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An Experimental Investigation into Aspects of Wear in Boiler Ash Disposal Pipelines

Peter Goosen
Paterson & Cooke Consulting Engineers (Pty) Ltd
P O Box 23621, Claremont 7735, Cape Town, South Africa
Tel: +27 21 683 4734, Fax: +27 21 683 4168, E-mail: pete@pcce.co.za

Isaac Malgas
ESKOM Technology Research and Investigations
Private Bag 40175, Cleveland, 2022, Johannesburg, South Africa

Synopsis

This paper presents the results of an experimental investigation into wear rates in boiler bottom ash disposal pipelines. Pipeline wear rate data has been measured for small (typically 50 mm to 90 mm) diameter pipe using a re-circulating pipe loop test facility.

The effect of velocity on pipeline wear rate is investigated. This data was used to establish values for the wear exponent for mild steel and plastic pipe. Predictions made from the small scale data are compared to full size (300 mm pipe) data from a power station installation and shown to be in excellent agreement.

The performance of a number of pipe materials under both pipe flow and bend / fitting flow conditions have been investigated. The results are reported in terms of wear rates relative to mild steel.

The potential for wear rate reduction through the addition of fly ash to the boiler bottom ash slurry was investigated. It is shown that a significant wear rate reduction is achieved in this way.

1. INTRODUCTION

South Africa's electricity generation and distribution utility, ESKOM, operates a number of large capacity (typically 6 x 600 MW units per station) coal fired power stations. Five of these stations employ "wet ash" disposal systems, the ash from the boilers being transported to disposal sites by slurry pipeline.

The ash which results from the combustion of coal in the boilers either falls down to the bottom of the boilers (coarse, highly abrasive ash and clinker referred to as bottom ash) or is carried out of the boiler with the flue gas (fine, spherical ash particles, referred to as fly ash) which is extracted by means of filters or electrostatic precipitators.

The highly abrasive nature of the bottom ash results in high wear rates in the pipelines conveying the ash slurry, which at present are mostly of unlined mild steel. Wear on these pipelines has been identified by ESKOM as a problem requiring urgent attention. To address this, a research programme was initiated by ESKOM's Technology, Research and Investigations Group (TRI). Paterson and Cooke Consulting Engineers (Pty) Ltd were contracted by TRI to assist with the investigation. This paper presents some of the results of this work.

2. PIPELINE WEAR AND WEAR RELATIONSHIPS

Pipeline wear is an important consideration in the design and operation of slurry pipeline systems. Wear will in most cases result from a combination of mechanical action (abrasion) and chemical processes (corrosion).

Abrasion of the pipe wall results from the dynamic action of moving particles on the internal surface.

Corrosion is caused by the conveying fluid and is an electrochemical process. Postlethwaite *et al* (1972) report that the presence of solids in commercial concentrations can greatly increase the rate of corrosion in pipelines.

It is generally accepted that pipeline wear rate increases exponentially with conveying velocity, i.e.:

$$W_a = k_a V_m^{\,n} \quad , \qquad \textbf{(1)}$$

where W_a = absolute wear rate (normally expressed as mm per year)
k_a = empirical constant for a particular pipe material and slurry
n = empirical exponent.

It is also useful to express wear rate in terms of wall thickness lost per unit mass of solids transported (specific wear rate). In this case:

$$W_s = k_s V_m^{(n-1)} \quad , \qquad \textbf{(2)}$$

where W_s = specific wear rate (normally expressed as µm per 1000 tonne)
k_s = empirical constant for a particular pipe diameter, pipe material and slurry.

Note that the value of the exponents in equations 1 and 2 differ by 1. It is thus important to be aware of whether values of the wear rate exponent reported in literature refer to absolute or specific wear rates. It appears that there has been some confusion over this point in the past.

Faddick (1975) proposed that specific wear rate is inversely proportional to the cross-sectional area of the pipe:

$$\frac{W_{s\,2}}{W_{s\,1}} = \left[\frac{D_1}{D_2}\right]^2 , \qquad \textbf{(3)}$$

where D = internal pipe diameter (m),
1 denotes the test pipe,
2 denotes the prototype pipe.

This equation is based on the assumptions that the concentration and velocity are the same in both pipes and the time rate of loss of wall thickness (absolute wear rate) is the same in both pipes.

3. RESEARCH SCOPE AND METHODOLOGY

Wear rate data for bottom ash slurry from ESKOM's Kriel Power Station was obtained from tests performed in a recirculating pipe loop. The Warman Slurry Test Facility, which is operated by PCCE, on the premises of the pump manufacturer Warman Africa in Johannesburg, South Africa was used. The work was spread over a period of 18 months and was essentially split into four components:

(i) Pipe loop tests to investigate the relationship between flow velocity and wear rate for the bottom ash slurry.

(ii) Pipe loop tests to provide wear rate data for a number of pipe materials under pipe flow (50 mm nominal bore) and bend / fitting flow conditions.

(iii) The measurement of wear rates in an operating ash slurry pipeline (using a PVC wear test pipe) to provide wear distribution data and to confirm the scale up of small scale test data.

(iv) Pipe loop tests to investigate the effect on wear rate of the addition of fly ash to the bottom ash slurry.

The relationship between the various components of the investigation is illustrated in Figure 1. The output from the project can be summarised as follows:

(i) Determination of the wear exponent n (Equations 1 & 2) for mild steel and plastic pipe.

(ii) The wear resistance ranking of a number of pipe materials under pipe flow and bend / fitting flow conditions.

(iii) The prediction of full scale pipe life for various pipe materials including for the effects of the wear distribution pattern.

