entire tank is kept covered by a rubber canopy that prevents splashing and spray from the mixer blades and the jet-impact facility from escaping from the tank.

Centrifugal Pump

The pump is a Warman 4/3D solids-handling centrifugal pump, which consists of a rubber-lined cast-iron casing and a five-vaned rubber impeller. The pump is driven by a hydraulic motor capable of a variable speed.

Instrumentation for the Measurement of Concentrations

In order to evaluate the relative density of the slurry, it was necessary to physically weigh the slurry. This is achieved by the use of a weigh tank of known volume. The mass of the empty tank is determined (W_t),and the mass of water to a given mark, in this case a hole in the side of the tank, is determined (W_W). A sample of slurry is diverted to the tank and the mass noted (W_S). Water is then added to the slurry sample, taking it to the predetermined mark (the hole in the tank), and the mass is noted (W_{SW}). The relative density (Sm) is evaluated from these masses and the following equation:

$$Sm = W_S - W_t / [(W_W - W_t) - (W_{SW} - W_S)].$$

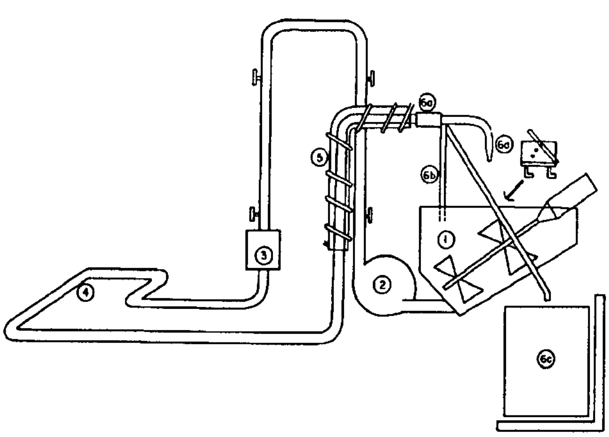


Fig. 1 – The closed-loop test pipeline

1 Slurry reservoir
2 Centrifugal pump
3 Magnetic flowmeter
4 Test pipeline
5 Heat exchangers
6a Ball-valve switchover
6b Bypass pipeline
6c Weigh tank
6d Jet-impact nozzle

Instrumentation for the Measurement of Velocities

The velocity of the slurry in the pipeline is monitored by a Krone Magnetic flowmeter. This instrument is positioned in a vertical section of the pipeline where the solids are uniformly distributed across the pipe section.

The Pipeline

The closed-loop pipeline facility consists of pipelines of various nominal bores. On the return section of each pipeline, there is a 2 m section of clear PVC piping that allows the flow regime in the pipeline to be observed. The test section of the piping consists of straight sections of the material under test.

The straight sections of pipe are joined as shown in Fig. 2, and all three sections are of the same material. This method allows for the central section of pipe to be aligned accurately with the lead-in and lead-out sections of pipe[5-8]. With this method, the lack of misalignment between joints results in a smooth flow of slurry through the central section, ensuring a constant flow regime through the test section, which is then used in the measurement of wear rates calculated from mass losses.

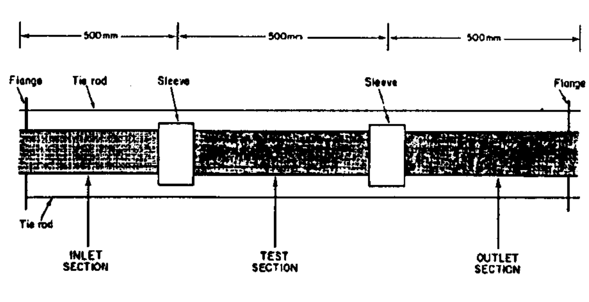
Heat Exchangers

Much of the energy generated by the pump and friction is transferred to the slurry as heat. This heat is removed from the slurry as it passes through annular-type mild-steel heat exchangers. A 4 kW Techniheat refrigeration unit circulates glycol through the heat exchangers, removing the heat generated and cooling the slurry. This system has subsequently been replaced by a mains supply of water, which is more efficient in removing heat.