(iv) Quantification of the degree of wear reduction that can be achieved through the addition of fly ash to the bottom ash slurry.

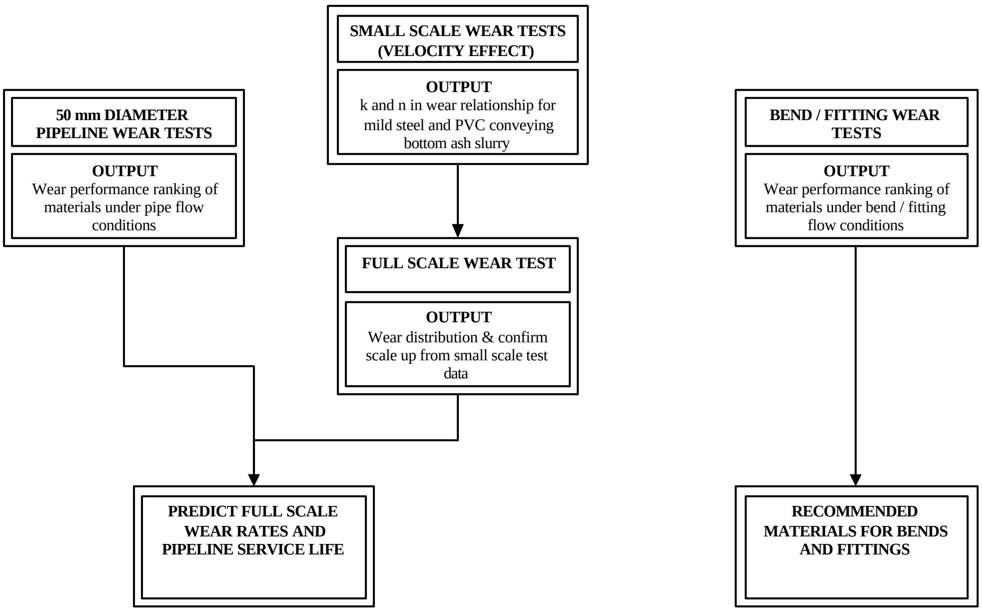

Figure 1: Relationship between components of the investigation

4. THE SLURRY PIPE LOOP TEST FACILITY

Figure 2 shows schematically the layout of the Warman Slurry Test Facility as set up for this work. For purposes of the wear test work, pipeline wear spool pieces and bend / fitting wear sample holders were installed in the horizontal legs of the pipe loop.

Slurry is pumped from the tank by means of the 3/2 centrifugal pump, through the pipe loop and back into the tank to form a recirculating system. Heat exchangers incorporated in the pipe loop limit heat build up in the system.

Slurry flow rate is measured by a magnetic flow meter. The slurry density is measured by means of a counter-flow meter arrangement.

Pipe wear spool pieces and the bend / fitting wear samples were supplied by material vendors as shown in Figure 3. The entry and exit pieces to each wear spool piece ensure that uniform flow conditions are achieved in the wear spool piece.

The bend / fitting wear samples were installed in sample holders shown in Figure 4. These holders can be installed in series, allowing for a number of test specimens to be tested simultaneously, all being exposed to the same slurry flow conditions. The bend / fitting wear test arrangement is intended to simulate the flow conditions encountered in pipe fittings and bends where the flow is highly turbulent and the flow stream impinges onto the bend or fitting surface.

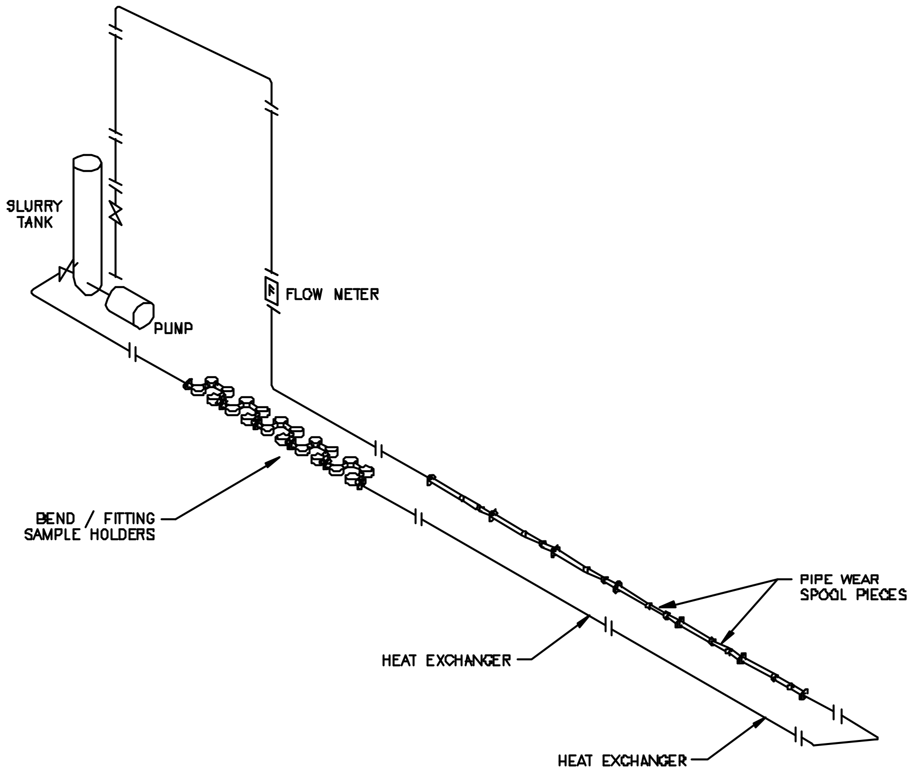

Figure 2: Pipeline wear test facility

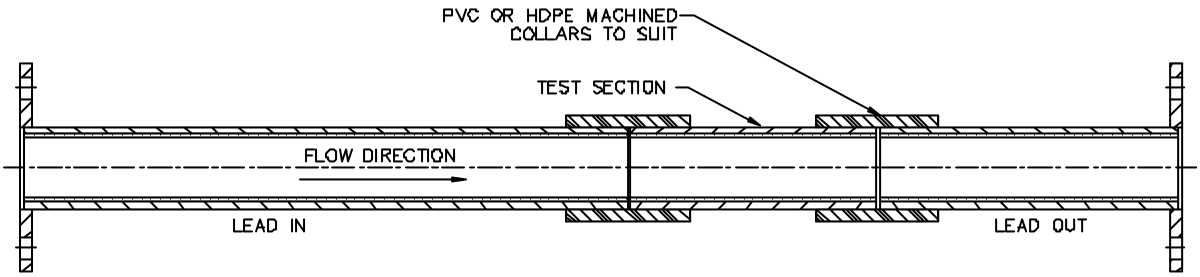

Figure 3: Pipeline wear spool pieces

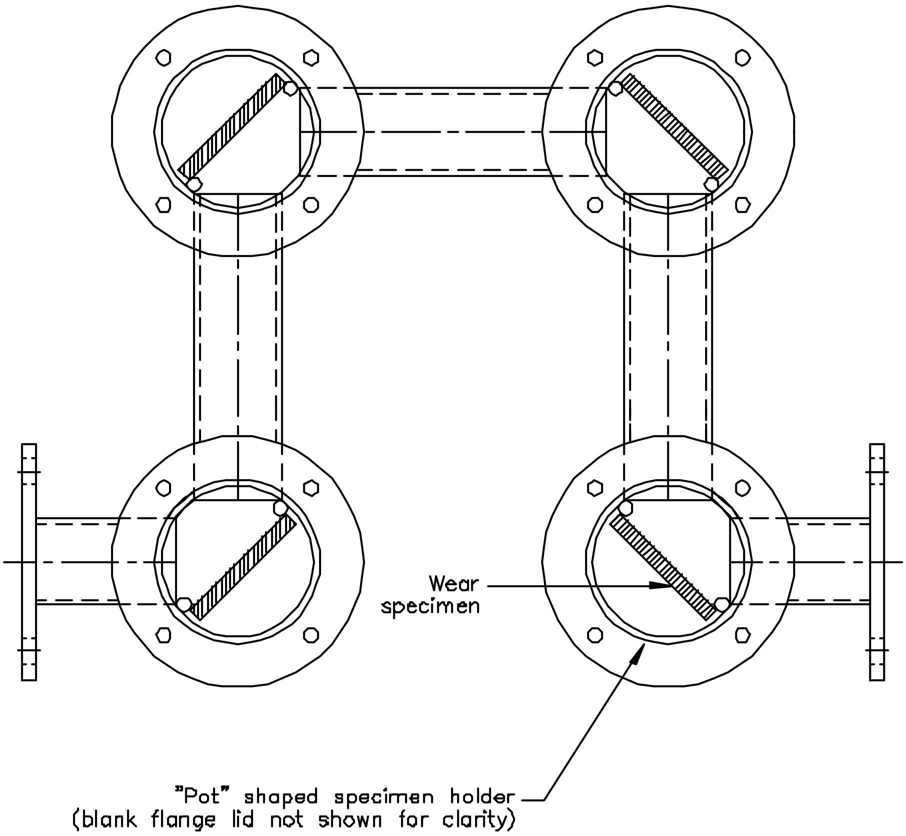

Figure 4: Bend / fitting wear sample holders

The experimental procedure for the pipeline wear test was as follows:

(i) Previous experience has shown that plastic materials gain mass due to water absorption. The samples were kept submerged in water prior to the start of the wear tests and also between tests to try to keep the samples saturated, thereby minimising weight change due to water absorption during the tests.

(ii) The wear spool pieces and bend wear samples are dried to remove any surface moisture using absorbent cloth and hot air. The mass of each sample is measured to 0.01 gram before being installed in the pipe loop.

(iii) Clear water is pumped through the pipe loop and the operation of all instrumentation verified. Dry ash is added into the sump until the desired solids concentration is obtained. The pump rotational speed is adjusted to maintain the required slurry flow rate.

(iv) The slurry flow rate is monitored and maintained constant throughout the test.

(v) During tests in which the slurry degradation effects were evaluated, the slurry was replaced during the test period at specific intervals.

(vi) After the test period, the slurry is flushed from the pipeline, the pipeline spool pieces and bend / fitting wear samples removed from the pipe loop, dried and weighed.

(vi) The mean wear rate (calculated as if the wear occurs uniformly around the pipe circumference) is calculated from the sample mass loss.

5. EVALUATION OF FLOW VELOCITY EFFECT ON WEAR

Two pipe materials were evaluated - mild steel and PVC. Although PVC is not considered to be a suitable material for abrasive slurry application, it was used to highlight differences between the behaviour of steel and plastic materials. A range of flow velocities for otherwise identical slurry conditions were achieved by using wear spool pieces of three different diameters in series. All test pieces experience the same slurry (particle properties, concentration) and total throughput during the test. The test slurry flow rate was 15.3 ℓ/s. The details of the wear test spool pieces and resulting velocities are presented in Table I.