TEST RESULTS

The pipe specimens were weighed to an accuracy of 0,01 g prior to testing. Fresh slurry was then run at the required relative density and velocity through the closed-loop pipeline for 9 hours. The loss in mass was converted to a reduction in wall thickness per ton of material transported.

The results obtained during this test programme are given



Pipe od -
Pipe id -
Flanges - SABS 50 NB Table D
Sleeves machined from PVC, tight slip fit

Fig. 2—Spool configuration

TABLE I
Pipeline test results

Relative density	Velocity m/s	Pressure gradient kPa/m	Pipe diameter mm	Wear rate µm
1,61	2,60	1,50	54,00	0,02500
1,65	2,60	2,00	54,00	0,02000
1,65	4,00	3,50	54,00	0,07800
1,65	4,20	4,00	54,00	0,08800
1,65	5,60	6,00	54,00	0,20000
1,70	3,00	8,00	26,20	0,06300
1,70	4,50	13,60	26,20	0,11000
1,70	1,99	2,60	39,50	0,02400
1,70	3,00	5,90	39,50	0,02600
1,70	4,50	7,15	39,50	0,05200
1,70	3,00	4,10	54,00	0,01200
1,70	3,60	4,40	54,00	0,02300
1,70	2,60	2,65	54,00	0,01500
1,70	4,50	5,20	54,00	0,02700
1,70	4,90	6,00	54,00	0,03300
1,70	5,60	7,80	54,00	0,05000
1,70	6,50	9,00	54,00	0,06500
1,70	3,00	2,60	69,20	0,00070
1,70	3,43	3,62	69,20	0,00100
1,70	4,50	4,30	69,20	0,00130
1,70	2,62	2,00	74,10	0,00026
1,70	3,00	2,20	74,10	0,00032
1,70	3,92	3,70	74,10	0,00055
1,70	4,50	4,10	74,10	0,00068
1,75	5,60	8,00	54,00	0,05000
1,75	2,00	3,10	54,00	0,01300
1,75	4,00	5,70	54,00	0,03600
1,76	2,60	4,00	54,00	0,01200

in Table I.

The wear rate, which is given in micrometres of pipe wall lost per tonne of solids transported, was determined from the loss in pipe mass by use of the following formula:

Wear rate = $A / t \cdot W$,

where

A = loss in pipe material per length of test sample (m^3),
t = tonnes of solids recirculated through the pipeline (t),
W = wetted perimeter of the test pipeline (m^2).

The perimeter wetted is that pipe area in contact with the slurry, calculated from the inner diameter and the length of the test pipe.

DISCUSSION

Particle Degradation

Fig. 3 is a graph showing the percentage change in particle abrasivity, a direct result of particle degradation, against the slurry lifetime. The changing particle abrasivity on the vertical y-axis is given as a percentage of the slurry's original abrasivity. The particle degradation is due to a change in the particle shape, sharpness, and size that leads to differences in the transport parameters and, more importantly, the characteristics of the placed backfill, which is optimized during the cycloning operation on the surface as regards its physical properties and placing.

The wear rates achieved during this research need to be doubled to give the true absolute wear rate. The reason for this is that, after a slurry lifetime of 9 hours, significant particle degradation has occurred from the recirculation of solids through the centrifugal pump, resulting in a halving of the solids abrasivity; i.e. after 9 hours of pumping, the ability of the solids to remove pipe-wall material is approximately half that at the start of the test.

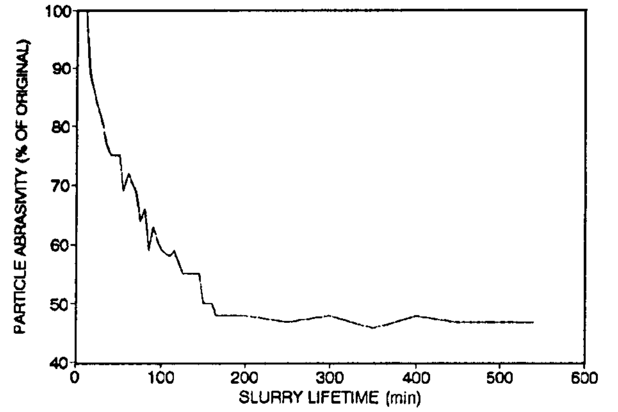


Fig. 3 —Particle degradation as a percentage of particle abrasivity

Relative Density of Solids

Fig. 4 is a plot of relative density versus wear rate for various slurry velocities. It can be seen that, as the relative density increases, the wear rate decreases—an effect that has also been reported by Hinde[9]. The decrease in the rate of pipe wear with increasing relative density is explained in terms of the particles' mean free path.