Table I
Nominal wear test parameters - pipe size and velocity

Slurry flow rate = 15.3 ℓ/s			
Steel pipe internal diameter (mm)	91.2	77.9	62.7
Flow velocity (m/s)	2.34	3.21	4.96
PVC pipe internal diameter (mm)	93.6	76.6	63.8
Flow velocity (m/s)	2.22	3.32	4.79

When conducting pipeline wear tests in a recirculating system, there is a change in slurry abrasivity with time due to degradation of the solid particles. To account for this effect and determine wear rates for fresh (un-degraded) slurry, the following procedure was followed: Wear tests of three different durations were performed (4 hours, 2 hours and 1 hour) as detailed in Table II. By plotting the measured wear rate as a function of slurry test time, the wear rate for fresh slurry can be estimated by extrapolation. This procedure follows the method developed by Cooke (1996). The test results for PVC and mild steel are presented in Figures 5 and 6 respectively.

Table II
Wear test parameters - test duration

Parameter	**4 hour**	**2 hour**	**1 hour**
Slurry test time [hrs]	4	2	1
Number of slurry batches	1	2	3
Total test duration [hrs]	4	4	3

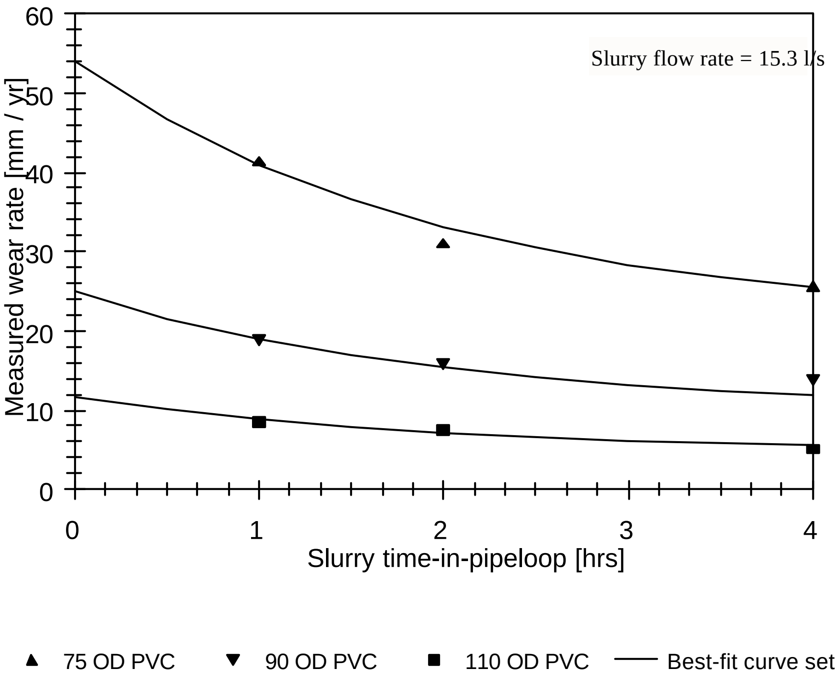

Figure 5: Averaged wear rate versus slurry test time - PVC pipe

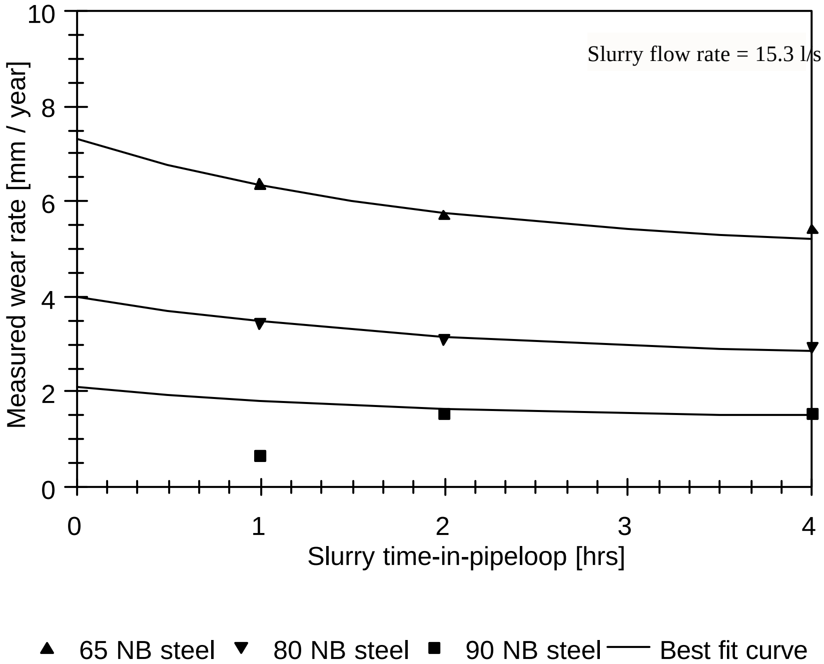

Figure 6: Averaged wear rate versus slurry test time - mild steel pipe

Curves of the form of Equation 1 have been fitted to the measured data and the extrapolated fresh slurry wear rates. The results are presented in Figures 7 and 8. The value of the exponent n (the same value for all test durations) and k_a for fresh slurry are presented in Table III.

Table III
Wear parameters for fresh slurry, s_m = 1.20, w_a [mm/year]

	k_a	n
Mild steel	0.75	1.4
PVC	2.36	2.0

It is significant that the exponent n is a function of the pipe material. A value of 2 is commonly assumed based on particle kinetic energy considerations. This assumption is supported by the measured data for PVC, where mechanical abrasion is the only wear mechanism. The lower value of n for mild steel could be attributed to the different material properties (harder and tougher than the PVC) and also corrosion effects. It is also likely that n and k will be functions of other factors such as water chemistry and dissolved oxygen content which are not considered here.

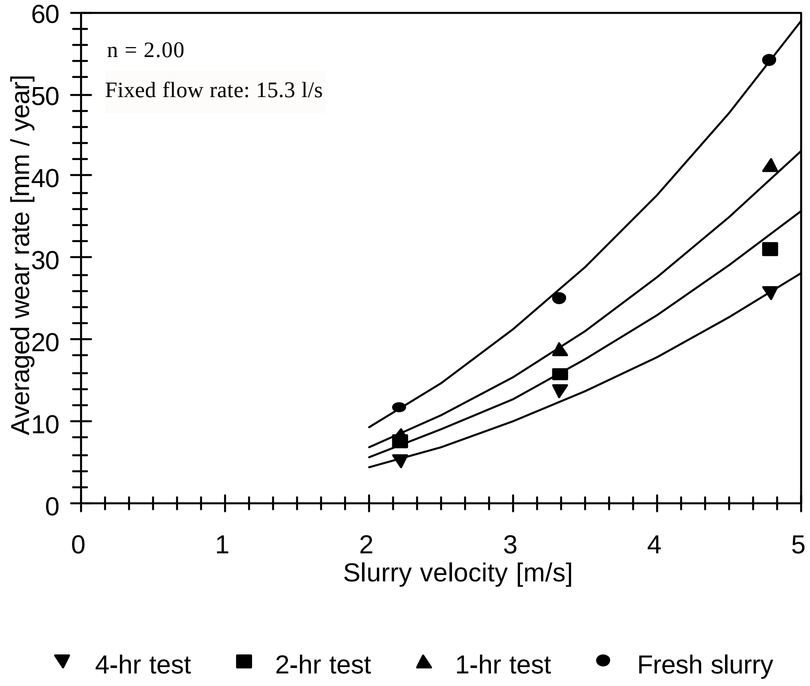

Figure 7: Effect of slurry velocity on wear rate - PVC pipe

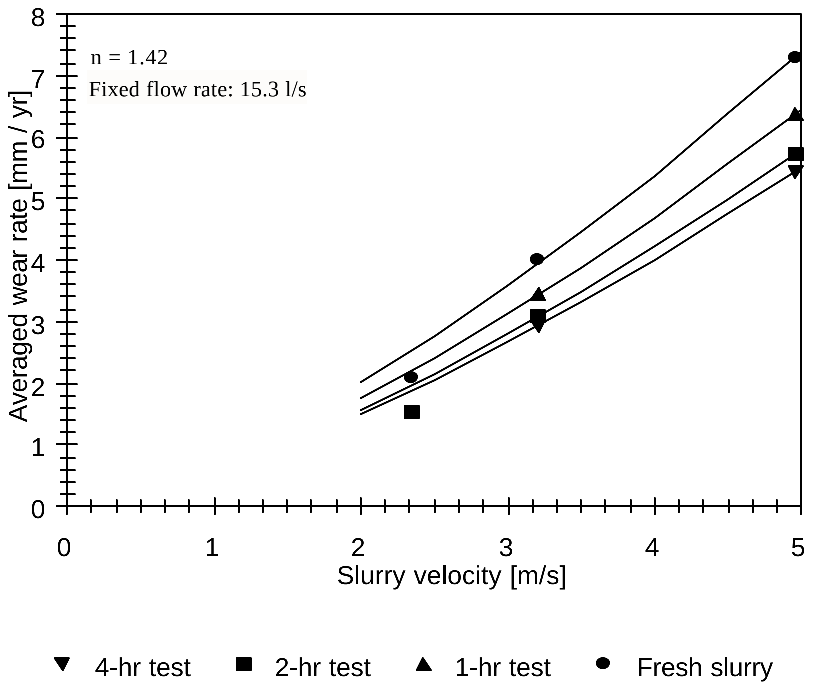

Figure 8: Effect of slurry velocity on wear rate - mild steel pipe

6. MATERIAL EVALUATION TESTS: PIPE FLOW AND BEND / FITTING FLOW CONDITIONS

A summary of the materials for which results are reported is given in Table IV.

Table IV
Pipe and pipe lining materials tested

Material	Pipe wear tests	Bend wear tests
Mild steel	U	U
600 BHN steel	-	U
3CR12 Stainless steel	-	U
Epoxy-ceramic composite	U	U
Ceramic tile	-	U
Cast basalt	-	U
PVC	U	-
HDPE	U	-
Polyurethane Shore 90	U	U

All pipe wear tests is this component of the work were conducted with 1.20 relative density slurry in 50 mm nominal bore piping at a nominal velocity of 4.5 m/s. Small differences in internal diameter, and thus velocity in the pipe wear spools, were corrected for using Equations 1 and 3 and the wear exponents determined from the work described before. The value 1.4 for the wear exponent was used for mild steel and the value 2 used for other (non-corrosive) materials.

The pipe wear test results, adjusted to a diameter of 50 mm and a flow velocity of 4.5 m/s, are presented in Figure 9 in terms of wear rate relative to mild steel. No results are reported for polyurethane from the pipe wear tests as, despite the steps taken, the pipe wear sample gained mass due to water absorption during the tests. It was clear from visual inspection, however, that polyurethane performed best out of all the pipe wear test materials. It is interesting to note that none of the other materials performed better than mild steel in this test.

The bend / fitting wear test results are presented in Figure 10 in terms of wear rate relative to mild steel. These results show that a number of the materials tested performed significantly better than mild steel (600 BNH steel, ceramic, and polyurethane).