During the transport of slurries low in solids, there are eddies within the slurry that can increase the average velocity of a particle[10], subsequently increasing its energy and, therefore, its ability to remove pipe-wall material on impact. The angle of impact due to random motion can vary from 0 to 90 degrees.

This effect of mean free path and impact frequency is also discussed by Bain and Bonnington[11].

As the relative density of the mixture being transported increases, the quantity of solids in the pipe increases, thus decreasing the mean free path of individual particles. This decrease in mean free path means that less energy, due to motion ($E = mV^2$), is available to be transferred on impact.

The filling of the pipe with more solids prevents the generation of eddies and the associated random movement of particles at high-angle impacts. This effect decreases the

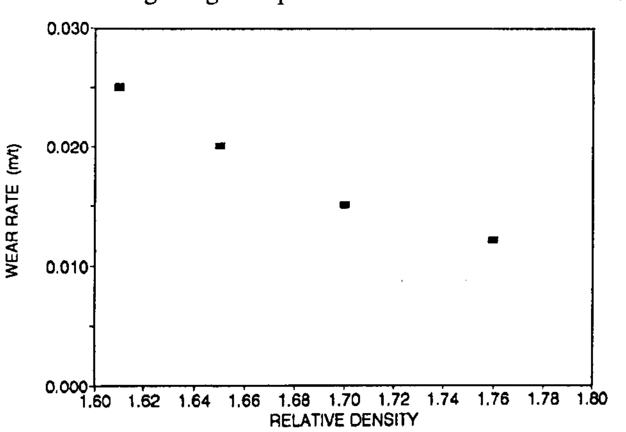


Fig. 4—Relative density of slurry versus rate of pipe wear

particles' ability to remove pipe-wall material, and their impacts become more glancing, tending towards abrasion and away from abrasion/erosion, i.e. the average angle of impact decreases.

Link and Tuason[12] reported that the increase in the rate of pipe wear at concentrations of 30 and 60 per cent by mass was only 10 per cent. The results reported in the present study involved concentrations of between 60 and 70 per cent by mass, and there appears to be no literature currently available on wear rates at these concentrations.

These results show that higher relative densities lead to decreases in pipe wear. However, thorough work has not been carried out at relative densities in excess of 1,75, and a limiting relative density may be achieved beyond which no benefit in terms of decreasing wear rate is realized. The relative density has been limited to a maximum of 1,75 since this is the maximum relative density that can readily be achieved with the currently installed cyclone preparation