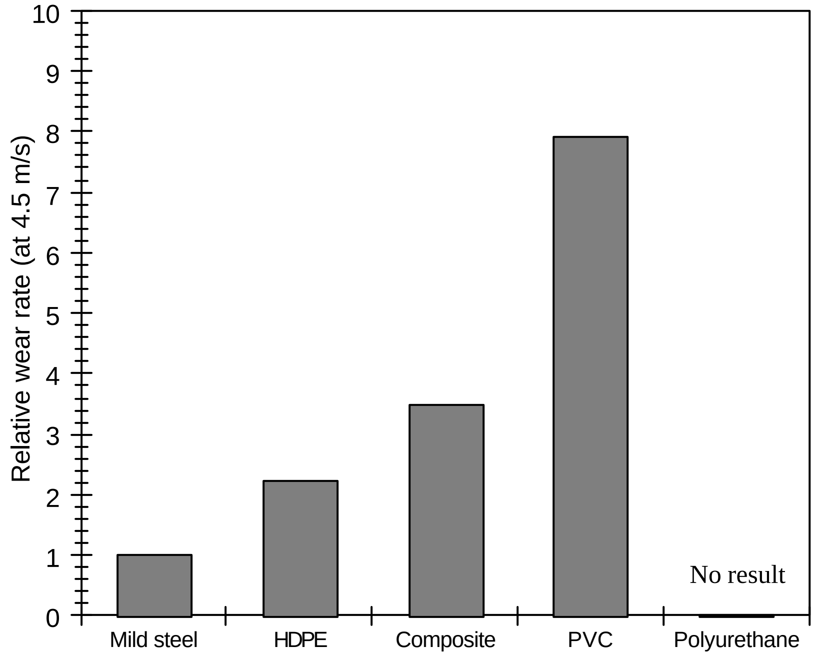

Figure 9: 50 mm pipe wear test results - relative wear rates (at 4.5 m/s) for materials tested

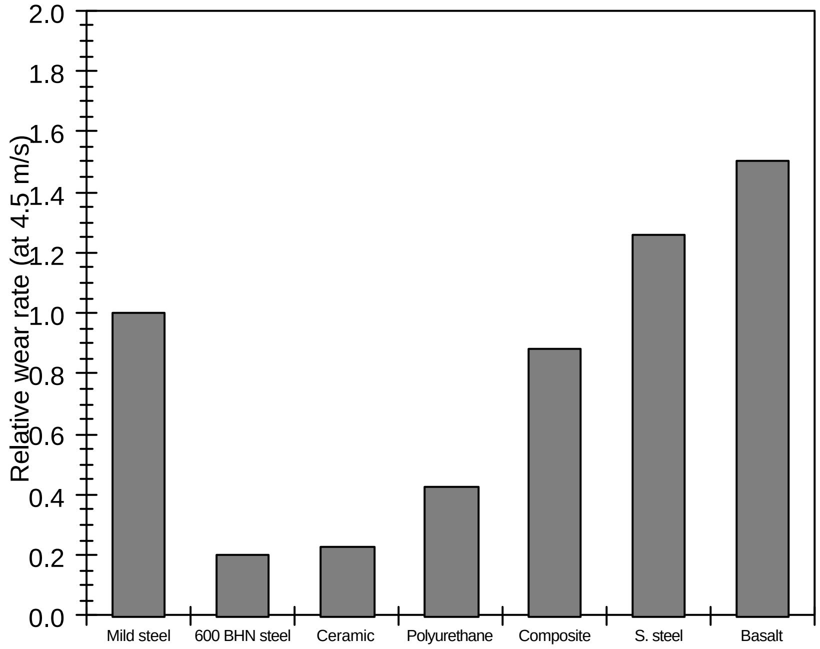

Figure 10: Bend / fitting wear test results

7. FULL SCALE PVC PIPE TESTS

A three-metre length of 332 mm inside diameter PVC pipe, closely matching the inside diameter of the steel slurry pipeline, was installed in an ash disposal line at ESKOM's Kriel power station. The outside of the pipe was marked for measurement at three sections along its length. At each section, the pipe circumference is divided into 16 measurement points spaced at 22.5 degrees.

Before being installed, the wall thickness was measured around the circumference to a precision of 0.1 mm using an ultrasonic thickness gauge. The pipe wall thickness was measured again at the marked up points after a period of about 2 weeks and again after a further 2 months. During this time the test pipe experienced the normal ash flow from the boiler.

The ash tonnage discharged down the pipeline was estimated at 18 240 tonnes from the total power output of the boiler / generator unit, which was logged for the duration of the test, and the known calorific value and ash content of the coal. This calculation is shown in Equation 4.

$$\text{Bottom ash [tonnes]} = 0.51 \times 0.307 \times 0.18\ E \ , \qquad \textbf{(4)}$$

where E = Electrical energy output of boiler / generator unit [MW hrs],
0.51 = Coal [tonnes] burnt per MW hr,
0.307 = Coal mass fraction converted to ash,

0.18 = Fraction of ash reporting to the boiler bottom.

As there is no flow measurement instrumentation in the system, the mean flow velocity in the pipe was estimated for the intersection of the pump and system curve. This gives a flow rate of 189 ℓ/s and a mean flow velocity of 2.2 m/s.

The measured wear averaged over the three measurement sections is shown in Figure 11. A useful result of this work is the relationship between the average wear rate (averaged around the pipe circumference) and the maximum wear rate (occurring at the pipe invert). The ratio of maximum to average wear rate is 2.1 in this case. It is important to consider this ratio when working from wear rate data derived from the mass loss of a pipe spool piece (giving an average wear rate around the pipe circumference) as it is the local maximum wear rate will be of interest for design purposes.