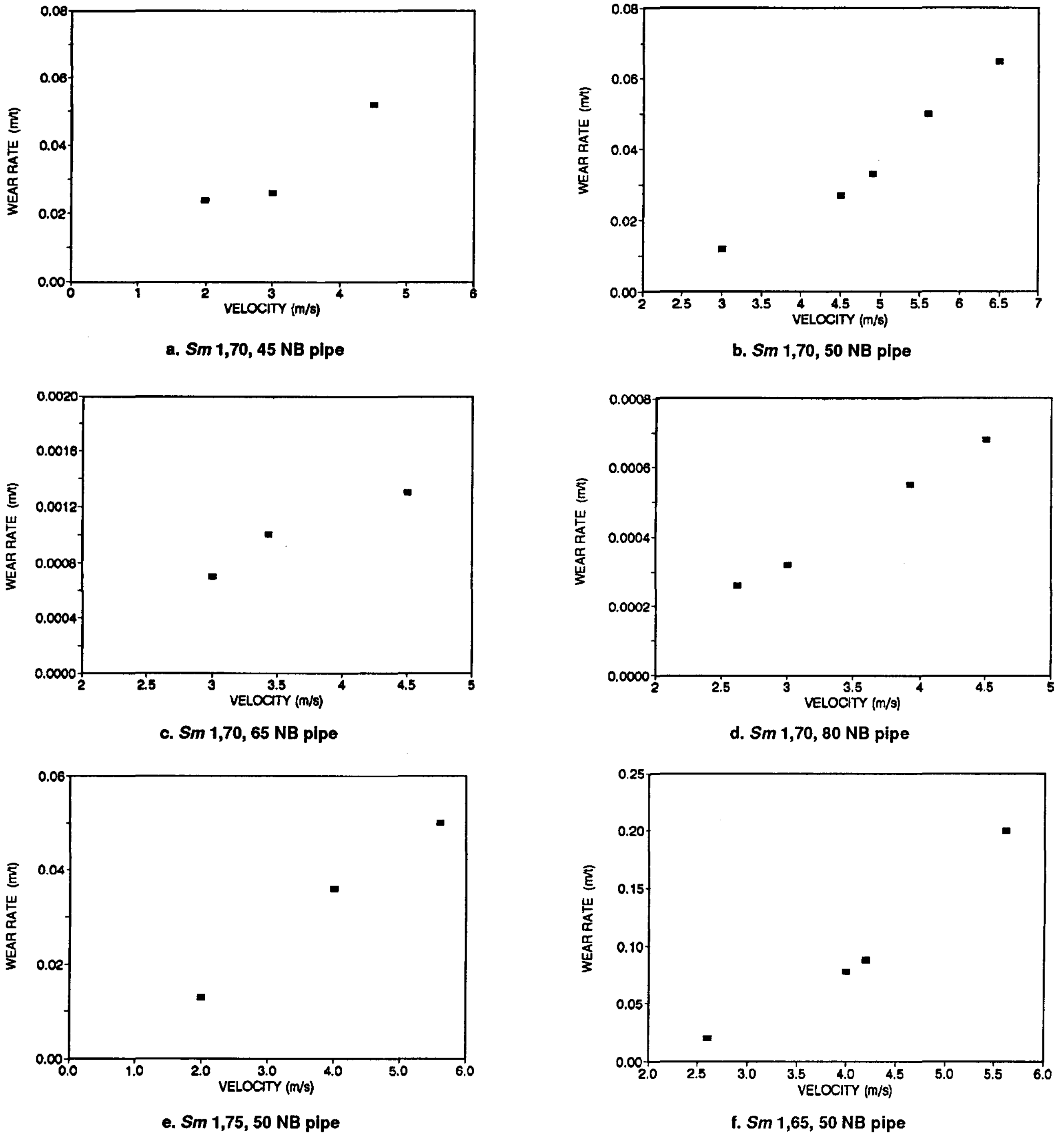


Fig. 5—Velocity of slurry versus rate of wear

plants.

Velocity of Solids

Fig. 5 gives graphs of pipe wear versus slurry velocity for various relative densities and pipe diameters. As the slurry velocity increases, the wear rate increases exponentially, following the general formula

$$W = kV^n .$$

The constants k and n change as the relative density changes. Table II reports the results of the constants n and k for the relative densities and pipe diameters featured in the tests.

TABLE II
Experimentally determined constants *k* and *n*

Relative density	Pipe nominal bore	k	n
1,65	50	0,00154	2,82
1,70	45	0,00345	1,78
1,70	50	0,00234	1,78
1,70	65	0,00009	1,78
1,70	80	0,00005	1,78
1,75	50	0,00642	1,20

Exponent n has the greatest effect upon the relationship determining the degree of material loss. It appears that, even as the pipe diameter changes, exponent n remains constant for a specific relative density, and this aspect will be confirmed in further research.

Constant k, however, changes to characterize the relationship's position within the x–y co-ordinates.

The effect of constant n remaining the same for a specific relative density regardless of the pipe diameter tends to confirm the theory regarding the particle's mean free path and relative density. The mean free path should remain constant for a specific relative density regardless of the pipe diameter. This would result in the same type of impact occurring on the pipe wall for any pipe diameter, providing the relative density remains constant.