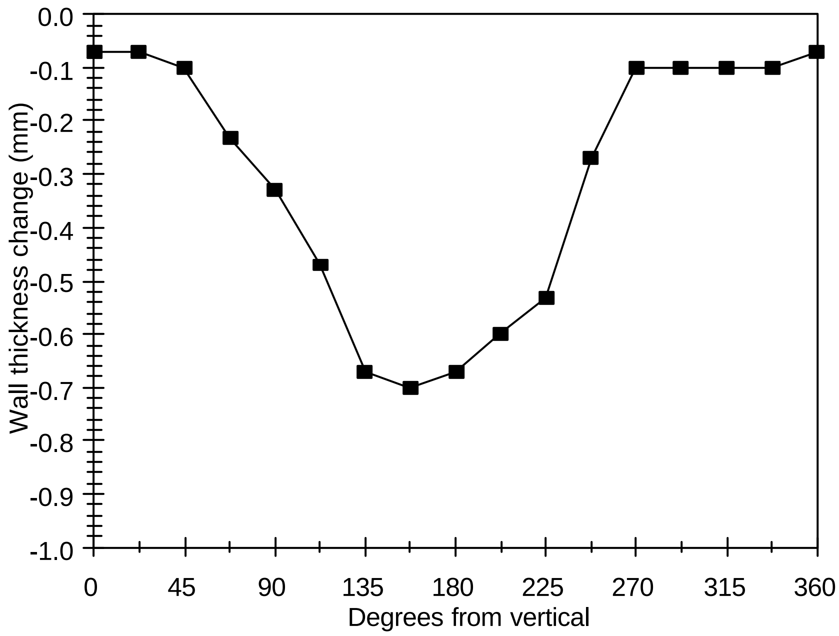

Figure 11: Full size PVC pipe wear distribution

The wear rate results are summarised in Table V. For comparison, the expected wear rate calculated using the values of k_a and n determined in the work presented earlier. The calculated wear rate shows good agreement with the full scale measurements. This is very encouraging, considering that this has involved scaling from test pipes of less than 100 mm diameter to a full scale pipe of 332 mm diameter.

Table V
Results of full scale PVC pipe wear tests

Average wall thickness lost	0.33 mm
Specific wear rate	
Ash transported	18 240 tonne
Specific wear rate	18.3 µm / 1 000 tonne
Absolute wear rate	
Total days operation	60 days
Absolute wear rate	2.0 mm / yr
Load factor (4 hrs / day)	17%
Wear rate (considering load factor)	11.8 mm / yr
Calculated absolute wear rate (based on experimental work)	
k_a (assumed independent of pipe diameter)	2.36
n	2.0
Absolute wear rate (at 2.2 m/s)	11.4 mm / yr

8. WEAR RATES FOR MIXED BOTTOM ASH / FLY ASH SLURRY

An objective of these tests was to determine whether the addition of fly ash to a bottom ash slurry will have the effect of reducing pipeline wear rates, and if so, quantify the amount of wear rate reduction achieved.

Four different slurries were tested. These slurries were produced by mixing bottom ash and fly ash as follows (in terms of percentage fly ash): 0%, 20%, 40% and 60% fly ash. A bottom ash slurry of relative density 1.16 (C_v = 11.6%) was selected as the base case (0% fly ash mix). The other mixes were made up such that the amount of bottom ash in the slurry remained the same, but with fly ash added to make up 20%, 40% or 60% of the total solids in the slurry. In other words, the same amount of bottom ash passes through the wear spool pieces in each test, but in a fly ash slurry of increasing density. The slurry parameters for each mixture are summarised in Table VI.

Table VI
Mixed bottom ash / fly ash wear test parameters

% Fly ash	Fly ash : bottom ash	Bottom ash volume conc.	Fly ash volume conc.	Slurry rel. density
0%	0	11.6%	0%	1.16
20%	0.25 : 1	11.6%	2.9%	1.20
40%	0.67 : 1	11.6%	7.2%	1.26
60%	1.50 : 1	11.6%	16.7%	1.39

Wear spool pieces of three different diameters and of two pipe materials (mild steel and PVC) were used in series in the pipe loop. This allows for the measurement of wear rates at three different velocities and for both pipe materials simultaneously. All test pieces experience the same slurry and total throughput during a test.

A test flow rate of 15 ℓ/s was chosen. The details of the wear test spool pieces and resulting velocities are presented in Table VII.

Table VII
Wear test parameters - pipe size and velocity

Slurry flow rate = 15.0 ℓ/s			
Steel pipe internal diameter (mm)	91.2	77.9	62.7
Flow velocity (m/s)	2.30	3.15	4.86
PVC pipe internal diameter (mm)	93.6	76.6	63.8
Flow velocity (m/s)	2.18	3.26	4.69

The measured wear rate data is plotted against slurry fly ash content in Figures 12 and 13, for the mild steel and PVC pipe respectively. There is clearly a reduction in wear rate as a result of the addition of fly ash. There is a degree of scatter in the data and it is thus not possible to state a clear relationship between fly ash content and the degree of wear rate reduction achieved.

The mechanism by which the wear rate reduction occurs is thought to be as follows: The addition of fly ash to the bottom ash slurry has the effect of creating a more dense and more viscous medium in which the course bottom ash particles are carried. The increased density and viscosity of the carrier medium has two effects on the conditions inside the pipeline:

(i) The larger particles in the slurry, which travel predominantly along the bottom of the pipe, are more effectively suspended in the more dense carrier medium. This reduces contact between these particles and the bottom of the pipe.

(ii) The increased viscosity of the carrier medium results in a reduction in the degree of turbulence at a given slurry velocity. This, in turn, reduces contacts between large particles and the pipe wall.