Velocity has the largest effect on the rate of pipe wear, and therefore limiting the solids velocity is the most effective method of decreasing the rate of pipe wear.

Pipe Diameter and Pressure Gradient

Fig. 6 shows the relationships between pipe diameter and wear rate. Fig. 6a demonstrates that a decreasing wear rate is experienced with increasing pipe diameter. Fig. 6b is a plot of the log of wear rate versus the pipe inner diameter. From this plot it can be seen that a predictable relationship has still not been achieved.

The result of integrating the pressure gradient into some wear prediction is the relationship given by the linear equation determined through empirical evaluation:

$$\ln(\text{wear rate}) = \ln(k) + (D/\Delta P)\cdot n,$$

where k is the slope, n the constant, D the pipe inner diameter, and P the pressure gradient. When this equation is converted to the exponential form, the following is obtained:

$$\text{Wear rate } (\mu\text{m/t}) = k \cdot e^{(D/\Delta P)\cdot n}.$$

TABLE III
Constants for the wear equation

Method	k	n
Least squares	0,08816	-0,1612
Robust fit	0,10880	-0,1668

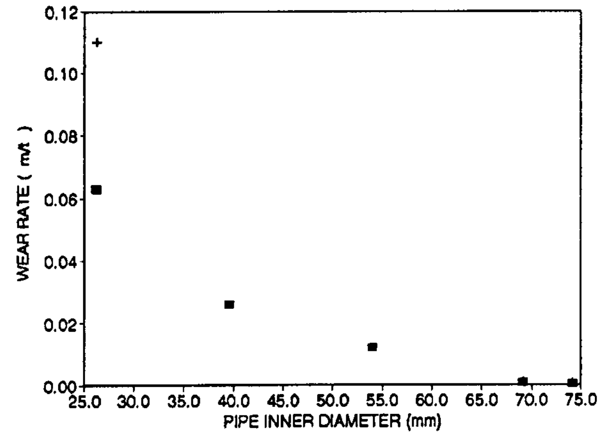


Fig. 6a—Pipe inner diameter versus rate of pipe wear

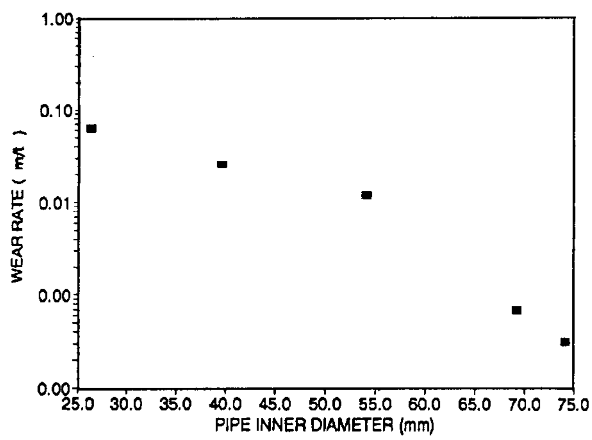


Fig. 6b—Pipe inner diameter versus log rate of pipe wear

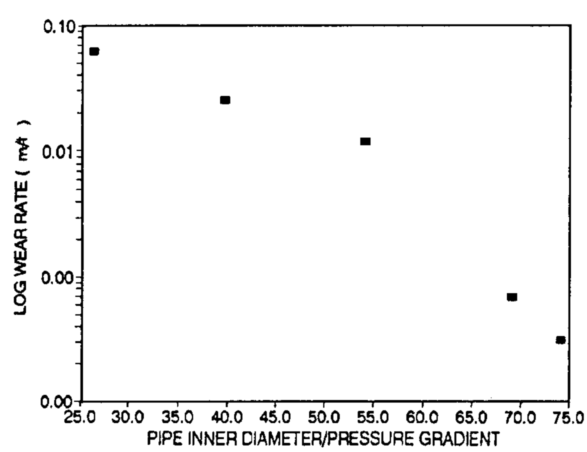


Fig. 6c – Pipe inner diameter/pressure gradient versus rate of pipe wear (3,0 m/s)

The above relationships and constants were calculated by two methods: least-squares regression and robust fit. The essential difference between the two methods is that the robust fit is less affected by outlying data points. The resulting constants are given in Table III.