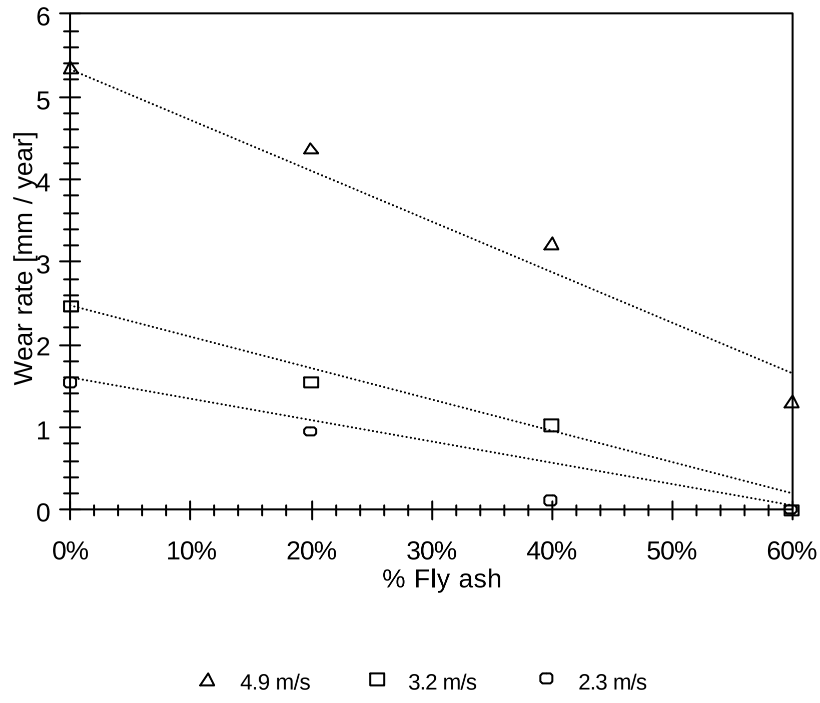

Figure 12: Wear rate as a function of slurry fly ash content - mild steel pipe

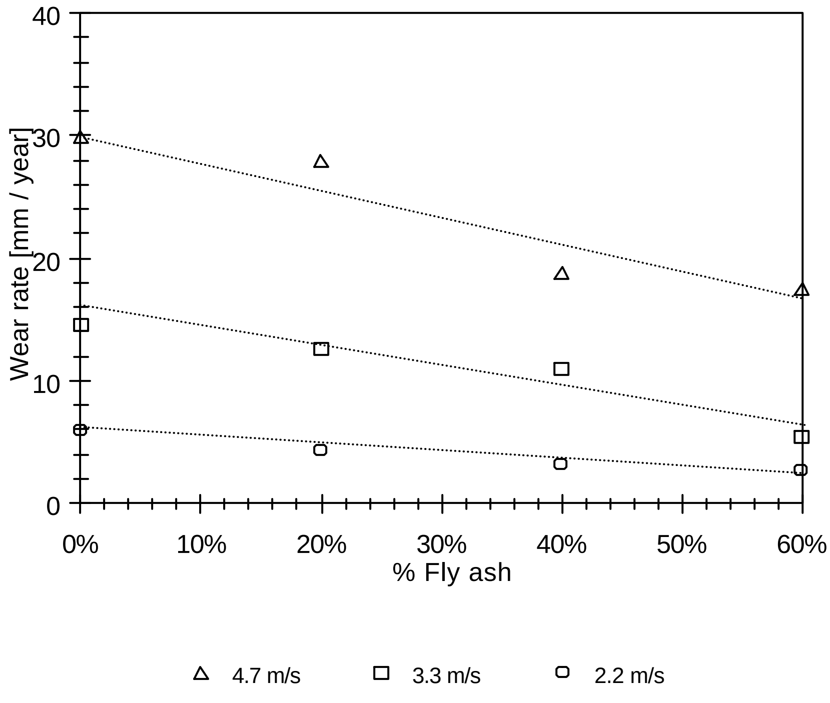

Figure 13: Wear rate as a function of slurry fly ash content - PVC pipe

9. CONCLUSIONS

The results of an investigation undertaken to gain a greater understanding of the wear occurring in boiler bottom ash slurry pipelines have been presented.

The test procedures used in this work have been refined by Paterson and Cooke Consulting Engineers (Pty) Ltd over a number of years. These procedures take into account the effects of slurry degradation in a recirculating pipe loop system and allow for the evaluation of the wear constant and exponent in the wear rate - flow velocity relationship for fresh slurry. The wear rates of mild steel and PVC pipe conveying the bottom ash slurry were measured and the wear rate - flow velocity relationship for these materials presented.

Full scale wear rate data was collected for a PVC test pipe installed in an operating ash slurry pipeline. The distribution of wear around the pipe circumference was recorded. The ratio between the local maximum and average wear rate was 2.1 : 1. The expected wear rate in the full scale PVC test pipe, calculated using the results from the pipe loop tests, is compared with the measured full scale wear rate. These are within 5% of each other.

The performance of a number of pipe materials under both pipe flow and bend / fitting flow conditions have been investigated. The results are reported in terms of wear rates relative to mild steel.

The potential for wear rate reduction through the addition of fly ash to the boiler bottom ash slurry was investigated. It is shown that a significant wear rate reduction is achieved in this way.

This work by no means answers all questions regarding wear occurring in boiler bottom ash slurry pipelines but, it is felt, presents reliable procedures by which further research can follow. It is hoped that the results presented here will provide a solid base for further research.

10. ACKNOWLEDGEMENTS

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