The robust relationship achieved has the better correlation coefficient (0,999).

The explanation for the decrease in pressure gradient with increasing pipe diameter would require a knowledge of the frictional resistance in pipes[13-15].

In the case of water, the head loss per metre of pipe can be calculated from Lazarus's equation[13]

$$\text{Head loss} = 2f \cdot L \cdot V^2/g \cdot D$$

where

f = pipe friction factor
L = pipe length (1 m)
V = velocity (m/s)
g = gravitational constant (m/s^2)
D = inner diameter of pipe (m).

From this equation, it can be seen that, as the pipe diameter increases, the head loss decreases.

In the transportation of solids, the prediction of head loss is more complicated owing to the increased number of variables[13-15]. The effect of decreasing head loss on the abrasivity of transported solids is related to the shear stress of the pipe wall, which also decreases with a decreasing head loss. The shear stress affects the mechanical sliding friction of the solids being transported, and it is this parameter that is altered to, and affects, the wear rate. A complete discussion of this parameter, its determination, and performance, is given by Cooke[16].

Transportation Relationships

The transportation parameters considered during this research are solids velocity, pipe pressure gradient, pipe inner diameter, and relative density. The following relationships were determined:

$$W \propto V$$
$$W \propto D/\Delta P$$
$$W \propto Sm,$$

where

W is the wear rate
Sm is the relative density
D is the pipe inner diameter
V is the slurry velocity
ΔP is the pressure gradient.

When these relationships are combined, the following empirical relationships are achieved:

$$\log W \propto V \cdot D / \Delta P \cdot Sm$$

$$\Delta P \propto V \cdot Sm/D.$$

Figs. 7a and b are graphs of the relationship between wear rate and the relative transport parameters. The best-fit relationship for this data is logarithmic:

$$\log W = y \cdot [\, V \cdot D / \Delta P \cdot Sm \,] + C,$$

where y and C are constants. Two distinct data sets can be seen: one for relative densities 1,70 and 1,75 (Fig. 7a), and

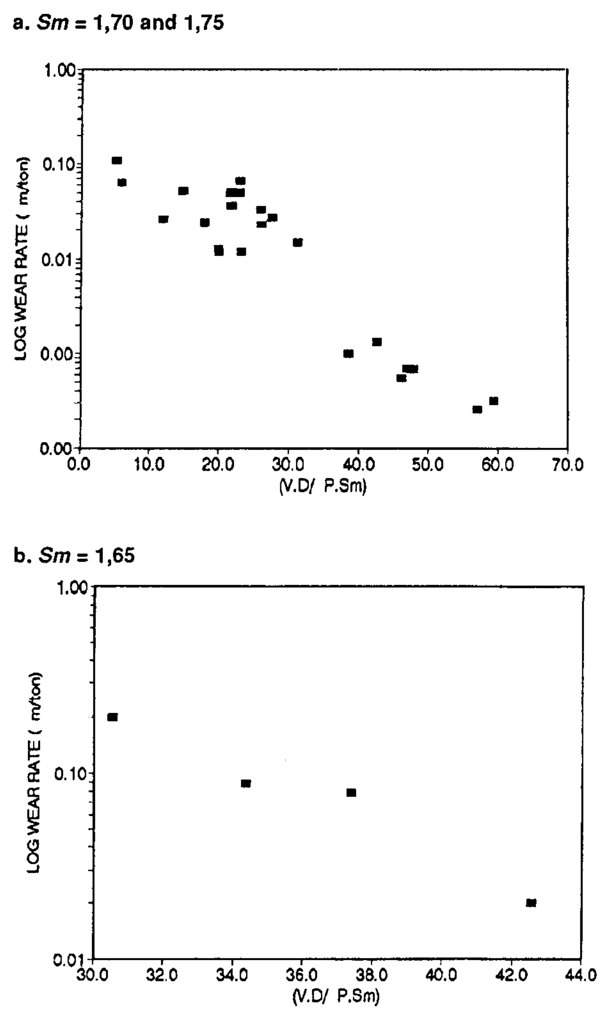


Fig. 7—Transportation parameters versus rate of wear

TABLE IV
EXPERIMENTALLY DETERMINED CONSTANTS y AND C

Relative density	y	C
1,65	-0,0799	1,7534
1,70 – 1,7	-0,0519	-0,5468

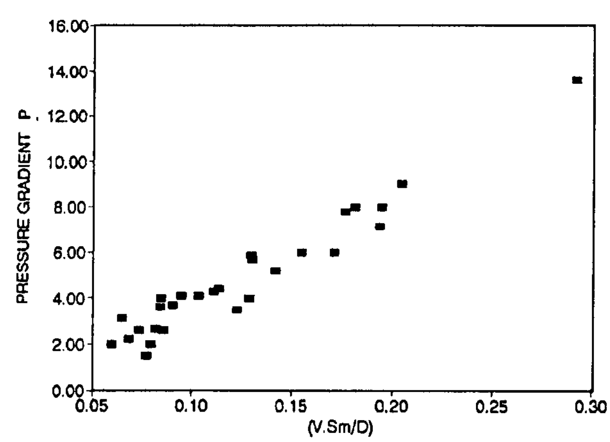


Fig. 8 – Pressure gradient versus transportation parameters

another for a relative density of 1,65 (Fig.7b). Table IV reports the values for the constants *y* and *C*.

The difference between the two relationships is probably due to the wear mechanism. As discussed in the section on solids velocity, erosion as a mechanism of material removal is more aggressive than abrasion under typical pipeline conditions. At a relative density of 1,65, material is probably removed by a mixed mechanism of erosion and abrasion but, at a relative density of 1,70, the rate of pipe wear decreases. This implies that the mechanism of material removal becomes more abrasive in nature.

Fig. 8 is a graph of pressure gradient against relevant transportation parameters. The relationship has a good fit for the conditions and environment used in this testwork.

The pressure gradients for most of the data on wear rate were interpolated and extrapolated, approximating the results from the available data obtained on 25, 40, and 80 NB piping. The solids for the pressure-gradient data used in this study was underflow material from the 600 mm diameter cyclones at Vaal Reefs East Plant. The pressure gradients for the new cluster cyclone material at Vaal Reefs East Plant are similar to those for the old 600 mm cyclone material[13,17].

It is important to note that the relationship

$$\Delta P = 40{,}418 \cdot [V \cdot Sm/D] + 0{,}798$$

holds only for the solids used and the conditions of the test procedures, i.e. a relative density of 1,65 to 1,75, a velocity of 1,99 to 6,5 m/s, and a pipe inner diameter of 26,2 to 74,1 mm.

Pipeline Materials

There are many reports on the performance of pipeline materials transporting various solids[3,4,6–8,18–23]. Two points are apparent from these reports.

a. Polymeric materials such as high-density polyethylene and elastomeric materials such as rubber and polyurethane generally perform better than steel and alloy materials in the transportation of hard-mineral slurries. A further benefit of these non-metallic materials is that corrosion is eliminated.
b. No theory regarding the abrasivity of different solids and the accompanying rates of pipe wear is available. Thus, until such a theory can be derived, the optimum available material for a specific transport application in a solid pipeline has to be determined from tests on such pipelines.

As a guideline only, Fig. 9 is a comparison of the relative abrasivity of various backfill materials based on an accelerated jet-impact type of test, which involves a jet of slurry blasted onto a plate of the test material. However, it can be assumed that the performance of other backfill pipelines will follow similar trends, although the degree of wear will vary.

CONCLUSIONS

It is concluded that the design and operation of a successful backfill-distribution system requires a prior knowledge of pipeline, material, and transportation parameters.

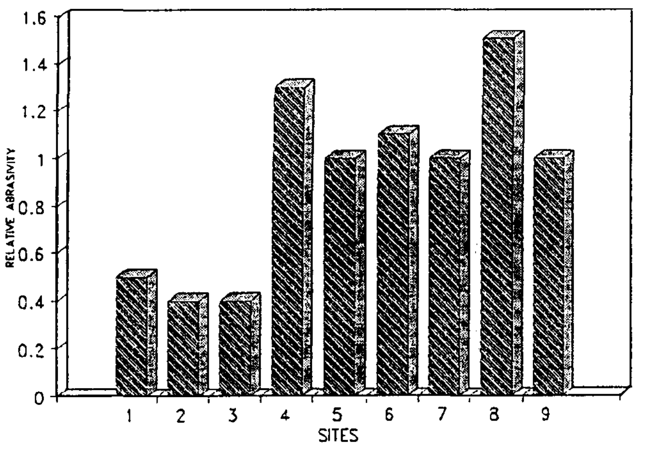


Fig. 9—Backfill sites versus relative abrasivity

1. **Full plant tailings from Vaal Reefs East**
2. **Full plant tailings from President Steyn**
3. **Full plant tailings from Western Deep Levels**
4. **Cyclone underflow from Elandsrand**
5. **Cyclone underflow from Western Deep Levels**
6. **Cyclone underflow from Vaal Reefs South**
7. **Cyclone underflow from Western Deep Levels North**
8. **Cyclone underflow (600 mm) from Vaal Reefs East**
9. **Cyclone underflow (165 mm) from Vaal Reefs East**

Pipe lifetime, and thus ultimate cost effectiveness, is dependent on the control of the relative density, velocity, and pressure gradient of the slurry. A balance between these parameters is necessary to limit pipe wear. To ensure the most cost-effective design, prior knowledge of these parameters and their interrelationships is essential.

For the purposes of existing backfill operations, the relationships determined during this study provide necessary information for the optimization of distribution systems with the least possible expenditure. The determination of pressure gradients is particularly vital considering the trend towards underground storage and distribution dams. The relationship between the pressure gradient and the transportation parameters reported here is acceptable for the environment under which the tests were conducted, and will be expanded in future. As previously mentioned, the findings pertain specifically to the cyclone underflow from Vaal Reefs East Plant and, for other materials, absolute wear rates would need to be determined.

In future research, it is hoped that only the relative abrasivity, which is determined in a relatively quick and inexpensive test, will be needed.

RECOMMENDATIONS

Good design for backfill pipelines should include the following considerations, which can be balanced to achieve the required volumetric flowrate:

1. a low mixture velocity (2 to 3 m/s, but more than the settling velocity),
2. the highest practical relative density,
3. piping of a large nominal bore (full flow),
4. wear-resistant pipe materials.

A method of controlling the slurry velocity and pressure gradient safely needs to be devised to ensure long pipeline lifetimes.

ACKNOWLEDGEMENTS

The authors thank the Gold and Uranium Division of the Anglo American Corporation of South Africa for permissions to publish this paper. Thanks are also due to Mr R. Cooke for his technical contribution to this work.

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Mineral Processing

The Universities of Stellenbosch and Cape Town, under the auspices of the Western Cape Branch of the SAIMM, hold annual meetings to discuss research topics in minerals processing. In 1989 this meeting was in the form of an International Column Flotation Colloquium. In 1990 the Symposium was extended to two days.

For this, the 11th meeting, the Symposium will be held over two days, and speakers from other research groups and industry are invited to take part in this national meeting. Papers on materials engineering and chemical engineering are also invited.

The Symposium will be held in Gordon's Bay on the 6th and 7th August, 1992. Registration will take place on 5th August, and a banquet will be held on 6th August, 1992.

The object of this Symposium, the 11th Annual Minerals Processing Symposium, is to

- discuss current research areas and findings
- keep abreast of recent developments in the industry
- elicit debate on relevant topics
- serve as a forum for informal contact
- encourage young researchers.

All interested persons are invited to participate in this event. Papers and posters may be presented. Only abstracts of the papers will be distributed, and presenters are welcome to publish their findings elsewhere. The dates for submissions are as follows:

30th April, 1992	Title with extended abstract (500words)
31st May, 1992	Notice of acceptance of paper or poster.

Further information is available from

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